Field-measurement based recharge assessment in Wadi Natuf, shared Palestinian-Israeli Western Aquifer Basin

Thesis submitted in partial fulfilment of the requirements of the degree
Doctor rer. nat. at the Faculty of Environment and Natural Resources,
Albert-Ludwigs-Universität, Freiburg im Breisgau, Germany

by

Clemens Messerschmid

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This thesis is dedicated to my partner Kerstin Cademartori,
to my parents Barbara and Ulrich

و لكل اطفال الصخور
and to all the children of the rocks

Original motivation

This research spans a period of twenty years. It combines field work, such as measurements and mapping; practical project work, such as well drilling; and testing and desktop work, such as studies and analyses under many different projects and cooperative arrangements. The results of this work are presented here insofar as they are relevant for and contribute to the main research question.

The research on recharge estimation and the selection of Wadi Natuf as a study area goes back to the SUSMAQ project in the year 2002. SUSMAQ, *The Sustainable Management of the West Bank and Gaza Aquifers*, was a joint Palestinian-British project between the Palestinian Water Authority (PWA) and the University of Newcastle upon Tyne, in collaboration with the British Geological Survey (BGS) and other institutions. The project was funded mainly by the UK Department for International Development (DFID); my position on the project was also supported by the German Centre for International Migration and Development (CIM).

SUSMAQ aimed at deepening knowledge and understanding of the Western Aquifer Basin, the largest, freshest and most productive basin in Historical Palestine and the heart of the Palestinian-Israeli water conflict and eventual future water negotiations. One of its main activities was the development of a groundwater flow model – the first fully three-dimensional flow model of the basin under transient conditions. For the first time, this model integrated and the already previously modelled coastal plain areas with the more demanding and complicated areas in the West Bank Mountains. 'Putting the WAB on the map' became an important goal because of the clear lack of observations in this most central basin for Palestinian water resources development. Apart from a handful of so-called replacement wells, from 1967 onward Israel prevented Palestinians from drilling even one single additional new well in the WAB. In particular, the entire recharge zone in the slopes and mountains had remained almost untouched and ungauged.

For these reasons, and because an earlier study by SUSMAQ (McKenzie, 2001) had proven somewhat speculative and inconclusive, SUSMAQ decided to start a study and field measurement campaign to investigate recharge conditions and rates in the replenishment areas of the aquifer outcrops located in the mountains and slopes of the West Bank. From the beginning (in late 2002), I was in charge of the campaign, conceptually and in the field. After an inception phase in 2002 and the selection of Wadi Natuf as the study area, we started with mapping and field observations of physical features and hydrological processes, and with occasional measurements. The installation of field measurement instruments began in autumn 2003, with 2003/04 as the first measurement season. SUSMAQ ended in late 2004, but it was decided to continue measurements for a few months beyond the project duration, i.e. for another winter in 2004/05. However, due to several unfavourable circumstances and many delays (during the Intifada!) the project was not able to satisfactorily finish the recharge component by the end of the project.

It was at this point that I decided to continue and expand the measurements on my own in the following years for the purpose of a doctoral research. Some changes in instrumentation were necessary, besides repair, replacement and new purchase at my own expense. Some components remained unchanged (e.g. runoff gauges, spring readings and automatic weather stations), while others were expanded (e.g. precipitation gauges and soil moisture measurements). All measurements from 2005 onwards were taken by me alone, if not stated otherwise (e.g. daily spring readings by local staff, see Appendix 6.2). Already before the end of the SUSMAQ project in 2004, I had been the main person responsible for conceptualization, planning, selection of instruments and locations, and development of the research strategy. Likewise in the implementation, I was in charge of the practical field work, including the purchase, setting-up, installation, maintenance, operation, repair and replacement of the measurement equipment. Field recordings were carried out until season 2009/10 and with partial continuation until 2011/12 (under increasing instrument failure and break-down). The last field measurements were taken in summer 2013, over ten years after the first measurements.

In March 2012, I registered as PhD-student at University of Freiburg/Br., with Jens Lange as 1st supervisor and Martin Sauter from the University of Göttingen as 2nd supervisor. The Rosa-Luxemburg Foundation also granted me a two-year PhD scholarship, starting in October 2012.

This work builds on the valuable contributions, encouragement, help and advice of many friends and colleagues and of course the active collaboration of my colleagues from the SUSMAQ team during the first years, but all errors and mistakes are mine alone.

Summary

The main objective of this doctoral research is the determination of groundwater recharge and its spatial distribution in a mountainous karst catchment area of the eastern Mediterranean. The basin was previously almost ungauged and it is characterised by very limited data availability and strong obstacles to any observation of the underground processes (except spring discharge). Therefore the study used the more readily accessible surface features, such as geology in the outcrop, soils and land use and land cover observations.

The study area, Wadi Natuf, shows a high spatial variability of these land forms. All lithostratigraphic formations of the regional Western Aquifer Basin (WAB) crop out and most of the land use and land cover (LU/LC) types of the WAB can be found here (with the exception of the arid zone types of the Negev). A dense measurement network for precipitation and other meteorological drivers and for hydrological processes such as surface runoff, spring discharge and soil moisture was established and operated for almost a decade, in order to obtain a data set of empirical field measurements that is unique in this region. The physical characteristics and their classification were comprehensively and intensively recorded and related to each other.

The starting point was a detailed description of the WAB's litho-facies and its spatial distribution. Special attention was paid to the refinement of the conventional regional litho-stratigraphy and especially the hydro-stratigraphy of the catchment area and overall aquifer basin. Previously unknown aquifer properties of the so-called "aquicludes" were detected, measured and described. The location and separation of the different catchment areas within the WAB was studied; this was a fundamental prerequisite for the spatial differentiation of groundwater recharge.

In the Wadi Natuf catchment area, a close correlation between geology and soil thickness, as well as land cover and land use was observed. These patterns were spatially recorded (mapped) and categorized as classes of different recharge potential, they were integrated into a specific basin classification framework of Wadi Natuf. In addition and for the first time in the West Bank, the occurrence of shallow, perched aquifers was recognized and documented. These perched groundwater reservoirs are bound to certain surface landforms in central Wadi Natuf, erosionally isolated hilltop aquifers. Hereby it was noted that these isolated perched aquifers lack any lateral subsurface flow connections. Instead, all recharging groundwater either emerges in the respective measurable spring groups of the hilltops or seeps further downward into the underlying regional aquifers as downward leakage.

For study of *indirect groundwater recharge*, the surface runoff behaviour was examined in more detail and five stations were equipped with pressure transducers for runoff measurements in high temporal resolution. The five stations form three so-called "reaches", two of them midstream and one downstream. One of the studies then examined changes over time in total annual and main

event runoff. These changes were found to be the result of rapid land use changes in Wadi Natuf, which were documented and analysed in high spatial resolution under additional consideration of changes in the other two landform groups – soil and geology. Most wadis showed increases in runoff and decreases in transmission losses as a consequence of land use changes upstream and inside the wadis, but to very different degrees. Some Wadis remained almost stable (Shibteen-North and Wadi Zarqa), while others showed strong and very strong increases in event and annual runoff (Ne'alin and Shibteen-South).

For the first time, transmission losses through the wadi gravels into underlying aquifer bedrock could be measured in the field and quantified in high temporal resolution and, above all, in their spatial distribution. Hereby, a clear dependence on the respective rock facies and water absorption capacity of the respective formations could not only be postulated, but spatially determined and quantified. The runoff generation in Wadi Natuf was found to be exceptionally low, not only as a result of the transmission losses, but also due to the pronounced development of epikarst. Annual runoff leaving the catchment area amounts to merely 0.11 % of annual area, much less than hitherto assumed and reported.

Therefore, the focus in the determination of groundwater recharge was laid on the determination and description of *direct recharge processes*, and the modelling and calculation of deep percolation from the soil cover into the aquifer bedrock. Attention was paid to the use of quantitative process descriptions and models, which are as simple as possible and easy to use and which are considered particularly suitable for unmeasured basins; these parsimonious but empirically based methods mark a departure from the current trend towards increasingly refined calculation models with increasingly sophisticated mathematical codes and model parameter diversifications, which however rely less and less on robust, observable and empirically verifiable field data as input. In this dissertation, all model parameters are based on real-time measurements in the field. The parsimonious model used only one parameter, soil water absorption capacity, which was found spatially variable at the eight soil moisture measuring stations in the work. The only drivers were precipitation and real evapotranspiration in daily time steps. The model then considered and calculated percolation as a function of soil moisture saturation excess.

As already described in neighbouring semi-arid areas of the West Bank, recharge was determined to be primarily a process of brief, separated pulses of intensive precipitation events during the winter months. In the rest of the year, no recharge occurred – in spring and autumn because the soils were insufficiently saturated and in summer because there was no precipitation and the soils dried up completely. This semi-arid, typically Mediterranean seasonality facilitates the model description, as well as the verification of model results, e.g. by comparing modelled and observed soil moisture, which oscillates between minimum values at the end of summer and maximum at the height of the rainy season.

The eight individual models at the respective soil moisture measurement stations resulted, for the first time in the region if not far beyond, in spatially distributed annual recharge coefficients, which can be considered as representative for respective formations on the catchment area scale: These formation-specific recharge coefficients were based on empirically observed and measured processes and derived by simple, globally applicable methods. The research approach was based on the novel combination of parsimonious modelling with a description and classification of the three

groups of physical basin characteristics (basin form) under high spatial resolution that can be observed on the surface and used as a proxy for the hydrogeological processes (basin impact) above and below surface.

Based on these model results and with the help of a basin classification framework, which was empirically recorded on site, the specific recharge coefficients could be applied to the non-modelled formations and thus extrapolated to the scale of the entire catchment area (103 km^2). This categorization and extrapolation was carried out separately for each of the groups of physical features. The three independent calculations resulted in similar sums of annual groundwater recharge in Wadi Natuf in a range between 24 and 28 million cubic meters per year as multi-annual averages; on the catchment scale, this rate is equivalent to values between 235 and 274 mm/year or a portion of 39.4–46.1% of the annual area precipitation. It should be noted that these values match well with the conventional recharge estimates by other studies, which however were performed on the overall basin scale of the WAB.

Finally, the formation-specific recharge coefficients were applied to the local, perched groundwater deposits on isolated hilltops in the central study area; local water balances for each of these perched aquifer formations then compared this recharge with the formation-specific outflows of the respective catchment areas, which in total issued discharges in over one hundred small and very small field-recorded springs. This simple water budget calculation resulted in average annual rates of *downward leakage* from the floating groundwater deposits into the regionally widespread aquifers below; it should be noted here that from the point of view of the receiving regional aquifers underneath, such leakage can also be considered as recharge. The annual leakage rates thus obtained ranged between 64 and 89% of the annual groundwater recharge of the respective perched aquifers (or 169 to 287 mm/year). These simple methods of leakage determination by empirically recorded groundwater flow budgets can only be used in areas where any other – lateral – groundwater losses can be excluded, i.e. in areas with controlled boundary conditions and a well-defined groundwater catchment area. This requirement somewhat limits the applicability of the method used. Nevertheless, such quantifications of downward leakage, based on empirical observations and measurements, are globally so rare that the a.m. results deserve special attention and reporting.

Zusammenfassung

Ziel der Dissertation ist die räumliche Erfassung der Grundwasserneubildung und ihrer Verteilung in einem bergigen Karst-Einzugsgebiet im östlichen Mittelmeerraum mit stark eingeschränkter Datenlage und Messbarkeit, unter Zuhilfenahme gut zugänglicher oberflächlicher Beckencharakteristika (*physical features*) wie Geologie, Boden und Landnutzung und -bedeckung.

Das Untersuchungsgebiet, Wadi Natuf, weist eine hohe räumliche Variabilität dieser Landformen auf. Alle leitenden Serien des regionalen Westlichen Aquiferbeckens (WAB) sind darin aufgeschlossen und die meisten, außer den ariden Landbedeckungsformen des WAB, sind darin zu finden. Ein dichtes Messnetz für Niederschlag und andere meteorologische Treiber und für hydrologische Prozesse wie Oberflächenabfluss, Quellschüttung und Bodenfeuchte wurde errichtet und über eine Dekade betrieben, um einen in dieser Region einmaligen Datensatz aus direkten empirischen Geländemessungen zu erhalten. Die physischen Charakteristika und ihre Einteilung wurden ausgiebig und intensiv erfasst und in Beziehung zueinander gesetzt.

Begonnen wurde mit einer detaillierten Faziesbeschreibung und ihrer räumlichen Verteilung und mit besonderem Augenmerk auf die Verfeinerung der gängigen regionalen Litho- und insbesondere Hydro-Stratigraphie im Einzugsgebiet wie Gesamtaquiferbecken. Bisher unbekannte Leitereigenschaften von Stauern, sog. „*aquicludes*“ wurden erfasst. Die genaue Einteilung der Einzugsgebiete wurde untersucht, grundlegend für die räumliche Erfassung und Unterscheidung bei der Grundwasserneubildung.

Im Einzugsgebiet Wadi Natuf wurde eine enge Korrelation zwischen Geologie und Bodenmächtigkeit, sowie Landbedeckung und -nutzung beobachtet, räumlich erfasst (kartiert) und in Klassen unterschiedlichen Neubildungspotentials als *basin classification framework* kategorisiert. Zudem wurde - erstmals in der West Bank - das Auftreten von flachgründigen, schwebenden Grundwasservorkommen erkannt und als an bestimmte Oberflächenformen – erosiv isolierte Hügelkuppenaquifere – gebunden dargestellt. Hierbei wurde festgestellt, dass keinerlei laterale unterirdische Grundwasserabflüsse zu verzeichnen sind, sondern alles neugebildete Grundwasser entweder in an diese Hügelkuppen gebundenen Quellgruppen oberflächlich messbar austritt oder aber als *downward leakage* in die darunter liegenden, regional verbreiteten Aquifere hinab sickert.

Für die indirekte Grundwasserneubildung wurde das Oberflächenabflussverhalten genauer untersucht und 5 Stationen und drei sog. *reaches* mittels Druckzellensensoren gemessen. Eine Studie untersuchte die Veränderung jährlicher Gesamtabflüsse als Folge von Landnutzungsänderungen in hoher räumlicher Auflösung und unter Einbeziehung der anderen beiden Gruppen von Oberflächenformen, Boden und Geologie. In den meisten Wadis nahm der jährliche und Event-Abfluss zu, aufgrund geänderter Landnutzung im Einzugsgebiet sowie auch im Wadi selbst – allerdings in höchst unterschiedlichem Maße: Relative stabile zeigte sich das Abflussverhalten in

Wadi Zarqa und Shibteen-North, wohingegen Ne'alin und v.a. Shibteen-South starke und sehr starke Zuwächse verzeichnete.

Erstmalig konnten Abflussverluste in den Untergrund, sog. *transmission losses*, also Einsickerungen durch die Talkiese ins unterliegende Aquiferfestgestein im Gelände gemessen, zeitlich hoch aufgelöst quantifiziert und v.a. in ihrer räumlichen Aufteilung erfasst werden, wobei sich eine deutliche Abhängigkeit zur jeweiligen Festgesteinsfazies und Wasseraufnahmekapazität nicht nur postulieren, sondern räumlich bestimmt quantifizieren ließ. Nicht nur als Folge der transmission losses, sondern auch aufgrund der ausgeprägten Epikarst-Bildung ist die Abflussbildung in Wadi Natuf außergewöhnlich niedrig, viel geringer als üblicherweise angenommen und dargestellt – nur 0,11% des jährlichen Gebietsniederschlags verlassen das Einzugsgebiet als Oberflächenabfluss.

Der Schwerpunkt der Bestimmung der Grundwasserneubildung lag daher auf der Erfassung, Prozessbeschreibung, Modellierung und Berechnung der direkten Grundwasserneubildung als tiefe Perkolation aus den Bodenauflagerungen ins Festgestein der Aquifere. Hierbei wurde auf den Einsatz möglichst einfach anwendbarer quantitativer Prozessbeschreibungen und Modelle – sog. *parsimonious methods* – geachtet, die besonders für ungemessene Becken als besonders geeignet betrachtet werden und sich klar absetzen vom gegenwärtigen Trend zu immer stärker verfeinerten Rechenmodellen mit immer anspruchsvolleren mathematischen Codes und Auffächerung der Modellparameter, aber mit immer weniger empirischer Feldbeobachtung als Input. In dieser Dissertation beruhen alle Modellparameter auf Echtzeitmessungen im Gelände. Das einfache Modell arbeitet lediglich mit Bodenwasser-Aufnahmekapazität als räumlich veränderliche Parameter der acht betriebenen und modellierten Bodenfeuchtemessstationen im Arbeitsgebiet. Als zeitlich variable Treiber agieren lediglich Niederschlag und reelle Evapotranspiration in Tagesschritten für das Modell, welches Perkolation als Funktion des Sättigungsüberschusses im Boden betrachtet und berechnet.

Wie schon in benachbarten semi-ariden Gebieten der West Bank beschrieben, wurde auch hier die Neubildung als Folge kurzer, zeitlich eng-umgrenzter Pulse während Starkregenereignissen im Winter festgestellt. Im Rest des Jahres hingegen tritt keinerlei Neubildung auf, im Frühjahr und Herbst, weil die Böden nicht ausreichend gesättigt sind, und im Sommer, weil dort keinerlei Niederschlag auftritt und die Böden vollständig austrocknen. Diese typisch mediterrane, semi-aride Saisonalität erleichtert die Modellbeschreibung und empirische Verifizierung von dessen Resultaten durch den Vergleich von modellierter und beobachteter Bodenfeuchte, die zwischen minimalen Werten am Ende des Sommers und maximaler Sättigung nach starken Winterregen oszilliert

Die acht Einzelmodellierungen an den jeweiligen Bodenfeuchtemessstationen ergaben erstmals in der Region, wenn nicht weit darüber hinaus, räumlich hoch auflösende, jährliche Neubildungskoeffizienten, welche zudem auf der Einzugsgebiets-Skala repräsentativ für die jeweilige lithostratigraphische Einheit sind (sog. *formation-specific recharge coefficients*), und zwar aufgrund empirisch beobachteter und gemessener Prozesse mit einfachen, weltweit anwendbaren Methoden. Diese Besonderheit beruht auf der Verschränkung von einfach gehaltener (*parsimonious*) Modellierung mit räumlich hochauflösender Beschreibung und Klassifizierung der drei Gruppen physischer, und an der Oberfläche zu beobachtender Becken-Charakteristika (*basin form*), die Rückschlüsse auf die darauf basierenden hydrogeologischen Prozesse (*basin impact*) erlauben.

Darauf aufbauend konnten mit Hilfe des empirisch im Gelände erfassten Klassifizierungsrahmens (*basin classification framework*) die spezifischen Neubildungskoeffizienten auf die nicht modellierten lithostratigraphischen Einheiten angewendet und damit auf die Skala des Gesamteinzugsgebiets von 103 km2 extrapoliert werden. Diese Kategorisierung und Extrapolation wurde für jede der Oberflächenformengruppen gesondert durchgeführt. Sie führte zu sehr nahe beieinander liegenden Gesamtsummen an jährlicher Grundwasserneubildung in Wadi Natuf zwischen 24 und 28 Millionen Kubikmetern im jährlichen Durchschnitt; das entspricht im Gebietsmittel Werten zwischen 235 und 274 mm pro Jahr oder 39,4–46,1 % des Jahresgebietsniederschlags. Diese Werte stimmen gut mit herkömmlichen Neubildungs-Abschätzungen anderer Untersuchungen auf der Gesamtbeckenskala des WAB überein.

Schließlich wurden die ermittelten Neubildungskoeffizienten auf die im zentralen Arbeitsgebiet liegenden lokalen, schwebenden Grundwasservorkommen angewandt und in einer lokalen Wasserbilanz für jede dieser isolierten Hügelkuppen mit dem Gesamtquellabfluss des jeweiligen Einzugsgebiets – insgesamt über hundert kleine und kleinste Quellen – verglichen. Daraus resultierte die Rate der vertikalen Durchsickerungen von den schwebenden Grundwasservorkommen in die darunterliegenden regional verbreiteten Aquifere, welche vom Standpunkt jener aufnehmenden regionalen Grundwasserleiter ebenfalls als Neubildung zu betrachten sind. Die so erhaltenen jährlichen *Leakage*-Raten lagen, je nach Aquifer, bei Größen zwischen und 64 und 89 % der jährlichen Gebietsneubildung an Grundwasser (oder 169 bis 287 mm im Jahr). Diese einfachen Methoden der empirisch erfassten Grundwasserbilanzierung zur Bestimmung von *Leakage* sind nur in Gebieten mit kontrollierten Fließgrenzen (*boundary conditions*) mit bekannter Grundwassereinzugsgebietsgröße anwendbar, in denen zudem jegliche anderen lateralen Grundwasserverluste ausgeschlossen werden können. Diese Voraussetzung engt zwar die Anwendbarkeit der hier verwendeten Methode ein; gleichwohl sind solche auf empirischen Beobachtungen und Messungen der vertikalen Sickerung weltweit so selten, dass die hier erzielten Ergebnisse durchaus Aufmerksamkeit verdienen.

Structure of this dissertation

This PhD thesis selects and presents results from over twenty years of conceptual research, practical field work and hydrogeological measurements.

The main text of the thesis consists of seven thematic chapters. Two of the chapters, Chapter 1 - Introduction and Chapter 7 - Conclusions, at the beginning and the end of the main text, stand alone as text chapters; the other five chapters refer to, summarize and are based on the publications, documented in the Appendices.

Chapter 1, *Introduction*, gives an overview of the state of the art in the investigation of hydrogeological processes such as runoff and groundwater recharge and discusses the applicability and limitations of standard methods under the special conditions of the WAB and Wadi Natuf. Based on this, it identifies current research gaps and briefly introduces the main research objectives (some additional minor objectives are spelled out under the summaries of the respective appendices).

Chapter 2 then provides a *Geological Background* for the Western Aquifer as a whole, describing the spatial distribution and facies content of aquifer formations (Appendix 2.1) and aquitards (App. 2.2), as well as the boundary conditions of and within the basin (App. 2.3). In addition, it draws on an overview book chapter (App. 2.4) and a poster, providing information on groundwater use and allocation issues (as well as some of the other objectives of the SUSMAQ project, App. 2.5).

Chapter 3 further proceeds with a *Hydrogeological Frame* of the study area, the Natuf catchment or Wadi Natuf. Physical conditions and geographic features, as well the geology are complemented here with an introduction to the hydrological and hydrogeological conditions (App. 3.1). The local hydrostratigraphy is presented together with various field observations such as runoff, spring discharge, perched aquifers (App. 3.2) and abstractions from the one existing production well. The chapter also lists some important conceptual considerations, including the correlation of land use and land cover features and soil conditions with the underlying geology, and the availability of field observations and the applicability of investigation methods and their limitations.

Chapter 4 then introduces the *Design, Setup and Instrumentation* of field measurement devices, based on the already mentioned conceptual considerations in Chapter 3, the preparatory works and the development of a conceptual recharge model (App. 4.1, 4.2). It presents the purchase and installation of instruments (App. 4.3) and gives an illustration (poster) of some of the conditions and results of the first season of the field measurement campaign in 2003/04 (App. 4.4).

Chapter 5 deals with *Runoff*, presenting a paper on spatial runoff variability (App. 5.1). This latter paper focuses on field observations and measurements of transmission losses in Wadi beds and quantifies their spatial patterns in relation with the underlying consolidated bedrock geology.

Chapter 6 then presents two consecutive papers on the spatial distribution of *Recharge*. The first paper describes an empirical, parsimonious percolation model under soil moisture saturation excess and with formation-specific recharge coefficients as result (App. 6.1). The second paper regionalises these findings to the catchment scale and adds another component – the estimation of downward groundwater leakage in the local and shallow perched aquifers (App. 6.2).

Chapter 7, finally, spells out the conclusions of these studies with respect to the different types of recharge and in previously ungauged basins, relevant also for other scarcely gauged aquifers worldwide.

The appendices should be read as follows: They are grouped into five parts, according to the structure of the main text, corresponding with five of the chapters (Ch. 2 - 6). Each of the parts contains between one and five appendices (in sum: 13 appendices), numbered according to the chapter structure. The appendices comprise of two peer-reviewed articles in scientific journals (Appendices 5.1 and 6.1) and one draft article for peer review (App. 6.2), one chapter in a scientific book (App. 2.4), two conference proceedings (App. 2.2 and 4.2) and one conference poster (App. 2.5), as well as one internal workshop poster (App. 4.4) and six published reports (App. 2.1, 2.3, 3.1, 3.2, 4.1 and 4.3) from the SUSMAQ project

List of Figures

1.1	Overall research procedure	38
2.1	Late Cretaceous – global setting	41
2.2	Tithonian-Barrêmian facies	43
2.3	Aptian facies	43
2.4	Albian facies	44
2.5	Cenomanian facies	44
2.6	Senonian facies	45
2.7	Sedimentary mega-cycles	45
2.8	Stratigraphy of Ramali, Kobar and Judea groups, Cretaceous	46
2.9	Stratigraphic scheme of the Kurnub-, Kobar- and West Bank groups	46
2.10	Location map of the 4 new boreholes	47
2.11	Fractured formation Tammun d), 425m bgl	28
2.12	Deformed, but otherwise smooth shale of Tammun c), 483m bgl	28
2.13	Zones of a structural boundary (geo-structural divide)	50
2.14	No-flow boundary – fault type	50
2.15	Flow connections to other basins	50
2.16	Aquifer productivity in the WAB (Upper & Lower Aquifer)	51
3.1	Overview location maps of Wadi Natuf (regional and within the West Bank)	54
3.2	Elevation versus precipitation heights for groups of rain gauges (2003/04-2010/11)	56
3.3	Simplified geological map of Wadi Natuf	38
3.4	Nabi Ghayth from west	61
3.5	Nabi Ghayth from south	61
3.6	Landscapes – upstream, terraced slopes	61
3.7	Landscapes – midstream, undulating hills	61
3.8	Landscapes – downstream, karstic foothill plains	61
3.9	General concept of local perched aquifers, underlain by leaky aquitards	63
3.10	Conceptual, schematic representation of perched leaky aquifers on isolated hilltops	63
3.11	Photo from Beitillu overlooking Ein Al-Kos and Ein Al-Balad springs	64
4.1	Recharge potential of the different formations in Wadi Natuf	65
4.2	Hydrostratigraphical units – A) regional flow model; B) local recharge model	68
4.3	Cross sections through Wadi Natuf (SW-NE)	68
4.4	Karren landscape with soil pockets in the lower slopes of Wadi Natuf	69
5.1	Rain gauges in lower, central and upper Wadi Natuf	71
5.2	Annual area rainfall in Wadi Natuf 2003/04 – 2011/12	73
5.3	Precipitation event, April 2006	74
5.4	Geology, subcatchments and gauging stations in the Wadi Natuf catchment	76
5.5	Rainfall-runoff relationship	77
5.6	Headwater run-off versus transmission loss (m^3/event)	78
6.1	One reservoir SM-SEP model (“tank model”)	80
6.2	Geological relief map and cross section through Wadi Natuf	81
6.3	Recharge map of Wadi Natuf (recharge coefficients of soil-based group 2)	85
6.4	Water budgets of the three leaky sub-aquifers in Wadi Natuf	86

List of Tables

2.1	Formation thickness and aquifer properties in the literature and the 4 new boreholes	48
3.1	Comparison of regional and local hydrostratigraphy (simplified lithological description)	57
4.1	Recharge potential of the different formations	66
5.1	Annual precipitation heights at nine rain gauges in Wadi Natuf	72
6.1	Annual precipitation and recharge (DP) at representative SM locations	82
6.2	Schematic conceptual basin classification framework	83
6.3	Extrapolated recharge coefficients per group of landscape features	84
7.1	Total annual average recharge in Wadi Natuf by groups of landscape features	68

Abbreviations

WAB	Western Aquifer Basin
EAB	Eastern Aquifer Basin
WBWD	West Bank Water Department
PWA	Palestinian Water Authority
SUSMAQ	The Sustainable Management of the West Bank and Gaza Aquifers (project)
BGS	British Geological Survey
UN-ESCWA	UN-Economic and Social Council for Western Asia
BGR	German Federal Institute for Geosciences and Resources
oPt	occupied Palestinian territories
ICJ	International Court of Justice
mcm	million cubic meter
mcm/a	million cubic meter per year
mm/a	millimetre per year
m^3/a	cubic meter per year
m^3/h	cubic meter per hour
min	minute
Ma	million years
TB	tipping bucket (automated precipitation gauge)
AWS	automatic weather station
SM	soil moisture
SM-station	soil-moisture measurement station
LU/LC	land use & land cover
P	precipitation
ET	evapotranspiration
DP	deep percolation (groundwater recharge)
TL	transmission loss (of surface runoff)
RC	recharge coefficient (as share of annual area precipitation)
SM-SEP	soil-moisture saturation-excess percolation

Table of Contents

		Page
1.	**INTRODUCTION**	**21**
1.1.	Background on recharge methods	21
1.2.	Approaches to spatial variability in ungauged basins	23
1.3.	Applicability of methods, existing studies in the wider study area	31
1.4.	Research gaps	36
1.5.	Research hypothesis, indicators, assumptions and objectives	36
2.	**THE WESTERN AQUIFER BASIN – GEOLOGICAL BACKGROUND**	**39**
2.1.	Compiled base data of the WAB	39
2.1.1.	Structure and summary	40
2.1.2.	Facies distribution and lithostratigraphy of the Cretaceous	42
2.2.	Aquitards in the West Banks's Mountain Aquifers	47
2.3.	Boundary conditions in the WAB	49
2.4.	Western Aquifer Basin overview	51
2.5.	Conceptual and numerical flow models of the WAB	32
3.	**WADI NATUF – HYDROGEOLOGICAL FRAME**	**53**
3.1.	Field measurement campaign	54
3.1.1.	Wadi Natuf study area – history and climate	55
3.1.2.	Local hydrostratigraphy	57
3.1.3.	Landform correlation	59
3.1.4.	Existing studies and literature on Wadi Natuf	62
3.2.	Perched springs	63
4.	**DESIGN, SETUP AND INSTRUMENTATION**	**65**
4.1.	Preparatory work for the conceptual model	65
4.2.	Development of a conceptual recharge model of Wadi Natuf	67
4.3.	Purchase and installation of field measurement equipment	69
4.4.	Wadi Natuf field measurement campaign 2003/04	70
5.	**RUNOFF**	**71**
5.1.	Transmission losses from runoff – indirect recharge	74
6.	**RECHARGE**	**79**
6.1.	Modelling formation-specific recharge	79
6.2.	Recharge regionalisation and leakage estimation	83
6.2.1.	Regionalisation of groundwater recharge	83
6.2.2.	Groundwater leakage estimation	85
7.	**CONCLUSIONS**	**87**

Page

References 89
Acknowledgments 97
List of publications and declaration of authorship 99

APPENDICES

List of Appendices 105

Appendices to Chapter 2 – Geological background 107
Appendices to Chapter 3 – Hydrogeological frame 243
Appendices to Chapter 4 – Design, setup and instrumentation 275
Appendices to Chapter 5 – Runoff 323
Appendices to Chapter 6 – Recharge 341

CHAPTER 1

INTRODUCTION

The role of groundwater as supply for a large part of world population (Ford and Williams, 2007) is expected to increase with climate change (IPCC, 2008). Much of the most productive basins in the world are karstified regional aquifers (Ford and Williams, 2007) – and often transboundary basins shared between different countries (UNESCO-IHP, 2010). And it is estimated that karst aquifers supply about one quarter of world population (Hartmann et al, 2014); however, many of these basins, especially the not yet fully utilised aquifers, remain poorly gauged or ungauged. But even in intensively utilized and investigated karst basins worldwide, the governing processes of recharge and their spatial distribution in the upstream zones all too often remain poorly understood (Hartmann et al. 2012a). The understanding of the spatial distribution of key hydrological processes such as recharge or runoff is as pressing an issue for exploration, sustainable management, protection and equitable allocation of water resources as it is complex and challenging for hydrogeological research: this is especially the case in karstified aquifers and even more so in the many ungauged basins around the world.

1.1 Background on recharge methods

The study of hydrological processes such as groundwater recharge and its spatial variability should start with a general distinction of *direct and indirect research approaches* (Lerner et al., 1990; Bredenkamp et al., 1995); not to be confused with the distinction between direct (in-situ or autogenic) recharge from precipitation over the outcrop areas and indirect (allogenic) recharge from surface flows originating in adjacent areas (Gunn, 1983). With Lerner *et al.* (1990), the process of *direct recharge* can be defined as "water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone" (see also Hughes and Mansour, 2005). This understanding of percolation and deep percolation (DP) was applied by Schmidt et al. (2014) and Sheffer (2009) in the vicinity of the study area of this doctoral research. By contrast, allogenic or *indirect recharge* stems from surface runoff and is considered as the portion that infiltrates into the alluvial gravel fill of ephemeral streams (wadis) and percolates further into the bedrock of the underlying aquifer formations. Downward *groundwater leakage* from local shallow perched aquifers usually is not considered as replenishment but rather as aquifer outflow, a reduction in groundwater storage. This

understanding is correct and appropriate, at the scale and from the view point of the leaking aquifers themselves. However, for the receiving formation, often a larger and deeper, regional aquifer, this leakage can and should be considered as contribution and therefore as yet another form of groundwater replenishment or recharge. Differentiation of these recharge process is scientifically challenging; it remains a matter of scale and requires a focus on and efforts in the investigation of the spatial distribution of recharge.

From a methodological view point, *direct approaches* try to understand and quantify as closely as possible the infiltration and percolation processes in the recharge zone by surface-near observations that allow for the parameterisation of recharge governing factors (Dörhöfer and Josopait, 1997). Such approaches focus on processes like surface runoff, which require no observations at the subsurface, or like interflow and soil moisture saturation. By contrast, *indirect approaches* usually model integrated basin behaviour, either based on observations of outflows and abstractions in the (often confined) productive regions or based on information on storage change, as far as it is measurable through monitoring wells in an aquifer. Such a conceptual water budget of in- and outflows only functions correctly when no downward leakage has to be accounted for.

Models are often used to characterize recharge processes of aquifer systems. Hartmann et al. (2013) distinguished between two types of process-based karst models, lumped and distributed. Distributed models discretise the basin into cells, which require at each element, spatial information on factors that control hydrological processes, whether at the surface (such as runoff, infiltration, soil and outcropping rock characteristics, epikarst etc.) or deep underground (such as karst properties, storage change or outflows, etc.). On the other hand, lumped models do not require spatial information but transfer input into output by a set of equations on a basin-wide scale. Still, in poorly gauged basins, lumped approaches have long been the preferred choice; yet, in most cases precisely in order to avoid over-parameterization and the problems with spatial differentiation.

This is why increasingly preferred research methods investigate the spatial differentiation and nature of hydrological processes directly. Hydrological predictions in ungauged basins (known as PUB), led by the International Association of Hydrological Sciences (IAHS), have occupied international research over an entire decade (2003-2012). Most PUB studies emphasized the need to use process-oriented models in order to represent complex spatial variability and advocated or observed a shift from lumped, integrated to distributed models and from indirect to direct approaches (Hrachowitz *et al.*, 2013; Sivakumar *et al.,* 2015). Yet, in large, deeply buried karst basins, even a well-calibrated basin response based on lumped outflows does not truly reflect upstream variability. Karst aquifers often act as uniform, interconnected regimes with low gradients in the downstream abstraction and flow zones. Excessive pumpage then often leads to fundamental alterations of their flow field (Dafny *et al.*, 2010). Thus, the non-Darcian behaviour of anisotropic preferential flow paths in developed karst often creates a disconnect between the uniform and rather easily controllable confined storage and abstraction zones on the one hand and on the other hand the highly complex, spatially distributed and localised recharge processes in the phreatic upstream areas with the outcropping aquifers. To illustrate this disconnect, Hartmann *et al.* (2012a) remind on the well-established fact that the principle spring outlets of large karst basins by no means need to be fed by the most nearby aquifer outcrops, recharge or infiltration zones.

1.2 Approaches to spatial variability in ungauged basins

To account for spatial variability in ungauged basins, the PUB decade has tried to find ways to differentiate and quantify the spatially distributed processes (Hrachowitz et al., 2013). Although most of these studies dealt with runoff and less frequently with recharge, general lessons that are applicable also to the challenges of distributed groundwater recharge could be learned. Ten of these lessons shall be presented in the following (numbered A-J).

A: Process orientation - distributed models, direct approaches and observable processes

Indirect methods of groundwater modelling based on integrated outflows and storage changes, are insufficient to live up to the complexities of the distributed in-situ processes of groundwater recharge, which in the following is simplified and understood as the combination of soil infiltration and deep percolation into the unsaturated zone – see Schmidt et al., (2014) and Sheffer et al. (2010). It is here, where the correct, realistic and reliable parameterisation of the crucial factors that govern the highly complex recharge processes, such as runoff, infiltration into the soil or unconsolidated rock cover and percolation into the deeper bedrock, often remains untested and unprepared; and the search for other methods to describe observable processes becomes crucial in order to estimate, qualify and as far as possible, quantify such distributed processes, their governing parameters and the resulting basin responses.

Pomeroy (2011) summarizes the findings of the PUB decade with three principle aims in order to improve the realism of the conceptual approaches: to demonstrate the value of observations, to reduce the reliance on calibration and to enhance the capability to predict based on process understanding.

Many authors have commented on the difficulties and challenges faced in studies of distributed recharge. They postulated a need for a better comprehension of the links between the hydrological function (the way a catchment responds to input) and the form, (i.e. the physical properties) of a catchment (Hrachowitz, et al., 2013). Especially in data scarce basins, there is a need to infer hydrological function from metrics of catchment form. Over the decade of PUB, the vision gradually developed that such a target could only be reached by an improved understanding of the underlying hydrological processes, demanding a shift of the research focus away from parameter fitting and towards process understanding and model structural diagnostics. This strategy implied a major paradigm shift in scientific hydrology, traditionally rooted in empiricism, since it emphasized the need to move away from data- and calibration-focussed methods to methods that are more strongly based on theoretical insights into physical processes and system understanding. PUB was designed to benefit the science of hydrology through providing greater coherence to the hydrological science agenda, greater coordination and harmony of scientific activities (Hrachowitz, et al., 2013; Sivapalan et al., 2003a).

B: Basin classification frameworks – catchment characterisation, form and function

As already mentioned, in order to account for spatial variability in ungauged basins, it is imperative to find ways to differentiate and quantify the spatially distributed processes (e.g. soil saturation, runoff, recharge, etc.). Possible ways to identify organizing principles and to formulate a unified theory start with a synthesis of data, process understanding and the link between catchment form and function (Hrachowitz et al., 2013). To this end, PUB advanced the formulation of a holistic hydrological theory by setting up new catchment classification and similarity frameworks. As a first step towards comprehensive classification schemes, PUB researchers explored the utility of catchment structure (Hrachowitz et al., 2013). Conceptually, they based on approaches that relate observable landscape elements to hydrological diversity – or in other words that relate physical characteristics such as spatially distributed field parameters, hydraulic properties and climatic drivers to yet ungauged hydrological response patterns (Berne *et al.,* 2005); in short, they related form to function in various ways.

To deal with uncertainty of predictions in ungauged basins, Sivapalan et al. (2003) summarized that predictive systems should contain three components – (1) a model that describes key processes, (2) climatic input with the meteorological drivers of basin response and (3) parameters of landscape properties that govern these processes. McDonnell and Woods (2004) suggested grounding the comparison of the dominant controls of water movement patterns on similarities of hydrological function. However, the step from form to function remains a translation.

C: Physical characteristics – identification and parameterization

In the absence of flow observations, many authors of the PUB decade have worked on the use of readily observable physical features (sometimes also called structural features) of landscape characteristics and their complex relation with hydrological responses (or impacts) such as the local and spatially diverse processes of runoff or recharge generation. Therefore, a widely acknowledged understanding developed that it is desirable to ensure that parameters are well constrained and that models have a complete and physically realistic representation of dominant processes (e.g. Franchini and Pacciani, 1991).

The description of physical parameters is an empirical work, based on mapping, measurements and field observations. However, the selection of the appropriate set of parameters to understand and describe a hydrological system setting remains highly location-specific and includes conceptual efforts. A great variety of selected parameter sets can be found in the different studies on distributed basin processes. Hrachowitz et al. (2013) give an overview over many of these studies and their diverse selections of parameter sets: Some studies accounted for land use, soil and lithology (Batelaan and de Smedt, 2001), or for land use, soil and topography (but not geology) but calculated with parameters based on literature values (Batelaan and de Smedt, 2007). Other studies (Aish, Batelaan and de Smedt, 2010) used land use and soil-type as physical parameters or emphasised the importance of soil texture and vegetation cover (Zomlot et al., 2015). A highly simplified approach was used by Sanz et al. (2011) over large areas in Spain, accounting only for

rainfall and temperature as drivers and for ten classes of lithology as spatially governing parameters (reaching from clastics and carbonates to pelites and hard rock). Several studies tried to avoid data intensive models with extensive parameterization: Sarrazin et al. (2018) developed a large scale parsimonious integrated recharge-vegetation model for karstic aquifers. By contrast, Radulovic et al. (2011) used a great number of distributed physical parameters from geology, karst and structural features to topography, vegetation and land use for the estimation of groundwater recharge in Montenegro. However their parameters were not measured and quantified in the field but conceptually set up and weighted as dimensionless numbers in a matrix of factors, which were then used as variables in a basin-wide transfer function between spatial characteristics and hydrological response.

Somewhat generalizing, we can summarize that usually the physical catchment features (besides climate as a temporally variable driver) are grouped into three groups of spatial parameters governing recharge: (a) geology, (b) soil type and (c) topography, vegetation and land use, which can be lumped together as land use and land cover characteristics (LU/LC).

Unlike in recharge studies, most runoff investigations paid attention to the physical catchment characteristics at the surface. Yet, the process of transmission loss remains mostly overlooked as a form of indirect recharge, which may not only be a result of technical reasons, but partly be explained by epistemological reasons. This is because, on a more conceptual level, the process of transmission loss into consolidated bedrock strata concerns the two disciplines of hydrology and hydrogeology – or rather, falls into the gap between them. *Hydrogeologists*, on the one hand, show keen interest in hard rock aquifer recharge. Studies in this field abound, but most of them are informed by the understanding that the bulk of groundwater recharge occurs as direct in-situ recharge. From a purely quantitative point of view this may often well be true (CDM, 1998; De Vries & Simmers, 2002; Goldschmidt & Jacobs, 1958; Guttman & Zukerman, 1995; Rofe & Raffety, 1965; Hughes *et al.*, 2008; McKenzie, 2001; Simmers *et al.*, 1997; Zukerman, 1999). However, indirect recharge as wadi bed infiltration during storm runoff events may play an important role as a mechanism for infiltration of groundwater recharge and as a pathway for groundwater contamination, especially in karst areas. In a karst region, most of the indirect recharge through transmission losses occurs along complex epikarst structures. As a result, indirect point recharge such as transmission losses of surface runoff is nearly always neglected in conventional *hydrogeological* studies. On the other hand, classical *hydrological* studies mainly concentrated on surface runoff in streams and quantified transmission losses into the subsurface. Several authors tried to quantify the effect of landforms and surface features such as relief, vegetation, or land use, as Shanafield and Cook (2014) reported. However, their analysis usually does not cover the complexities of the subsurface geological material, such as the lithostratigraphy and hydrostratigraphy, the aquifer parameters and recharge potential of bedrocks, the degrees of karstification and the patterns of epikarst (Ries *et al.*, 2017).

In brief, it can be summarised that most studies on recharge through transmission loss so far focussed on unconfined, often unconsolidated shallow alluvial aquifers beneath and on the banks of wadis (Abboushi, 2013; Abdulrazzak, 1995; Costa et al., 2012; Dahan et al., 2007; Lange, 1999; Lange, 2005; Shentsis et al., 2001a, 2001b; Sorman et al., 1997, Schwartz, 2016). Some studies in this field based their investigations on streambed geometry (Constantz & Thomas, 1997; Costa et al., 2012) or channel width (Walters, 1990). And within the wider region of this doctoral thesis, in the

Negev, Shentsis et al. (1999) studied runoff in arid and hyper-arid catchments and developed methods to estimate lateral tributary inflows in desert wadis under transmission loss. However, in general, much less attention has been paid to losses from streams into consolidated bedrock, and available data and reports are scarce (Shanafield and Cook, 2014). This particularly applies to ephemeral streams and even more so karstic terrains, because here, many of the modern approaches listed in Shanafield and Cook (2014) are not readily applicable.

D: Regionalisation of parameters and features

In many empirical studies, the correct linkage and translation of point- and plot-scale observations into regionalised findings at the catchment scale remained a crucial challenge (Hartmann et al., 2013). One possibility is to compare and develop relationships between the calibrated model parameters and the physical catchment characteristics of landscape found in the field, like soil, lakes and forest (Seibert, 1999). Seibert and Beven (2009) statistically ranked 10.000 parameter sets according to their performance and selected the best 100 sets for further analysis. Yet, PUB emphasised that regionalisation of observable spatial parameters remains connected to the empirical efforts of field observation and measurements, with the help of maps, aerial photography, satellite imagery and of course field visits.

E: Translation of form into function

Many authors have pointed out that parameters could be regionalised by using physiographic similarity as a proxy for functional similarity (Arheimer and Brandt 1998, Parajka et al. 2005, Dornes et al. 2008, Masih et al. 2010), thus by regionalising dynamic catchment response characteristics (such as runoff or recharge) based on physical characteristics (Yadav et al., 2007). However, as already noted, the translation of physical form into hydrological function is crucial but not straight forward since it involves two separate conceptual levels and an extraordinary complexity of interactions. Physical features (i.e. the form, whether metric or unquantifiable) can serve as indicators of basin impact (i.e. the function of the basin), but are far from being uniquely correlated to each other. While these observable, often quantifiable physical parameters clearly serve as the material basis of hydrological processes, there is by no means a simple, clear-cut relationship between one parameter and one hydrological process outcome (Beven, 2000). Therefore, Oudin et al. (2010) asked whether physical similarities in basins translate into truly hydrological response similarities. They found that the role and impact of the catchment's underground properties on its hydrological behaviour have to be accurately described and that more relevant catchment descriptors should be sought to better describe the geological and lithological context in hydrological terms.

McDonnell *et al.* (2007) added to this that for the investigation of hydrological processes in general and of recharge in particular, the catchment scale is the correct scale of investigation, i.e. the scale in which the entire complexity of distributed recharge processes and their interactions is fully at play (see also Hrachowitz et al., 2013). On their part, Sivakumar et al. (2015) offered a three-step procedure for an effective formulation and verification of a catchment classification framework: (1)

the detection of possible patterns in hydrologic data and determination of complexity and connectivity levels; (2) the classification into groups and subgroups based on data patterns, system complexity and connections; and (3) the verification of the classification framework.

Although no comprehensive overview is intended here, a selection of some notable recharge studies and their complementary findings shall be provided: In order to associate physical form with hydrological function, Savenjie (2010) suggested assigning individual hydrological processes and distinct hydrological functions (in his case, runoff) to different landscape units by dissecting catchments in a semi-distributed way and according to a hydrologically meaningful landscape classification metric. The parameters of such landscape characteristics could be quantified as physical parameters or ranked according to function as dimensionless numbers in order to relate form, hydraulic properties and climate to hydrological response patterns (Berne et al., 2005). Woods (2003) called them dimensionless similarity parameters representing different aspects of topography, soil, vegetation and climate. Similarly, Radulovic (2011) used many different types of landscape characteristics and weighed them as dimensionless numbers in his matrix of parameter classes and his basin-wide transfer function for karst recharge in Montenegro. Also Berne et al. (2005) used dimensionless numbers to relate form to function, based on the assumption that hydrological catchment characteristics (function) should be reflected in the structures that characterize the physical landscape (form).

Götzinger et al. (2006) used transfer functions of physical catchment characteristics (such as LU/LC, soil and geology) to estimate model parameters and then calibrated the parameters of the transfer function but not of the model. Ali et al. (2012) compared the interactions between catchment structural and functional properties in 36 Scottish sites and found soil properties the most useful structural and mean transit times the most useful functional properties to discriminate catchments.

Batelaan & de Smedt (2001) accounted for spatial variation of physical features in distributed recharge by a GIS-based model for an extensively gauged basin in Northern Belgium, and in which recharge was determined from a spatially distributed water budget of rain, evapotranspiration and runoff. Batelaan and de Smedt (2007) found that to a large extent, long-term average recharge depends on soil and LU/LC differences, in a spatially distributed water balance model, in Belgium and the Netherlands, calculated with parameters based on literature values. Aish, Batelaan and de Smedt (2010) applied this model to the Gaza Strip with a spatially distributed model of long-term annual average recharge (runoff and actual evapotranspiration), accounting besides the landscape parameters for meteorological conditions and the slope of groundwater levels and again, by integrating its water balance into GIS.

Sanz et al. (2011) attributed assumed specific recharge coefficient values (RC-values) to their ten differentiated lithological classes and combined them with assumed parameters for the maximum moisture storage capacity of the soil, the maximum infiltration capacity and the recession coefficients of the aquifers. Zomlot et al. (2015) noted the problem of multicollinearity. They assessed the weight and correlation of the spatial variability of controlling factors of recharge and baseflow (as a moderate proxy to recharge) in 67 watersheds in Flanders, Belgium; and they found that groundwater recharge variation was explained - in order of importance - by precipitation, soil texture and vegetation cover, whereas baseflow was only a moderate proxy of groundwater recharge.

Dripps and Bradbury (2007) suggested a simple soil-water model for daily recharge estimates in moderate climates at the basin scale, which was based on soil-water balance calculations and operated with readily available data (for well gauged basins), differentiating recharge areas and quantifying its rates. And for the English Chalk, Finch (2001) developed a distributed soil water balance model that estimated the changes in mean annual groundwater recharge as a response to changes in land cover.

F: Use of signatures and their regionalisation

The link between form and function can thus be established through transfer formulas, but, as already mentioned, always includes an element of deduction, attribution or extrapolation between different conceptual levels. Another avenue of methods is the employment of basin-specific links between physical features and basin response. Many authors therefore suggested the use of so-called hydrological system signatures to describe emergent properties of the system (Eder et al., 2003; Hartmann et al., 2013), with metrics that describe different response characteristics of a catchment, such as flow duration curves or spring hydrographs; in other words, these signatures represent observable patterns of hydrological processes (runoff or recharge) and therefore already belong to the conceptual category of hydrological basin function, not physical form. Signatures therefore can act as indicators that justify the regionalisation of plot-scale findings into basin-wide overall processes and to infer the expected behaviour of ungauged catchments (e.g. Castellarin et al., 2004; Bulygina et al., 2009 and Pallard et al., 2009). Yadav et al. (2007) extrapolated flow metrics and used them to constrain model parameterizations at ungauged sites, thereby avoiding problems of structural and parameter calibration errors in models. In order to determine the limits of validity and acceptability of specific signatures, Winsemius et al. (2009) suggested the use of combinations of quantitative and qualitative information from the local or basin scale. Sawicz et al. (2011) used available hydrologic information on generally available physical descriptors in 280 catchments in the Eastern USA to create a first order grouping of catchments based on their hydrological similarity. Importantly, they clustered similar catchments according to signatures of observable basin responses with respect to runoff behaviour. Conceptually, they came up with a simple cooking recipe for regionalisation consisting of three steps: (1) Classification (to give names), (2) regionalisation (to transfer information) and (3) generalization (to develop new theory), or in brief terms: Name it, attribute it, theorize it (Sawicz et al., 2011).

G: Goal of parsimony (and equifinality problems)

A major concern of PUB (Sivakumar et al., 2015) was the trend of hydrologic models often being far too complex, and with too many parameters that require too much data (more than what may actually be needed) and that these models lay too much emphasis on specific and often pre-selected independent concepts and mathematical techniques, rather than on their possible coupling or integration to capture the salient features of hydrologic systems. Instead, it would be desirable to employ simple models with a focus on process and using physical parameters derived directly from the basin. For the UK Chalk, Limbrick (2002) suggested ways around this challenge, and promoted simpler recharge models that avoid too many unknown parameters in order to be practically

applicable. Other authors noted the problem of up-scaling the findings of the quantification of point-scale groundwater recharge – they found it "challenging but possible given sufficient temporal and spatial resolution of field observations" (Ireson and Butler, 2013). Also in this context, Sivapalan (2003a) noted that despite the heterogeneity and complexity of local parameters and processes, the response at the catchment scale is often characterized by surprising process simplicity, and that often, a minimal number of the right field observations can describe the main characteristics of a process (Seibert and Beven, 2009). Therefore, use can be made of simple physical parameters derived directly from the basin itself: Beven & Kirkby (1979) differentiated the hydrological response of contributing areas and found a good empirical fit to the basin response even with exceedingly simple models (Nash, 1957; Dooge, 1959; Lambert, 1969). Beven & Kirkby (1979) described this as a three way compromise between the advantages of model simplicity, the complex spatial variability of basin hydrological response and the economic limitations on field parameter measurement. As Juston et al., (2009) and Seibert and Beven, (2009) noted for ungauged basins, sometimes few measurements and short time series data, contain most of the information found in long term extensive measurements. And at the local scale, even short observation periods may provide a detailed understanding of the catchment response (Blume et al. 2008a). In sum, many authors of PUB emphasized an increasing realization of the need for simplification in hydrological models and a common framework for hydrological modelling, such as Sivakumar et al. (2015), Grayson and Blöschl (2000); Woods (2002); Sivapalan et al. (2003b); McDonnell and Woods (2004); Sivakumar (2004b, 2008a); Wagener et al. (2007); Young and Ratto (2009) and Olden et al. (2012). In particular, Sivakumar et al. (2015) pointed out the usefulness of simple hydrologic models such as simple water balance equation and tank models.

In addition, it can be concluded that the steps of interpretation, conceptualisation, classification and quantification should be kept transparent and the number of parameters used and tested should be kept at a minimum. PUB-discussions repeatedly emphasised maintaining of model parsimony as a goal (Hrachowitz et al., 2013), because a reduction in the number of governing spatial parameters and driving temporal factors does not diminish but rather adds to the reliability and controllability of process outcomes in ungauged basins. This is particularly the case in karstic environments, known for their non-Darcian flow; anisotropic flow fields (Dafny, 2009) and increased problems of equifinality and multicollinearity. As noted by Hartmann et al. (2012b), the high spatial variability of karst systems poses challenges to the adequate representation of the dominating recharge processes in hydrological models, especially in data scarce basins. Hrachowitz et al. (2013) pointed out that the presence of equifinality in calibrated parameters limits the use of the methods for extrapolating individual parameters, and Bárdossy (2007) suggested that instead, complete parameter sets should be transferred to ungauged sites.

The determination and regionalisation of such physical parameters is however not without its problems and limits. When parameters are not gauged and measured on site but estimated directly and a priori from physical properties of the catchment, they may show little consistency (Kapangaziwiri et al., 2012). This hints to the so-called PUB paradox, according to which data-rich catchments are needed to test methods for data-poor environments (Seibert and Beven, 2009).

H: Grounding in observations and their constraints

Proper hydrological interpretation and conceptualisation of processes therefore have to be firmly grounded in observation - at least some observations, as Sivapalan et al. (2003a) pointed out. Also McDonnell et al. (2007) addressed the enormous heterogeneity and complexity of rainfall-runoff processes in different hydroclimatic regimes and at different scales. They emphasised that new theories must be embedded in observation, designed for specifically targeted measurements. Therefore, what Seibert and Beven (2009) called a 'hydrologically intelligent choice' can be understood as the correct interpretation of the dominant, most relevant features that govern a process. However, at the same time, under conditions of the PUB paradox and for practical reasons – such as measurement costs and field accessibility – observations and measurements should be kept simple and at the necessary minimum (Seibert and Beven, 2009).

I: Start somewhere – PUB classification as a learning process

Binley and Beven (2003) and Seibert and Beven (2009) emphasized that particularly in poorly gauged basins the choice of an intelligent design remains a learning process that has to start somewhere, even with insufficient data and then adds data as required by the application.

J: The need to extrapolate and the integration of inductive and deductive measures

While one of the strengths of the decade was the development of new methods for classification and regionalisation approaches, some difficulties remain: Sivapalan et al. (2003) stated that predictive systems must be inferred from observed data, they have to obtain process understanding from empirical experiments (whether at the catchment scale or in labs) and they should be based on fundamental physical theories. Direct field observation of dominant processes and empirically derived field parameters are often the only way to avoid problems of equifinality, if however these results can successfully be generalised and regionalised from plot scale to catchment scale (Hartmann et al., 2013). And in the absence of extensive gauging, predictions must be firmly based on local knowledge of the observable landscape (and climate) controls of hydrological processes.

On the other hand, McDonnell et al. (2007) argued that any mapping or characterization of landscape heterogeneity and process complexity must be driven by a desire to generalize and extrapolate observations from one place to another, or across multiple scales. A certain degree of extrapolation is therefore inevitable when attributing physical features and feature ensembles to processes and basin responses (or from the observed to another location). This therefore involves deductive steps. But the need for direct observation remains. PUB theory therefore postulates the imperative of a combination, or better: integration of inductive (experimental and empirical) and deductive approaches in regionalisation (Pomeroy, 2011).

Summary of the findings A- J:

The basic problem and challenge of PUB can be described as dealing with highly complex and overlapping processes that are spatially variable and often difficult to directly measure and observe. We can summarize the ten most relevant findings of the PUB decade for our purposes, i.e. distributed recharge in karstic aquifers, as follows:

A. There is a need to use process-oriented models to represent complex spatial variability; this requires distributed, not lumped models and direct not indirect approaches, as well as a focus on the description of observable processes.
B. Basin classification frameworks try to characterise or compare different basins, based on the distinction between form and function.
C. The first step is the identification of physical landscape characteristics and their parameterization.
D. The next task and challenge lies in the regionalisation of such basin form, their features and parameters
E. and most crucially in the translation of form into function.
F. Alternatively, or in addition, PUB can employ the use of signatures to describe basin impacts and their regionalisation.
G. Hereby, PUB states the goal of parsimony and the avoidance of equifinality.
H. All this has to be grounded and firmly based on knowledge of and from the field; but the need for observation and measurements is juxtaposed against the practical constraints (such as costs and access), which forms the basis of the PUB paradox.
I. However PUB has to start somewhere and should be treated as a learning process.
J. Finally, there remains a need to extrapolate and PUB should strive to integrate inductive and deductive steps in basin classification, process quantification and regionalisation.

1.3 Applicability of methods, existing studies in the wider study area

The study area of this doctoral thesis, Wadi Natuf, is a 103 km^2 large mountainous and mostly carbonatic surface catchment with variable degrees of karstification – see chapter 3. It lies in the recharge area of the Western Aquifer Basin (WAB) – see chapter 2. The WAB is the by far largest, freshest and most productive transboundary aquifer in Historical Palestine or Israel and the occupied Palestinian territories (West Bank & Gaza Strip). In the literature (UN-ESCWA-BGR, 2013), its size ranges between 9,000 and 14,167 km^2, depending on the type and position of the basin boundaries, as discussed in chapter 2.3. While in the Coastal Plain, the basin is well developed, monitored and gauged through hundreds of Israeli deep wells, its recharge and accumulation areas in the mountains, slopes and foothills of the West Bank remain almost untouched, ungauged and unexplored, not least due to Israel's long-standing military occupation that imposes extreme restrictions on Palestinian water sector and infrastructure development (World Bank, 2009) – see chapter 2.4.

Direct, autogenic recharge

Recharge in the Western aquifer has been the subject of many studies, dating back to the British Mandate and the 1950's. Yet, until now, most studies have approached recharge as basin-wide uniform process and by simply equating it with observable natural spring flow (Goldschmidt and Jacobs, 1958) or with outflows from springs and wells in the Israeli Coastal Plain, under the assumption of mass conservation or by accounting for storage change (Guttman et al., 1988; Guttman and Zukerman, 1995; Guttman, 2000; Berger, 1999; Abusaada, 2011; Dvory et al., 2016 and Abusaada and Sauter, 2017). On a regional scale such simplified water budget is permissible because the regional aquitard beneath the Lower Aquifer is impermeable (Messerschmid, 2003) and overall basin losses through downward leakage into the Lower Cretaceous (Aptian - Lower Albian) series are either absent or negligible. But on a local scale, the hydrostratigraphy is more complex and downward leakage occurs between the different local aquifer units. Therefore, while these integrated approaches work relatively well at a basin-wide scale of average basin recharge, they helped little to understand the spatial variability of distributed recharge in the outcrop areas of the West Bank Mountains.

Some of the lumped models then were partially distributed in the recharge zone, however without independently establishing and verifying the sensitive field parameters (physical form) and their impact on the complex hydrological processes governing groundwater recharge. Instead, these sensitive upstream parameters were then calibrated and adapted according to basin-wide responses in the remote discharge zone, thus opening the field of equifinality problems and neglecting the complexities of the karstic flow field, as Dafny et al. (2010) remarked.

So far, few authors have attempted to approach recharge distribution in the WAB. Sheffer et al. (2010) used a hybrid of lumped and distributed approaches. They coupled simple water budget calculations (over 3,300 soil moisture "tank" models, one at each at grid cell) in the recharge zone with a lumped flow model of overall basin response, which in their own words, aimed at 'the understanding of temporal influence on recharge processes', rather than on the spatial influence (Sheffer, 2009; Sheffer et al., 2010). However their distributed tank models lacked in local empirical observation and insights into the complex distributed recharge processes and their dominant features. Governing parameters of their soil percolation model were taken as not further verified estimates from the literature (e.g. Dingman, 1994) and then adjusted by repeated lumped model calibration runs, which exposed them to problems of equifinality. In addition, they accounted only for two groups of geological characteristics – either aquifers with more permeable layers of limestone and dolomite or less permeable aquitards of marl and chalk.

Hughes and Mansour (2005) and Hughes et al. (2008) published results of a fully distributed approach. Their so-called 'objected oriented' recharge model separated different inputs and processes, such as runoff, spring flow, soil infiltration and deep percolation into individual objects in their soil moisture sub-model. Although their model used a high spatial resolution, it did not distinguish between sub-basins but lumped all distributed input together into one integrated basin-wide model. More crucially, their model parameters like field capacity and wilting point were not grounded on local field observations but simply based on estimated parameters taken directly and a priori from the physical properties of the catchment. Some of the objects, like spring flow, employed unverified virtual data. According to Kapangaziwiri et al. (2012) and Hughes and Kapangaziwiri

(2007), such approaches can lead to serious problems of lacking consistency between physical features and modelled basin response. By contrast, this doctoral thesis applies the findings from the PUB-decade, i.e. that a thorough understanding of the dominant processes at play must be firmly based on observations and descriptions of physical features, such land use, soil, geology and structural characteristics (compare also: Abusaada, 2011 and Martínez-Santos and Andreu, 2010).

Finally, three studies from other aquifer basins adjacent to Wadi Natuf shall be presented. Two empirical field studies in a nearby catchment of the Eastern Aquifer Basin (EAB) fitted a soil-moisture saturation-excess model for percolation (SM-SEP) to the field measurements of soil moisture (once with three and another time with 4 soil moisture plots) and identified seasonal recharge pulses on an event basis (Ries et al. 2015, 2017). In line with the findings of Lange et al. (2003a; 2003b and 2010), Ries et al. (2015, 2017) showed that soil moisture saturation was the principle process of runoff and recharge generation in the specific field conditions of Wadi Natuf and the adjacent mountain areas of the EAB under sub-humid climate conditions and an abundance of epikarst. Schmidt et al. (2014) in another nearby catchment on the Eastern slopes that stretches from of the West Bank Mountains down to the Jordan Valley, successfully employed a parsimonious recharge and groundwater flow model with two components: they coupled a soil moisture saturation model for deep percolation inputs, similar to the WAB-model by Sheffer et al. (2010), with a double porosity karst aquifer component for groundwater flow to a field-monitored spring outlet. However, again, their soil parameters and time series data of soil saturation were not based on empirical measurements but taken from the general literature and refitted through model calibration against the basin wide response in form of the hydrograph of the principle drainage point (Al-'Aujah spring).

During the past two decades, other approaches of field-based and empirical investigations at the sub-catchment, local and plot-scale were realized, however mostly without further regionalisation efforts. Individual empirical field studies, based on winter observations in very localised sub-catchments, investigated local processes of soil saturation, runoff and infiltration on a scale <1km^2 (Steinmann, 2010 and Grodek et al., 2011). However, they focussed on runoff rather than on recharge and their findings were found difficult to extrapolate from the plot and local scale to larger areas in the WAB, where different geology and surface characteristics prevail (Steinman, 2010). Lange et al. (2003a; 2003b) used tracers in local sprinkler tests to investigate rainfall-runoff relationships and – important for the process understanding – pointed out the importance of soil saturation excess for surface runoff and recharge (Lange et al., 2003a; 2003b). No regional tracer tests to investigate recharge were carried out in the WAB so far. The reasons are not entirely clear but may stand in connection with the difficulties to find appropriate intake points, especially in light of the severe cap on well drilling in the upstream West Bank recharge zone.

In other studies, simple chloride mass balance calculations were carried out in the adjacent Eastern Aquifer Basin (EAB) (Marei et al., 2010; Schmidt et al. 2013), as well as in the central WAB (Jebreen et al., 2018); but these approaches contributed little to the spatial differentiation of distributed recharge and its processes. In Wadi Natuf, Shalash (2006) and Shalash and Ghanem (2008) described spring chemism and discussed the spring water types and genesis but did not focus on recharge.

Several authors conducted cave-drip experiments in the region providing some valuable insights into percolation processes through soil and the unsaturated epikarst and delay times between event rainfall and drop formation at the roof of caves (Sheffer, 2009; Frumkin et al., 1994; Arbel et al.,

2010 and Lange et al., 2010). Nevertheless, regionalisation is severely limited as contributing areas are unknown and because caves may develop their own hydraulic environments (Ford and Williams, 2007) and thus may not be representative for larger areas (Ries et al., 2015; Lange et al., 2010.

Indirect, allogenic recharge

The region of this study – the Eastern Mediterranean – is entirely void of studies that quantify transmission losses into consolidated, karstified bedrock. The absence of such studies in the wider study area is remarkable; because Ford and Williams (2007) emphasize that in the West Bank Mountains most runoff in streams recharges the bedrocks via ponors in the thalwegs. Shanafield and Cook (2014) provided an overview of numerous methods for direct field measurements and calculations of transmission losses. Yet, most of their methods apply to sandy channels, only very few to transmissional losses into consolidated substrata. Those remaining methods can be divided into approaches of either groundwater observation or streamflow measurements. The first group is inapplicable in this doctoral thesis, because no groundwater observation wells exist and the underlying deep aquifer is complex, karstified and overlain by a more than a hundred-metre-thick unsaturated zone. Streamflow observations, on the other hand, were applicable and carried out intensively for this research – see chapter 5.

Groundwater leakage (subsurface replenishment to the regional aquifers)

The literature on leakage is much sparser than that on recharge, although leakage from one hydrostratigraphic unit to another – whether downward, upward or laterally – is relatively common (Todd, 1980). In Israel, several authors have investigated flow connections between aquifers or units, but mostly in form of lateral basin exchange. For practical reasons of exploitability, some research was also invested in the study of upward leakage from the deep Mountain aquifers, or even the Jurassic in the Northern Negev (Weinberger et al., 1994, Weinberger and Rosenthal, 1994). Despite the importance and ubiquity of groundwater exchange between hydrostratigraphic units and entire aquifer basins (Messerschmid, 2010), the literature on leakage and other exchange flows in the region remains sparse.

While upward leakage into a leaky confining layer is readily observable through wells and has been widely conceptualized and quantified, downward leakage through bottom aquitards or within a multi-layered system of aquifers and aquitards, except for rare exceptional cases, cannot be observed directly and therefore is much more difficult to quantify and determine (Hantush, 1960, 1967; Todd, 1980). Downward groundwater leakage therefore is a hydrogeological process that poses particular challenges in areas, where almost all subsurface observations are either inapplicable or otherwise impeded. In the absence of direct underground measurements through wells and monitoring boreholes, the researcher is only left with option to approach this matter by balancing outflows and inflows from and to groundwater reservoir. This in turn requires an exceptionally close control of the groundwater recharge area, its boundaries and lateral flow connections.

Some desktop studies have worked on flow diversion by faults, acting as semi-barriers that allow only reduced lateral leakage (Dafny et al., 2010, Dafny et al., 2013). In the Eastern aquifer, Ben-

Itzhak & Gvirtzman (2005) modelled the leakage between upper and lower sub-aquifers. Only Frumkin and Gvirtzman (2006) presented empirical field-work based results on leakage, albeit here only as cross-formational rising of groundwater in a geothermal artesian karstic saline anomaly of the WAB.

Besides the piezometric regime, groundwater leakage is largely a function of the hydrogeological characteristics of the leaky aquitards. However, by comparison to aquifers, relatively little work has been undertaken in the investigation and description of aquitards, especially in the regions of the so-called Mountain Aquifers in the West Bank and the WAB. Yet a general understanding of the nature of these leaky aquitards, their lithological content, structural features and flow behaviour, forms the basis of any approach to characterize leakage realistically and reliably. An exception to the general lack of studies forms the description of the physical and flow characteristics of aquitards, found in deep drillings in the West Bank by Messerschmid (2003) – see chapter 2.2.

As a consequence and since downward leakage through the bottom layer of an aquifer cannot easily be quantified, only very few authors studied perched aquifer systems per se. In the wider region of this doctoral research, two studies stand out performing water budget calculations under controlled conditions of perched aquifers on isolated hillsides of less than 3km^2 in area with a well-controlled recharge area and relatively controlled spring outflows (Peleg and Gvirtzman, 2010 and Weiss and Gvirtzman, 2007). The studies followed an indirect approach and calculated recharge through rainfall-spring discharge relationships as indicator for (strictly localised) groundwater recharge. They reconstructed spring outflow and recession curves and evaluated the hydrological characteristics of the different litho-types and formations mathematically through flow models.

In Weiss and Gvirtzman (2007), the model configuration was set-up without a bottom aquitard beneath the perched groundwater body and instead, the next phreatic aquifer layer below the perched aquifer was “treated as if is saturated”. Peleg and Gvirtzman (2010) accounted for quantified downward leakage into the deeper layers. Their model simulated spring discharge from these units by numerical models and assumed a spring leakage coefficient without further empirical grounding, adjusted only through repeated calibration. Both studies depended on an incomplete historic set of monthly spring flow measurements, which did not reflect the event character of recharge, particularly at the local scale and under conditions of rapid recharge processes (Schmidt, 2014; Ries, 2016).

Also outside the WAB, leakage remains poorly understood. In the Eastern aquifer, Ben-Itzhak & Gvirtzman (2005) integrated leakage between Upper and Lower Aquifer into their flow model. And only Frumkin and Gvirtzman (2006) presented empirical and field-work based results on leakage, however, for a highly exceptional case of a cross-formational groundwater rise within a geothermal artesian karstic saline anomaly of the WAB. Despite their deficiencies, it is however important to note that the studies by Weiss and Gvirtzman (2007) and Peleg and Gvirtzman (2010) stand out as the only ones of their kind, i.e. an attempt to quantify downward groundwater leakage, which otherwise is a particularly elusive factor in most catchments worldwide.

1.4 Research gaps

As in most, if not all ungauged basins worldwide, also in the WAB, the general problem of a severe lack of primary field data from observation and measurements cannot be circumvented by ever more sophisticated advances in modelling. This remains a challenge, as the IAHS-led decade on PUB concluded. Instead, new methods are needed that focus on the understanding of the spatially variable and complex recharge processes and find ways for their conceptual description and classification as well as their parameterisation. Surface- and process-based direct methods in the recharge area and at the catchment scale are called for. The description and quantification of dominant parameters should be firmly anchored in field observation and where possible, field measurements. In ungauged and poorly gauged basins, the basin classification and process understanding should start with observable physical features and their patterns and interactions. At the same time, models should adhere to the goal of parsimony and avoid over-calibration and the problems of equifinality. Finally, the regionalisation of the observed and modelled field results will have to include at least some measure of extrapolation but should be grounded on and adapted to the basin classification framework. Assessment of spatially distributed recharge that is anchored in field observation, understanding and classification of physical parameters as well as on field measurements and performed at the catchment scale remains a gap to be filled.

1.5 Research hypothesis, indicators, assumptions and objectives

My **research hypothesis** was that

a) recharge is controlled not only by 'outer' meteorological variations in rainfall (and evaporation), but also and especially by land-intrinsic physical features, such as bedrock lithology, soils and land forms (which encompass relief, soil, natural vegetation, land use and land cover)
b) processes (basin impact) such as runoff, initial infiltration, soil saturation, as well as percolation into and through the unsaturated zone are all strongly reliant on these physical features (basin form)
c) it stands to be verified through field work, that these land forms correlate with and are almost strictly attributed to the diverse lithostratigraphic formations with their particular geology and rock content, e.g. limestone & dolomite, chalk & chert, clay & marl, etc. or different mixtures between them

Indicators and assumptions:

This correlation approach can only be successful at a basin-wide scale, if

- the entire WAB recharge zone shows these attributed and spatially distributed features
- the particular overall feature of the anticlinal setting that folds up the West Bank results in a distinct distribution of topographic elevations for each formation outcrop throughout the West Bank: The Lower Aquifer always and only crops out along the anticlinal axis in the mountains, while the Upper aquifer outcrops are all restricted to the lower slopes and

foothills region; this distribution results in the remarkable coincidence that each formation outcrop typically can be attributed to one of several climatic zones, with rainfall decreasing and temperatures increasing from the mountains down to the Coastal Plain
- in this respect, Wadi Natuf catchment is representative for the entire recharge areas of the WAB

In effect, it is justified to expect distinct and pronouncedly different recharge coefficients not only for each land form of land use and land cover (LU/LC) and soil, but also for the distribution of geological formations. (Wadi Natuf shows for each geological formation a distinct landform, but not vice versa can each single land form be attributed to only one formation)

Here, however, the matter of scale becomes significant: Only under a detailed differentiation of lithostratigraphic formations, under a much higher resolution than the usual regional distinction between Upper Aquifer and Lower Aquifer, physical features and the resulting expected recharge coefficients be attributed to distinct types of lithology or other physical features that govern recharge.

This is an innovative approach that has never before been tested and carried out before; this research presents a novel combination of existing techniques (based on observable processes, parameters and signatures) that adheres to the goal of parsimony, integrates inductive and deductive steps and – with slight modifications – is applicable to many basins around the world in order to advance the crucial but challenging task of a realistic representation of distributed recharge.

Objectives:

The objective of this doctoral research was to investigate spatially distributed recharge in a largely ungauged karst aquifer catchment (in the form of formation-specific recharge coefficients).

The procedure can be described as a succession of three steps:

- (1) field observations and development of a conceptual basin classification framework that reflects the dominant physical parameters and processes in the catchment
- (2) modelling, calculations and quantifications based on field-measured time series data
- (3) extrapolation of the modelled and calculated results by attributing them to other formations with similar features, using the adapted basin classification framework, i.e. regionalisation to the catchment scale

Alternatively, an overview over the general approach can discriminate by type, e.g. between indirect and direct recharge:

a) *Indirect recharge*: For the assessment of indirect, allogenic recharge, the objective was to assess and quantify transmission losses from runoff in ephemeral streams and their entry into the underlying consolidated aquifer bedrock. The second task was to regionalize and differentiate this process spatially by relating it to the geology of the receiving formation. At the main channel, minimum rates of transmission loss could be observed and measured empirically. The investigations

presented in this paper reflect both, spatial and temporal variability of infiltration from ephemeral streams, that is, variations in geology at the catchment scale and precipitation at the event scale.

b) *Direct recharge*: In-situ processes of deep percolation were approached by direct methods of soil moisture saturation excess and percolation modelling (SM-SEP modelling), whereby deep percolation into the bedrock was equated with recharge. This simplification was admissible in the regional aquifers directly underlying the outcrops under phreatic conditions. However, at the local scale, also small leaky aquifers under perched conditions were encountered in the study area. Here, it was necessary to also account for downward leakage. The leaky perched aquifers were found only to occur on erosionally isolated in central Wadi Natuf. Hence, their leakage rates could be approached through a simple water budget approach accounting for modelled in-situ recharge and for aquifer outflows from monitored local springs. At the scale of the isolated hilltops, downward leakage could be equated with the difference between local recharge as inflows and spring discharge as outflows.

The result of this research is – for the first time in the WAB – a set of formation-specific annual average recharge coefficients that reflect the complex variability of spatially distributed recharge processes, which are based on a comprehensive reflection of physical features and their spatial variability. This was achieved by a novel combination of inductive (empirical) and deductive (conceptual, extrapolative) procedures under strict adherence to the goals of parsimony, process understanding and spatial differentiation. Figure 1.1 thematically differentiates between the three conceptual components of my overall research procedure.

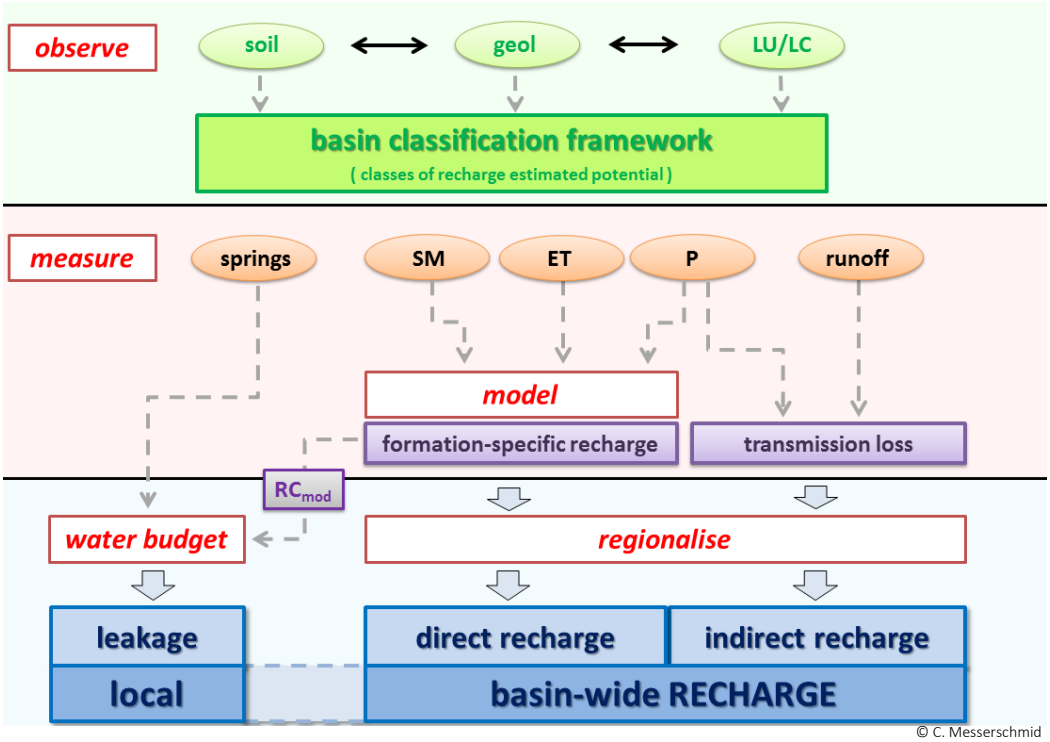

Figure 1.1: Overall research procedure. Observations of physical features lead to a *basin classification framework*; modelling and calculation with field-measured time series data lead to *formation-specific results*; combining the two allows *regionalisation* of recharge estimates to the catchment scale. Colour code: *observations* in green, *measurements* in orange, *results* in purple, *final results* in blue and *activities* in red (abbreviations as in page 18).

CHAPTER 2

THE WESTERN AQUIFER BASIN – GEOLOGICAL BACKGROUND

2.1 Compiled base data of the WAB

This doctoral research deals with a catchment – Wadi Natuf – that lies in the recharge zone of the Western Aquifer Basin (WAB), often also addressed as Western Mountain Aquifer or according the basin's former principle spring outlets as Yarkon-Tanninim Basin in Hebrew and as 'Aujah-Tamaseeh Basin in Arabic. Therefore this thesis starts with an introduction into the physical properties of the basin, chiefly its geology and hydrogeology, but also other geographic features.

In order to reflect the geological diversity within the Western Aquifer, a detailed desktop study was carried out in the framework of the SUSMAQ project, named: Compiled Base Data report (SUSMAQ, 2002). Base data on geography, geology, hydrogeology and water utilization were selected and compiled in a report. Section E of this report, which was written by me (see App. 2.1), is a detailed compilation of the lithographic succession and its spatial distribution in the WAB throughout Earth history from the Precambrian to recent and covering the entire country from the Galilee in the North to the Negev in the South.

Since the entire chapter would be too detailed and long, Appendix 2.1 presents only excerpts, focussing on the Cretaceous Era with a focus on the Upper Albian to Turonian stages. In addition, the excerpts are restricted to the facies realms in the northern, central and southern West Bank, whereby in a first approximation, Wadi Natuf can roughly be equated with the central West Bank mountains and slopes. In the following, the chapter presents a brief overview over the general structural setting of the changing conditions in the sedimentary basins spanning from the Pre-Cambrian to recent (Ch. 2.1.1) – for more details, explanations and fully referenced sources, please refer to the original document of the Compiled Base Data study (see: References and List of publications and declaration of authorships). Ch. 2.1.2 then provides a briefly introduces the rich facies diversity during the Cretaceous, i.e. the main phase of sedimentation of today's aquifers in the WAB.

2.1.1 Structure and summary

PRE-CRETACEOUS

The crustal block pattern of the crystalline basement was formed in the Late **Precambrian**. During the Mid-Carboniferous Asturian orogenic phase the area was uplifted and exposed to erosion.

In Permian and **Lower Triassic**, a shallow widespread and uniform transgression lapped over the Arabo-Nubian Craton (Negev and Ra'af groups). This phase of calm carbonatic sedimentation in the northern Negev came to an end with the tectonic inversion and southeast tilting during the late Hercynian phase in the Middle Triassic. A slight folding, mainly adjacent to NE-trending faults, was produced and in the Late Triassic block movement and folding differentiated along NE trends. This led to the subsidence of grabens such as Judea and Pleshet grabens that were filled with thick evaporites and carbonates until sea levels dropped at the end of Triassic.

In the **Jurassic**, the differential block movements were rejuvenated, along NE trending, but this time also along NW-trending fault systems. Thick carbonate series accumulated in the grabens. Transgressive and regressive cycles allowed the deposition of Inmar-Zohar formations. The regression was reflected in fluviatile and deltaic facies in the SE, while in the centre sands and carbonates prevailed and in the west the facies remained limy to argillaceous. Towards the Middle Jurassic volcanism, fracturing and westward tilting occurred. The Jurassic sedimentation was brought to an end by the Late Kimmeridgian inversion, with both block tectonics and broad upfolding of regional anticlines, as well as with volcanism (Kidod, Beer Sheva, Haluza, Gevar'am formations).

LOWER CRETACEOUS

In Early to Middle Cretaceous times, extensional movements and volcanism (Tayasir) were accompanied by a wide-scale sea-level drop. Jurassic and older strata were exposed and eroded. The erosional products were deposited as sands and turbidite sands in the central basin (Yoav Group, Kurnub Group). In the east, a carbonate platform developed (Ga'ash Group) and on the west, along the continental margin, the clastic marly Talme Yafe prism was built.

UPPER ALBIAN

During Early and Middle Cretaceous (144 –90 Ma), the area underwent a gradual transition from exposure to the establishment of a stable carbonate shelf. The sequence started with extensional movements and volcanism, accompanied by a sea-level drop with subaerial exposure of edge areas, followed by erosion and accumulation of sands. Shale and marl accumulated during the Upper Aptian and Lower Albian in the northern and central part of the area (Kobar Group). A carbonate platform was established here from **Upper Albian** throughout Cenomanian and Turonian with the deposition of >1000 m thick carbonates (Judea or West Bank group). Offshore, the clastic sedimentation of carbonatic detritus and marl continues in the form of a basinal marly prism (Talme Yafe Formation).

UPPER CRETACEOUS (CENOMANIAN - TURONIAN)

Throughout several sedimentary cycles, **platform conditions** prevailed in the entire area (Fig. 2.1), except for the western margin, where Talme Yafe continued with its basinal and slope facies pelitic clastics. At the end of the long Upper Cretaceous platform sedimentation, compression and tectonic conversion formed a series of asymmetric folds. This **Syrian Arc** folding pattern followed older, Palaeozoic patterns (Bahat, 1999): Deep faulting, due to pre-Senonian crustal movements, reaches down to the Palaeozoic formations on the entire width of the Syrian Arc folding belt and especially on its edges, near the border between Israel and Gaza and near the Jordan Rift Valley. The basement normal faults were reactivated into reverse faults, on which the Syrian Arc folds are leaning.

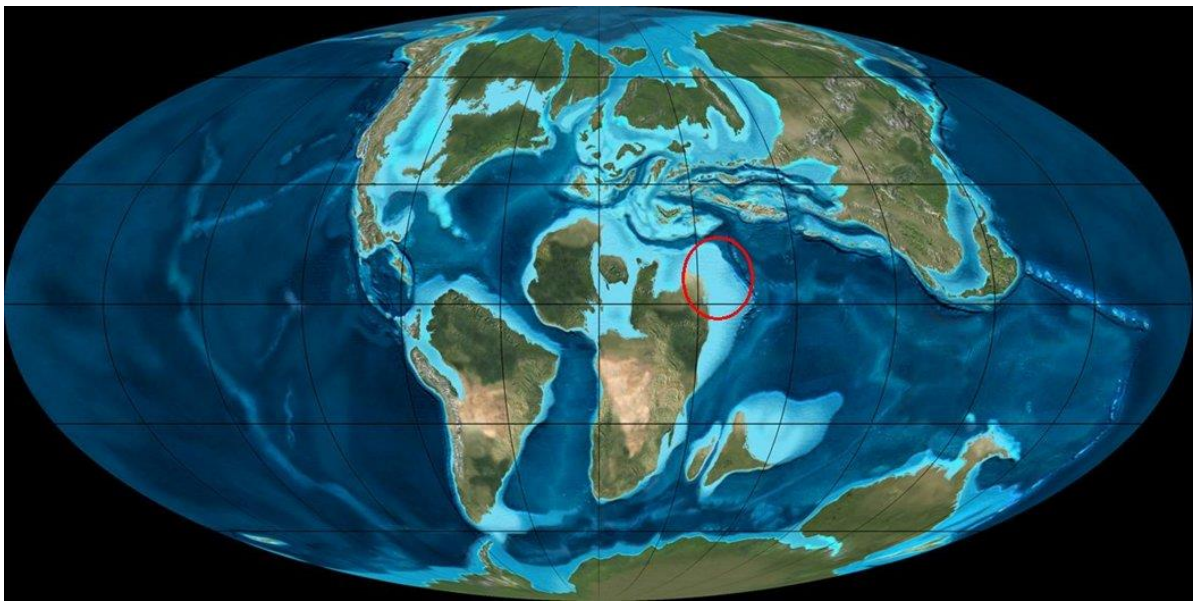

Figure 2.1: Late Cretaceous (90 ma). Entire Arabian Peninsula (red circle) submersed; passive continental margin and equatorial Tethys shelf. (DOI:10.1016/j.tree.2013.09.012.)

UPPER CRETACEOUS TO RECENT

The typical Syrian Arc pattern with its NE-SW strike follows Palaeozoic patterns (Bahat, 1999). During the Mid-Carboniferous Asturian orogenic phase the area had been uplifted and exposed to erosion; pre-Senonian deep faulting reaches down to these depths. The phase of calm sedimentation in the northern Negev came to an end with the tectonic inversion and southeast tilting during the late Hercynian phase. A slight folding, mainly adjacent to NE-trending faults was produced.

Late Cretaceous – Early Tertiary (90 – 40 Ma) [Coniacian-Eocene]: Structural movements started in the early Upper Coniacian; they deepened and continued until approximately Eocene. As an effect of the northward movement of the Arabian plate compression and tectonic inversion occurred. The result is a series of asymmetric blocks of the so-called “Syrian Arc System” (around 40 Ma) that are leaning on reverse faults caused by re-activation of basement normal faults. Therefore, thickness and facies changes in the overlying Senonian and Eocene sediments are controlled by the structural development. Where Cretaceous rocks were exposed on the structural highs, erosion took place. The Syrian Arc system is present with NE-SW directed faults and lineaments, as well as folds.

Early Tertiary – Recent (40 – 0 Ma): In the Early Tertiary, a drastic drop in the sea level occurs. Deeply incised channels developed and the folding during Oligocene was accentuated. Subsequently, the channels were filled in Late Oligocene - Early Miocene. The most prominent of these channels is the Afiq-channel between Gaza and Beer Sheva.

Initiation of the Dead Sea Graben: Extensive rifting starts and holds on during middle Miocene. The Dead Sea – Jordan valley – Wadi Araba depression is part of the > 6000 km long East African Rift system, reaching from the Taurids down to Rwanda. The prominent direction of the sinistral strike slip is around 10 degrees NNE. Lineaments of this orientation are usually considered to be associated to this rift system. The Dead Sea itself was formed by a pull-apart basin, with a secondary extensional movement of around 70 degrees ENE. Still in the Miocene, started the formation of the Levantine basin in the SE Mediterranean and of small intra-continental basins filled with conglomerates and sandstone, mainly along the future Jordan Rift Valley.

Seawards, a NE-SW step-faulting and rifting development was accompanied by a reactivation of the NW-SE faulting. Also, widespread volcanism can be registered. Finally the Miocene – Pliocene was characterised by a recurrence of a drastic sea level fall and desiccation (evaporation) of the Mediterranean Sea in late Miocene time and a subsequent rise in early Pliocene.

2.1.2 Facies distribution and lithostratigraphy of the Cretaceous

The Arabian plate and its split-off, the Palestinian micro-plate form the passive continental margin of the old African Craton and the southern shores of the Mesozoic Tethys Ocean. In the Upper Cretaceous it was positioned near the equator (Fig. 2.1). During early Cretaceous, the sea successively transgressed from north and northwest over Palestine, thus ending the late Jurassic to early Neocomian hiatus. First carbonate platform conditions were reached as early as the Aptian in Lebanon and the northernmost part of Palestine and as late as late Cenomanian in the south. The successive sea level oscillations during this retarded overall transgressive movement split up the sedimentary realm into many different sub-facies realms, thus laying the conditions for the diachronous facies throughout the Western Aquifer basin. This rich facies diversity encountered in the WAB, as well as its impact on hydrostratigraphy becomes a key element of research under the topic of spatially distributed recharge.

The transgressions started in the Neocomian and lasted until the Turonian. The stable shelf conditions, which created over 1000 m thick carbonate platform sediments, ended with the Senonian deepening of sea water levels and its typical chalk and chert facies found worldwide. This general pattern makes the WAB and its sub-catchment Wadi Natuf exemplary for many basins around the world, among which many of the largest, most productive water yielding basins on the globe. It should also be reminded here on the predictions of IPCC (2008), according to which, the role of groundwater will likely increase under conditions of global climate change.

Several facies maps from the Compiled Data Base report (after Hirsch, 1990) illustrate the five different stages during the Cretaceous (Fig. 2 -6), of which two early transgression stages, two main sedimentation stages (Albian and Cenomanian-Turonian, Fig. 2.4 and 2.5) and one post transgressive stage (Senonian, Fig. 2.6).

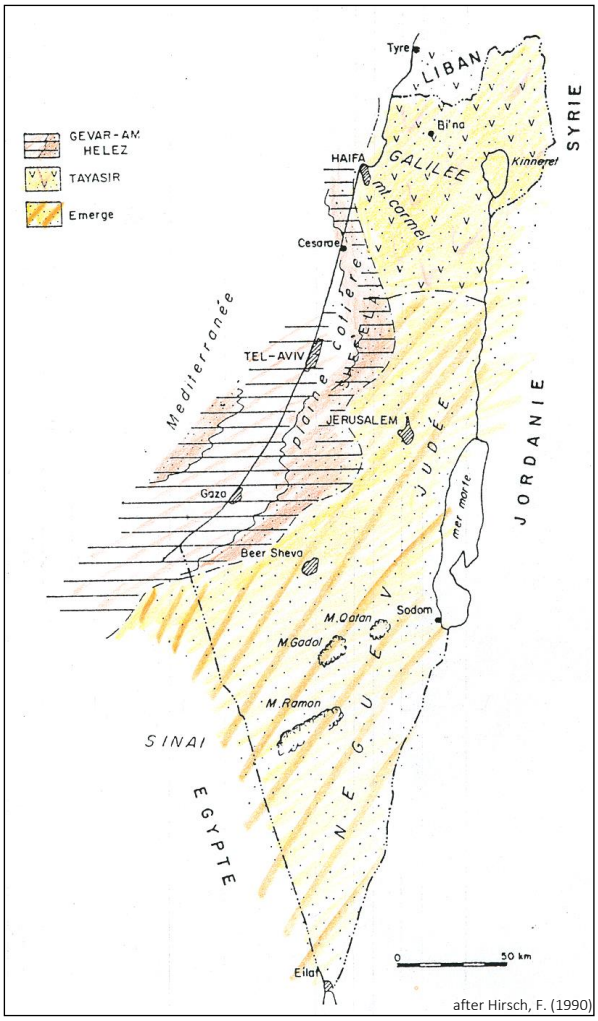

Figure 2.2: Tithonian-Barrêmian facies. Continental facies in most of the country with volcanics in the north. Proximal and deltaic facies on the coast, detritic marine facies offshore. (s.a. App. 1.1)

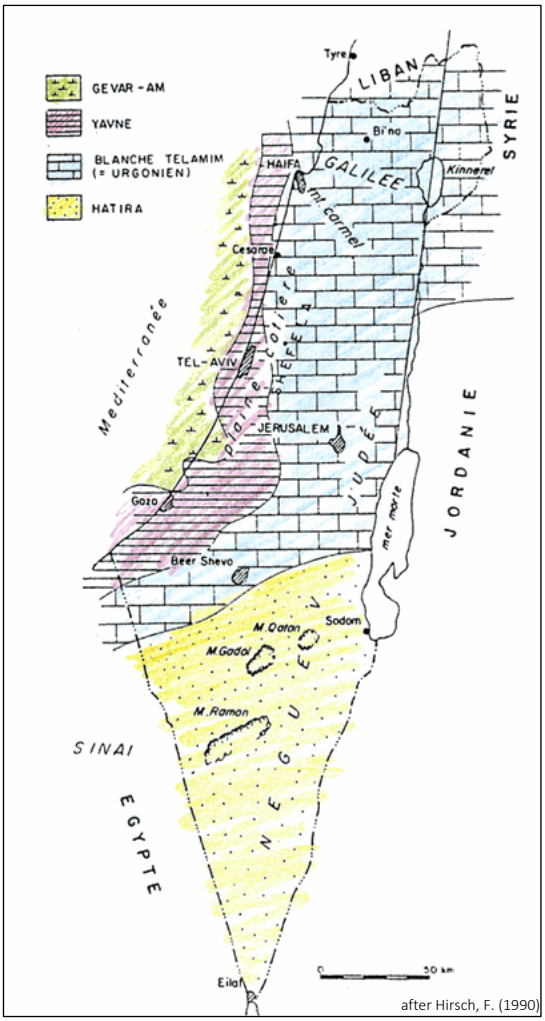

Figure 2.3: Aptian Facies. Continental facies in the south; carbonate platform in the centre and north; *Yavne* shale along the coast; marly facies offshore. Source: SUSMAQ, 2002 (s.a. App. 1.1)

In the early transgressive stages, the South of the country still remained exposed with a sedimentary hiatus. Figure 2.2 shows the Tithonian-Barrêmian stages. The main sedimentation facies remained shallow and proximal but further deepened towards and during the Aptian, often represented by shales with differing degrees of carbonatic content and intercalations (Fig. 2.3).

During Albian and Cenomanian the stable carbonatic shelf platform with tropical reefs were established, reaching the peak transgressive stage in the Cenomanian (Fig. 2.4 and 2.5).

Finally, the Senonian (Fig. 2.6) develops a chalk facies, again gradually from north and north-west towards south and south-east.

It should be noted that minor local aquifers were also formed before and after the second mega-cycle (*Wasia*), during the first and third mega-cycles (*Thammama and Aruma*) – see Fig. 2.7.

Figures 2.8 and 2.9 summarize the distribution of Cretaceous formation names (Fig. 2.8) and visualize the diachronous facies distribution in a simplified from (Fig. 2.9).

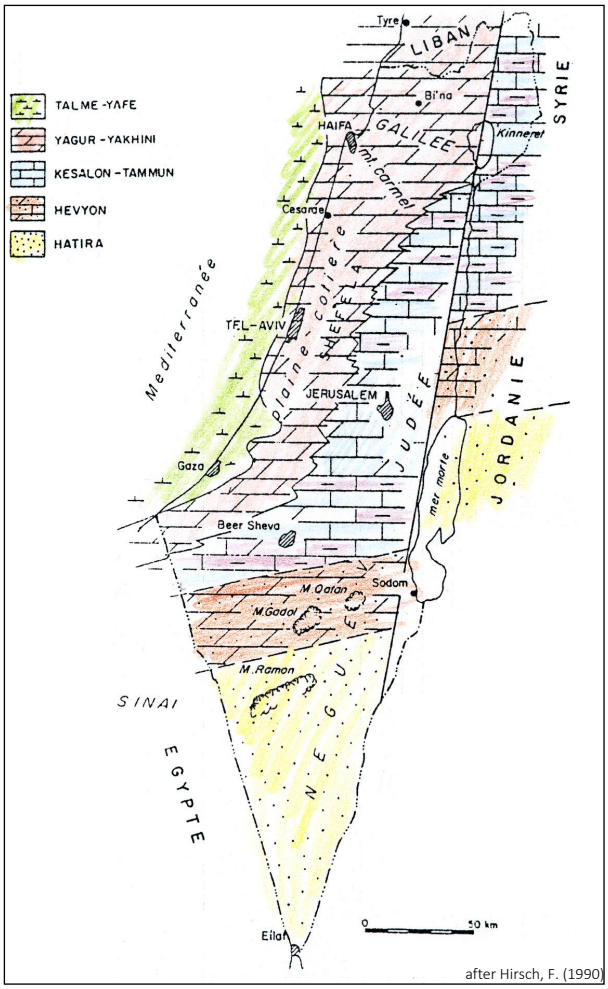

Figure 2.4: Albian facies. Terrigenous facies in the south, proximal facies in the Negev, marl-limestone facies in the West Bank, reefal facies in the coastal plain and deep basin off-shore. Source: SUSMAQ, 2002 (s.a. App. 1.1)

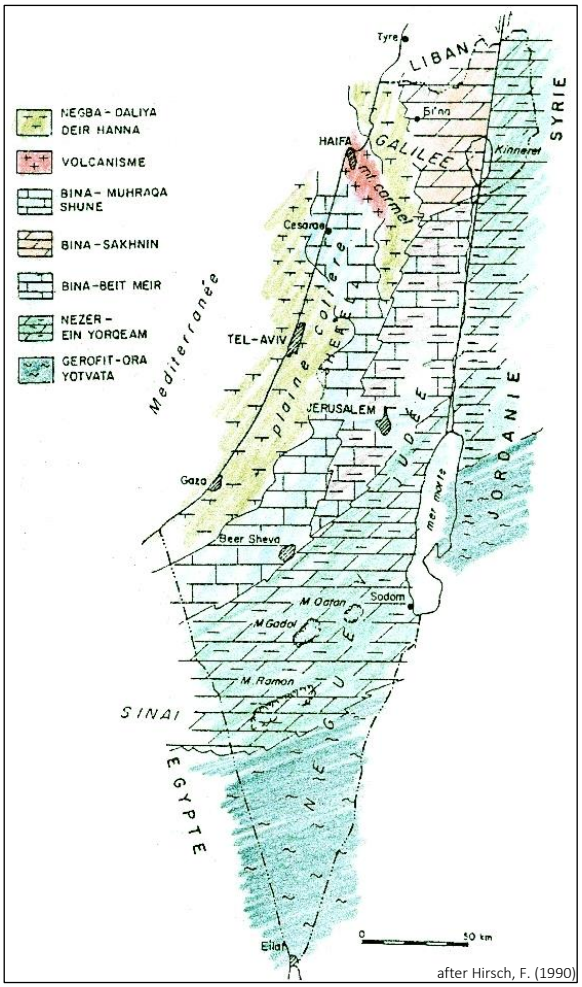

Figure 2.5: Cenomanian facies. Peak of the Cretaceous transgression = Upper Cenomanian, with shallow facies in S-Negev (*Gerofit-Ora*). More differentiated in the northern Negev: Ein *Yorqe'am-Nezer*; West Bank: *Beit Meir-Bi'na*; Galilee: *Sakhnin-Bi'na*; Western foothills along the green line: reefal barrier (*Muhraqa/ Bi'na*) with some volcanics intercalations at Mt. Carmel. Most pelagic along the coast (*Negba-Daliya*), (s.a. App. 1.1).

As Fig. 2.4 and 2.5 indicate, the sedimentation over the Palestinian micro-plate was diachronous, with large waves of transgressions (sedimentation cycles) starting from northwest as early as the Neocomian and reaching full carbonate platform conditions in the south of the country only by late Albian, in parts of the Negev even in the Lower Cenomanian. Hence, chrono- and litho-stratigraphy did not develop synchronously but successively, starting each sedimentation cycle with continental and proximal facies conditions, gradually deepening under the NW transgressions until reaching carbonate platforms that provided the principle realm of today's main aquifers. In other words, laterally the lithofacies in one and the same formation or its equivalent chronostratigraphically, undergoes considerable changes from the karstified limestone and dolostone aquifers to somewhat marly and chalky aquitards and finally to full confining aquitards (or 'aquicludes') of marl and clay. This lateral facies change is important to be pointed out, since it has a far reaching impact on the spatial distribution of aquifer characteristics and recharge potential as well as physical landscape features such as soil distribution, land cover and even vegetation and ensuing land use (Ch. 3).

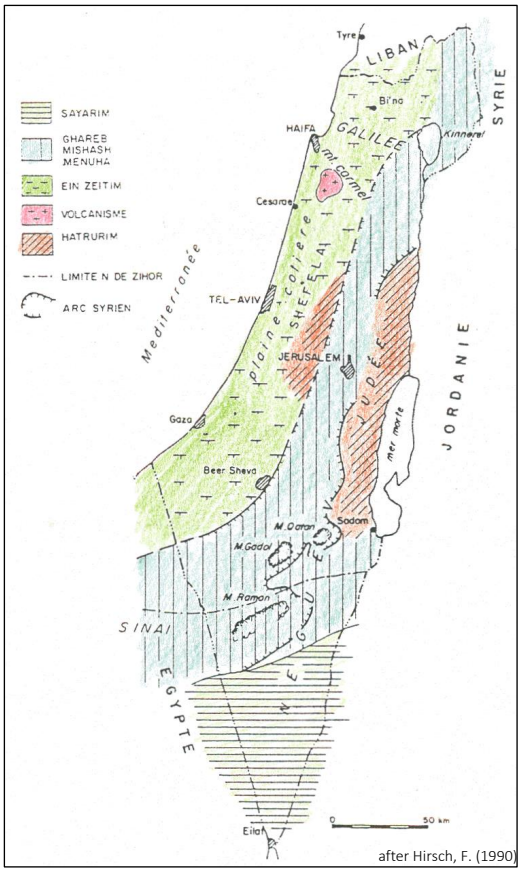

Figure 2.6: Senonian facies with deepening water from SE to NW. S – SE: shallow with chert & phosphate (*Sayarim & Mishash*); NW: open pelagic chalks (*Menuha-Ghareb, Ein Zeitim*). Near the Jordan Rift Valley and west of Jerusalem (edge of the Syrian Arc): Maastrichtian *Ghareb* series, together with overlying *Mishash & Menuha* formations and up to Eocene age with *Hatrurim* formation (that underwent auto-metamorphosis of the self-combustion type due to high bituminous content). In Mt. Carmel: volcanism. Source: SUSMAQ, 2002 (s.a. App. 1.1)

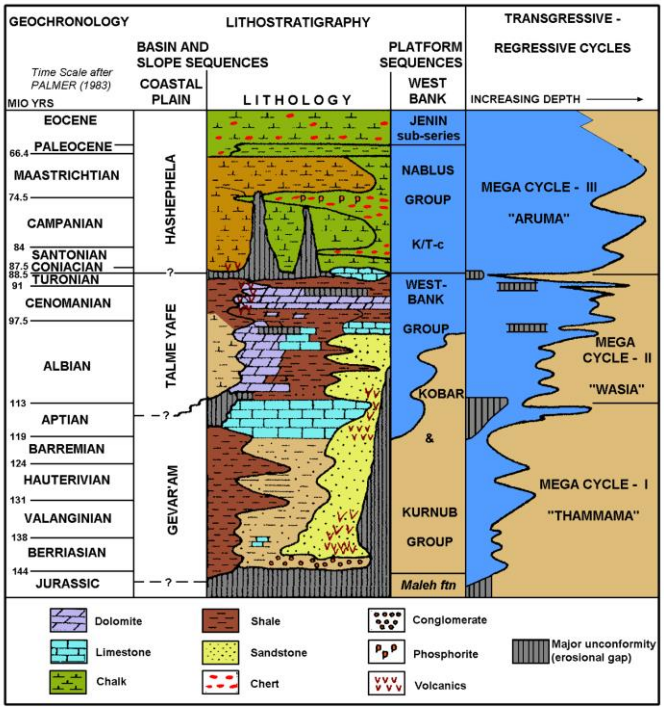

Figure 2.7: Sedimentary mega-cycles (after Aliewi, Al-Masri and Messerschmid, 2015)

In most of the literature, two major aquifers are differentiated on the regional scale, divided by one regional aquitard. The Upper Aquifer (UA) stretches from the Middle Cenomanian to the Turonian, whereas the Lower Aquifer (LA) comprises of Upper Albian formations. The regional Middle Aquitard separating the two consists of Lower Cenomanian formations.

In the Palestinian nomenclature, these formations are as follows: Upper Beit Kahil and Lower Beit Kahil (UBK and LBK) formations for the Lower Aquifer. The Middle Aquitard is called Yatta formation and the Upper Aquifer comprises of Hebron, Betlehem and Jerusalem formation. Together they from the West Bank group (*Judea Group* in Israeli terminology). Lower Albian and Upper Aptian form the Kobar Group and Lower Aptian and Neocomian age formations form the Kurnub Group (Ramali formation in the diagram), also known as Nubian sandstone in North-African Arab states, such as Egypt (including the Sinai). The type location Kurnub (the ancient Mampsis) lies in the Northern Negev, 10 km south of the West Bank. Figure 2.8 below shows mostly Israeli formations names and one column with Palestinian formation names, applicable in the West Bank (in capital letters).

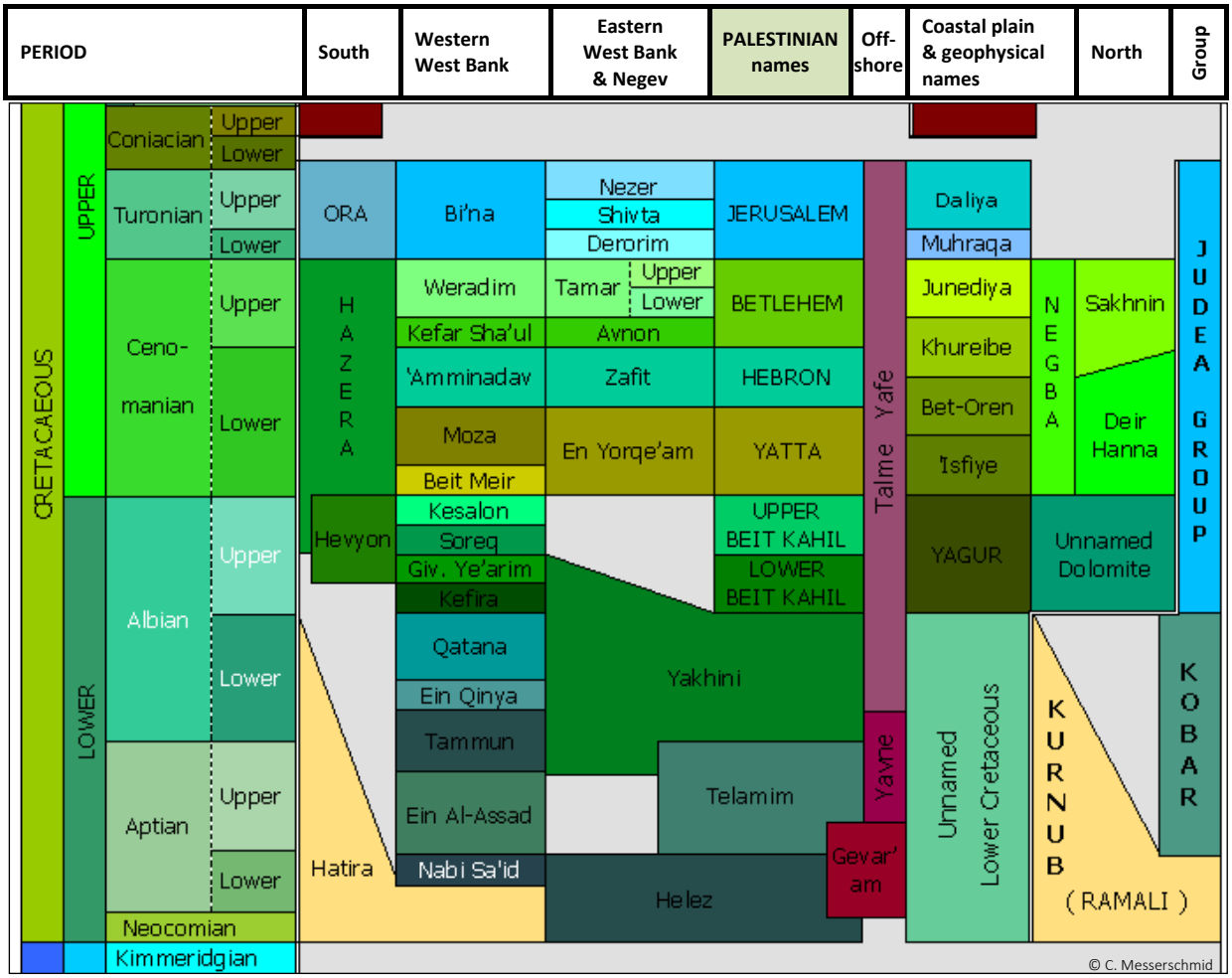

Figure 2.8: Stratigraphy of Ramali, Kobar and Judea groups, Cretaceous - (s.a. App. 2.1)

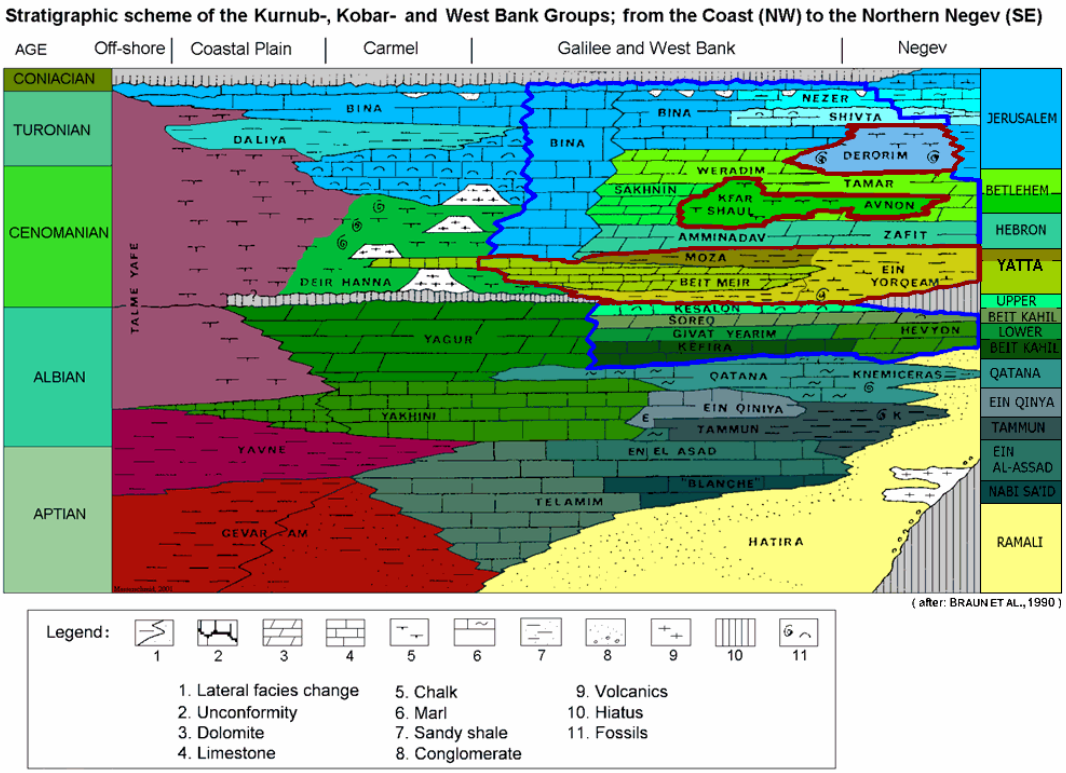

Figure 2.9: Stratigraphic scheme of the Kurnub-, Kobar- and West Bank groups (App. 2.1)

2.2 Aquitards in the West Bank's Mountain Aquifers

The existing hydrogeological literature of the Mountain Aquifers so far has almost exclusively focussed on the aquifers of the basins and here mostly on the main, regional aquifer complexes, Lower Aquifer and Upper Aquifers (LA & UA). However, also the series commonly addressed as aquitards contain aquiferous sections with productive water resources. Despite the fact that these horizons have been identified and targeted by productive wells, little attention was given in the literature. Therefore Appendix 2.2 presents the findings from four well drillings in the Central and Northern West Bank, near Ramallah and Nablus Fig. 2.10). It describes the geological and hydrogeological field findings of rock cuttings from the borehole, geophysical logging and pumping tests.

Figure 2.10: Location map of the 4 new boreholes

Two of the boreholes (Ein Senia # 7 & Beit Dajan well) reach down to stratigraphically very low formations of the Lower Cretaceous (Kurnub Group), deep below the bottom of the regional Lower Aquifer. Up to date, almost no literature exists on these very deep, mostly overlooked, yet productive aquifers. The two other wells (Audalah and Ein Samia # 6 well) target the Lower Aquifer (Upper Albian). Only one of the wells (Ein Senia # 7) turned out unproductive, while the other three are operative. Important for the question at hand is the productive well potential of the local aquifers, usually subsumed under regional "aquitards" and not described in the literature on aquifers.

Important for the question at hand is the productive well potential of the local aquifers, usually subsumed under "regional aquitards" and not described in the literature on aquifers. Only one of the four wells (Audalah well) has a classic design with only the regional Lower Aquifer tapped for water production. All other three wells successfully tapped local sub-series either within the regional aquitards alone or in combination with the regional aquifers.

The regional Middle Aquitard is usually assigned Lower Cenomanian age (see Fig. 2.9) and called Yatta formation in the Palestinian literature. Israeli nomenclature divides Yatta into two formations; Moza formation at top and Beit Meir formation at bottom (see Fig. 2.8). The very deep aquifers belong to the Kurnub Group (Neocomian to Lower Albian, Table 2.1). It reaches down to the proximal, even continental facies (sandstone) at the onset of the Cretaceous transgressions after the Upper Jurassic Hiatus in Historical Palestine (Israel). The following table (Table 2.1) gives an overview over the four wells and its productive and unproductive horizons.

Table 2.1: Formation thickness and aquifer properties in the literature and the 4 new boreholes

Age		Formation	Literature	EinSamia # 6 [m]		Audalah [m]		EinSenia # 7 [m]		Beit Dajan [m]	
Cenomanian	Up.	'Amminadav	**Upper Aquifer**	Upper Aquifer	122	dry aquifer – water level at bottom	103	not drilled		not drilled	
	Lower	Moza	**Aquiclude (YATTA)**		21		27				
		Beit Meir b			59		80				
		Beit Meir a		Aquiclude	35		22				33.5+
Albian	Upper	Kesalon	**Lower Aquifer**	"middle" Aquifer	22	Aquifer	33			dry	18
		Soreq		Aquitard	79		76				80
		Giv.Ye'arim		Lower Aquifer	68		60	dry	43+		58.5
		Kefira			147		120	weak: no recharge	185		74
	Lower	Qatana	**Bottom Aquiclude (KOBAR)**	Bottom Aquiclude	48+	Bottom Aquiclude	5+	Aquiclude	52	weak: 5m fract	82.5
		Ein Qinya		-		-		weak Aquifer	72	good: 18m fract	57
Aptian		Tammun d						Aquiclude	89	weak: 14m fract	46.5
		Tammun c							86	Aquiclude	71.5
		Tammun b							43		61
		Tammun a							37		48
Neocomian		Ein Al-Assad						Aquitard	38		47+
		Nabi Sa'id						weak Aquifer	67	-	
		Hatira	**Deep Aquifer**						113+		

In Table 2.1, Ein Samia well # 6 shows a productive horizon at the upper part of Beit Meir formation, which forms the middle part of the regional Middle Aquitard (the Yatta formation in Palestinian nomenclature). Ein Senia well # 7 targeted the very deep Kobar Group and found some aquifer formations at its top and bottom, yet without sufficient recharge to make it a productive well. By contrast, Beit Dajan well exhibited exploitable formations within the regional Bottom Aquitard – Ein Qinya formation and the uppermost part of Tammun formation (Tammun d) with active water conducting fractures, as shown in Fig. 2.11. By contrast, Tammun c) further below, exhibited soft, deformable shale with a smooth non-porous surface in the camera logs of Beit Dajan well (Fig. 2.12). As the report (App. 2.2) states, in Beit Dajan well, a multi-layered aquifer was discovered in Upper Kobar, while Lower Kobar is a strong aquiclude, predominantly built-up of shale.

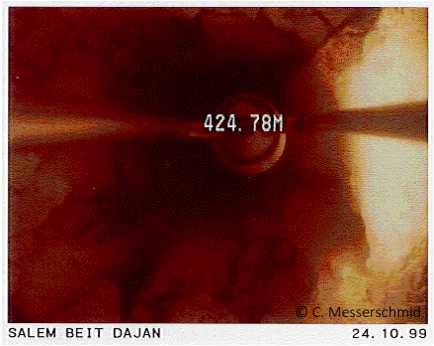

Figure 2.11: Fractured formation Tammun d), 425m bgl

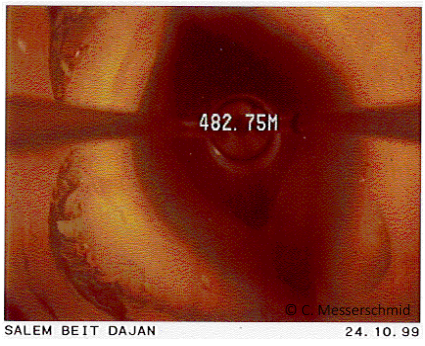

Figure 2.12: Deformed, but otherwise smooth shale of Tammun c), 483m bgl

The extended abstract concluded: "Future well drilling has to take these findings into account. Well design and the testing program must pay attention to the specific nature of the 'aquicludes' in each of the different well locations. Failure to address these issues can lead to surprises in the findings, technical problems during construction and problems in the long term operation."

Tracking the facies changes and the change in hydrogeological characteristics of the "aquicludes" more closely allows for a better design and thus better results in the long term operation of the deep wells in the West Bank. Taking into account all sub-aquifers or confining layers at new well sites will result in higher yields, lasting sustainability and more effective use of the water resources that are so crucial for any development in an environment like Palestine.

2.3 Boundary conditions in the Western Aquifer Basin

Another important question for the initial investigation of the WAB was the matter of boundary conditions (Schmidt, 2014, Hartmann, 2013), especially, but not only for the task of groundwater flow modelling under the SUSMAQ project. The selection of the boundary conditions for the Western Aquifer Basin is difficult because of the complex geology and hydrogeology of the basin itself. Boundary conditions are important because they not only define the basin area but belong to one of the determinants flow patterns of an aquifer system.

In the published literature a large of different delineations of the basin boundaries can be found. This is testified by the abundance of different findings of basin area (in km^2), which lies between a total of 9,000 and 14,167 km^2 and with a hydrologically most active area between 6,035 and 6,250 km^2 in size (see App. 2.5). The investigation was carried out with the help of geological maps and literature. In addition, eleven cross sections were constructed and compiled.

The report conceptually differentiated between two groups of boundaries, flow boundaries and no-flow boundaries. The first group consists of specified head and specified flow boundaries as well as head-dependant flow boundaries. The second group consists of different forms of structural divides (due to erosion, facies change or faulting, etc.). The report defined these four types as follows:

(1) Specified head boundaries, such as seas, lakes, reservoirs – where heads are known (helpful in numerical modelling). This type is relatively rare in the WAB, not least due to the absence of rivers and lakes. Al-Aujah (Yarqon) spring may be an example of this type.

(2) Specified flow boundaries, which can be can be surface water bodies and spring flows but also subterranean hydraulic connection between aquifer basins (Tamaseeh or Tanninim springs in the north of WAB). Also the boundaries with the adjacent Eastern Aquifer are such flow boundaries, but their heads are often difficult to specify, especially where wells are missing.

(3) Head-dependent flow boundaries can occur as leaks from or to a river, lake or reservoir (not encountered in the WAB).

(4) No-flow boundaries, such as structural divides, especially at the top of the anticlines where deep erosion severed any possibility of groundwater flow connections. This is typically found at the deep formation outcrops in the central West Bank Mountains, as for example at the Ramallah anticline in Wadi Natuf (Fig. 2.13). But also deep faults with a high vertical throw can form a structural divide (Fig. 2.14), such as the Benyamina fault near the Tamaseeh springs at the southern edge of Mt. Carmel. In some cases, also a facies change towards impermeable rock within one formation may create a no-flow boundary.

In addition to boundaries around the basin, the report also listed prominent examples of internal divides within the basin, that compartmentalize the basin and its groundwater flows. The most outstanding example is the so-called Afiq-channel that runs in SE-NW directions between Beer Sheva and Gaza (Fig. 2.15). It is a Miocene to Pleistocene drainage channel that was filled with

impermeable evaporates. However, Afiq channel does not cut through the entire depth of active aquifers and therefore only constitutes a semi-barrier. Yet, the disconnect is strong enough to make it the divide between the active northern basin and a dormant southern corner with hardly any recharge and almost no discharge (and higher salinities as well). Thus it forms the southern border of the hydrologically active zone of the WAB.

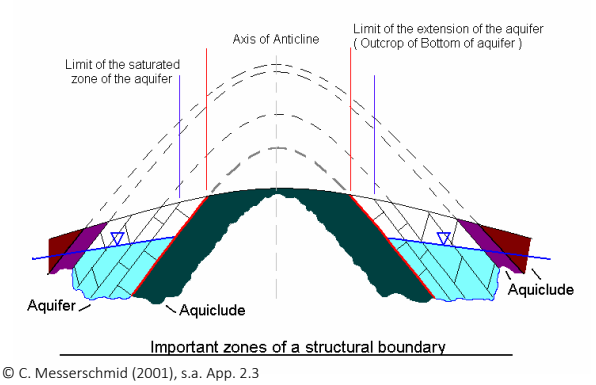

Figure 2.13: Zones of a structural boundary (geo-structural divide) - (s.a. App. 2.3)

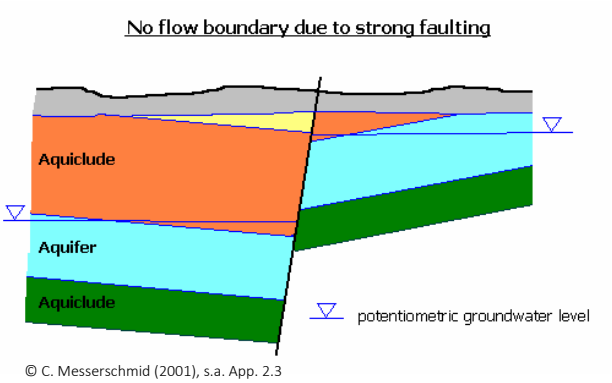

Figure 2.14: No-flow boundary – fault type (App. 2.3)

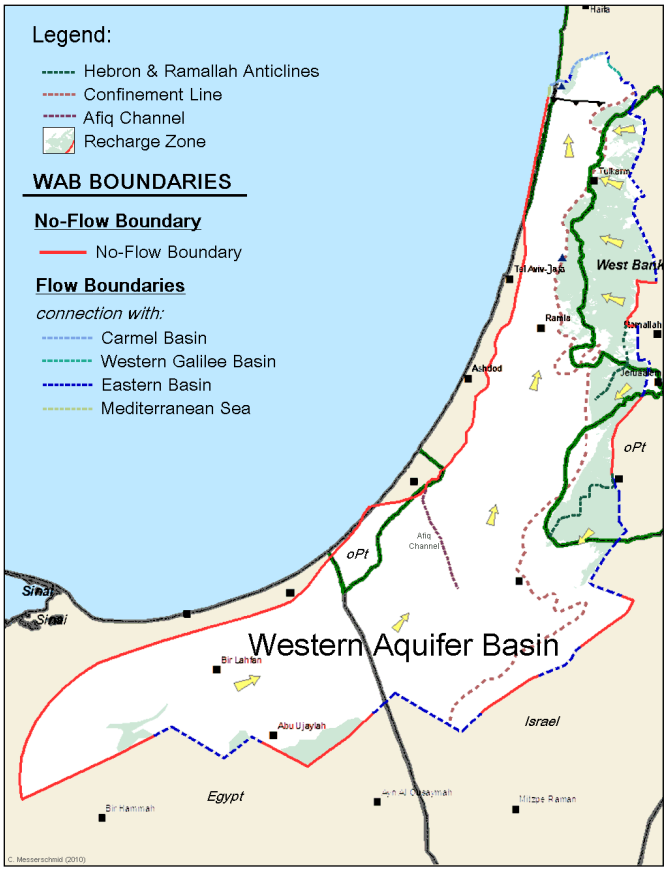

Figure 2.15: Flow connections to other basins.

In the West Bank Mountains, most of the boundaries are groundwater divides with flow connections to the eastern and north-eastern Basins. However, in some places, due to strong upfolding and erosion, the entire thickness of the Lower aquifer is eroded and the deep series of the regional

Bottom Aquiclude crop out – thus making it a no-flow erosional divide in these places. Such an example is Wadi Natuf, where deep erosion fully divides the Eastern and Western groundwater basins at the crest of the Ramallah anticline, which runs in N-S directions approximately 3-4 km West of the topographic mountain crests, which form the surface water divides between the regional Mediterranean and Dead Sea surface drainage systems.

Figure 2.15 shows the distribution of flow boundaries (dotted and continuous lines in different colours) and no-flow boundaries (red continuous line) in the WAB. Another article by Messerschmid (2010) focussed on groundwater flow connections between adjacent basins in Historical Palestine (Israel and the oPt).

2.4 Western Aquifer Basin overview

Source: Compiled by ESCWA-BGR based on Messerschmid and Abu-Sadah, 2009.

Figure 2.16: Aquifer productivity in the WAB (Upper & Lower Aquifer), source: UN-ESCWA & BGR (2013) - s.a. App. 2.4

A general overview over the Western Aquifer Basin is provided in Appendix 2.4 (Fig. 2.16). This report is chapter 19 of the Inventory of Shared Water Resources in Western Asia. The work on this chapter, data collection, provision of diagrams and tables and the writing-up of the text was commissioned by UN-ESCWA, the United Nations Economic and Social Commission on Western Asia and BGR, the German Federal Institute for Geo-Sciences and Resources (*Bundesanstalt für Geowissen-schaften und Rohstoffe*).

The chapter comprises of four thematic sections:
a) Aquifer Characteristics,
b) Groundwater,
c) Groundwater Use and
d) Agreements, Cooperation and Outlooks.

Section a) introduces the stratigraphy, thickness and main aquifer parameters. Section b) then presents the state of the art on aquifer recharge and discharge, groundwater quality, flow regime, sustainable yield and exploitability, directly relevant to this thesis (Fig. 2.16). Section c) gives an overview over the development of riparian abstraction and use in the basin, as well as the more and more pressing issues of sustainability and inequality of riparian use, not only due to management issues and climate change but also as a consequence of the hydro-political situation, generally known as the water conflict between Israel and the Palestinians under its occupation. This is the only place in the thesis, where the development and current status of utilization is addressed.

Section d) finally, depicts the current trends of the water conflict and introduces the current routines of cooperation and its prospects under the Oslo-II Agreements from the year 1995, which were meant to be solved by Final Status Negotiations already twenty years ago. Although this doctoral thesis does not deal with the water conflict, this issue is indirectly connected to its main topic on groundwater recharge: among other things, it shows why and how recharge is relevant and a central theme of the current conflict and its eventual resolution.

2.5 Conceptual and numerical flow models of the WAB

Initially, the central objective of the SUSMAQ project was its groundwater flow modelling component under steady state and transient conditions, later developed into a doctoral thesis by Muath Abusaada (Abusaada, 2011). The recharge investigations in Wadi Natuf were originally planned as an auxiliary component only.

Therefore, the poster in Appendix 2.5 provides an overview over the main components of the SUSMAQ project at its early stages, with a focus on the steady state and transient flow models of the WAB (not subject of this thesis). In addition, it introduces and visualises many of the features of the WAB, namely its geography and geology, its basin geometry and boundaries, as well as its aquifer characteristics. Finally it provides information of wells, rainfall, water levels and recharge in the WAB.

CHAPTER 3

WADI NATUF – HYDROGEOLOGICAL FRAME

Up to the beginning of this research, there was no comprehensive assessment of recharge in Palestine that was based on fieldwork and primary data. The available literature on recharge only provided broad assumptions about recharge, mostly based on overall lumped basin modelling and assumptions, whereas primary empirical fieldwork and gauging on distributed recharge were sparse or missing. And unlike other West Bank aquifers, most of the WAB recharge areas had remained largely ungauged since the onset of the occupation in 1967. As already mentioned, this doctoral research was about generating an understanding and estimates of groundwater recharge in the WAB in general and in particular on its spatial distribution in the replenishment areas of the mountains and upper slopes of the West Bank where groundwater observation is severely impeded but aquifers are accessible at outcrop. As a consequence, the first aim of the field exploration campaign was to provide a good qualitative understanding of physical catchment features controlling recharge, develop an understanding of its main processes and to integrate this into a basin classification framework for recharge. The second aim was to collect field-measured time series data on meteorological drivers of recharge and on basin responses, such as runoff, soil moisture variation and spring flow. The importance of carrying out fieldwork for recharge estimation also laid in the fact that only primary data generated from such empirical research would effectively help validating the recharge model that was to be developed in this study.

Since the catchment is the appropriate scale to develop an understanding of the different individual and overlapping hydrological processes involved in recharge, an experimental catchment near Ramallah had to be selected. The idea was to instrument several Wadis and hillsides within this catchment (see Fig. 3.1) as a means of collecting good primary data for use in recharge estimation. The salient requirements for this catchment (see Appendix 3.1) included:

- a relatively small and therefore controllable area,
- secure access from Ramallah (particularly during the 2nd Intifadha)
- representativeness for the whole WAB in terms of outcropping formations of the regional Upper and Lower Aquifers and “middle aquitard” (if possible also including the top cover and bottom aquitards)
- if available, at least some access to direct or indirect groundwater observation (wells or springs, respectively)

In sum, the tasks and objectives of the catchment study were a) to choose a representative recharge area and assess its observable physical features, b) to instrument this catchment near Ramallah and collect selected primary time series data for recharge estimations in high resolution, c) to use the results from the field observation and measurement programmes in order to provide insights into the recharge processes and d) to provide data for the recharge model.

3.1 Field exploration campaign

Selection of the study area

Wadi Natuf was selected as representative study area for the investigation and measurement of hydrological processes in the Western Aquifer Basin, such as runoff, spring discharge and groundwater recharge. The choice was based on scientific and practical considerations, e.g. its unrivalled lithostratigraphic diversity and its proximity to Ramallah. Wadi Natuf houses the only WAB production well of Ramallah governorate, well Shibteen # 4. It should however be noted here that initial hopes to use this well and two old unequipped boreholes nearby (Shibteen # 1 and # 2) for direct groundwater monitoring, had to be abandoned. The production well, although a Palestinian WBWD well, remains under Israeli military control, which prevents pump testing and the installation of measurement equipment. In addition, a TV-log at the unequipped borehole Shibteen # 1, performed by SUSMAQ and PWA, indicated major technical problems, such as a broken casing with groundwater inflows that disturb and mix the piezometric regimes of different perforated aquifers.

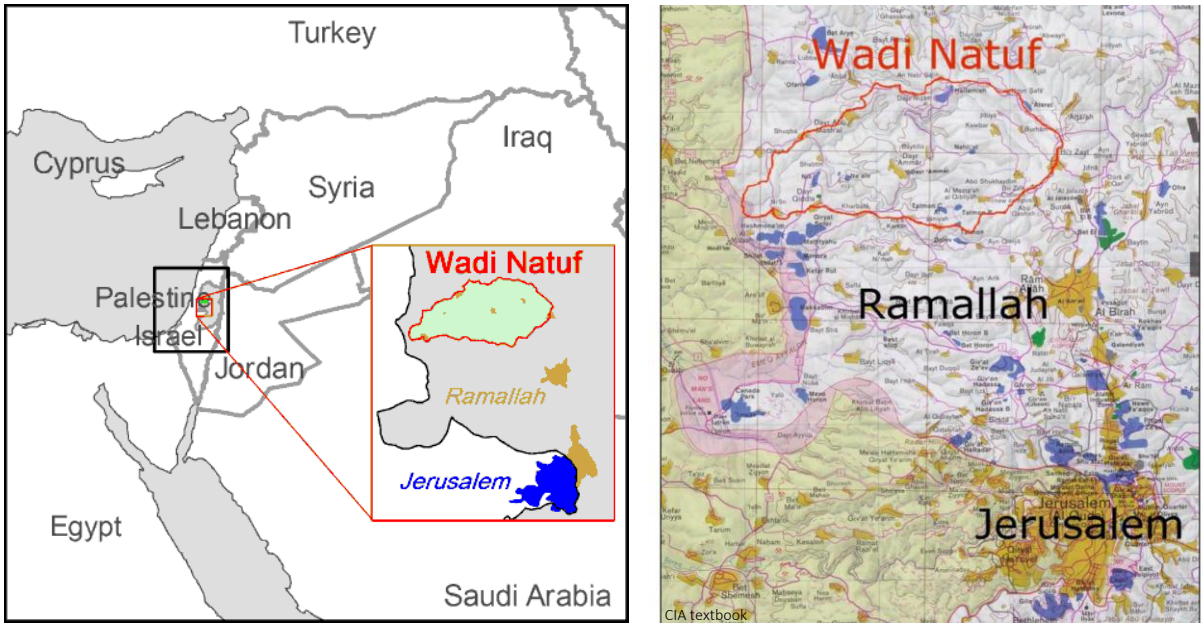

Figure 3.1: Overview location maps of Wadi Natuf (regional and within the West Bank)

3.1.1 Wadi Natuf study area – history and climate

Wadi Natuf is a 103 km^2 large surface catchment 7 km northwest of Ramallah. It stretches from the Green Line (the 1949 Armistice Line between the West Bank and Israel) near Ne'alin in the west at 138 m above mean sea level (asl) to the West Bank mountain crest in the east at 816 m asl near Birzeit (see Fig. 3.1).

Historical background of settlement and land use

Among archaeologists Wadi Natuf is best known for the findings of the over 14,000 year old 'Natufian' culture, an Epipalaeolithic or Proto-Neolithic semi-sedentary culture found at Shuqbah cave between Shuqbah and Shibteen in lower Wadi Natuf (Garrod, 1929). The Natufian culture started during the warm and moist Bølling-Allerød interstadal (before the Younger Dryas) and also settled in the area to become Jericho. It stood on the edge to a settled, cultivating and domesticating civilization and was long considered one of the oldest of these early transition forms. Since then and as most of the West Bank, Wadi Natuf was continuously inhabited by settled farmer communities; since the chalcolithic with the construction of ancient but still functioning terraces as the most visible and noticeable traces of human landscaping. From later periods, many Islamic tombs and shrines (or *Maqāms*, مقام) of Islamic, often Sufi saints or *prophets* (*Nabi*, نبي) can be found in Wadi Natuf, lending their names to the locations – Nabi Ghayth, Nabi An-Neer, etc. The shrines are often located on hilltops, overlooking the landscape and partly served as watchtowers against invaders, such as the Mamlukian *Maqām* Sheikh Al-Qatrawani, strategically located on the north-eastern catchment boundary 1.5 km north of Bir Zeit, or the *Maqām* Nabi Ghayth on a hill near Beitillu and Deir Ammar (central Wadi Natuf). Thee shrines date back to Ottoman or older times but still play a role in the contemporary village culture (Attallah, 2019). The sanctuaries are spared from farming and therefore today, many of them are surrounded by groups of trees or small forests, creating markers in the landscape. Interestingly, these wooded hilltops can be related to several typical geological formations in Wadi Natuf, such as l-UBK, and especially l-Bet formation – which underlines the strong link between relief, land use and underlying geology (see section 3.1.3).

Wadi Natuf was not only continuously inhabited by local pre-historic, Canaanite and Palestinian communities, but also considered very fertile and wealthy. Testimony to this Ottoman agricultural wealth is the presence of so-called 'throne villages', such as Ras Karkar at the southern border of Wadi Natuf, which housed the Ottoman tax collectors. Today, Wadi Natuf is a rural area with 19 Palestinian villages and one town, Bir Zeit at its eastern border. Since the 1970s, five major Israeli settlements were established by force and the number of smaller outposts spread at the upper and lower slopes keeps growing steadily. Of these, the largest settlement, the Talmun-Halamish bubble, forms one spatially continuous zone from the northern to the southern catchment border of central to upper Wadi Natuf.

Climate - general overview

Wadi Natuf lies in a semi-arid to sub-humid climate zone with an average annual area precipitation of 602 mm during the nine seasons measured (2003/04-2012/12) – see chapter 5. Following the FAO-definition (Brouwer and Heibloem, 1986), the 600-mm isohyet marks the division line between semi-arid and sub-humid climates (and with 3-4 and 4-6 months of rainy season, respectively). Accordingly, the eastern half in the upper slopes and mountains belongs to sub-humid climate, while the eastern foothills and parts of central Wadi Natuf belong to the sub-humid climate. Spatially, precipitation is monotonously rising with elevation from the western foothills with a mean annual value of 525 mm/a (around Ne'alin, NEA) to the eastern mountains with 673 mm/a, at Bir Zeit University (BZU) – see chapter 5. Figure 3.2 shows the relation between elevation and precipitation heights for several groups of rain gauging stations and as mean annual values for the period from 2003/04 until 2010/11.

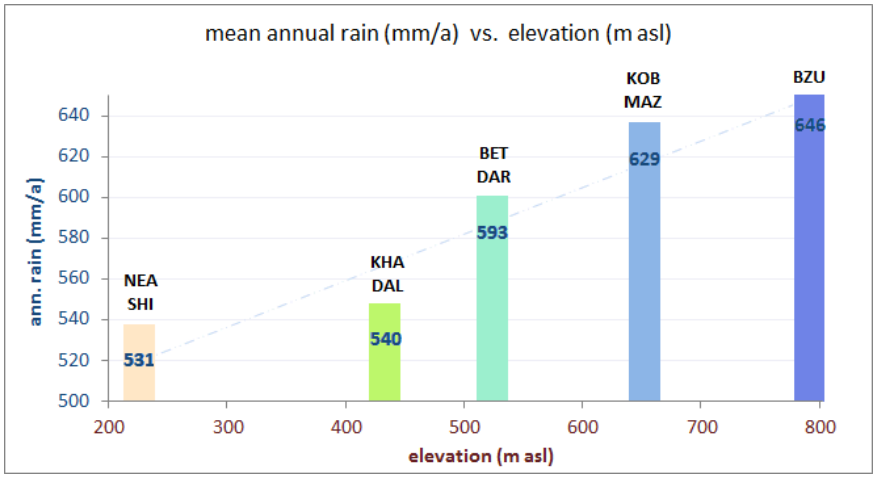

Figure 3.2: Elevation versus precipitation heights for groups of rain gauges – different groups of gauges were sorted and averaged by elevation and mean annual precipitation in 2003/04-2010/11). At the lower end in the east, Ne'alin (NEA) and Shibteen (SHI) gauges at 222 and 229m asl, respectively. On the lower slopes, the gauges Kharbatha (KHA, 396 m) and Deir Abu-Mash'al (DAL, 471 m asl) lie at the southern and northern catchment border. Central Wadi Natuf stations are Deir Ammar (DAR, 540 m) and Beitillu (BET, 506 m asl). Precipitation at the upper slopes was measured in Kobar (KOB, 649m) and Mazra'ah Al-Qabiliyah (MAZ, 655 m asl). The rain gauge at the mountain crest at Bir Zeit University (BZU) lies at 792 m asl.

Long, dry summers and short winters with intensive precipitation characterize the catchment as typical Mediterranean with prevailing western winds during most of the year and especially during winter. Long-term mean annual air temperatures range between 18 °C in the mountains and almost 20 °C in the western foothills (as measured in the automatic weather stations and indicated by spring water temperatures). Short episodes of snowfall are frequent in the mountains, mostly between late December and mid-February, but snow usually does not remain longer than one or two days at the most. In summer, daily temperatures mostly range well above 30 °C but mostly below 40 °C at noon (heat events, called '*Khamseen*' are caused by south-eastern winds from the Saudi-Arabian desert). Additional, usually unmeasured precipitation in summer also comes from dew that forms in the mountains when humid air masses from the Mediterranean cool down at night. This additional water provision from dew can reach up to 90mm per year and for some local plants constitutes an important additional water source during the long dry months from June to September (more details on rain measurements, see Chapter 5).

3.1.2 Local hydrostratigraphy

A complete sequence of all aquifer formations and hydrostratigraphic units of the Western Aquifer Basin from the Aptian to the Senonian is present in Wadi Natuf and can readily be observed and studied at outcrop (Fig. 3.3).

The regional hydrostratigraphy commonly refers to two major aquifer complexes, an Upper Aquifer (UA) of Upper Cenomanian to Turonian age and a regional Lower Aquifer (LA) of Upper Albian age. The regional Middle Aquitard is usually assigned Lower Cenomanian age (although the facies distribution more correctly should be considered diachronous, with different periods of transgressive onset from north to south). However, at a local scale and under closer scrutiny, all of the regional aquifer and aquitard complexes can be further sub-divided into individual more and less permeable layers and formations. Table 3.1 shows the differences in coarse regional and more refined, local hydrostratigraphy. This difference is essential for the investigation of the spatial distribution of hydrological processes such as runoff and recharge.

Table 3.1: Comparison of regional and local hydrostratigraphy (simplified lithological description). The local aquifer potential is marked as: excellent, regional (+++); very good (++); good (+); weak and slightly aquitardal (±); aquitardal (-); nil / '*aquicludal*' (--). Abbreviations: Lst = Limestone; Dol = Dolostone; *italic* = accessory or other character; (in brackets) = separate, secondary rock layer. Note: Equivalent Israeli formation names are listed in Table 4.1 and Appendix 3.1.

Age	Group	Symbol	Formation	Lithology	Local	Regional
Senon.	Abu Dis	AD	Abu Dis	Chalk	- -	Top Aquiclude
Turon.	West Bank Group	JER	Jerusalem	Lst, *karstic*	+++	Upper Aquifer
Cenomanian		u-BET	Up-Bethlehem	Lst / Dol, *karstic*	+	
		l-BET	Low-Bethlehem	Lst, *chalky* (+ Marl)	- / ±	
		HEB	Hebron	Lst (Dol), *karstic*	+++	
		u-YAT	Up-Yatta	Marl	- -	Middle Aquiclude
		l-YAT	Low-Yatta	Lst (+ Marl, *chalky*)	+ / -	
Upper Albian		u-UBK	Up-UBK	Lst, *karstic*	++	Lower Aquifer
		l-UBK	Top low-UBK	Dol, *marly*	+	
			Low-UBK	Marl, *twin bands*	-	
				Dol, *chalky* (+ Marl)	±	
		u-LBK	Up-LBK	Lst, *fractured*	++	
		l-LBK	Low-LBK	Lst, *karstic*	+++	
Lower Albian / Upper Aptian	Kobar	QAT	Qatannah	Lst, *marly* (+ Marl)	- -	Bottom Aquiclude
		EQ	Ein Qinya	Lst	++	
		TAM	Tammun	Marl & Shale	- -	

In the **Lower Aquifer**, the main aquifer unit consists of the bottom l-LBK and u-LBK formations with karstic limestones (also some fractured dolostones). Above that follows a unit with rhythmic alterations of dolostone in dm- and marls in cm-layers. Locally, these carbonatic banks may allow some low rate spring discharge (as often observed in neighbouring Ramallah city). Towards the top a conspicuous twin band of yellow marls was observed in the outcrops of central Wadi Natuf, thus

forming an impermeable aquitard below the only somewhat chalky and marly dolomite. Therefore this upper section is a separate aquifer unit on the local, as observed by the many contact springs emerging at the contact with the twin marl bands. This top of l-UBK is separated from the overlying u-UBK by a 2-m thick layer of slightly carbonatic, bright yellow marl. U-UBK, sequence consists of highly porous and karstified limestone from the detritus of a back-reef lagoon of mostly corals and some molluscs and gastropods. The reefal limestone forms excellent aquifer, however with reduced thickness.

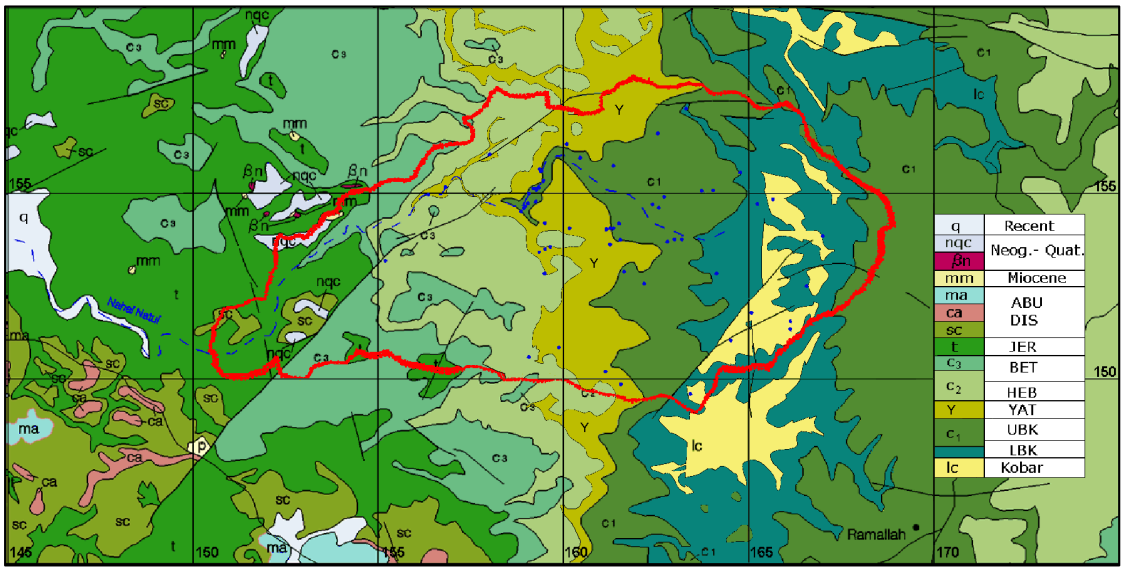

Figure 3.3: Simplified geological map of Wadi Natuf (abbreviated formation names as in Table 3.1)

Upper and lower Yatta formations are generally considered the **regional aquitard** that separates the Lower Aquifer from the Upper Aquifer. Its upper 10 to 15 m thick yellowish marls and sometimes clays form the regional aquiclude. However, the colourful facies of the main and lower part, an up to 110 m thick mixture of dolomite, limestone, marl, chalk, quartzolite and chert, has considerable aquifer potential in central Wadi Natuf. It gives rise to many perched springs (see chapter 3.2).

The **Upper Aquifer** again can be subdivided into at least two aquifer units with a separating somewhat marly layer in between. At the bottom, Hebron formation of pure massive limestone is highly karstified with strong features of epi-karst at outcrop thus forming a highly permeable aquifer. Hebron formation is overlain by lower Bethlehem, which in Wadi Natuf alternates colourful plated limestones with thin marl interlayers. By contrast, upper Betlehem consists of pure and karstic hard, thin-bedded limestone. This local facies stands in contrast to the Eastern slopes of the West Bank, where the lower part is aquiferous and the upper part impermeable, well studied in Ein Samia well field, 13km east of Wadi Natuf (Ries, 2016, Schmidt, 2014). In Wadi Natuf, upper Bethlehem has a tendency to thin out and can completely disappear, as near Shibteen, where lower Bethlehem is directly overlain by the thick Turonian limestone of Jerusalem formation, an excellent karstified aquifer. Again, this hydrostratigraphy is local. In the eastern slopes, the Turonian is divided into three different lithostratigraphic formations with a somewhat impermeable marly unit at its bottom, while here Jerusalem is one unified formation. In the East, Jerusalem often forms an independent so-called “uppermost aquifer” (Wolfer, 1999; Toll, 2001, Toll et al., 2009), separated from lower Bethlehem. However, in Wadi Natuf, the lack of drill records and piezometric data does not allow a definite conclusion whether it is connected or separate from upper Bethlehem.

The regional 'aquicludes' also comprise of the Senonian chalks (Abu Dis group), which form the impermeable **top cover** series; however, they have sparse outcrops in Wad Natuf. The Aptian and Lower Albian sequence (Kobar Group) marks the initial Cretaceous transgressions over the then tropical Palestinian micro-plate before the Upper Albian to Cenomanian carbonatic shelf platform facies was established. It usually is assigned aquitard characteristics and its formations (Tammun, Ein Qinya and Qatannah) are therefore considered as the regional **bottom 'aquiclude'** of the Mountain Aquifer. However, on the local scale, individual aquifer horizons can be discerned (see chapter 2.2), such as Ein Qinya formation, named after the productive Ein Qinya springs, just 2.5 km outside the SE-border of Wadi Natuf and on the outskirts of Ramallah. Elsewhere in the West Bank, the Kobar group formations rarely crop out.

In sum, it can be said that the regional Upper Aquifer breaks up in at least two aquifer units, separated by l-Bet aquitard. The Lower Aquifer is represented by LBK only, whereas UBK and l-Yat form small local intermediate aquifers to be discussed in further detail in chapter 6.2. The precise hydrostratigraphy in Wadi Natuf was given much attention as it formed the basis for the basin classification framework (see also chapter 6 and Appendices 6.1 and 6.2).

3.1.3 Landform correlation

This section briefly presents some of the field observations and findings on the physical features and landscape characteristics, aka landforms, such as the relief, soils, vegetation and land use. As discussed in the introduction, the *basin form* can serve as a proxy to indicate hydrological processes representing *basin impact*. More details and illustrations of the field findings can be found in the excerpts of the SUSMAQ-report on the field measurement campaign (Appendix 3.1).

Relief

Rising from roughly 150 m asl to elevations of over 800 m asl, most of Wadi Natuf is dominated by slopes. As a first approximation, the study area can be divided into three major zones: *Upper Wadi Natuf* is dominated by relatively steep but terraced slopes, for the most part still maintained as olive orchards. A more moderate relief with undulating hills and occasionally small inland plains can be found in the *central part*. The foothills in *lower Natuf* border on the coastal plain with more gentle slopes and with plains at the western edge of the catchment. Appendix 3.1 relates typical relief forms to the underlying geological formations and in more detail.

Soil

Although older Israeli soil maps (Dan et al., 1975) indicated the presence of brown and pale rendzinas in the central and southern catchment area, this could not be confirmed by the field surveys. Only one soil type, terra rossa was confirmed throughout the study area. The prevalence of this red Mediterranean relict soil is not a surprise, given Wadi Natuf's sub-humid to semi-arid climate and overall carbonatic lithology. Field sampling showed slightly varying degrees of clay and silt content (see Appendix 5.1). The most important, hydrologically active soil feature therefore was

its thickness, which was studied in a systematic field exploration and sampling campaign by the SUSMAQ-project with hundreds of samples taken and with dozens of sites where soils were dug up by hand until the underlying bedrock was exposed. These depths were then inserted in a soil matrix, and listed together with underlying geology, relief, land cover and vegetation (see Tables 1 and D1 in Appendix 6.1). Soil thickness was found to usually range between 20 and 100 cm and to correlate with the other physical features above.

Vegetation

Wadi Natuf is still an overwhelmingly rural area with 'natural' vegetation cover, all of which is actually formed by millennia of human action, e.g. cultivation, pasture, deforestation and afforestation, etc. For example, little is left of the main native tree, the Palestinian oak (*quercus calliprinos*). Most of the landscape is covered with grassland and sclerophyllous vegetation. The mountains and upper slopes are characterized by olive groves on man-made terraces. Some olives are also found in the lower Western foothills. Small areas in central Wadi Natuf are covered by recently planted needle-tree forests (mostly pines). Here we also find complex vegetation and much reduced areas under cultivation, usually in garden-size plots, occasionally in extended fields on small plains within the otherwise hilly relief. Depending on the geological formation, rocky outcrops can reach sizeable portions of the areas, namely the very karstic formations (l-LBK, Hebron and Jerusalem). Again, typical types of vegetation can be assigned to different areas with varying climate, soil cover (thickness) and geology.

Land use

In the immediate vicinity of Wadi Natuf, Lange et al (2001) studied and reported on the effects of urbanisation on hydrological processes such as the enhancement of runoff. By contrast, almost all of Wadi Natuf remains rural. Here, the Palestinian traditional agriculture interferes with nature and alters the landscape with the opposite effect, partly intentionally, partly involuntarily. The construction and maintenance of agricultural terraces, mostly with rainfed olive orchards follows a conscious decision to diminish runoff and soil erosion in order to enhance soil water uptake by the tree roots. Supporting walls of terraces are constantly maintained and repaired, the small terraces are ploughed and weeded around the olive trees twice a year and therefore, after heavy rain storms, even on steep slopes, the horizontal terrace plots were observed to trigger minimal runoff; instead, ponding over periods of several days was noticed. In turn, and involuntarily, these traditional methods enhance soil infiltration and percolation (ground water recharge). Where terraces are abandoned, runoff almost immediately increases. To less an extent, but similarly, human-made landscape features such as planted forests and cultivated fields in the small plains can lead to decreased runoff. By contrast, modern human land use activities often enhance runoff (and thereby decrease recharge): Over the study period, the instalment of unregulated solid waste dump sites and of small (Palestinian) and large (Israeli) quarries right inside the wadis could be observed. Their effects on runoff behaviour were studied and are discussed in Messerschmid (2014).

Again, the different types of land use were mapped and could be linked to the other forms of physical landscape features, such as natural vegetation, relief, soils and geology (examples of these findings in Appendix 3.1).

A stunning example of this linkage between different groups of landforms is the wooded hilltop of Nabi Ghayth, 500 m northeast of Deir Ammar (Fig. 3.4, 3.5). Here, four geological formations crop out, each with a distinct type of relief, vegetation, soil thickness and land use. At the bottom, **lower Yatta** formation, the somewhat marly aquitard with intercalated carbonatic aquifer layers forms a stepped relief of soft and rounded natural terraces, mostly uncultivated (see Fig. 7, 8 in App. 3.1) but spring bearing at the bottom of the perched aquifer outcrops. The overlaying pure marls of **upper Yatta** formation erode more easily; they form decreased slopes or steps in the landscape, which at times develop into small inland plains with thick soils, well prepared for field crop farming. This levelled step in turn is followed by steeper slopes of the highly karstic **Hebron** formation. The active epi-karst develops into barren rock outcrops and a *karren & schratten* landscape with small soil pockets and without larger vegetation, entirely void of farmed land use. Finally, the hilltop is formed by the small forest surrounding the Nabi Ghayth shrine, standing on **lower Bethlehem** outcrops. By contrast to Hebron formation, the colourful plated limestone outcrops of l-Bet are intercalated with thin marl layers and allow the development of soil layers, to which the woodlands are bound.

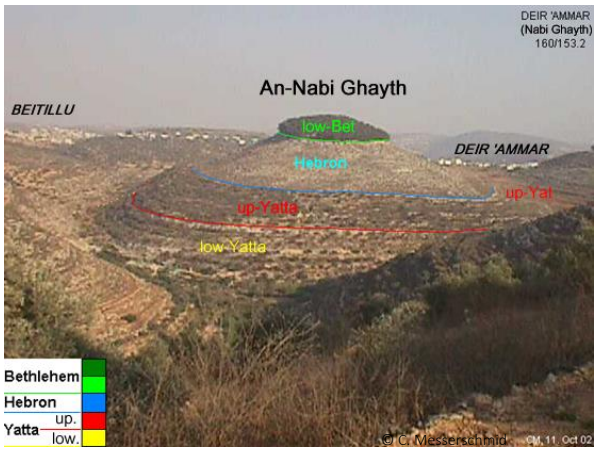

Figure 3.4: Nabi Ghayth from West

Figure 3.5: Nabi Ghayth from south

As an overview, three general, typical types of landscape in the eastern mountains (upstream), the central area (midstream) and the western foothills (downstream) are shown in Fig. 3.6, 3.7 and 3.8.

Figures 3.6, 3.7, 3.8: Landscapes – upstream terraced slopes, midstream undulating hills and downstream karstic foothill plains

3.1.4 Existing studies and literature on Wadi Natuf

Before the occupation in 1967, only Rofe and Raffety (1963) in their important hydrogeological assessment of the West Bank for the Jordanian water authority provide some cursory introduction into the regional hydrogeological setting of Wadi Natuf but without any detailed discussion of the catchment. Drilling records and pumping test reports for the only well in Wadi Natuf (Shibteen #1), drilled by the Jordanian water authorities in May 1967 were probably written but could not be found despite repeated efforts and requests in Amman. Some scattered water level recordings from the years under Israeli occupation are available at the West Bank Water Department (WBWD) and PWA database. An Israeli Master thesis dealt inter alia with Natuf, a post-factum reconstruction of palaeo-floods during the century rainfall event in winter 1991/92 (Ettinger, 1996), but without any real time hydrological time series data.

In 1999, University of Freiburg, Br., together with Palestinian Hydrology Group (PHG) and others started a research programme with field investigations on runoff, either as impact of urbanization in the Ramallah area or through sprinkler experiments using natural tracers in natural environments in immediate vicinity of Wadi Natuf. The publications of this research overlapped with and inspired the SUSMAQ project (Lange et al., 2001; 2003a; 2003b). Otherwise, studies were mostly local as from Bir Zeit University and focussed for the most part on spring water quality and possible pollution problems (Shalash, 2006; Shalash and Ghanem, 2008). Fischhendler and Frumkin (2008) mapped and counted some caves in parts of Wadi Natuf and correlated their types to different formations. While highly interesting as an approach, their assigned formations stand in stark contrast to almost all the field findings of this doctoral research and cannot be reconciled with the official geological maps by the Geological Survey of Israel (GSI). Otherwise, the focus on spring water quality continues until recently, with Ghanem et al. (2017) and Atta (2018).

The most recent publication, a PhD-thesis by Jebreen (2019) gave a rough estimate of groundwater recharge in the central West Bank region (including Wadi Natuf), based on the chloride mass balance (CMB) method and with monthly precipitation data (see also: Jebreen et al., 2018a; 2018b). By comparison with the findings of this research, Jebreen's largely hydrogeochemical investigations slightly underestimated recharge, as is often the case with the conventional CMB method, especially in karstified and semi-arid basins with point recharge (Somaratne and Smettem, 2014; Hiscock, 2009) an during few events or pulses per season (Schmidt, 2014). Otherwise, only Andrew Hughes, who had participated in the SUSMAQ project, published recharge models on his own or with British colleagues after the end of SUSMAQ project. In their studies, Hughes and Mansour (2005) and the BGS (Hughes *et al.*, 2008) applied their pre-existing, so-called object-oriented model to Wadi Natuf, albeit without any reliable field data and based mostly on artificial or even arbitrary synthetic input data. This trend of increased mathematical model sophistication at the expense of solid, reliable field investigations and in quasi-lumped integrated approaches was already discussed and the lessons drawn from this global development by the international literature under the IAHS-decade on PUB were already presented in the introduction (chapter 1).

In sum and for all ends and purposes, at the onset of this research, Wadi Natuf could be considered a classical ungauged basin with lack of both, hydrological observation and field measurements. And up until now, no research has been published that really addresses the spatial distribution of groundwater recharge in the WAB, based on solid field measurements.

3.2 Perched springs in Wadi Natuf

As already mentioned earlier, the coarse regional hydrostratigraphy with its division into only two aquifers (Lower and Upper Aquifers) and one aquitard in between, may be adequate for lumped flow models at the basin scale, but it does not suffice for the purpose of investigations into the spatial distribution of groundwater recharge processes within the recharge zone of the mountains and slopes of the WAB. In particular, extended field investigations and mapping in Wadi Natuf showed that, at least at the local scale, important deviations from the unifying regional stratigraphy can be observed. One such example is presented in SUSMAQ report # 65 (Perched springs), see Appendix 3.2: This report documents and illustrates some field investigations on the perched local aquifers in central Wadi Natuf and their abundant spring outlets positioned stratigraphically above the main, regional aquifers (Fig. 3.9). In Wadi Natuf, these local perched aquifers occur on isolated hilltops, each issuing at a spring group, which is aligned on their western to west-north-western flanks (according to the direction of general dip in Wadi Natuf), see Fig. 3.10.

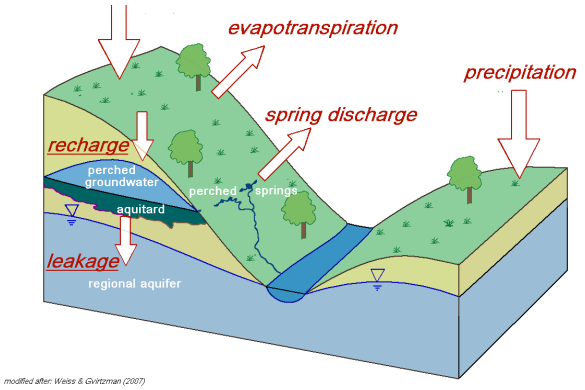

Figure 3.9: General concept of local perched aquifers underlain by leaky aquitards and contributing groundwater to the deeper regional aquifers through downward groundwater leakage.

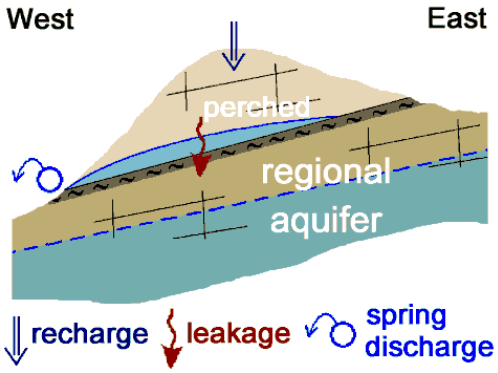

Figure 3.10: Conceptual, schematic representation of perched leaky aquifers on isolated hilltops in Wadi Natuf. Note that the underlying aquitard (dark brown) is outcropping on all sides.

After discussion of practical field access problems due to army and settler presence, the first report (on July 13, 2003) introduces some of the springs visited in Beitillu (Fig. 3.11), their issuing formations and catchment areas. The report concludes, based on the alignment of springs and their stratigraphic positions, that some of these local aquifers are perched aquifers.

The report of the next field visit (July 19, 2003) already introduces over 40 additional springs in the Beitillu and Wadi Zarqa areas, their location, the lithology of their issuing rock formation and their stratigraphic position together with a list of some discharge measurements. Again, springs were grouped by hydrostratigraphic and geographic positions in distinct spring groups belonging to and issuing from three different perched aquifers in Lower Yatta formation (*Beit Meir* in Israeli nomenclature), Upper UBK formation (*Kesalon*) and the uppermost part of Lower UBK (*Soreq*) formation. It should be noted that this hydrostratigraphy departs form the conventionally used

regional hydrostratigraphy, in which all of Yatta formation is seen as the regional *Middle Aquitard* and all of UBK and LBK formations together as one combined regional *Lower Aquifer* (LA).

Figure 3.11: Photo taken from Beitillu (*hill at 596 m asl*), view towards East overlooking Harat Al-Wad neighbourhood with the springs Ein Al-Kos and Ein Al-Balad.

All springs encountered in Wadi Natuf were found to be contact springs according to the classification system of Fetter (1994). Due to their large number and small catchment areas, the springs of these spring groups are small and very small springs with low and very low discharge. For example, in the third report from July 23, 2003, the ~40 springs measured were discharging in a range between 0.24 and 57.41 l/min (0.004 – 0.96 l/sec).

Later, five of the perched springs were selected for daily discharge measurements. In the first measurement season (2003/04), we tried to install conventional 1.5 inch water meters (Arad Co.) for the daily reading, which however proved unreliable due to clogging and manipulation by by-passers. Also, such water metres attracted the attention to uninvited visitors (be it Palestinian children from the villages or Israeli settlers and army). Therefore, in late 2003, we switched the daily measurement procedure back to the conventional bucket and stop watch method, which proved robust and reliable throughout the following years of measurements to come. Two of the five springs are located in Wadi Zarqa (Ein Salem and Ein Al-'Akkari) and three in Beitillu, Harat Al-Wad neighbourhood (Al-Qos, Al-Bibi and Ein Abu Sa'efan). Each spring was measured by local youth and young adult volunteers who reside in the immediate vicinity of the spring. They were field-trained in the procedure and visited in monthly or bi-monthly intervals to discuss their findings, new developments of the springs and obtain their field records.

All in all, over 100 springs were found to discharge in central Wadi Natuf (mostly in the surroundings of Beitillu and Wadi Zarqa). Most of these springs could be attributed to one of seven different spring groups, the names of which were introduced by me and refer either to the closest landmark nearby (*Zarqa bridge, Ein Ayoub station*), or to the area and village, where they are located (*Beitillu, Wadi Zarqa*) or were named after the most productive, principle spring of the group (*Nabi An-Neer, Shakhareek*). It was of course not possible to measure all these springs regularly, let alone on a daily basis. Instead, it was decided to carry out four key date campaigns for flow measurements at all measurable springs of the seven spring groups at each of the perched hilltop aquifers in central Wadi Natuf. These comprehensive key date measurement campaigns were carried out four times, i.e. during summer 2003, winter 2003/04, summer 2004 and summer 2007 (see Appendix 6.2).

CHAPTER 4

DESIGN, SETUP AND INSTRUMENTATION FOR THE WADI NATUF MEASUREMENT CAMPAIGN

4.1 Preparatory work for the conceptual model

Building on the field observation of the exploration campaign, the physical features and observation of hydrological processes, the development of a first tentative conceptual methodology framework was approached (see App. 4.1 - SUSMAQ report # 64). It deepened many of the aspects in the former report, particularly with respect to the local hydrostratigraphy and boundary conditions of Wadi Natuf. It also provided a first, still relatively rough and tentative estimate of Natuf's flow budget in terms of both inflows and outflows. The resulting estimate of this initial analysis led to a prediction of an approximate range of groundwater recharge between 25 and 30 mcm/a in Wadi Natuf. It should be noted that this initial estimate lies very near the final result of the doctoral research: the model and calculations resulted in a final estimate of average groundwater recharge between 24.1 and 28.1 mcm/a (chapter 6.2).

The already described landforms (Ch. 3, App. 4.1) were summarized and grouped according to the main aquifer and aquitard units. And, based on the main landscape features and types of parameters enabling or inhibiting recharge, the report attributed different degrees of *estimated aquifer potential* to the lithostratigraphic units (Table 4.1), the range of which was qualitatively estimated according to field observations – reaching from 'excellent' aquifers to impermeable aquitards ('poor' or 'very weak', see Fig. 4.1 and Table 4.1).

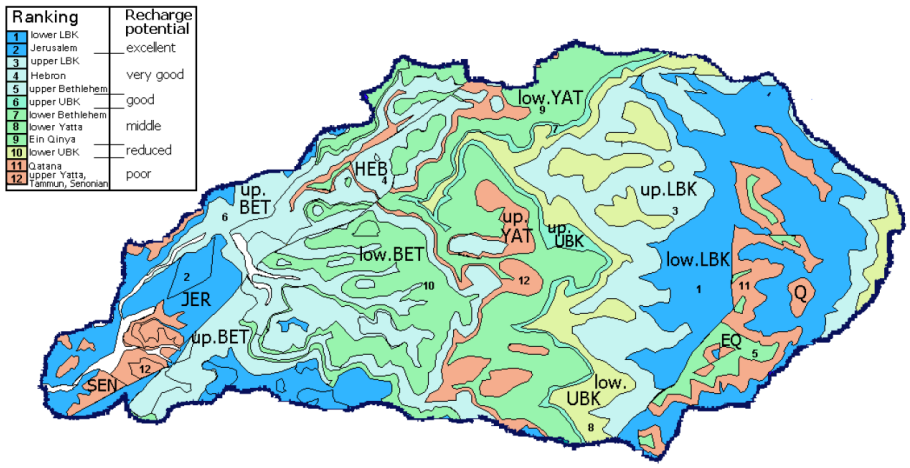

Figure 4.1: Recharge potential of the different formations in Wadi Natuf

Table 4.1: Recharge potential of the different formations. The potential ranges between excellent potential in karstic aquifers to impermeable aquitards, with the symbols: +++ (excellent), ++ (very good), + (good), ± (middle), - (weak), -- (very weak).

Formation name		Recharge potential	Perched springs	Aquifer potential	Ranking	Notes
Palestinian	**Israeli**					
JERUSALEM	Bi'na	+++	NO	+++	1	Eastern aquifer forms two aquifer systems
Upper **BETHLEHEM** Lower	Weradim	+	YES (forced out by Kefar Sha'ul)	+	2	Dry in Eastern Aquifer as WT too low
	Kefar Sha'ul	+-	NO (possible)	+-/-	3	Poor aquifer/aquitard
HEBRON	Amminadav	++	NO	+++	1	
Upper **YATTA** Lower	Moza	--	NO	--	4	Not always present
	Bet Meir	+-	YES	-/+	3	Normally aquitard, but can be a good aquifer
Upper **UPPER BEIT KAHIL** Lower	Kesalon	+	YES (few)	+	2	Not always top Lower but locally intermediate aquifer.
	Soreq	+/+-	YES	+-	2	Horizontal layers of Marls inhibit vertical movement and produced perched system
Upper **LOWER BEIT KAHIL** Lower	Giv'at Ye'arim	++/+++	NO	++	1	Dependant on fractures
	Kefira	+++	NO	+++	1	Fractured, but always produces good flow from wells
QATANA	Qatana	-	NO	-	4	Aquitard
EIN QINYA	Ein Qinya	++	YES	++	4	Good local aquifer, but does not feed main aquifers

The report then went on to describe in more detail the prevailing mechanisms of recharge and runoff generation, and building on this, sketched out a preliminary conceptual approach for the measurement campaign and analysis of the measured data. This initial design was not yet based on quantitative results, but mostly on qualitative observations only and had to be adapted accordingly, but slightly, after the first season of measurements (2003/04). In addition, not all suggested tests were carried out successfully – that is: some were tried but proved unsuccessful, like the double ring infiltrometer tests. Others could not be carried out, partly for budgetary reasons.

In brief terms, this part of the report already discussed the reasons why some of the usually applied investigation methods were either not suitable or not applicable in Wadi Natuf, a previously ungauged basin as already detailed in the Introduction (chapter 1). Furthermore, under the prevailing circumstances of ultimately exclusive Israeli land control, the applicable observation methods, particularly for the underground, were severely limited. Therefore, so-called *direct approaches* were chosen. As Dörhöfer and Josopait (1997) prescribed, such methods employ surface-near observation methods in order to gain „*the most differentiated possible understanding of the infiltration process, taking into account evapotranspiration, as well as the portions of surface runoff and interflow*" (see also Lerner *et al.*, 1990). For the meteorological drivers of recharge, such surface-near observations include the recording of precipitation and of the atmospheric factors that enable or limit evapotranspiration. Hydrological drivers are approached by direct field measurements of runoff in the ephemeral streams (wadis) and of soil moisture content. In addition, physical features can be recorded by qualitative and quantitative methods such as mapping geology and hydrostratigraphy land use and land cover features, as well as soil types and thickness.

The report thus drew a general conclusion, i.e. that a combination of soil moisture budget calculations with an overall water budget approach of in- and outflows was the principle way forward under the particular field conditions in Wadi Natuf. This early decision has proven correct and remained unchanged throughout the following years of data collection and analysis.

As a last point, the report then gave an introduction into the field measurement programme, the instruments needed, their location and conditions of installation. As a word of caution and with hindsight it must be remarked here however, that some of the intentions, particularly with the intensity and frequency of field visits and data collections proved to be somewhat over-ambitious. Some of these components had to be cut-back in the following years, among other reasons due to lack of field staff.

4.2 Development of a conceptual recharge model for Wadi Natuf

Some additional conceptual considerations were prepared for and presented at the XXXIII Congress IAH & 7° Congress ALHSUD in Zacatecas, Mexico (Nov. 2004), here documented as an extended abstract: “Development of a conceptual recharge model of Wadi Natuf catchment, Palestine” (Messerschmid et al., 2004; see App. 4.2). The paper first presented the two hydrostratigraphies, i.e. at the regional and at the local scale for Wadi Natuf (Fig. 4.2 and 4.3 below). It then differentiated between three groups of recharge mechanisms, e.g. direct recharge (observable through soil moisture measurements *in-situ*), indirect recharge (observable as transmission losses from runoff in ephemeral streams) and a third mechanism, related to the perched aquifers on isolated hillsides, from which over 100 springs emerge.

However, it should be noted critically that some of the expectations, voiced at that early stage, were not confirmed in the course of field measurements and observation throughout the following years: Runoff turned out to be far below the expected rates, usually quoted in the literature for adjacent catchments in the WAB. It was found rather negligible, at least in the overall balance of recharge in Wadi Natuf (see chapter 6.2).

Also soil pockets had to be treated differently than expected back then. The extended abstract in App. 4.2 claims: “*Pure soil moisture balance approaches would be misleading since large areas of the catchment significantly, or even entirely, lack a continuous soil cover.*” However, and as shown later by Ries (2016) and Sohrt et al. (2012), in the epikarst landscape of the West Bank’s mountain range, most of the recharge takes place through the small patches of soil surrounded by karstified carbonate rock outcrops (with preferential flow paths along the soil-rock contact). The natural depressions (Fig. 4.4), usually in a size of decimetres to one meter, act as funnels, which redirect precipitation from the rock surface into the nearby soil stratum. In other words, most of the rain (or of that portion that is not intercepted or does not evaporate directly from the rock surface) ends up infiltrating into the soil, where then the process of percolation into the underlying aquifer bedrock must be considered as the principle recharge mechanism.

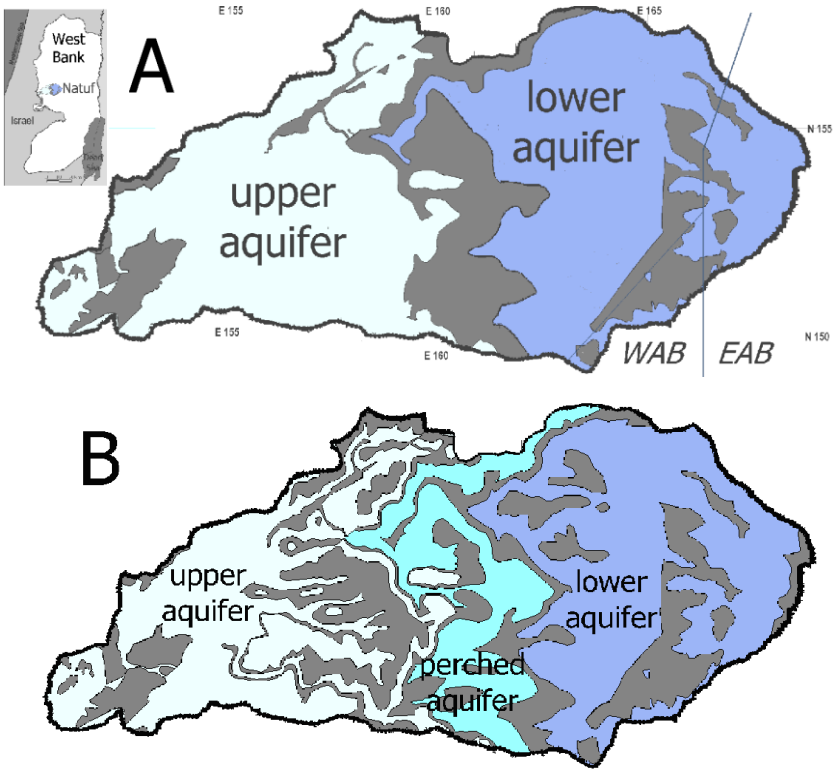

Figure 4.2: Hydrostratigraphical units – A) regional flow model; B) local recharge model

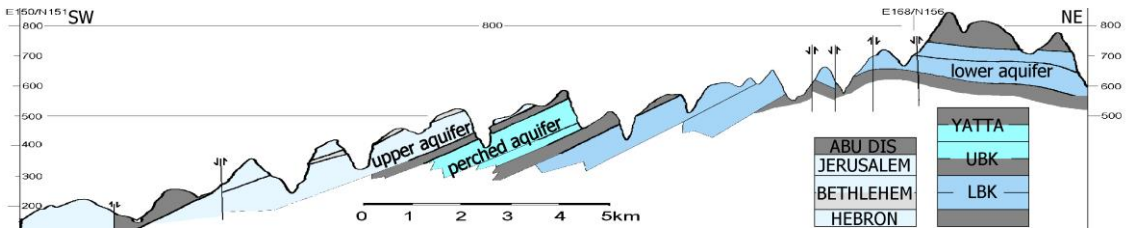

Figure 4.3: SW-NE Cross sections through Wadi Natuf (somewhat simplified hydrostratigraphic and lithostratigraphic layers)

And finally, as a side note, it should be remarked that the soil infiltration tests, by means of a double ring infiltrometer, although carried out at over twenty plots, proved to be inconclusive, or rather: misleading: Apparent infiltration rates into the soil were systematically “measured” far beyond the rates and speed expected and reasonable. The test results therefore had to be dismissed and were not included in the further analysis.

Besides these critical points, most other expectation of the report were met and confirmed and applied successfully in this PhD research.

Figure 4.4: Epikarst in the lower slopes of Wadi Natuf – karren landscape with soil pockets, Upper Bethlehem formation near Deir Abu Mash'al.

4.3 Purchase and Installation of field measurement equipment

The report SUSMAQ # 68 (Purchase and installation of field measurement equipment for Wadi Natuf recharge assessment study) gave a short overview of the field equipment used for the Wadi Natuf recharge measurement campaign in the winter season 2003/2004. It provided summary data on the prices of the items and equipment used and an overview over the status of equipment. It then proceeded to give a short overview over the main activities in the campaign and its results from a performance point of view. It did not tackle the technical results of the campaign as they were still under process of being generated and thus were to be addressed in more detail in the reports to follow. Finally this paper presented the main lessons learnt (again on the performance side) and the most important conclusions and recommendations for the following years (season 2004/05 and beyond).

It should also be noted here that in the years to follow, more, new equipment was purchased by me and employed in the measurement campaigns, as for example the soil moisture measurement devices ECH_2O…, which successively replaced the theta probe sensors and loggers used in the two first seasons. Details on this additional equipment are provided in App. 6.1.

4.4 Wadi Natuf field measurement campaign

The poster in Appendix 4.4 provides a visual presentation of the instrumentation at Wadi Natuf used for the measurement of precipitation and other atmospheric drivers, as well as for runoff, soil moisture and spring flow recordings. (In addition, a TV-log was performed at Shibteen well # 1, an old unequipped borehole with a broken casing that rendered it unfit for observations). The maps include geography and drainage, the locations of field instruments, regional hydrostratigraphy and the ranking of lithostratigraphic formations as to their recharge potential. The poster was produced for an internal SUSMAQ project workshop at the end of the first measurement season (2003/04) and remains unpublished to this day.

CHAPTER 5

RUNOFF

Wadi Natuf lies in a semi-arid to sub-humid climate zone with an average annual area precipitation of 602 mm during the nine seasons measured during 2003/04 and 2011/12 (Fig. 5.1, Table 5.1).

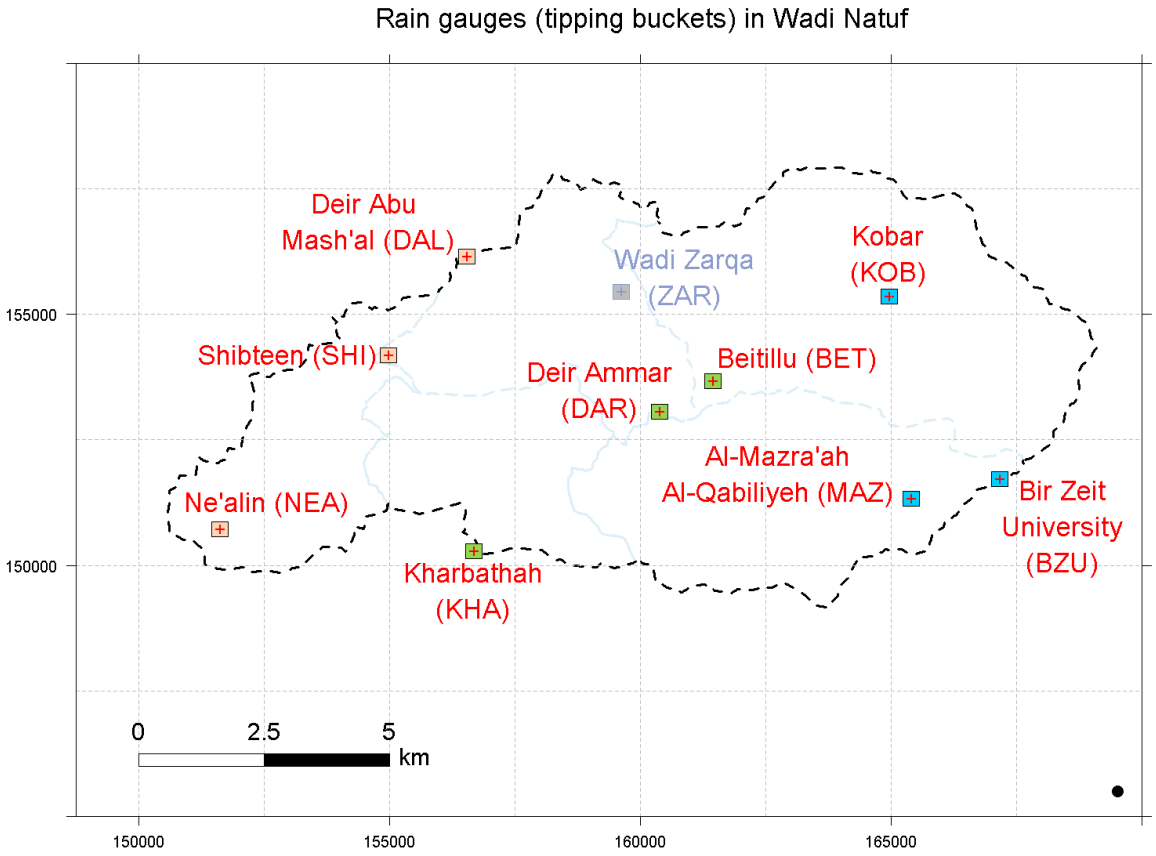

Figure 5.1: Rain gauges (tipping buckets) in lower, central and upper Wadi Natuf. Complete record from 2003/04 until 2011/12 (Wadi Zarqa tipping bucket was installed in 2006/07).

During the measurement period, the driest winter was the rainy season 2007/08 with only 483 mm/a and the wettest the winter season 2011/12 with 768 mm/a of catchment-wide area precipitation. In individual years, the driest and wettest annual station values were 414 mm/a (NEA, 2007/08) and 884 mm/a (BZU, 2011/12), respectively. Figure 5.2 shows interpolated area rainfall (IDW-Method) for these nine seasons 2003/04 – 2011/12. (Measurements were continued until the

end of the season 2012/13, but only for selected stations. Only one station continues to be read until now, Beitillu station, BET).

Table 5.1: Annual precipitation heights at nine rain gauges in Wadi Natuf (mm/a). Lower part: Ne'alin (NEA), Deir Abu Mash'al (DAL) & Shibteen (SHI); Central area: Kharbatha (KHA), Deir Ammar (DAR) & Beitillu (BET); Upper part: Mazra'ah Al-Qabiliyah (MAZ), Kobar (KOB) and Bir Zeit University (BZU).

Year / (mm/a)	NEA	DAL	KHA	SHI	DAR	BET	MAZ	KOB	BZU	Area Ø
Elevation (m asl)	*222*	*471*	*396*	*229*	*540*	*506*	*655*	*649*	*792*	*496*
2003/04	487	479	479	504	542	569	543	552	547	**522**
2004/05	620	650	656	668	718	778	784	883	828	**732**
2005/06	550	550	603	611	591	612	598	731	698	**616**
2006/07	558	581	613	591	612	677	650	669	702	**628**
2007/08	414	445	459	480	476	508	540	550	477	**483**
2008/09	487	529	539	532	560	596	600	611	646	**567**
2009/10	499	532	552	545	574	612	615	626	669	**580**
2010/11	450	483	498	491	517	551	554	564	602	**523**
2011/12	660	709	730	721	759	809	813	828	884	**768**
mean precipitation 2003/04-11/12	**525**	**551**	**570**	**572**	**594**	**634**	**633**	**668**	**673**	**602**

Much of the annual precipitation occurs in a series of events between November and April. When daily precipitation is very low and remains below the rate of evapotranspiration, it cannot be considered hydrologically effective precipitation (HEP). But at rain heights of $\geq$ 5 mm of daily rainfall, this surplus precipitation (HEP) can be considered to accumulate in the soil. During the measurement period 2003/04 to 2011/12, an average rainy season had 77 days of precipitation, of which between 17 and 32 days (in average 26.2 days) had 5 mm or more. This event precipitation ($\geq$ 5mm/d) constituted between 89 % and 97 % of total annual precipitation, with a mean value of 92 %. In other words almost the entire annual HEP occurred during these 26 days in average.

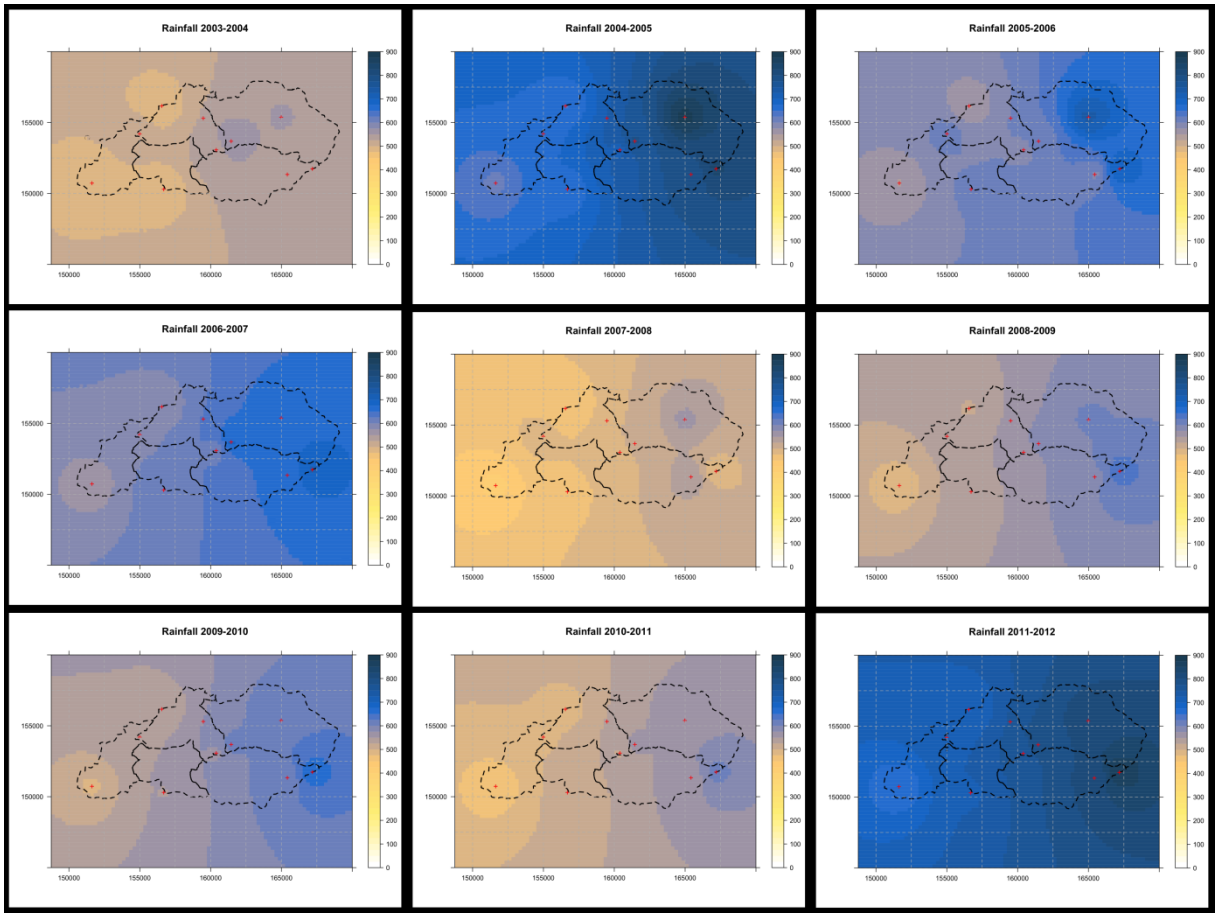

Figure 5.2: Annual area rainfall in Wadi Natuf 2003/04 – 2011/12 (in mm/a)

Even more important is the pattern and contribution of very large events; i.e. events that were observed to trigger runoff during the observation period (2003/04-2010/11). The average number of such events was lying between one and eight events per rainy season, with a mean value of 4.3 events per winter season. Individual precipitation events at this large scale lasted between 10 and 110 hours with an average of 46 hours, equivalent to almost two days. These events usually had a precipitation rate of 50-193 mm (in average 86 mm). The mean accumulated large event rainfall amount per season was found between 193 mm and 591 mm (in average 306 mm/a), which was equivalent to 40 % to 80 % of the respective total annual precipitation or in average, 53% of annual rain. In other words, large events accounted for around half of the annual area precipitation.

The most intensive and largest precipitation event occurred in the night from 1. to 2. April, 2006. Over 125.7 mm poured down in 24 hours (station Kharbatha, KHA) with a short-duration maximum of 42.9 mm/h in Bir Zeit (BZU) at 8 am on the 2. April, 2006. An overview over the rainfall distribution in this night is given in Fig. 5.3 (in hour-steps – mm/h).

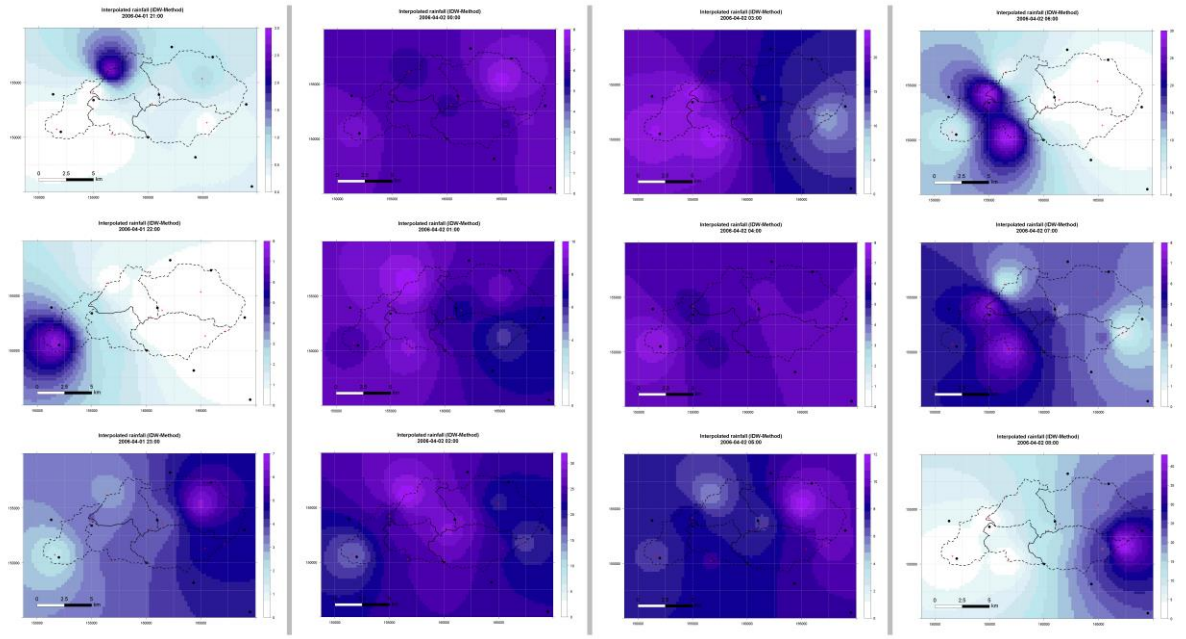

Figure 5.3: Precipitation event, April 2006: Hourly precipitation, 1.4.2006, 9 pm – 2.4.2006, 8 am (mm/h)

5.1 Transmission losses from runoff – indirect recharge

The main focus of this research lies on the spatial distribution of hydrological processes; therefore, temporal changes in runoff are not included in this thesis (for further reading on the impact of land use and land cover changes on runoff in the catchment, see Messerschmid (2014)).

Proper maintenance of the stepped relief, i.e. terraces with intact stone walls such as in the upstream areas and with soils regularly loosened up by seasonal ploughing, plays a key role for the reduction of runoff generation and by that effect enhancement of direct rain infiltration into the soil. Uncontrolled dumping of solid waste directly into the wadi beds locally blocked and slowed flows in the main wadis while at the same clogging of the naturally well sorted coarse gravel in the wadi beds could be observed in the field midstream in central Wadi Natuf and more pronouncedly downstream: Here, large Israeli quarries – and to a lesser degree also small Palestinian quarries – sprang up during the observation period, dumping their rock debris directly into the wadi and onto its banks, thus, simultaneously clogging the wadi gravel fill and channelling the flow inside the walled-in stream. This led to the occurrence of large lagoons of standing water developed in low sections (sinks) of the wadi, prevailing over weeks after an event and in stark contrast to the previously here and elsewhere still found conditions freely running flows in the clean, well sorted gravels. Although not further detailed here, these field observations confirm earlier findings of distinct hydrological feedbacks from human action in local plot- and small-scale studies on the impact of urbanisation in the vicinity of Wadi Natuf, such as by Lange *et al.* (2001), Steinmann (2010) and Grodek *et al.* (2011).

Runoff in wadis is a source of potential groundwater recharge, also known as indirect recharge, as opposed to direct in-situ infiltration into soil or rock outcrops. This potential source of aquifer replenishment was therefore extensively studied and reported in the research article: "*Assessment of transmission loss in a Mediterranean karstic watershed (Wadi Natuf, West Bank)*", documented in Appendix 5.1 (Messerschmid et al., 2018).

As Shanafield and Cook (2014) have explained, transmission loss as a process is difficult to observe and measure and therefore much less studied and reported than other hydrogeological processes like runoff. It had never before been measured directly in the WAB. The special conditions in Wadi Natuf offered a unique opportunity for direct empirical field measurements under controlled conditions, and the design of the measurement campaign was crafted accordingly.

The configuration (Fig. 5.4) consisted of two sets of stations upstream (Wadi Zarqa and Ein Ayoub; their sub-catchments are indicated as *Zar* and *Ayb* in the bottom right map) and midstream (stations Shibteen1 and 2, just before the confluence of the northern and southern branches of the 1st order wadis in the study area). Another station was positioned downstream at the Natuf outlet (Ne'alin station). This distribution provided the study with three so-called *reaches*, i.e. main wadi sections of controlled inflows from upstream and outflows downstream. These reaches were located in the northern and southern branch of the main wadi midstream (*R-1* and *R-2*) and further downstream for the combined flow line (*R-3*), as indicated in the small bottom right map of Fig. 5.4.

In the five stations, 34 runoff events were recorded from 2003/04 until 2010/11. In these 34 events, total cumulative runoff was very diverse spatially, with their sums lying between 0.169 million m^3 (Shibteen Wadi 1 - culverts, midstream) and 2.912 million m^3 (Ayoub station, upstream).

Runoff generation analysis on the event basis (usually 1-3 days duration), when taking into consideration the pre-event wetting up of soils by cumulative pre-event precipitation, also confirmed earlier observations by Ries (2016) and Lange *et al.* (2003a; 2003b), namely that *saturation excess* forms the predominant mechanism of recharge generation. In every of the 128 individual events recorded in the 5 stations, runoff only followed after sufficient pre-wetting.

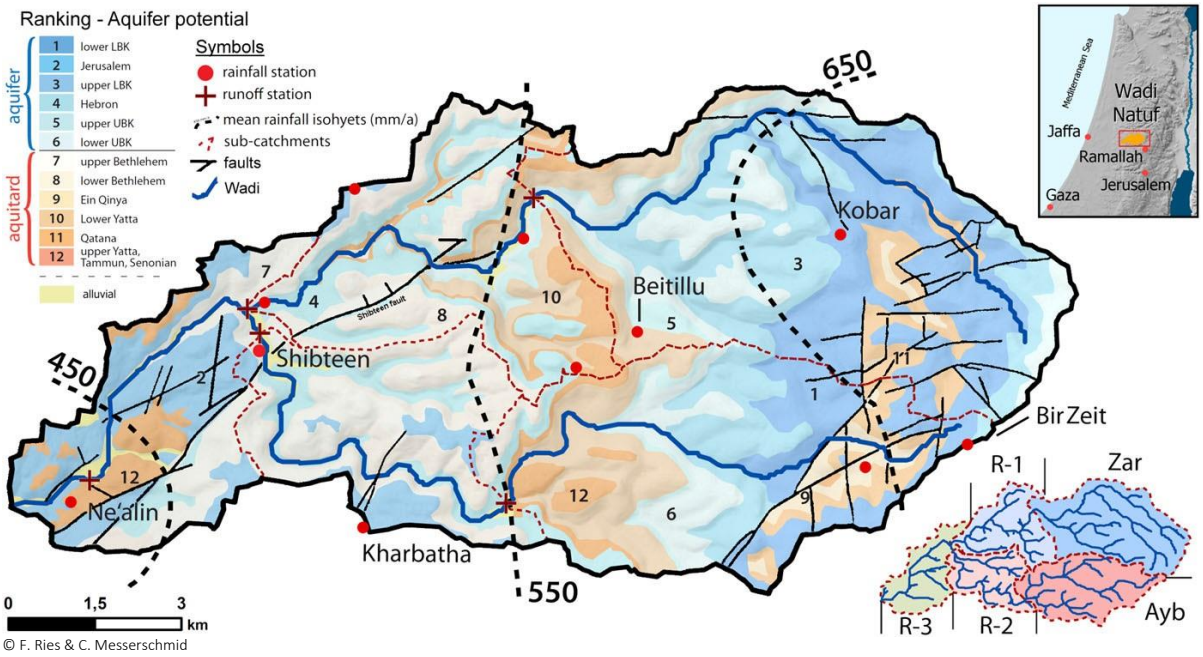

Figure 5.4: Geology, subcatchments and gauging stations in the Wadi Natuf catchment. Rainfall was recorded in nine tipping buckets between 2003/2004 and 2010/2011 (average isohyets) – red dots. Subcatchments are indicated by the dashed red line, their flow was measured in the main wadis at five runoff gauging stations (dark red crosses) by continuously recording level gauges (pressure transducers). Formations were ranked according to their aquifer potential (as qualitative estimates).

Total runoff near the outlet of the entire catchment (Ne'alin station) was 0.328 million m^3 (over 8 seasons), equivalent to an overall runoff coefficient of 0.11 % only. This value, it should be emphasized, lies considerably below the usual estimates for the wider area of the Western Aquifer Basin, where mostly values between 3 % and 6 % had been assumed, measured or estimated (Rofe & Raffety, 1965; SUSMAQ, 2002). Only one in the five stations, the average runoff coefficient was larger than 1 % and reached the ranges from the literature; this was Ayoub station with 3.35 %, due to the outcrops of impermeable marl in the vicinity of the station. The generally very low runoff coefficient in Wadi Natuf was due to two main factors: a) the karstic outcrops of many of the formations allowed for rapid (autogenic) in-situ infiltration and percolation and b) allogenic runoff from the different main and lateral branches did not accumulate downstream but to the contrary, mostly diminished along the course of the streams. This persistent pattern was a clear expression of the strong transmission losses in Wadi Natuf. Often, full transmission loss was observed – meaning, flow was recorded in the wadis upstream but no flow whatsoever further downstream (see Fig. 5.5).

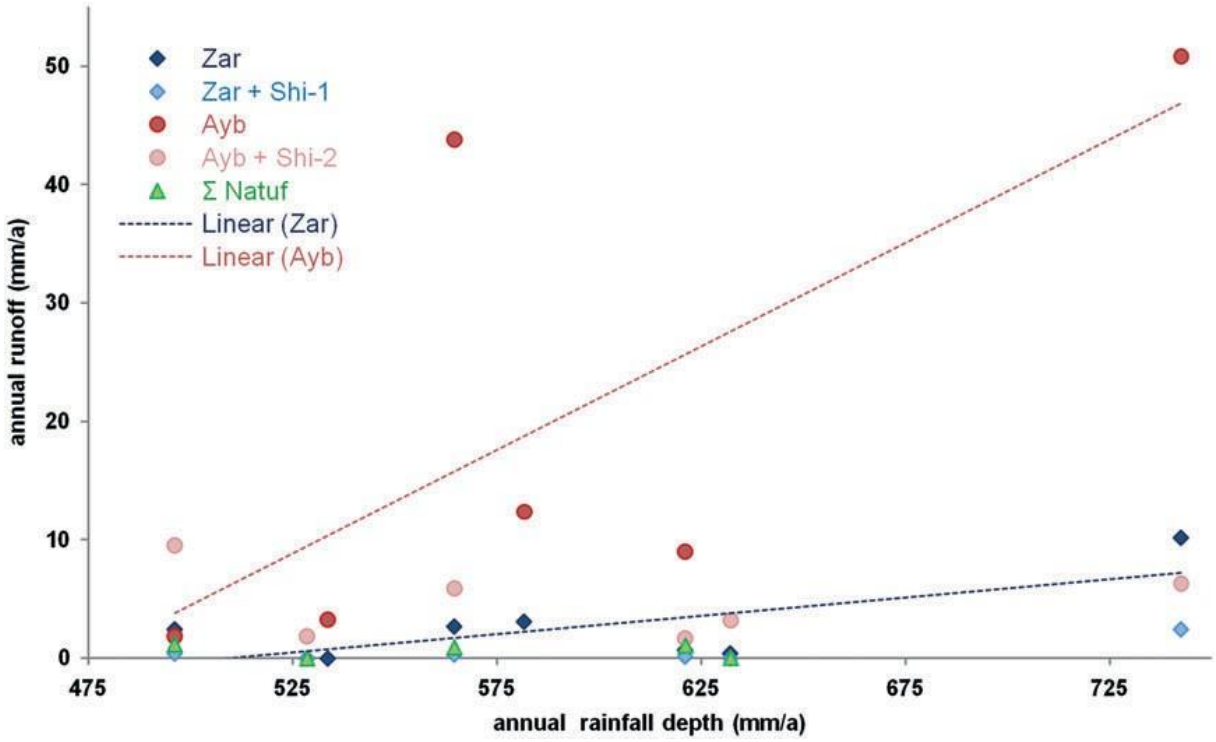

Figure 5.5: Rainfall-runoff relationship. Annual rates of run-off (mm/a) at the five stations versus annual rates of rainfall at the cumulative subcatchments (all rain upstream a station is considered here). Due to the transmission losses, observed wadi discharge did not increase gradually but rather decreased with increasing distance in downstream direction. The lowest run-off volumes and area normalized infiltration rates were measured at the outlet of the Natuf catchment at station Ne'alin (NEA; here in green as total catchment precipitation "Natuf").

It was found that the infiltration rates from the wadi gravels into the bedrock varied in a range between 14 mm/h for a reach with predominantly weak aquifers or aquitards (lower Yatta and lower UBK formations with marly limestones and/or marl interbeddings – Reach 2) and 40 mm/h for a reach dominated by strongly karstified, massive limestones (Hebron formation – Reach 1).

Figure 5.6 shows a correlation between headwater flow (x-axis) and transmission loss (y-axis in) and with the following relationship: Up to approximately 150,000 m^3 of event runoff (x-axis) most events showed near or total transmission loss. Transmission losses ranged between 62 % and 80 % of headwater flow in the reaches R-3 and R-2 (green and red), respectively.

The average event runoff coefficient of the 128 individual event periods recorded in the five stations (and including dry wadis during the event periods) was as low as 1.2 % of total event rainfall. Therefore and despite the high transmission losses, localized *indirect groundwater recharge* through wadi bed infiltration in Wadi Natuf amounted to a very low, almost negligible figure. This makes *direct* in-situ recharge as percolation from the soils into the aquifer bedrock the by far dominant recharge process (see chapter 6).

The analysis documented in Appendix 5.1 was also able to relate runoff and transmission loss to the underlying geology in the subcatchments and reaches. Differences in transmission losses could be directly correlated with bedrock lithology underlying the wadi sections in the different reaches. Again, this drew on the already familiar link between geology and landforms (relief, soil, LU/LC…) in

Wadi Natuf. This correlation was quantified both, in relative and absolute terms, i.e. as percentage (% of runoff) and as rate (mm/h, over the duration of each of the runoff events), respectively. This linkage between geology and transmission loss is an expression of the varying aquifer potentials of the different formations, which are ranked in Fig. 5.4 above, albeit only in a qualitative fashion, not in the form of quantified formation-specific recharge coefficients. Such quantifications of aquifer potential are the subject of the following chapter.

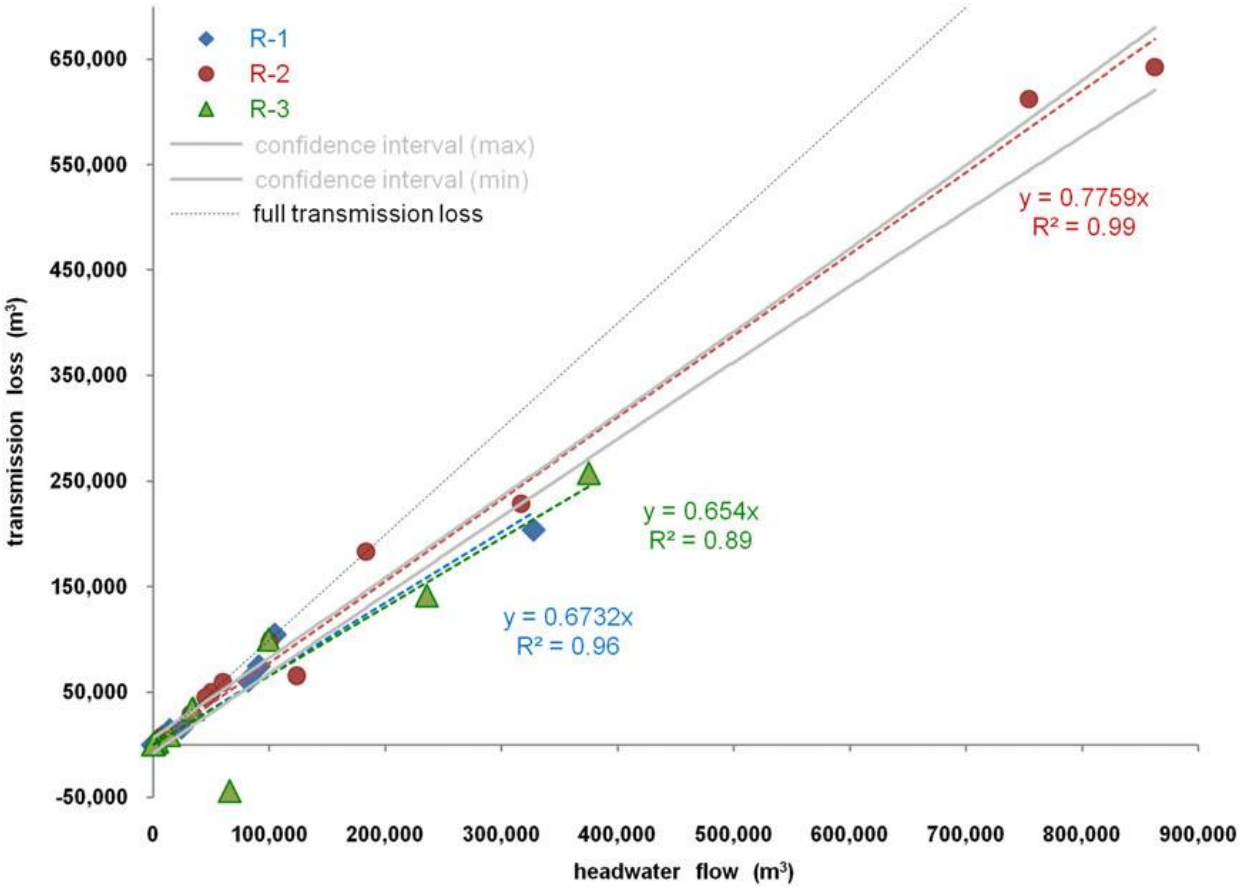

Figure 5.6: Headwater run-off versus transmission loss (m^3/event). The confidence interval is plotted for all reaches together. Note one example of transmission gain in R-3 (NEA) on 2.-4. April 2006; this was the event with the highest rainfall intensities (up to 137 mm/h) of the entire period. Note: 11.4 mm in 5 min measured on 2.4.2006 at 7:50 am in BZU rainfall gauge; 6.97 mm in 5 min in station NEA on 2.4.2006 at 3:00 am.

CHAPTER 6

RECHARGE

6.1 Modelling formation-specific recharge

As was shown before, with around 1 % of area precipitation, indirect recharge through wadi bed infiltration (transmission loss) is an almost negligible factor in the overall water budget of the Natuf catchment. Therefore, the focus for recharge calculations lies in the understanding, observation and as far as possible, quantification of *direct recharge* as in-situ infiltration (into the soils) and deep percolation into the underlying bedrock (the unsaturated zone of aquifers).

As discussed in the previous chapters, only surface and surface-near observations were available under the special conditions in Wadi Natuf and in fact, the entire recharge zone of the West Bank. Since the main objective was the spatial differentiation of recharge, the conceptual approach was based on the differentiation of physical features, whereby soil and LU/LC patterns were correlated to the lithostratigraphy (geology) at the outcrop. Hereby, recharge was equated with percolation into the unsaturated zone of the aquifer formations.

The approach chosen was a parsimonious soil moisture (SM) percolation model, based on saturation excess (modified after Sheffer *et al.*, 2010). The model was calculated in daily steps, encompassing measured precipitation, calculated evapotranspiration and observed physical soil parameters.

The model functions as follows:

(1) The time series data of daily precipitation were taken from ten automated rain gauges (in the first years nine tipping buckets), distributed over the catchment.

(2) Potential evapotranspiration was calculated from daily meteorological data, measured at two automatic weather stations in upper and lower Wadi Natuf, in addition to available records from nearby Jerusalem station.

(3) Daily rates of actual evapotranspiration were then calculated by assuming that they equalled potential evaporation in all times, when soils were sufficiently saturated (more details in App. 6.1 and in Schmidt, 2014). In the dry periods, actual evapotranspiration was limited by the available soil moisture storage (in mm) – see Fig. 6.1.

(4) Full saturation was reached, when the calculated daily soil moisture reached the maximum SM storage capacity, which was determined at each of the soil moisture stations independently over the period of eight consecutive SM measurement seasons. This

maximum storage capacity as a physical parameter of each soil was found to be highly variable in spatial distribution, but stable over time and with a strong dependency on soil thickness. (The distribution of soil thickness in the catchment area was empirically assessed in a separate activity – see chapter 6.2.)

(5) SM-values were measured in eight stations over a period of six years from 203/04 until 2008/09 (Fig. 6.2). Due to the lack of instruments and manpower, it was decided to maximize the amount of sites (reflecting spatial variability) on the expense of temporal coverage; SM measurements were carried out between one and four years at each site.

(6) The measurement locations were selected as representative sites for each respective lithostratigraphic formation, based on the extensive field surveys targeting geology and land forms and soil thickness, described in chapters 3 and 4.

As a result, the soil-moisture saturation-excess percolation model (SM-SEP) could be conceptualized as a simple site-specific tank or reservoir model (Fig. 6.1), in which each summer, soils fully dry up to a minimum water content (SM_{min}, empirically observed). During the rainy season, precipitation slowly accumulates in the soil and actual evapotranspiration is deducted daily according to the respective SM storage. When soils are fully saturated and reach the maximum storage capacity (site-specific physical soil parameter SM_{max}), all precipitation that is not lost to evapotranspiration, can be considered percolation (i.e. recharge into the unsaturated zone of the aquifer).

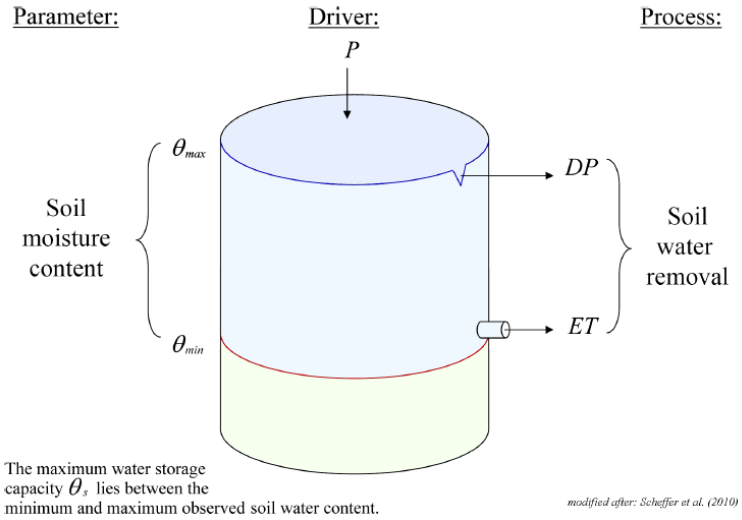

Figure 6.1: One reservoir SM-SEP model ("tank model")

The tank model in Fig. 6.1 shows the range of available SM-content as blue shaded area. Water content below SM_{min} – empirically measured at each station as a recurring physical feature of the soil – is considered immobile (green area), not subject to evapotranspiration; soils did not dry up further even during long months of intensive dry summer heat. Water leaves the soil only as evapotranspiration (ET) or deep percolation (DP). Runoff was not separated (see chapter 5.1). The figure does not indicate flow directions (DP = downward) but solely as processes, enabled by saturation: when SM rises above the red line, ET is enabled (daily flow rates) as rates limited by climate and soil water availability. At full saturation, when SM reaches the blue line), DP is enabled (as overflow, not limited), in addition to ET (for equations and further explanations, see App. 6.1).

It should be noted here that quantitatively, the model fully accounts for all recharge, whether direct or indirect. Under field conditions, during heavy storms, wetted soils may episodically trigger surface runoff that carries the water away from the site. However, the model treats all saturation excess that does not evaporate as deep percolation; in other words, the SM-SEP model includes these water quantities that trigger runoff in the field and treats them as deep percolation or autogenic direct recharge. Only for the sake of comparing the spatial distribution *between* different formations, may this conceptual distinction make a difference, but not for the estimation of overall recharge at the catchment scale. And the quantity that was hereby erroneously attributed to autogenic *direct* recharge, instead of secondary, allogenic *indirect* recharge through transmission loss (originating from other formation outcrops), was very small; the error was minuscule or negligible – < 1 % – just as the overall runoff rates in Wadi Natuf.

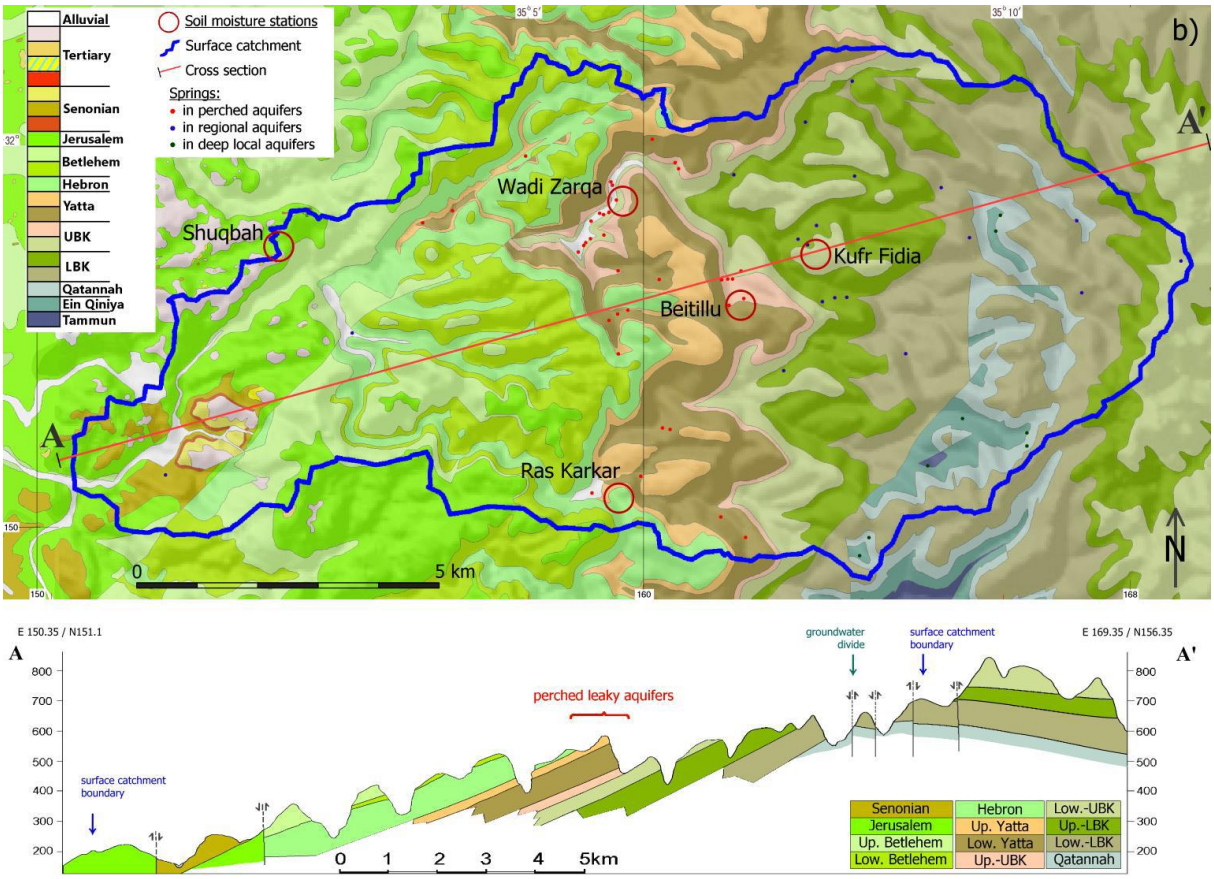

Figure 6.2: Geological relief map and cross section through Wadi Natuf. The geological relief map indicates a selection of the many small local springs, mostly fed by the perched aquifers in central Wadi Natuf (red dots), partly also locally from within the regional aquifers (blue dots) or from the deep local aquifers (green dots). Red circles inside the map indicate the five areas of the eight soil moisture stations. The cross-section indicates the surface catchment of Wadi Natuf and, further to the west, the groundwater divide that separates the Western and Eastern Aquifer Basins at a stratigraphically low position where the Lower Aquifer is fully eroded and the deep aquifers crop out. Sources: stratigraphic column, modified after Dafny et al. (2010); geological map, modified after GSI (2000 and 2008); cross section: this study.

The model was tested in two different ways. A quantitative examination compared modelled to observed SM-levels – the model showed a close performance, with an average Nash-Sutcliffe efficiency coefficient of 0.73 for all stations but one. A semi-quantitative examination used observed signatures of peak spring discharge and compared them to modelled periods of recharge (DP), again with a very close match.

As a result, formation-specific average annual recharge coefficients (RC – recharge relative to annual area precipitation, in %) were obtained for the eight different stations, representing five hydrostratigraphic units (aquifer formations). The observed formation-specific correlation with soil depth and land form ensured the representativeness of maximum water storage capacity over each formation and for long-term conditions of wet and dry years. The results also demonstrate that even in ungauged basins a realistic model of distributed groundwater recharge can be obtained through limited field observations of key parameters of the complex percolation process. Deep percolation or recharges rates in Wadi Natuf were found lying in a range between 118 mm/a (stations KF-E in 2008) and 519 mm/a (station WZ-gh in 2004/05). The corresponding recharge coefficients (RC) at the stations were spatially highly variable (but not temporally in most of the years), with averages between 30% and 57% of annual precipitation (see Table 6.1, last line); marly aquitards were considered to be void of recharge with RC = 0%. The representative formation-specific RC-values could then directly be used in the recharge regionalisation analysis (see chapter 6.2).

Table 6.1: Annual precipitation and recharge rates (DP) modelled at representative SM locations. The table shows area precipitation of the respective sub-catchments of the SM stations (from Messerschmid et al., 2018). *West* (W) uses the average rain of the Ne'alin and Shibteen-1 sub-catchments. *Centre* refers to the average between Shibteen-1 and Wadi Zarqa. *Northeast* (NE) is the precipitation in Wadi Zarqa. *Southeast* (SE) represents the average of the Shibteen-2 and Ein Ayoub catchments (Fig. 4). The daily rates of deep percolation were modelled with these area precipitation values. Minimum and maximum values of DP are bold (WZ-gh in 2004–2005; KF-E in 2008–2009). All units are in mm/a, except for the soil depth (mm) and recharge coefficients (expressed as DP_{avg} / P_{avg} as a percentage).

	Deep percolation (DP)								**Precipitation (*P*)**			
Year	**Shuqbah**	**Bet**	**WZ-gh**	**WZ-upT**	**KF-W**	**KF-E**	**RK-W**	**RK-E**	**W**	**Centre**	**NE**	**SE**
2003/04	291	217	289	235	188	140	238	238	547	532	524	507
2004/05	475	448	**519**	465	452	405	442	442	811	755	724	674
2005/06	319	206	293	223	192	145	218	218	666	628	609	585
2006/07	319	259	331	277	241	194	278	278	663	636	629	596
2007/08	287	221	293	239	196	149	240	240	522	501	493	466
2008/09	258	180	251	197	165	**118**	204	204	594	570	561	528
2009/10	286	228	299	245	208	160	247	247	614	586	578	543
Average DP	319	251	325	269	235	187	266	266	–	–	–	–
Avg. *P* (03/4–09/10)	557	601	601	601	631	631	588	588	**631**	**601**	**588**	**557**
Soil depth (mm)	320	500	400	770	650	940	400	400	–	–	–	–
RC (DP_{avg}/P_{avg})	**57 %**	**42 %**	**54 %**	**45 %**	**37 %**	**30 %**	**45 %**	**45 %**	–	–	–	–

6.2 Recharge regionalisation and leakage estimation

6.2.1 Regionalisation of groundwater recharge

Regional recharge was approached through a *conceptual basin classification framework*, highly relevant for many, especially ungauged or poorly gauged basins around the world. This framework, in the absence of extensive hydrological time series data, draws on the understanding of the role of physical features in the determination of hydrogeological processes such as recharge. These features were divided into three groups, such as geology, soil thickness and land use and land cover (LU/LC) patterns (see Table 6.2).

Table 6.2: Schematic conceptual basin classification framework: The order of formations (a, b, c, etc.), differs from group to group, thus indicating different ranking orders of formations as to their recharge potential (classes) in each group.

		Groups of physical features					
		LU/LC		Soil thickness		Rock lithology	
		Ftn.	Phys. features	Ftn.	Phys. features	Ftn.	Phys. features
High	Classes of recharge potential	a)	Rock	b)	Thin	c)	Karst
↑		b)	Grassland	a)	Medium	b)	Limestone
		c)	Forest	c)	Thick	a)	Marl
Low		etc.	etc.	etc.	etc.	etc.	etc.

Different expressions of such features were attributed to different classes of recharge potential for each group independently (see Table 4 in App. 6.2). This exercise drew on the extensive geological field work and land surveys described before.

Importantly, each lithostratigraphic formation (or hydrostratigraphic unit) was attributed a typical feature for each of the three groups. Some formations (e.g. upper LBK formation in the eastern mountains) are characterised by terraced slopes, used for olive orchards and with thin soils kept loose by human intervention (ploughing). By contrast, aquitards (e.g. upper Yatta formation) were found to exhibit thick soils, used as agricultural fields in inland plains. Strong features of epi-karst lead to thin soils or larger portions of rock outcrop (along soil pockets) with either sparse vegetation of grass- and scrub-land (e.g. Hebron and lower LBK formation in the eastern mountains) or alternatively to extended olive groves in the western foothills (Jerusalem formation). This example shows that the attribution of land features to the different formations had to be carried out for each group of physical features independently and separately. (The attribution, specific for Wadi Natuf is shown in Table 3 in App. 6.2).

While the SM-model was based on empirical (inductive) approaches, the regionalisation also entailed deductive steps of extrapolation, as recommended by PUB (chapter 1). The average recharge coefficients of the five modelled formations could be used directly – within the group of soil thickness. Before, a survey had already delivered representative typical thicknesses for each outcropping formation in Wadi Natuf – a so-called soil thickness matrix (see Table D1 in App. 6.1).

As already detailed above, *maximum RC-values* were found in the two strongly karstified formations (lower LBK and Jerusalem formations) and the alluvial, whereas the five impermeable aquitard layers were assigned *minimum RC-values* of zero (Tammun, Qatannah, upper Yatta, and Senonian chalk formations). This spanned the range of formation-specific RC-values between 57 % and zero. Accordingly, recharge coefficients for the other formations of different aquifer potential (such as lower and upper Bethlehem, lower and upper LBK and Ein Qinya formations) had to be extrapolated (see Table 3 in App. 6.2) according to their soil thickness. This procedure was repeated for each of the other two groups: In the LU/LC group maximum values were chosen for cliff-forming formations or series with abundant rock outcrops. Minimum values were assigned to lands with agricultural plains and forests. Olive terraces, grass- or shrub-lands and mixed transitional woodlands were assigned intermediate RC-values. In group 3 – geology, ranking was carried out according to the lithological rock content with well-developed karst (and wadi gravels) as maximum and with pure marl and chalk formations on the bottom end (see Table 3 in App. 6.2,). Table 6.3 and Fig. 6.3 below show the results of this extrapolation routine.

Table 6.3: Extrapolated recharge coefficients per group. The modelled RC-values from Messerschmid *et al.* (2020a) are indicated in red and bold fonts under the second group (soil conditions). Aquitards void of recharge are shaded grey.

	Wadi Natuf			**1. LC/LU**		**2. Soil**		**3. Geology**	
	Area	**Precipitation**		**Recharge**		**Recharge**		**Recharge**	
Formation	**km²**	mcm/a	*mm/a*	RC (%)	*mm/a*	RC (%)	*mm/a*	RC (%)	*mm/a*
Alluvial	1.53	0.85	*553*	45.3%	*250*	57.3%	*317*	57.3%	*317*
Senonian	2.38	1.31	*552*	0.0%	*0*	0.0%	*0*	0.0%	*0*
Jerusalem	9.24	5.07	*549*	45.3%	*249*	**57.3%**	*315*	57.3%	*315*
u-Betlehem	7.65	4.26	*557*	44.7%	*249*	45.3%	*252*	49.4%	*275*
l-Betlehem	9.77	5.58	*571*	41.8%	*239*	41.8%	*239*	49.4%	*282*
Hebron	10.06	5.77	*574*	45.3%	*260*	**45.3%**	*260*	54.1%	*311*
u-Yatta	4.93	2.92	*592*	0.0%	*0*	0.0%	*0*	0.0%	*0*
l-Yatta	10.18	6.14	*603*	41.8%	*252*	**41.8%**	*252*	41.8%	*252*
u-UBK	2.44	1.50	*615*	54.1%	*333*	**54.1%**	*333*	54.1%	*333*
l-UBK	8.44	5.26	*623*	44.7%	*279*	**44.7%**	*279*	49.4%	*308*
u-LBK	13.16	8.21	*624*	45.3%	*283*	54.1%	*338*	54.1%	*338*
l-LBK	16.4	10.23	*624*	45.3%	*283*	57.3%	*358*	57.3%	*358*
Qatannah	4.56	2.80	*613*	0.0%	*0*	0.0%	*0*	0.0%	*0*
Ein Qinya	1.82	1.12	*613*	41.8%	*256*	45.3%	*278*	41.8%	*256*
Tammun	0.06	0.04	*614*	0.0%	*0*	0.0%	*0*	0.0%	*0*
SUM / avg.	**102.6**	**61.1**	***595.3***	**39.5%**	***235***	**43.8%**	***261***	**46.0%**	***274***

The resulting sum of area recharge for the soil-based group (2. group, middle column) takes an intermediate position, close to the arithmetic mean of the three groups. The values of this group were also used for the recharge map in Fig. 6.3.

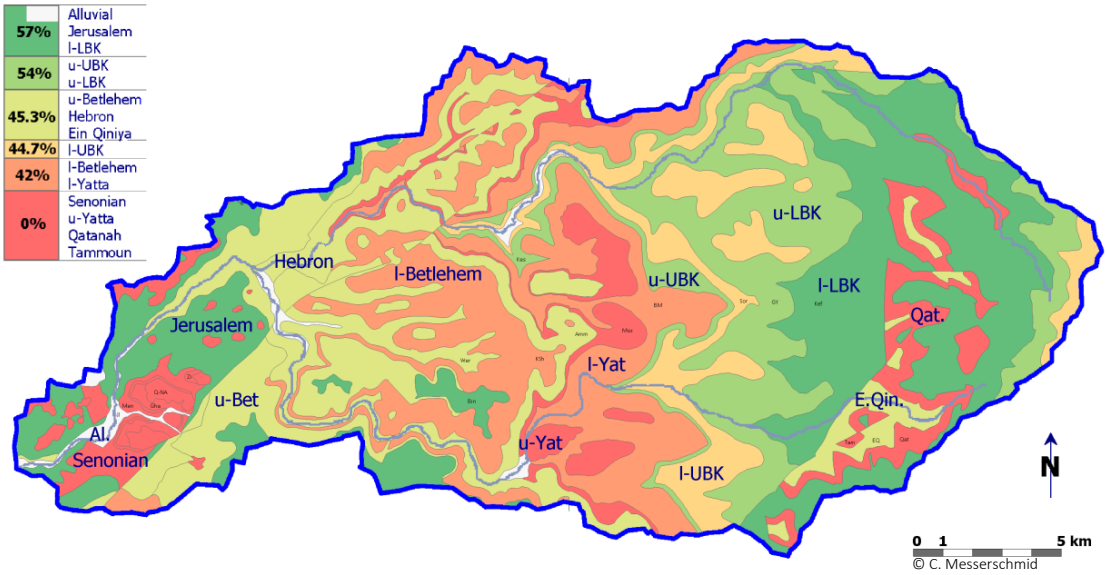

Figure 6.3: Recharge map of Wadi Natuf with recharge coefficients of the soil-based group 2. (RC-values in % of annual precipitation)

By applying these RC-values to the outcrop areas in Wadi Natuf the resulting average area recharge rates of the entire catchment could be compared for each group of physical features independently and compared to the values of the other groups. Notably, the overall average catchment recharge was found to lie in a close range between 24.1 and 29.1 million m^3 per year, for the LU/LC- and geology groups, respectively and with the soil group at an intermediate value of 26.8 million m^3 per year. This is equivalent to an overall area recharge of 39.4 % (LU/LC group), 43.8 % (soil) and 46.1 % (geology), respectively. These values match well with the comparable findings in the literature (Table H1 in App. 6.1,).

Thus for the first time, the spatial variability of basin features and impacts and of resulting hydrogeological processes such as recharge could be reflected appropriately at the catchment scale and despite the challenges of the study area (inapplicability of indirect approaches and lack of access to underground observation). The general approach of the conceptual basin classification framework along physical landscape features can be adapted and applied to many, even previously ungauged basins around the world.

6.2.2 Groundwater leakage estimation

A last, additional step was the estimation of downward groundwater leakage in the small perched aquifers in central Wadi Natuf, which was enabled by their particular geometry: These local hillside aquifers of between 1 and 10 km^2 area are fully erosionally isolated by the surrounding wadis. Under these particular and somewhat exceptional boundary conditions, all inflows stem from in-situ direct recharge. All outflows can be observed and measured at the many local springs, which were surveyed over nine consecutive hydrological years (2003/04 – 2011/12) at five daily read representative springs and by four key date measurement campaigns (details of the key date campaigns are given in App. 6.2 and chapters 3.1, 3.4 and 4.3).

Thus, the leakage estimation was based on a simple water budget calculation, accounting for annual recharge and annual spring outflows at each of the perched hillside aquifer formations. These three locally perched formations are upper UBK, the top of lower UBK and lower Yatta formations (see chapter 3.2 and App. 3.2). The simple water budget Equation reads:

$$L = R - Q \quad (1)$$

whereby L represents leakage (in m^3/a), R is the mean recharge amount (m^3/a) and Q stands for the total annual spring group discharge (m^3/a) from each isolated perched aquifer; each of the variables can also be expressed as % of annual rain.

The resulting average annual leakage rates for the three perched aquifer formations (l-Yat, u-UBK and top of l-UBK) were found to be 1.9, 0.7 and 0.1 million m^3 per year, respectively. These values can be translated into area-normalised annual flows of 185 mm, 287 mm and 169 mm per year, respectively. Alternatively they can also be expressed as leakage coefficients (percentage of annual recharge) of 75 %, 89 % and 64 %, respectively (see App. 6.2, Table 7).

Figure 6.4 depicts a cross section, schematically intersecting the spring groups of the three different perched aquifers, together with the coefficients of average annual recharge (R), spring discharge (Q) and downward groundwater leakage (L). Spring discharge rates at the perched aquifers were found to amount to a range between 11% and 36% of local recharge (average annual values).

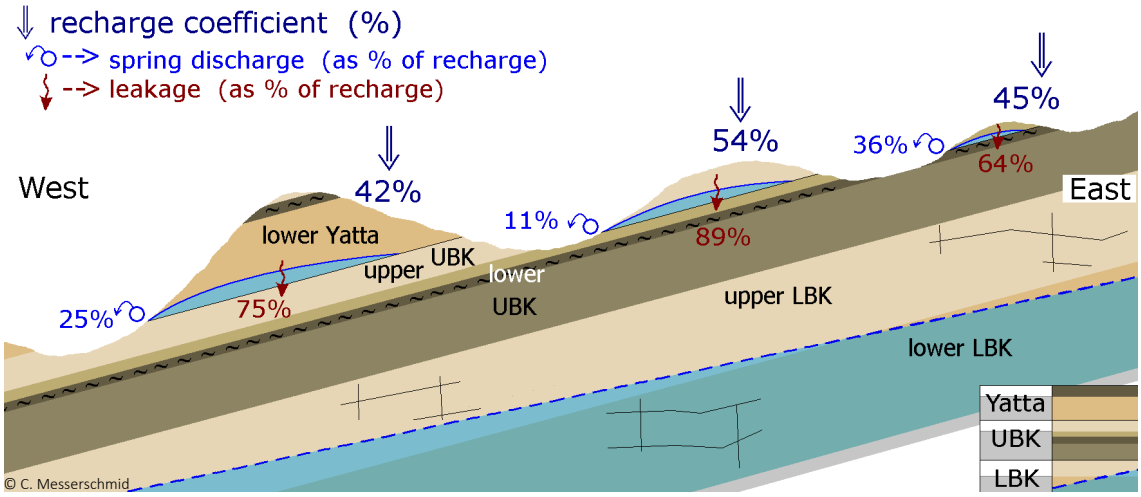

Figure 6.4: Water budgets of the three leaky sub-aquifers in Wadi Natuf (as percentage of rainfall)

These leakage estimations are quite unique and can only be carried out under the exceptional field conditions, i.e. aquifer geometries, of Wadi Natuf, or where similar isolated aquifer deposits can be encountered. Yet they give insights into another important hydrological process of what could be called a form of indirect recharge or *underground throughput*, which is relevant when calculating the yields of the underlying regional aquifer formations. Again the spatial diversity and variability should be pointed out, with leakage coefficients between two thirds and almost 90 % of inflowing percolation rates into the respective perched aquifers.

CHAPTER 7

CONCLUSIONS

Prior work has pointed out the applicability of direct approaches (Dörhöfer and Josopait, 1997; Lerner et al., 1990), where underground observations are prevented. PUB-researchers established several lessons for hydrological investigations in ungauged basins, albeit mostly focussing on surface water (Hrachowitz et al., 2013), such as the use of physical features (basin form) as a proxy for hydrological processes and impacts (basin function), the need for parsimony, the importance of empirical observations and at the same time the need for deductive, explorative measures. However, most studies in this field did not deal with the challenging issue of groundwater recharge. In addition, hardly any attempt has been undertaken to spatially differentiate recharge at the catchment scale but in high resolution, especially not in previously ungauged basins.

In this research I combined direct approaches of intensive field measurements (precipitation, runoff, soil moisture, runoff, etc.) with a conceptual basin classification framework that drew on three different groups of physical features (soil, geology and LU/LC).

I found that three types of recharge or recharge-related processes can be differentiated in Wadi Natuf – a) *direct*, as soil-moisture saturation-excess percolation (SM-SEP), b) *indirect*, through transmission loss and c) as downward groundwater *leakage* from isolated leaky and perched hilltop aquifers into the underlying regional aquifers. This also applies worldwide.

For the first time, PUB lessons were fully applied to groundwater recharge processes. The spatial differentiation followed and confirmed central PUB recommendations, e.g. that the distribution and physical characteristics of well accessible landscape features and their parameters (at the surface) can provide guidance to the distinction, evaluation and quantitative determination of key hydrological processes and basin functions such as recharge.

Furthermore, in this semi-arid to sub-humid terrain with a typical Mediterranean climate and short but very rainy winters (a), with carbonatic rocks and often strong epi-karst features at outcrop (b), associated typically with thin terra rossa soils (c) and with a hilly landscape under human use, for example by tended terraces with olive groves (d), recharge almost exclusively occurred as direct, in-situ percolation process of SM saturation excess.

Most notably, this is the first time, to my knowledge in any basin, but certainly for the WAB and wider Mt. Aquifers of the Levant, that formation-specific recharge coefficients have been established and quantified in a robust, realistic and reliable manner.

And only through the spatial analysis could an important quality be established: Although indirect recharge (TL) and leakage are almost negligible at the basin scale, they nonetheless may make up a considerable portion at the local scale – either on the isolated hillsides of the perched aquifers or as line recharge directly under the main Wadis, which were proven to be an important source of potential (and in one instance: actual) groundwater pollution. However, the model accounted for this allogenic recharge by including all saturation excess.

My results provide compelling evidence that spatially distributed recharge is not only distinguishable in high resolution and with specific recharge coefficients – and therefore an important venue of future research – but that it also opens entirely new fields and possibilities for more sustainable exploration, management and conservation of vital groundwater resources around the world.

Still, some limitations are worth noting. Although my results were examined and tested through qualitative and semi-qualitative procedures, still no comparable studies exist that would allow comparison of these findings from Wadi Natuf with the results from other basins. And although in some parts, such as indirect TL recharge, I worked under a high temporal resolution on the event-scale, the focus of my research was not the temporal but spatial variability of recharge.

Last, not least, my results for Wadi Natuf have not yet been further extrapolated and applied outside Wadi Natuf. Future work should repeat this approach in neighbouring catchments and further extrapolate and apply the RC-values of this study to other catchments and on a basin-wide scale to the entirety of the WAB; this would allow comparison of the resulting overall basin recharge from spatially distributed recharge estimations with the findings from conventional, lumped flow and recharge models at the basin-scale.

QUANTITATIVE RESULTS

The average area recharge of the Wadi Natuf catchment can be summarized as shown in Table 7.1: Between 39 % and 46 % of annual area precipitation infiltrates and percolates into the aquifer bedrock and constitutes groundwater recharge.

Table 7.1: Quantitative results for total annual average recharge in Wadi Natuf, calculated for separate groups of landscape features (average values for the years 2003/04–2009/10).

		Overall annual average area recharge in Wadi Natuf		
	Unit	Group 1 landform-based	**Group 2** **soil-based**	Group 3 lithology-based
Catchment area	(km^2)	102.6		
Precipitation	(mm/a)	595		
Annual recharge	(mcm/a)	**24.1**	**26.8**	**28.1**
	(mm/a)	234.8	**261.4**	274.1
Recharge coefficient	(%)	**39.4 %**	**43.8 %**	**46.1 %**

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List of publications and declaration of authorships

(all photographs by the author, if not indicated otherwise)

Appendix 2.1: Compiled Base Data of the WAB (Chapter in SUSMAQ working report # 07)

Author: Clemens Messerschmid

Reference: Messerschmid, C. (2002): Section E – Geology. In: Compiled Base Data for the Numerical Groundwater Flow Model of the Western Mountain Aquifer Basin, Volume 1 - General Background. Report No.: SUSMAQ-MOD Report No. # 07 V0.4, The Sustainable Management for the West Bank and Gaza Aquifers, Palestinian Water Authority and University of Newcastle upon Tyne, UK, Ramallah, Palestine, 84 pp., available at: http://hwe.org.ps/Projects/SUSMAQ_Reports/Flow%20Modeling/Compiled%20Base%20Data%20for%20the%20Numerical%20Groundwater%20Flow%20Model%20of%20the%20Western%20Aquifer%20Basin-full.pdf

Author contribution: The manuscript was published in a working report of the SUSMAQ-Project (Report No. SUSMAQ-MOD # 07 V 0.4). Appendix 2.1 documents excerpts of the report, as section E – Geology. The lead author, Clemens Messerschmid, performed the desktop study, review of literature and field investigations for the section. He conceptualised the content, compiled the data, prepared the figures and tables and wrote the draft of the chapter. Amjad Aliewi as SUSMAQ Team leader assisted in the concept of the chapter and reviewed the manuscript. Abbas Kalbouneh and Raslan Yassin of the SUSMAQ-Team commented on the chapter. Omar Awwad, Khalil Saleh, Omar Zayed, Adel Yassin, Deeb Abdelghafour of PWA contributed to the chapter.

Appendix 2.2: Aquicludes in the West Bank's Mt. Aquifers (Presentation and Paper at IAH, 2003)

Author: Clemens Messerschmid

Reference: Messerschmid, C. (2003): Deep-seated aquicludes in a fractured carbonate environment, West Bank. In: Krásný, J., Hrkal, Z. and Bruthans, J. (Eds.): Proceedings of the International Conference Groundwater in fractured Rocks; IAH (Intern. Assoc. of Hydrogeologists); full papers and extended abstracts, 15-19 September 2003, Prague, Czech Republic, p. 77-78, The extended abstract is available at: http://core.ac.uk/download/pdf/60171.pdf#page=86.

Author contribution: This study was prepared for and presented at an IAH Conference in Prague. The paper appeared in the conference proceedings. The full paper, including data acquisition, measurements, analysis, processing, manuscript writing and presentation was carried out by the author, Clemens Messerschmid. All images, tables and diagrams were produced by the author.

Appendix 2.3: Boundary conditions in the Western Aquifer Basin (SUSMAQ working report # 6.1)

Authors: Clemens Messerschmid

Reference: Messerschmid, C. (2001): Boundaries of the Western Aquifer Basin and the Eocene Aquifer in the North-eastern Aquifer Basin. SUSMAQ-MOD Report No. # 6.1 V1.0, The Sustainable Management for the West Bank and Gaza Aquifers, Palestinian Water Authority and University of Newcastle upon Tyne, UK, Ramallah, Palestine, 64 pp., available at: http://hwe.org.ps/Projects/SUSMAQ_Reports/Flow%20Modeling/Boundaries%20of%20the%20Western%20Aquifer%20Basinand%20and%20the%20Eocene%20Aquifer%20in%20the%20Northeastern%20Aquifer%20Basin-full.pdf.

Author contributions: The manuscript was published as a working report of the SUSMAQ-Project (Report SUSMAQ-MOD # 6.1 V 1.0). The lead author, Clemens Messerschmid performed the analysis and literature review. He constructed the cross-sections and drafted the manuscript. Amjad Aliewi, as SUSMAQ Team Leader, contributed conceptually and reviewed the manuscript. Abbas Kalbouneh commented and assisted on the manuscript. Liana Nasser formatted the maps and cross-sections.

Appendix 2.4: Western Aquifer Basin overview (Book chapter in UN-ESCWA-Inventory)

Author: Clemens Messerschmid

Reference: Messerschmid, C.: Western Aquifer Basin. In: UN-ESCWA and BGR: Inventory of shared water resources in Western Asia, United Nations Economic and Social Commission for Western Asia and Federal Institute for Geosciences and Natural Resources, Beirut (2013), 23 p., available at: http://waterinventory.org/sites/waterinventory.org/files/chapters/Chapter-19-Western -Aquifer-Basin-web.pdf, 2013.

Author contribution: The manuscript was published as chapter 19 in the „Inventory of Shared water Resources“, published by UN-ESCWA and BGR. The Inventory is the first of its kind and consists of …six Surface Water chapters on international rivers in the Middle East and 26 Groundwater chapters on transboundary aquifer basins from Iran to Palestine and from Turkey to the Arab Peninsula. The author, Clemens Messerschmid was commissioned this chapter by UN-ESCWA. He performed all works of literature review, compilation, analysis, calculations, writing and preparing of the maps, figures and tables. The ESCWA-team in Beirut reviewed, corrected and formatted the final version of the chapter. The final design of the maps was produced by BGR.

Appendix 2.5: Flow models of the Western Aquifer (Poster)

Author: Clemens Messerschmid et al.

Reference: Messerschmid C., Aliewi, A.; Kalbouneh, A.; Yassin, R. and Abu Saadah, M., (2004): Conceptual and Numerical Flow Models of the Western Aquifer — Palestine / Israel. In: Zereini F., Jaeschke W. (Eds.): Water in the Middle East and in North Africa. Springer, Berlin, Heidelberg, pp. 251-262, DOI: http://doi.org/10.1007/978-3-662-10866-6_21.

Author contribution: This study was presented as a poster and published as a paper in the proceedings of a Symposium in Frankfurt/M, titled “*Water of the Middle East and North Africa: Resources, Protection and Management*”. The lead author, Clemens Messerschmid prepared the concept together with Amjad Aliewi. Clemens Messerschmid compiled the data wrote the manuscript for the paper and formatted the poster. Material for the poster was also contributed and prepared by the SUSMAQ-Team, Amjad Aliewi, Abbas Kalbouneh, Raslan Yassin and Muath Abu Saadah.

Appendix 3.1: Field measurement campaign (SUSMAQ working report # 48)

Author: Clemens Messerschmid

Reference: Messerschmid, C. (2003): Field Measurement Campaign for Wadi Natuf Recharge Estimation: Background, Design and Work Plan. SUSMAQ-NAT Report No. # 48 V0.3, The Sustainable Management for the West Bank and Gaza Aquifers, Palestinian Water Authority and University of Newcastle upon Tyne, UK, Ramallah, Palestine, 28 pp., available at: http://hwe.org.ps/Projects/SUSMAQ_Reports/Wadi%20Natuf%20catchment%20area/Field%20Measurement%20Campaign%20for%20Wadi%20Natuf%20Recharge%20Estimation%20-%20Background,%20Design%20and%20Workplan-full.pdf

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and produced all figures and tables. Amjad Aliewi contributed to the general concept, Bruce Dudgeon (Univ. Newcastle) to the concept of the measurement campaign. Together with Geoff Parkins (Univ. Newcastle), they reviewed the draft. Abbas Kalbouneh, Omar Zayed, Emad Sayfi, Deeb Abdelghafour supported, commented and contributed to the manuscript.

Appendix 3.2: Perched springs (SUSMAQ working report # 65)

Author: Clemens Messerschmid

Reference: Messerschmid, C. (2003): Field trips to the springs in Wadi Natuf, Final Report – SUSMAQ-NAT # 65 V 0.1. The Sustainable Management for the West Bank and Gaza Aquifers, Palestinian Water Authority (Palestine) and University of Newcastle upon Tyne (UK), Ramallah, July 2003, 21 pp., available at: http://hwe.org.ps/Projects/SUSMAQ_Reports/Wadi%20Natuf%20catchment%20area/Field%20trips%20to%20the%20springs%20in%20Wadi%20Natuf-full.pdf

Lead Author: The manuscript was published as a working report of the SUSMAQ-Project (Report No. SUSMAQ-NAT # 65 V 0.1). The lead author reported on the field trips, prepared the material and wrote the manuscript. Amjad Aliewi, Abbas Kalbouneh, Emad Sayfi and Majdi Zaydah contributed and commented on the manuscript. All photos by the author (CM).

Appendix 4.1: Preparatory work for the conceptual model (SUSMAQ working report # 64)

Author: Clemens Messerschmid

Reference: Messerschmid, C. (2003): Conceptual Model of Wadi Natuf Groundwater Recharge, Final Report – SUSMAQ-NAT # 64 V 0.3. The Sustainable Management for the West Bank and Gaza Aquifers, Palestinian Water Authority (Palestine) and University of Newcastle upon Tyne (UK). November 2003, Ramallah, 19 pp., available at: http://hwe.org.ps/Projects/SUSMAQ_Reports/Wadi%20Natuf%20catchment%20area/Conceptual%20Model%20of%20Wadi%20Natuf%20Groundwater%20Recharge-full.pdf

Author contribution: The manuscript was published as a working report of the SUSMAQ-Project (Report No. SUSMAQ-NAT # 64 V 0.3). The lead author, Clemens Messerschmid wrote the manuscript. Amjad Aliewi contributed to the research approach, Bruce Dudgeon to the measurement design. The draft was reviewed by Amjad Aliewi, Geoff Parkins, Andrew Hughes and Bruce Dudgeon. Abbas Kalbouneh from the SUSMAQ Study Team and Omar Zayed and Emad Sayfi from PWA contributed to the manuscript.

Appendix 4.2: Development of a conceptual recharge model of Wadi Natuf (IAH, 2004)

Authors: Clemens Messerschmid et al.

Reference: Messerschmid, C., Kalbouneh, A., Zayed, O., Sayfi, I. and Aliewi, A. (2004): Development of a Conceptual Recharge Model of Wadi Natuf Catchment, Palestine. Paper at the XXXIII IAH Congress (7th ALHSUD Conference), Zacatecas, Mexico, 5 pp.

Author contribution: The appendix 4.2 contains an extended abstract of a presentation held at the XXXIII IAH Congress in Zacatecas, Mexico. The publication was co-authored by Abbas Kalbouneh, Omar Zayed, Emad Sayfi and Amjad Aliewi. The lead author, Clemens Messerschmid, prepared the presentation and the extended abstract and all the material therein. The co-authors reviewed and commented on the manuscript.

Appendix 4.3: Purchase and installation of field equipment (SUSMAQ working report # 68)

Authors: Clemens Messerschmid et al.

Reference: Messerschmid, C.; Aliewi, A.; Kalbouneh, A.; Dudgeon, B.; El-Qutub, M. and Khawaldeh, N. (2004): Purchase and Installation of Field Measurement Equipment for Wadi Natuf Recharge Assessment Study. Working Report – SUSMAQ-NAT # 68 V 2.0. The Sustainable Management for the West Bank and Gaza Aquifers, Palestinian Water Authority (Palestine) and University of Newcastle upon Tyne (UK). June 2004, Ramallah, 17 pp., available at:

http://hwe.org.ps/Projects/SUSMAQ_Reports/Wadi%20Natuf%20catchment%20area/Purchase%20and%20installation%20of%20field%20measurement%20equipment%20for%20Wadi%20Natuf%20recharge%20assessment%20study.pdf

Author contribution: This working report (here, excerpts) of SUSMAQ documented the field work for the installation of field instruments. It drew on the field work and its documentation mainly by the lead author, Clemens Messerschmid, and the field staff Bruce Dudgeon, Mohammad El-Qutub, Nidhal Khawaldeh. The concept of measurements and instrumentation was worked out in cooperation between Clemens Messerschmid and Bruce Dudgeon, supported by Abbas Kalbouneh. The illustrations and tables were partly prepared by Nidhal Khawaldeh and Mohammad El-Qutub, otherwise by Clemens Messerschmid. The photo on report page Nr. 14, bottom left (*Infiltrometer Test*) © by M. Zaydah; on report page Nr. 15, top right (*Read Theta Probes*) © by N. Khawaldeh. The manuscript was written by Clemens Messerschmid. Advice and comments were given by Amjad Aliewi, Abbas Kalbouneh and Bruce Dudgeon, who also reviewed the draft report.

Appendix 4.4: Wadi Natuf field measurement campaign 2003/04 (Poster)

Author: Clemens Messerschmid

Reference: Messerschmid, C. (2004): Wadi Natuf field measurement campaign 2003/04. Poster for internal SUSMAQ workshop on 17 March 2004, Ramallah, 1pp. (unpublished).

Author contribution: This poster was prepared for an internal workshop of the SUSMAQ project on 17 March, 2004 that assessed progress in the different project components. The poster portrays the first field measurement season with a focus on the field instruments and their locations. The poster was conceived and prepared by Clemens Messerschmid. Abbas Kalbouneh, Nidhal Khawaldeh and Mohammad El-Qutub contributed to the material (photographs), supported and commented on the draft. Amjad Aliewi assisted in the concept of the poster and reviewed its draft version.

Appendix 5.1: Transmission losses from runoff – indirect recharge (Hyd. Proc., 2018)

Author: Clemens Messerschmid, Jens Lange and Martin Sauter

Reference: Messerschmid, C., Lange, J., and Sauter, M. (2018): Assessment of transmission loss in a Mediterranean karstic watershed (Wadi Natuf, West Bank). *Hydrol. Process*., 32, 1375–1390, http://doi.org/10.1002/hyp.11496.

Author contribution: All material for this paper, measurements, analysis, calculations and illustrations were provided by the lead author, Clemens Messerschmid, who also prepared the first draft of the manuscript. Clemens Messerschmid and Jens Lange developed the main concept. Jens Lange contributed by advice in preparing the data and reviewing the manuscript. Fabian Ries gave support in the data setup and preparation of maps. Jens Lange and Martin Sauter reviewed the manuscript.

Appendix 6.1: Modelling formation-specific recharge (HESS, 2020)

Author: Clemens Messerschmid, Martin Sauter and Jens Lange

Reference: Messerschmid, C., Sauter, M. and Lange, J. (2020): Field-based estimation and modelling of distributed groundwater recharge in a Mediterranean karst catchment, Wadi Natuf, West Bank. *Hydrol. Earth Syst. Sci*., 24, 1–32, available at: http://doi.org/10.5194/hess-24-1-2020.

Author contribution: All material for this paper, measurements, analysis, calculations and illustrations were provided by the lead author, Clemens Messerschmid, who also prepared the first draft of the manuscript. Clemens Messerschmid and Jens Lange developed the main concept. Jens Lange and Martin Sauter supported in the analysis and helped in developing the main concept. Sebastian Schmidt and Martin Sauter helped with the modelling code and preparation of the potential evapotranspiration data. Martin Sauter and Jens Lange reviewed the manuscript.

Appendix 6.2: Recharge regionalisation and leakage estimation (HESS, in preparation)

Author: Clemens Messerschmid, Jens Lange and Martin Sauter

Reference: Messerschmid, C., Lange, J. and Sauter, M., (2020a): Regionalisation of distributed groundwater recharge and leakage calculations in a Mediterranean karst catchment, Wadi Natuf, West Bank. *Hydrol. Earth Syst. Sci*. (in preparation).

Author contribution: All material for this paper, measurements, analysis, calculations and illustrations were provided by the lead author, Clemens Messerschmid, who also prepared the first and second drafts of the manuscript. Martin Sauter and Jens Lange helped in developing the main concept. Marcelo Rosensaft supported with GIS data for the geological map. Martin Sauter and Jens Lange will review and comment on the manuscript.

List of Appendices

AD CHAPTER 2 – WESTERN AQUIFER BASIN: GEOLOGICAL BACKGROUND . 107

Appendix 2.1: Compiled base data of the WAB (SUSMAQ # 07) 109
Appendix 2.2: Aquicludes in the West Bank's Mt. Aquifers (IAH, 2003) . . 149
Appendix 2.3: Boundary conditions in the WAB (SUSMAQ # 06) 159
Appendix 2.4: Western Aquifer Basin overview (Ch. 19, UN-ESCWA) 215
Appendix 2.5: Conceptual and numerical flow models of the WAB (Poster) 239

AD CHAPTER 3 – WADI NATUF – HYDROGEOLOGICAL FRAME 243

Appendix 3.1: Field measurement campaign (SUSMAQ # 48) 245
Appendix 3.2: Perched springs (SUSMAQ # 65) 263

AD CHAPTER 4 – DESIGN, SETUP AND INSTRUMENTATION 275

Appendix 4.1: Preparatory work for the conceptual model (SUSMAQ # 64) 277
Appendix 4.2: Development of a conceptual recharge model (IAH, 2004) . 297
Appendix 4.3: Purchase & installation of field equipment (SUSMAQ # 68) . 303
Appendix 4.4: Wadi Natuf field measuremt. campaign 2003/04 (SUSMAQ) 321

AD CHAPTER 5 – RUNOFF 323

Appendix 5.1: Transmission losses from runoff (Hyd. Proc., 2018) 325

AD CHAPTER 6 – RECHARGE 341

Appendix 6.1: Modelling formation-specific recharge (HESS, 2020) 343
Appendix 6.2: Recharge regionalisation & leakage estimation (HESS, *draft*) 375

Appendices of chapter 2

Western Aquifer Basin – Geological Background

2.1 Compiled base data of the WAB (SUSMAQ # 07) 109

2.2 Aquicludes in the West Bank's Mountain Aquifers (IAH, 2003) . 149

2.3 Boundary conditions in the WAB (SUSMAQ # 06) 159

2.4 Western Aquifer Basin overview (Ch. 19, UN-ESCWA) 215

2.5 Conceptual and numerical flow models of the WAB (Poster) . . 239

Palestinian National Authority
Palestinian Water Authority

السلطة الوطنية الفلسطينية
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Sustainable Management of the West Bank and Gaza Aquifers

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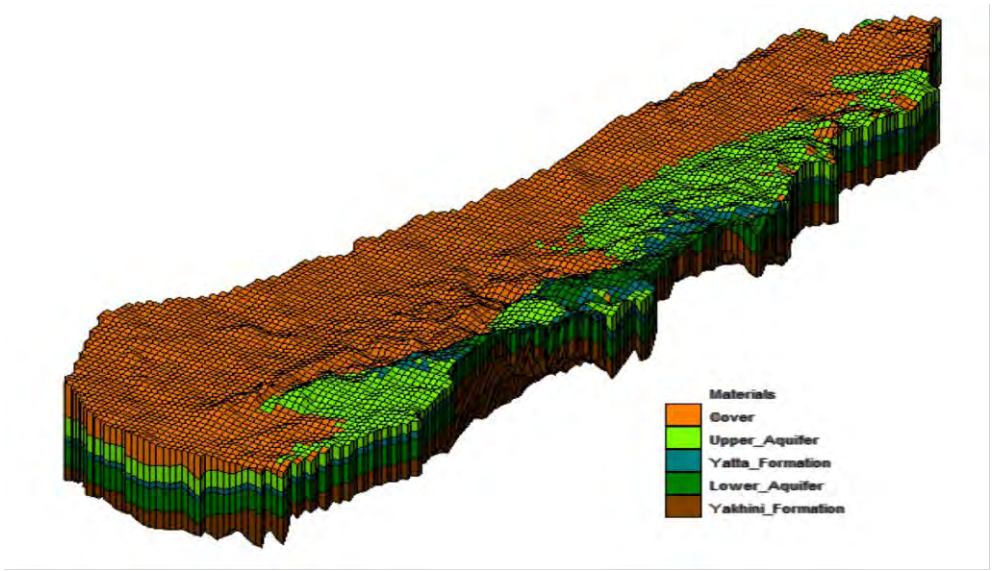
Compiled Base Data for the Numerical Groundwater Flow Model of the Western Aquifer Basin

Volume 1 – General Background



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SUSMAQ-MOD #07 V0.4

Prepared by:

SUSMAQ TEAM

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Disclaimer

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The SUSMAQ Project

The aim of the project is to increase understanding of the sustainable yield of the West Bank and Gaza aquifers under a range of future economic, demographic and land use scenarios, and evaluate alternative groundwater management options. The project is interdisciplinary, bringing together Hydrogeologists and groundwater modellers with economists and policy experts. In this way, hydrogeological understanding can inform, and be informed by, insights from the social sciences. The results of the study will provide support to decision-making at al levels in relation to the sustainable yield of the West Bank and Gaza aquifers.

The project runs from November 1999 to October 2004, and is a partnership between the Palestinian Water Authority, University of Newcastle and British Geological Survey. The project is funded by the United Kingdom's Department for International Development (DFID).

The Hydrogeology and Flow Modelling

is part of the SUSMAQ project.

The Modelling study focuses on the geology and hydrogeology of the Western Aquifer Basin (WAB), its inflows (recharge) and outflows (spring and well abstractions).

This report provides the data collected for the Basin which will help in modelling the flow system and its aquifers.

Bibliographical Reference

SUSMAQ-MOD #07 V0.4. Compiled Base Data for the Numerical Groundwater Flow Model of the Western Aquifer Basin

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Feedback

The SUSMAQ and PWA teams will appreciate any feedback on this report. Feedback should be sent to the above contacts.

– *Excerpts* –

SECTION E

GEOLOGY

	Page
1. Pre-Cretaceous	1
2. Lower Cretaceous	1
2.1 Regional setting	1
2.2 Names and limits	2
2.3 Historical geology, stratigraphy and facies	4
2.3.1 Berriassian – Lower Aptian	4
2.3.2 Upper Aptian	6
2.3.3 Lower Albian	7
2.3.3.1 West Bank (Galilee and Lebanon)	8
2.4 Structure and summary	9
3. Upper Albian	10
3.1 Regional setting	10
3.2 Names and limits	10
3.3 Historical geology, stratigraphy and facies	10
3.3.1 West Bank	10
3.3.1.1 Lower Beit Kahil Formations (LBK1, 2)	10
3.3.1.2 The Upper Beit Kahil formation (UBK1, 2)	12
3.4 Summary and structure	15
4. Upper Cretaceous (Cenomanian-Turonian)	16
4.1 General (regional) setting	16
4.2 Names and limits	16
4.3 The sedimentary sub-cycles	18
4.3.1. First Cycle: Lower Cenomanian	18
4.3.2 Second Cycle: Upper Cenomanian	19
4.3.3 Third Cycle: Upper Cenomanian – Lower Turonian	19
4.3.4 Fourth Cycle: Middle Turonian – lower Cenomanian	20
4.4 Lithofacies	21
4.4.1 West Bank	21
4.5 Summary and structure	28
5. Upper cretaceous to recent	28
5.1 Upper Cretaceous: Coniacian and Senonian (89-65 Mio a)	28
5.1.1 Abu Dis Group / Mt.Scopus group	29
5.6 Structure and Summary	33
References	-

Excerpts of Section E

SECTION E

GEOLOGY

Approach and Methodology

The following section presents a short overview over the historical and structural geology of the study area and adjacent areas concentrating on Cretaceous and Tertiary geology.

Existing data and available literature were gathered and evaluated. A large amount of references was collected for this purpose. The data sources are primarily the Geological Survey of Israel and the PWA Data Bank. Other sources are the Hydrological Service and Universities in Israel, as well as other West Bank water projects. The references are listed in Annex I of this report. Annexes III and IV contain a glossary of geological terms and hydrogeological terms, respectively. Maps and figures used in this section come from the above sources. Photographs used in the section were taken outside the framework of the project.

Since no Palestinian study has concentrated on the entire Western basin in the past, the section attempts to describe the geology of the basin in great detail. By this it shall serve as a key reference for future works in the area.

The section Geology reproduces the existing information about stratigraphy and nomenclature, lithology, ages and thickness and gives a brief overview over the structural setting of the area. In order to create a conceptual model based on the findings presented in the Compiled Base Data report, a detailed and updated table of the chrono- and lithostratigraphy is presented together with the division into main hydrogeological units.

1. PRE-CRETACEOUS

1.1 Late Precambrian - Carboniferous (600-286 Mio years)

...

2. LOWER CRETACEOUS

2.1 Regional Setting

With BRAUN ET AL. (1990) the Cretaceous sequence in Palestine and Israel can be described as a part of the Peri-Arabian hinge belt between the Gondwanaland (African – Arabian platform) and the Tethys realms.

Cretaceous (Aptian-Coniacian) carbonate platform sediments form up to >1000 m of the backbone of Palestine and Israel, including a variety of facies types such as bank facies (Late Albian), shelf lagoon sediments and rudistid bioherms[1] (Albian), marly shelf chalks (Early Cenomanian), rudistid bioherms, shelf basin and backreef lagoon sediments (Late Cenomanian – Turonian – Early Coniacian).
The various marine facies types of the Judea Group (*sensu latu*), generally consist of the Kobar and West Bank Groups according to Palestinian terminology and extend over wide regions of the Arabian platform. In the autochthonous terrains of the Taurus and Zagros belts (south Turkey), and parts of Saudi Arabia, Cenomanian laterites interrupt the sedimentation of platform carbonates.

The Cretaceous in Israel and Palestine underwent five major transgressional cycles. After the Jurassic transgression, the eustatic curve of the sea level reached its minimum 126 Mio years ago, in the Lower Neocomian (Valanginian), the lowest stand since the Permian/Triassic and Triassic/Jurassic boundaries. A slight transgression took place during the Upper Neocomian, until the Yavne event in the Late Aptian/Early Albian (105Ma). Then, during the Upper Albian, a strong transgression established the carbonate platform over most of the country, which deposited the sediments of the Lower Aquifer: Beit Kahil formations, Hevyon formation, Yagur formation and Lower Hazera formation respectively. It was interrupted shortly by the third low stand, the Kesalon event (97Ma, top Albian) that led to the deposition of the overlying aquitard series Beit Meir, Yatta, Ein Yorqe'am and Deir Hanna, respectively, since the transgression only shortly reached a high level that allowed for carbonate deposition. The deposition of the aquitard was both renewed and successively terminated by the Moza event (94Ma), followed by the strong Cenomanian-Turonian transgression that allowed for the establishment of the Upper Aquifer facies, a wide carbonate platform of the formations Hebron-Betlehem-Jerusalem, Sakhnin and Upper Hazera respectively. This worldwide transgression was terminated 90 Mio years ago by the regressional low stand of the "Avnimelech horizon" event. Since then, the transgression only came back shortly in the Lower Coniacian and then gave way to an oscillating but overall clear trend of a major regression with mainly chalky facies until the K/T boundary (5th low stand, 65Ma) that concluded the Cretaceous sequence.

2.2 Names and limits

RUSEGGER (1847) under the name "Nubian sandstone" first mentioned Lower Cretaceous sandstones in Egypt, Palestine and Jordan, and BLANCKENHORN (1914) first determined its stratigraphic position. QUENNEL (1951) introduced the present term **Kurnub** sandstone. He correlated deposits in Palestine, near the Dead Sea with such in Jordan. ROFE & RAFFETY (1963) introduced the term **Ramali** formation for the main part of the Kurnub Group that outcrops in the West Bank.
In Sinai and the Negev, the continental clastics are called the Hatira formation, while they are called the Helez formation in deltaic deposits offshore and under the Coastal Plain and Carmel areas.
Its marine equivalents, for the same period, in the North and West (mainly off-shore the Coastal Plain) have been given the name **Gevar'am** formation, followed by **Yavne** formation, among others by: BRAUN ET AL. (1990 - GUIDEBOOK); BARTOV ET AL. (1981).
The Neocomian clastics, predominantly sandstone with varying contents of clay and silt, especially in its upper part, truncate Middle to Late Jurassic carbonate horizons with a marked unconformity. They are capped by the marine Lower to Upper Cretaceous series of the Judean Group (here: Kobar and West Bank Groups).

Especially petroleum geology, the formation terms **Telamim**, **Yavne** and **Yakhini** are used for the series below the Judean Group in the Coastal plain subcrops. There, Telamim starts in the Aptian, Yavne starts with the Upper Aptian and is overlain by the Yakhini formation of Lower Albian (sometimes uppermost Aptian). In the coastal plain and Carmel area, the **Yagur** formation, of Upper Albian age, is the equivalent to the Beit Kahil formations in the West Bank (HIRSCH, 1990).

The series of the Judea group were first introduced by SHALEM (1925) as *Calcari a Radioliti* and as *Judean Limestone* by WELLINGS (1944) and by BALL AND BALL (1953) and were defined as comprising all Cenomanian to Turonian platform carbonates.
Up until today there are different definitions of the Judea Group to be found in the literature. BARTOV ET AL. (1983) summarize all Aptian-Coniacian carbonates that onlap over the Aptian-Cenomanian clastics

[1] Reef-, hill- or lense-shaped structure within a rock complex, formed of molluscs of the rudist type

under the term Judean Group. Other authors, such as SNEH (1968), KAFRI (1975), SASS AND BEIN (1978) and HIRSCH (1990) vary in the definition of the base of the Judea Group.

In the following, and for the purpose of this study, we will differentiate between the two types of the Judean Group. The Judean Group in the broad sense (*sensu strictu*) reaches from Kefira to Bi'na (Lower Beit Kahil to Jerusalem). The Judean Group in a more narrow sense (*sensu latu*) includes the marine sediments at its base that onlap on the generally Neocomian arenitic clastics (sandstones etc.) of continental and proximal facies.

For the former, the Judea Group (*sensu strictu)*, the term West Bank Group shall be introduced (see Table 2).

Period		Stage	Israeli		Palestinian		
			Group Name	Formation name	Group Name	Formation name	
UPPER	CENOMANIAN	Senonian	Mt.Scopus Group		Abu Dis Group		
		Turonian	Judea Group *(sensu strictu)*	Bi'na	**West Bank Group**	**Jerusalem**	
		Cenomanian		Weradim		**Upper Bethlehem**	
				Kefar Sha'ul		**Lower Bethlehem**	
				'Amminadav		**Hebron**	
				Moza		**Upper Yatta**	
				Beit Meir		**Lower Yatta**	
LOWER		Albian		Kesalon		**Upper Beit Kahil**	**UBK 2**
				Soreq			**UBK 1**
				Giv'at Ye'arim		**Lower Beit Kahil**	**LBK 2**
				Kefira			**LBK 1**
			-	Qatana	**Kobar Group**	Qatana	**Kobar***
			-	Ein Qinya		Ein Qinya	
		Aptian	-	Tammun		Tammun	
			-	Ein Al-Assad		Ein Al-Assad	
			-	Nabi Sa'id		Nabi Sa'id	
		Berriassian-Barrêmian	Kurnub Group	Hatira	**Kurnub Group**	Ramali (& Tayasir volcanics)	

Table 2: Introduction of the terms WEST BANK GROUP, comprising Lower Beit Kahil to Jerusalem formations, and KOBAR GROUP, comprising Ein Al-Assad to Qatana formations.
* The Name "Kobar" formation was introduced by Rofe and Raffety (1963), and was defined as the formations below Lower Beit Kahil and above Ramali Sandstone. No complete succession was found in outcrops and described by them. Thus, the term Kobar remains somewhat unclear as to its exact stratigraphic position.

The onlap of the West Bank and Kobar Groups (Judea Group *sensu latu*), is Hauterivian in the Galilee and northeastern West Bank. It is Late Aptian in the central and southern West Bank, and in the northern Negev and Early Albian in the central Negev (Figure 6).

The Albian-Cenomanian sediments of the Judea Group thin consistently towards the southeast, whereas the Turonian-Coniacian sediments (Jerusalem formation), which underwent partial truncation, are of variable thickness and even show some thickening in the southern Negev and Sinai.
The top of the Judea group is an erosional surface or discordant, a result of the folding and uplift of the Syrian Arc. It is overlain by Coniacian – Campanian chalks of the Mount Scopus group (Abu Dis Group).

Towards the west, in the subsurface of the coastal plain, the West Bank Group carbonates pass laterally into the basinal clastics, shales and chalks of the Talme Yafe formation.
Eastward and southward they interfinger with and gradually overlap the 500m thick Nubian-type sandstones and occasional volcanics of the Kurnub Group.

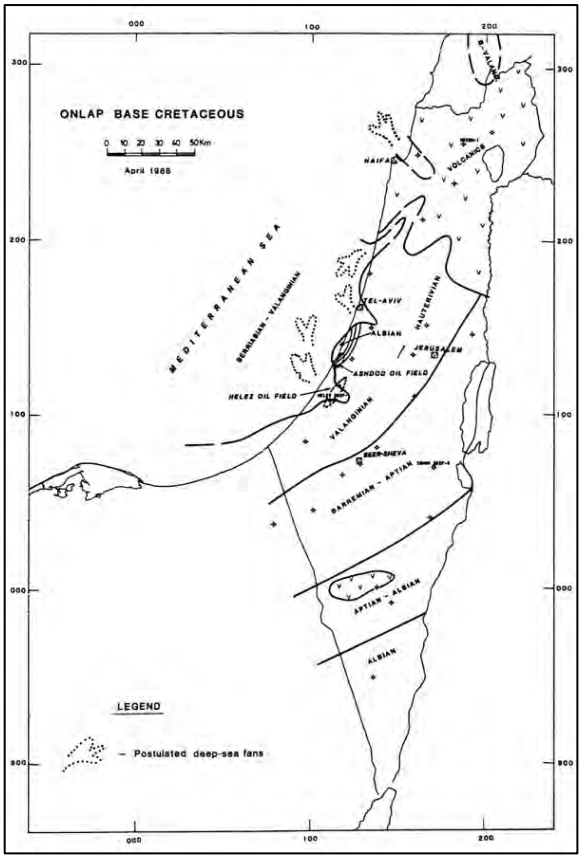


Figure 6: Age of onlap Base Cretaceous (COHEN, 1988)

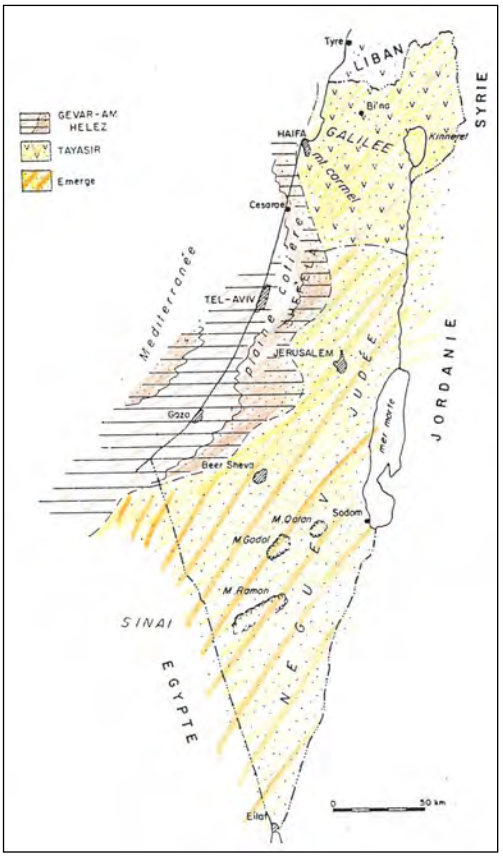


Figure 7: Tithonian-Barrêmian Facies Map (HIRSCH, 1990). Continental facies in most of the country with volcanics in the north. Proximal and deltaic facies on the coast, detritic marine facies offshore

2.3 Historical geology, stratigraphy and facies

2.3.1 Berriassian – Lower Aptian

The Lower Cretaceous is most commonly known as Kurnub sandstone of continental to proximal facies. This Nubian type sandstone has been widely described in adjacent countries (Jordan, Egypt), where it forms thick deposits.

However, due to the formerly more northern (pre-rift-) position of the West Bank (compared to Jordan across the Jordan rift valley), the Cretaceous NW-SE trending transgression started earlier than in Jordan. Thus the onlap of marine sedimentation started long before Cenomanian times (see Figure 6).

As a consequence, the fluvial and deltaic sedimentation of clastics is thinning from NNW to SSE. SHERTOK (1980) gives an overview of the findings in oil wells for the regions stretching from Northern Sinai until the West Bank and further to the Jordan Rift Valley. Within the approximate study area (between the wells Qeren 1 and Ramallah 1), there is a clear trend of thickening of the sandy and somewhat shaly facies towards the north. While the wells in the northern Negev and the southern coastal plain have a Neocomian thickness of only 150m, the clastic continental facies gradually thickens to values of up to 300m (in Ramallah 1) at the axis of the anticline in the central West Bank.

Most of the country, the Eastern coastal plain, Carmel, West Bank and Negev, was exposed during Tithonian to Barrêmian times (Figure 7).
In the West, in the Coastal Plain, fluviatile to deltaic conglomerates and sandstone were sedimented while further off-shore a more shaly facies marks the beginning of the Cretaceous transgression, starting as early as the lowermost Cretaceous (Berriassian), in some places even uppermost Jurassic (Figure 8).

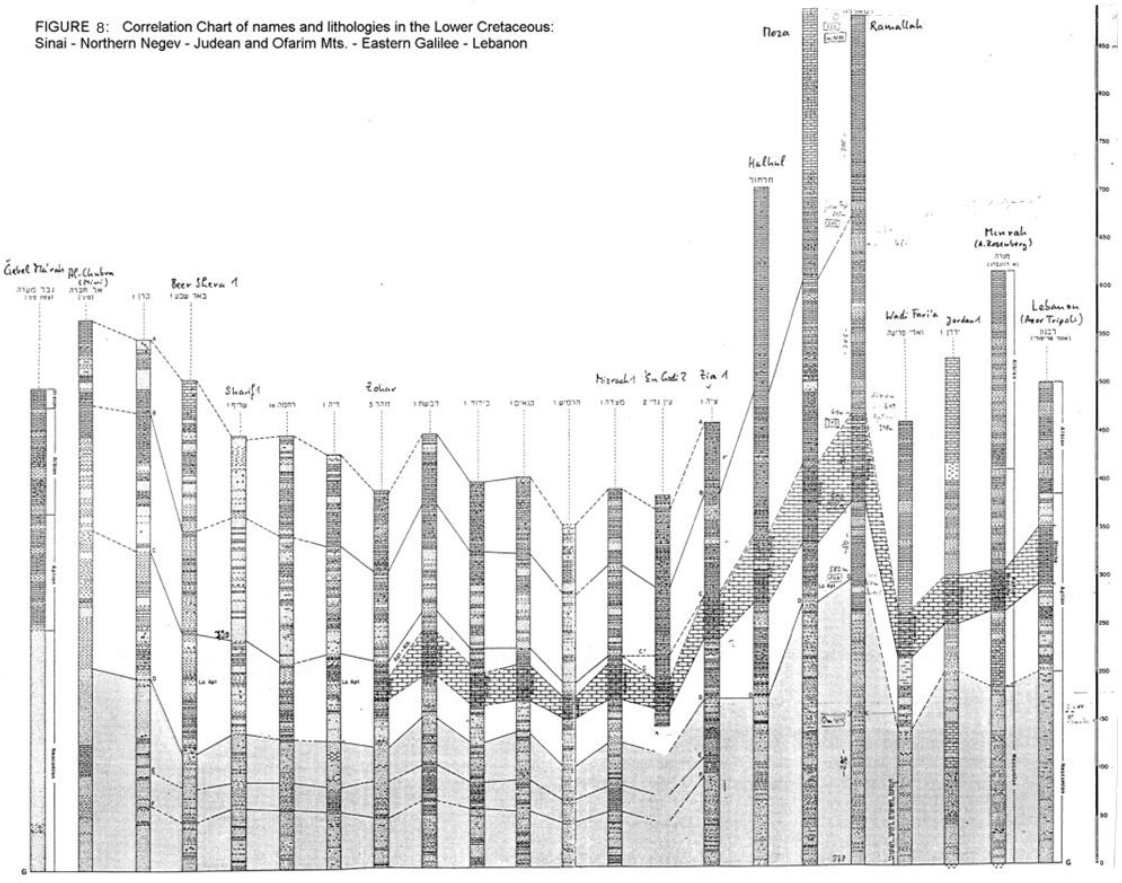


Figure 8: Correlation chart of names and lithologies in the Lower Cretaceous (COHEN, 1988)

During the Neocomian sedimentary gap, extensional movements lead to a sequence of alkaline extrusives, called **Tayasir** volcanics.

In the North, these tuffs and analcite-basanite basalts start shortly after the end of the Jurassic sedimentary cycle, as early as Lower Neocomian: Berriassian and Valanginian (HIRSCH, 1990).
In the East, the volcanics start in Hauterivian and last throughout Barrêmian, as in the type location of Wadi Malih in the Northeastern tip of the West Bank. There, volcanics sometimes interrupt the sandy sediments of the initial Lower Cretaceous transgression.

In the South, in the Negev, volcanics start not earlier than Barrêmian, but last up to Lower Aptian. Here, basalts underlie the Hatira sandstone formation and partly intrude this formation in the form of laccoliths and sills.

At the Northern edge of the Western aquifer basin, Tayasir reaches a thickness of 200m (Carmel 1) to 400m (Har Amir 1, near Um El-Fahm), and 230m at the type location in Wadi Malih. Only minor deposits of the volcanics crop out within the study area, predominantly in the North of the Western Aquifer and the Coastal plain.

In the Northern West Bank and the Galilee, carbonatic conditions were already reached during Lower Aptian times (see Nabi Sa'id formation). However, the sandy series of the Neocomian continue through the Aptian in the Negev, where they are referred to as the **Hatira** formation.

The Palestinian name of this formation is **Ramali** and was given by ROFE & RAFFETY (1963), referring to its sandy character. In the northeast of the West Bank, the Ramali sandstone has an incomplete outcrop in Wadi Malih, underlain and intercalated by the Tayasir volcanics, with a thickness of 120m (MIMRAN, 1995). Ramali lasts up to Lower Aptian.

Deltaic to basinal sedimentation starts with the **Gevar'am** formation in the subsurface of the western coastal plain and offshore. These sediments fill canyons in the deeply buried Upper and Middle Jurassic, among which is the so-called Gevar'am Channel. Gevar'am continues offshore throughout Aptian, while in the NW of the study area, in the northern Coastal Plain, it undergoes a gradual shift to the Yavne shales during Middle to Upper Aptian.

Adjacent E and SE, in the central and southern coastal plain, the facies during the deposition of the latter changes to more sandy conditions of a deltaic-fluviatile environment and is then referred to as **Helez** formation. Near the coastline and in the southern coastal plain, the Helez is overlain by Yavne shales in the Upper Aptian, but in the main and Eastern part of the Coastal plain, the Helez is overlain by the **Telamim** formation (see Upper Aptian).

2.3.2 Upper Aptian

Offshore and in the coastal plain, the first carbonatic event starts in the Mid Aptian (Lower Aptian to lower part Upper Aptian) with a sharp contact over the Gevar'am formation (and in places the Helez formation). This carbonatic event is referred to as the **Telamim** formation in the subsurface of the coastal plain. It covered a wide platform over most of the study area (Figure 9) under various names. It is found up to Lebanon, where it is referred to as Blanche, Falaise de Blanche or Nappe Blanche. It is the equivalent to the Nabi Sa'id and Ein Al-Assad formations (Lower and lower part of Upper Aptian) in the West bank and the Galilee (see Table 3).

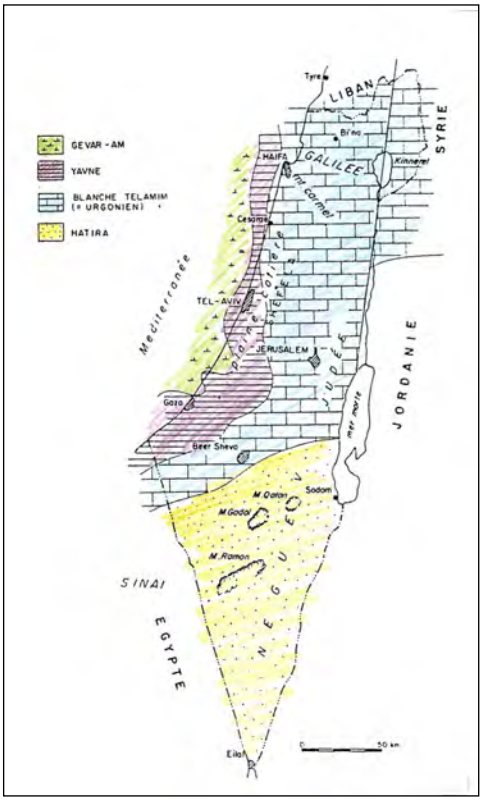


Figure 9: Aptian Facies Map (Hirsch, 1990)
Continental facies in the south, carbonate platform in the centre and north,
Yavne shale along the coast, marly facies offshore

The **Nabi Sa'id** formation is the West Bank equivalent of the lower part of Telamim (coastal plain) and of the Couches à Gastéropodes. It is transitional between the underlying sandstone and the carbonates and shales above. Therefore, it consists of a still somewhat sandy limestone (Photos 2 & 3) and usually does not exceed a thickness of a few tens of metres, though it has been drilled in boreholes with an apparent thickness of up to 80m (Ramallah 1).

Photos 2 & 3: **Core from Ein Senia Borehole No.7b**, 824m depth: Shale interbedded with slightly sandy limestone, transition zone between Tammun and Ramali formations (presumably ?Nabi Sa'id formation)

In the literature thickness data of the Nabi Said Formation are somewhat contradictory: ROSENFELD ET AL. (1995) report a thickness of only 57m; MIMRAN (1995, 1972) mentions a thickness of 86m, 90m respectively.

The Nabi Sa'id formation is capped by a cliff-forming, massive, hard, grey or light grey lithographic limestone: the **'Ein Al-Assad** formation. Outcrops of this prominent cliff are found outside the study area in the vicinity of the Lebanese border. The formation was first described in Lebanon by DUBERTRET (1937) as "**Nappe Blanche**" or "**Falaise de Blanche**". Both the facies and morphology of this limestone resemble the South-European "Urgonian" facies.

Contrary to the thickness of Nabi Sa'id, the thickness of 'Ein Al-Assad is given higher by ROSENFELD ET AL. (1995; 1998) – 77m – than by MIMRAN (1995, 1972) – 47m, 56m respectively. However, the thickness of both limestone formations together sums up to approximately the same value, which leads to the assumption, that the border between the formations was assumed at different levels.

The third West Bank member of the Upper Aptian is the shaly **Tammun** formation. It is very thick and lasts up to the Lower Albian where it is covered by the Ein Qinya and Qatana formations. Hence its lower part is equivalent to the upper part of Telamim in Carmel and the northern and eastern coastal plain, and is a time equivalent to the Yavne shales offshore and in the western and southern coastal plain. The upper part of Tammun is equivalent to the lower Yakhini formation in Carmel and most parts of the coastal plain.

2.3.3 Lower Albian

Off-shore, **Yavne** shale, starting from the Upper Aptian continues for the beginning of the Lower Albian and is then followed by the thick deposits of the **Talme Yafe** formation, that continues throughout Cretaceous times (Table 3).

Talme Yafe	
Time:	Albian-Turonian
Description:	A contour current shaped sedimentary prism
Position:	At the continental margin of the Arabian Craton
Size:	More than 3000m thick, ~20km wide and >150km long
Contains:	Calcareous detritus of biochemical carbonates and skeleton fragments
Source of the detritus:	From rudist reefs,
Transport over edge:	Probably by storms, tidal and seasonal currents.

Stage	Off-shore	Coastal Plain	Carmel	West Bank	Negev
Lower Albian	Talme Yafe / Yavne	Yakhini	Yakhini	Qatana / Ein Qinya / Tammun	Hevyon / Hatira
Upper Aptian	Gevar'am	Yavne (Telamim)	Telamim	Tammun / Ein Al-Assad	Hatira
Lower Aptian	Gevar'am	Gevar'am	Hatira	Nabi Sa'id	Tayasir
Barrêmian	Gevar'am	Gevar'am	Hatira	Hatira (Ramali)	Tayasir
Hauterivian	Gevar'am	Gevar'am	Tayasir	Tayasir	
Valanginian	Gevar'am	Gevar'am	Tayasir	Tayasir	
Berriassian	Helez	Helez	Tayasir	Tayasir	
Tithonian	Helez	Helez			

Table 3: Chronostratigraphy of the Lower Cretaceous: Offshore – Coastal plain – Carmel – West Bank – Negev (after BARTOV 1981, HIRSCH 1990 and PERATH 1982)

In the coastal plain and Carmel area, marine intercalations occur several times since the uppermost Aptian, but mostly since the Lower Albian. The latest of these intercalations brought the coastal plain area under carbonate platform conditions. This event is termed the Yakhini ingression. The **Yakhini** Limestone formation starts around the beginning of the Albian and continues diachronously until Early or Middle Albian, where it is followed by the dolomitic **Yagur** formation. As already mentioned, the Yagur formation is the coastal plain and Carmel equivalent of the Beit Kahil formations.

The Lower Albian: formations differ in name and facies for the various locations they occur. **Offshore**, some deposits of Yavne, but mainly Talme Yafe were sedimented. In the **coastal plain and Carmel** region, Yakhini was deposited. The **West Bank** formations are from bottom to top Upper Tammun, Ein Qinya and Qatana formations. In the **Galilee** in the same time, Upper Hidra, 'Asfuri and Rama formations were formed. The **Negev** is characterised by Hatira formation. The bottom of Hevyon has its roots in the uppermost part of Lower Albian

2.3.3.1 West Bank (Galilee and Lebanon)

As follows from Tables 3 and 4, Lower Albian formations have stratigraphic equivalents over wide areas, under different names. Tammun has the equivalents of **Hidra** in the Galilee, and "Couches à Orbitolines" in Lebanon. After Tammun, the succession follows with Ein Qinya and Qatana formations in the West Bank, **'Asfuri** in the Galilee and "Banc de Zumoffen" in Lebanon. The third formation of Lower Albian age is Qatana, with its equivalents **Rama** in the Galilee and "Couches à Knemiceras" in Lebanon.

Tammun
The early Albian sequence is called the Yavne event (BRAUN AND HIRSCH, 1987), because the Tammun-Ein Qinya-Qatana succession is correlated to the off-shore and coastal plain deposition of the Yavne shale that corresponds to a global drop in sea level (FLEXER ET AL., 1986) Other sea level drops that are found on a global scale are the top Kesalon event, the Moza event and the end of the Cenomanian (Braun and Hirsch, 1994). HIRSCH ET AL. (1983) concludes from Ostracode genera to a shallow that there was a rather warm, marine environment throughout Tammun, Ein Qinya, Qatana and Kefira.

In the subcrop, the Tammun (Hidra) formation is dominated by purple and brown, greenish shales and marly shales, but this formation also contains sands, iron oolites and locally some calcareous intercalations.

Only two outcrops exist in the West Bank: Ein Qinya and Wadi Malih area. Near Ein Qinya village, SHACHNAI (1969), divides the outcropping top 87.5m into three members, a lower hard member (14.5m), a middle weathered member (43.5m) and the limestone and marl member with *Engonoceras* sp. at the top (29.5m). The limestone is dark, due to its bituminous content. Limonite and Hematite are

found as well. Towards West and North, the clayey content increases, indicating deeper water conditions.

In the subcrop, in borehole Moza 1 (West of Jerusalem), Tammun was found 300m thick. In Ramallah-1 (near Bir Zeit, 5km N of Ramallah), the sequence of Ein Al-Assad, Tammun and Ein Qinya formation was drilled for 460m. Different interpretations of the geophysical logs conclude a thickness range between 120 and 170m. HIRSCH (1983) reports a total thickness of 178m in Ein Qinya and Ein 'Arik areas (W of Ramallah) in both, subcrops and outcrops. MIMRAN (1995) reports a thickness of 227 in Wadi Malih (NE tip). And the thickness in the Hebron area (Halhul wildcat) is reported 100m by BRAUN AND HIRSCH (1994).

Ein Qinya
Ein Qinya crops out at the village Ein Qinya, a few km West of Ramallah, with a thickness of 57m, where it is described as a continuous sequence of massive, hard fine grained or pseudoconcretional thin-bedded, mainly detritic limestones, well bedded and rich in micro- and macrofauna, including small rudistid patch-reefs. Between the limestone layers, there are horizons of fossiliferous marl. The lower half contains oolitic limestone.
ROSENFELD ET AL. (1995) report a West Bank thickness of only 38m. In the borehole Beit Dajan, East of Nablus, Ein Qinya was encountered 76m thick.

Qatana
The top of the Lower Albian in the West Bank is the glauconitic Qatana marl, named after the village of Qatana, WNW of Jerusalem at the green line.

SHACHNAI (1969) describes 40m of marly limestone, limestone and marl, alternating in thin beds, with a rich micro and macrofauna, including *Knemiceras sp.* The limestone is mainly biomicritic and pseudoconcretional, the marl is soft and yellow and heavily encrusted with Nari, a caliche-like weathering crust, typical for the West Bank.

Sometimes, marly limestone, marl and clay alternate places, rendering the formation into the bottom aquiclude of the overlying Judea group (West Bank group) aquifers. However, ROFE AND RAFFETY (1963) mention 15m thick, massive and highly jointed limestone at the top, that reveals good aquifer potentiality and should be seen as the base of the major aquifer of the lower part of Lower Beit Kahil Formation.

The thickness is given as 40-45m in most of the West Bank. Only MIMRAN (1995) reports a thickness of 82.5 m in Wadi Malih.

Stage	Lebanon	Galilee	West Bank
Lower Albian	Couches à Knemiceras	Rama	Qatana
	Banc de Zumoffen	'Asfuri	Ein Qinya
	Couches à Orbitolines	Hidra	Tammun
Upper Aptian			
	Falaise de Blanche	Ein Al-Assad	Ein Al-Assad
Berriassian - Upper Aptian	Couches à Gastéropodes	Nabi Sa'id	Nabi Sa'id
Hauterivian – Barrêmian	Hatira	Hatira	Ramali

Table 4: Comparison of the chrono-stratigraphy for the Upper Neocomian to Lower Albian
- in Lebanon, the Galilee and the West Bank

2.4 Structure and Summary

In Early to Middle Cretaceous times, extensional movements and volcanism (Tayasir) were accompanied by a wide-scale sea-level drop. Jurassic and older strata were exposed and eroded. The erosional products were deposited as sands and turbidite sands in the central basin (Yoav Group). In the east, a carbonate platform developed (Ga'ash Group) and on the west, along the continental margin, the clastic marly Talme Yafe prism was built.

3. UPPER ALBIAN

3.1 Regional Setting

In the Upper Albian, the entire country underwent a continuation and deepening of the Albian transgression with the establishment of a carbonate platform, reaching from approximately today's coastline (continental margin) to the areas of nowadays Southern Syria, then adjacent to the Palestinian plate in its pre-rift position (Figure 10). For the first time, the transgression also reached the areas of the Negev. Only the extreme South, near Eilat, remained exposed or predominantly under continental facies.

3.2 Names and Limits

For the West Bank, the terms Lower Beit Kahil and Upper Beit Kahil (LBK and UBK) have been introduced by ROFE AND RAFFETY (1963). Rofe and Raffety then assumed a Cenomanian age, based on a very incomplete fossil record and even back then with question marks as to the true chronostratigraphic position. In fact, Rofe and Raffety describe the formations as possibly having "maintained a relict Aptian/Albian fauna" (ROFE AND RAFFETY, 1965; Nablus report, p. 20). Progress in the placement of these formations was made since by numerous authors, such as Hamaoui (1965), LEWY AND RAAB (1976), LEWY (1986), HIRSCH (1983, 1990) and others.

The Israeli terms for the West Bank and adjacent areas subdivides both formations into two, with the succession of Kefira, Giv'at Ye'arim (LBK), Soreq and Kesalon formations (UBK), all of them introduced by ARKIN ET AL. (1965).

Towards Carmel and the Northwest, the sequence name changes to Yagur for the entire section, while the south continues in the beginning with Hatira sandstone formation (GREENBERG, 1968) and then starts with the Hevyon formation, transgressing successively from North to South during Lower and Middle Albian.

Only offshore, the facies remains that of the Talme Yafe formation outside the continental margin (clastic detritus from the platform reefs and biochemical carbonates).

Throughout the Western Aquifer Basin, the Upper Albian formations are referred to as the Lower Aquifer.

3.3 Historical Geology, Stratigraphy and Facies

3.3.1 West Bank

3.3.1.1 Lower Beit Kahil Formation (LBK1, 2), Kefira and Giv'at Ye'arim formations

In general, the West Bank's Beit Kahil formations consist of tidal-flat and supratidal dolomites, alternating with normal marine limestone, while the Galilee, Carmel and coastal plain's Yagur formation is built up almost entirely of monotonous dolomites. In the Negev, the transgressive facies of the Hevyon formation continues with more terrigenous sediments. All three series are interrupted at the Albian-Cenomanian boundary (HAMAOUI, 1965) by a sedimentary break with very low water stands.

With the type location near Beit Kahil (South of Hebron), Rofe and Raffety describe the Upper Beit Kahil and Lower Beit Kahil formations separately for the Nablus district and the Ramallah - Jerusalem district.

a) Northern West Bank

For the Northern West Bank, Rofe and Raffety (1965) describe Lower Beit Kahil, according to the outcrops in the East as limestone with occasional marl, shale, and dolomite that is massively bedded at base and becomes increasingly thin bedded and clastic towards the top.

Kefira
The lower part of Lower Beit Kahil is very karstic and due to its solution holes in both outcrop and subsurface, it is also called the "Emmentaler"-Formation. It is dominated by finely dolomitic limestone, sometimes pure limestone, with very light to white colours and bedded in m-banks. Dolomite can locally replace the limestone partly, or even completely, especially in boreholes. It is then buff to yellowish. No soft layers occur for most of the section, but the dolomite or limestone, though hard, can have some marly content.

Giv'at Ye'arim
In the upper part of Lower Beit Kahil, the dolomitization of the formation continues and deepens with dark grey and grey-brown, very hard, more massively bedded layered coarse crystalline dolomite. To the south of Nablus in the Audala well, some chert and marl was found in this upper, approximately 60m thick unit of Lower Beit Kahil (MESSERSCHMID, 2000).

Thickness
In the Nablus district, Rofe and Raffety report only one complete outcropping section, at Luhuf Jadir (No.3), with a maximum thickness of 280m. However, since Rofe and Raffety place the Ramali sandstone formation directly under the Lower Beit Kahil, and since the lower 139m contain shale in abundance and sandy content in its lower part, this section should be considered part of the Aptian/Lower Albian Kobar Group (Tammun, Ein Qinya, Qatana). The remaining part of LBK is then 141m thick, which matches more accurately the usual findings in the field. Rofe & Raffety (1965) believed, that true limestone conditions developed later in the North and Northeast than in the South and Southwest, i.e. the Ramallah area. This should be corrected based on the assessment that the lower part of what they describe as Lower Beit Kahil, in fact belongs to the Kobar group. In general, as mentioned before, the transgression started in the North and Northwest than in the South and Southeast.

In boreholes in the Nablus area (Audala well), Lower Beit Kahil was found 161.75m thick, with 108.25m for the lower part (Kefira, LBK1) and 53.5m for the upper part (Giv'at Ye'arim, LBK2). In the Beit Dajan borehole (5km East of Nablus) , LBK was found 130m thick (and UBK 93m).

b) Central and southern West Bank

The central and partly southern West Bank (Ramallah and Jerusalem districts) differs slightly in the reported descriptions. They are however better documented by Israeli reports. Lower Beit Kahil, according to the Israeli terminology, is divided into a lower formation, Kefira and an upper formation, Giv'at Ye'arim.

In the Ramallah district, the lower part of Lower Beit Kahil (Kefira, LBK1) consists of limestone, very light-coloured, not shiny but with a smooth fresh surface. It is well-bedded in m-banks, fine crystalline and highly karstic ("Emmentaler formation") (Photo 1, 2). It can be dolomitic in the upper part. Sometimes, intermediate marl layers intercalate the formation. In general, the marly content increases in a downward direction. Its thickness ranges from 120 m to 180 m.

Photo 4: Highly karstic Kefira ("Emmentaler") near Qatana, Wadi Kefira

Photo 5: Well bedded limestone of Kefira (near Qatana, Wadi Kefira)

The upper part of the Lower Beit Kahil (Giv'at Ye'arim formation, LBK2) consists of dolomite, dark grey, massively bedded, fine-crystalline and hard. It is also highly fractured and karstic, though less than the lower part of LBK. Its thickness ranges from 40 m to 90 m.

In the western part of Jerusalem district, Lower Beit Kahil formations were identified by ARKIN ET AL. (1965). They describe Kefira (lower LBK) and Giv'at Ye'arim (upper LBK) independently.

The type location of the **Kefira** formation is 10km W of Jerusalem, in Wadi Kesalon, south of Abu Gosh, at the coordinates (159.910/133.620), with its lower half examined at borehole Ein Karem #8, and its upper part in outcrops. In Kefira formation, well bedded limestone, mostly biosparite and biomicrite prevails (see photo). The limestone alternates with dolomite and some Oolites appear in the lower and middle part. Its thickness reaches up to 180m.

The type location of the **Giv'at Ye'arim** formation is adjacent to that of Kefira (159.350/133.620). Giv'at Ye'arim consists of well bedded dolomite, with beds, 0.5-1.5m thick. The dolomite is mostly fine crystalline, but coarse crystalline dolomite appears in the lower half. In the upper half, there is a 0.9m thick bed of platy quartzolite (silicified rudists). The type section has a thickness of 82.7m. In the area, the thickness lies in a range from 40-90m.

Due to its hardness, Giv'at Ye'arim stands out between the softer top Kefira and bottom Soreq. It is made up of massive dolomite, well jointed and fractured and with karstic features, both in the outcrop and subcrop. This makes it an excellent aquifer.

Photo 6: Giv'at Ye'arim, 3km west of Jerusalem. Massive light grey dolomite, weathering red (mobilised iron); jointed and fractured; soil in pockets in the subsurface

In the western Hebron foothills and Bet Guvrin area, Kefira consists mostly of cliff-forming, bedded fossiliferous limestone, alternating with nodular limestone and some dolomite. (90m thick)

Giv'at Ye'arim, in the Bet Guvrin area can be divided into three ledges, all built up of dolomite, but with the middle ledge in some areas made of fine crystalline limestone and partly silicified rudists. (30-50m thick).

3.3.1.2 The Upper Beit Kahil formation (UBK1, 2), Soreq and Kesalon formations

a) Northern West Bank

Also the Upper Beit Kahil reveals a relatively wide range of different facies. The most common rock is dolomite and dolomitic limestone. It is massively and thinly bedded, usually coarse crystalline, sometimes chalky. The formation becomes increasingly karstified upwards. It does not outcrop locally in Nablus, but outcrops further east along the flanks of the Fari'a anticline. Its reported thickness is 120 - 220 m. In the subcrop and in Israeli terminology, Upper Beit Kahil is divided in an approximately 150m – 200m thick lower member (Soreq, UBK1) and a thinner or disappearing upper member Kesalon (UBK2).

Soreq

In Soreq, a sugary, often primary dolomite, fine grained and buff or grey dominates throughout the section. Despite its fractured and karstic character, Soreq is an intermediate to sometimes bad aquifer.

This is due to the presence of marl or, in the outcrops, of chalk with clayey layers. Bands of marl or marly limestone and chert content, (in nodules rather than in layers) have been found in the boreholes close to Nablus City.

Kesalon
The uppermost Albian formation, Kesalon (upper UBK or UBK2) sometimes disappears, but if existent, forms cliffs. The facies become more monotonous with pure, hard dolomite, sometimes limestone as the main component. The marl disappears upward, but chert remains. Only from the outcrops, chalky content is reported. Some limy layers contain oysters and rudists. The maximum thickness is around 50m.

b) Central and Southern West Bank

RAMALLAH DISTRICT
ROFE AND RAFFETY (1965) reported the thickness of Upper Beit Kahil Formation in the Western Basin in a ranges 180 m to 260 m. However, it is seldom found as thick.

The lower part of Upper Beit Kahil (Soreq, UBK1) contains as a main rock type limy to marly dolomite, light and yellowish, fine crystalline sometimes soft and interbedded with thin marly layers. It shows over thick sections a rhythmic pattern of dm-m banks of dolomite, interbedded with cm-dm banks of marl. The usual thickness is between 60 m and 130 m.

The upper Part of Upper Beit Kahil (Kesalon, UBK2) consists of dolomite and limestone, usually coarse crystalline and rich in reefal fauna. It is massively bedded and often forms a prominent, so called Kesalon cliff that is easy distinguishable in the landscape. Its thickness ranges from 20 m to 35 m.

JERUSALEM DISTRICT
In the western part of the Jerusalem district, ARKIN ET AL. (1965) describe the Upper Beit Kahil formations on the type locations of the Israeli system.

Soreq (UBK1) has its type location in Wadi Soreq, 7km west of Jerusalem (160.940/129.080), where it is subdivided into two members. The formation starts with a basal, only 7m thick member of thin bedded, partly dolomitic limestone (pelsparite and biomicrite) with very thin marl intercalations. The main part is 120m thick and consists of argillaceous, soft dolomite that is very evenly bedded and again interbedded with yellow marl. Often the dolomite has a "chalky" appearance and contains quartz spherulites and flint concretions.

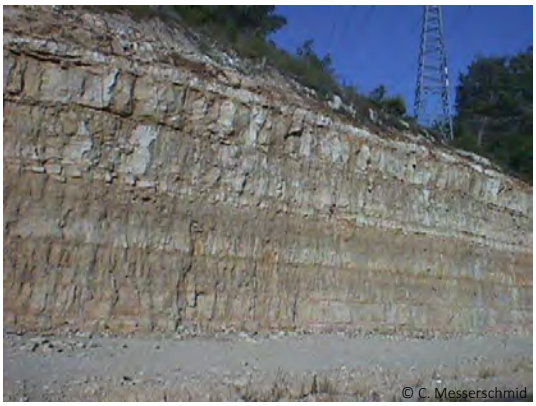


Photo 7: Soreq at the West of Jerusalem
Uniformly bedded

Photo 8: Soreq in N-Ramallah

It is interesting to notice that dinosaur traces have been found in this formation, at Beit Zayit, to the West of Jerusalem. This fact hints to exposed or extremely shallow water conditions, such as a tidal flat (AVNIMELECH, 1962; 1966), in which the dolostones, dolosiltites and dolomuds of Soreq could develop.

Photo 9: dm-banks in Kesalon cliff, SE outskirts of Jerusalem

Photo 10: Kesalon, soft karstic dolomite, Wadi Kesalon

Kesalon (UBK2) has its type location some 15km west of Jerusalem at the coordinates 153.600/132.030, at the lower end of Wadi Kesalon, where it forms a steep, well exposed, high cliff, with caves and karstic holes in abundance. Laterally it changes its morphology and continues as a broad, soil covered terrace. Kesalon at its type location is built up of massive dolomite with frequent remains of rudists and Nerinea. The dolomite contains lenses and thin beds of quartzolite in a range between a few, up to 50cm.

Photo 11: Kesalon cliff with caves, Wadi Kesalon

Photo 12: Karstic holes in Kesalon cliff, Wadi Kesalon

HEBRON DISTRICT

Soreq

Also further south, in the southern West Bank, Soreq (UBK1) continues with its typical alternation of dolomite, often primary but also secondary dolomite and marl or argillaceous dolomite. Northwest and West of Hebron, as well as in the Hebron foothills near the Green Line, Soreq consists of dolomitic limestone, calcareous dolomite and some dolomitic marl. In Wadi Sheikh Yusuf, the bottom 50m displays calcarenites in varying stages of dolomitization with silicified rudists, overlain by 80m of dolomicrites. Prevailing limestone biostromes and bioturbated nodular calcarenites with algal mats and marl are found in Wadi Rushrash. The thickness of Soreq is up to 130m in this area.

Kesalon

In the Western Hebron hills and foothills, Kesalon is regionally wedging out. While northwest of Hebron, Kesalon forms a prominent cliff of limestone and at the top fossiliferous limestone with up to 20m thickness, the formation laterally thins out southwards, until it disappears at around PGN 105

(immediately East of Hebron). This means that Soreq is directly overlain by the Cenomanian Beit Meir formation (lower Yatta in Palestinian terminology). Only further south, in the Samu'a area of the southernmost West Bank, Kesalon reappears with up to 26m thickness as a uniform limestone series (reappearance at the outcrops between Soreq and Beit Meir at around 99.5 PGN). It was mentioned before that the Kesalon event is one of the prominent phases of a eustatic sea level low stand. It seems that in these areas, between 106 and 100 PGN, the surface was exposed above sea level. This assumption is strengthened by the fact that in the NW and W Hebron hills and foothills, Kesalon is often encountered as a calcarenite, with the sandy content hinting to proximal conditions. This terrigenous character resembles the Hevyon formation in the Negev (Uppermost Albian). However, the calcarenite also appears as an oyster lumachelle and contains silicified rudists, foraminifera and algae. According to LEWY & RAAB (1976), the Kesalon formation trespasses the Albian/Cenomanian boundary and stretches with a few meters into the Cenomanian period.

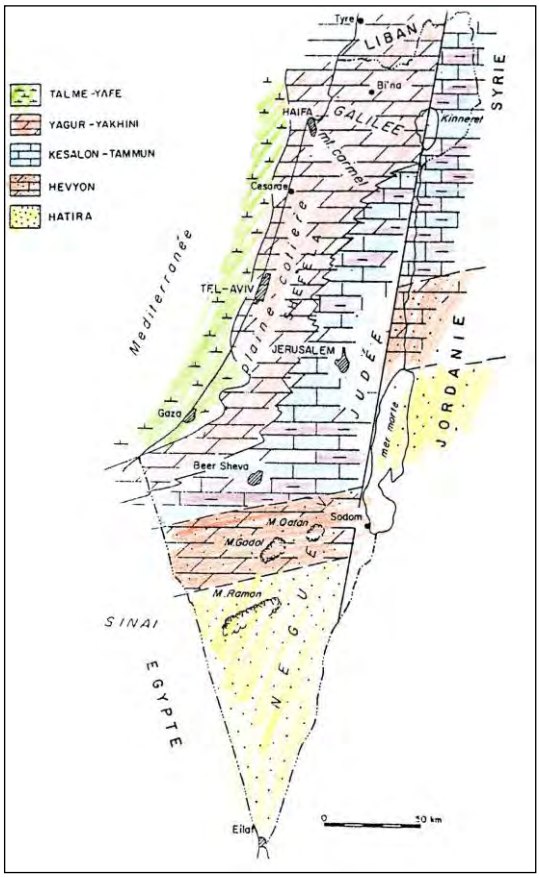


Figure 10: Facies map of the Albian (Hirsch 1990): Terrigenous facies in the south, proximal facies in the Negev, marl-limestone facies in the West Bank, reefal facies in the coastal plain and deep basin off-shore

3.4 Summary and structure

During Early and Middle Cretaceous (144 –90 Ma), the area undergoes a gradual transition from exposure to the establishment of a stable carbonate shelf. The sequence starts with extensional movements and volcanism, accompanied by a sea-level drop with subaerial exposure of edge areas, followed by erosion and accumulation of sands. Shale and marl accumulates during the Upper Aptian and Lower Albian in the Northern and Central part of the area (Kobar Group). A carbonate platform was established here from upper Albian throughout Cenomanian and Turonian with the deposition of >1000m thick carbonates (Judea or West Bank group). Offshore, the clastic sedimentation of carbonatic detritus and marl continues in the form of a basinal marly prism (Talme Yafe Formation).

4. UPPER CRETACEOUS
(Cenomanian – Turonian)

4.1 General (regional) setting

As described so far, the Cretaceous transgression is of Tithonian-Valanginian age in the Coastal plain, it is Aptian in the Galilee, Upper Aptian in the West Bank, uppermost Aptian in the Negev and Cenomanian in Eilat. This first sedimentary cycle ends diachronously approximately at the Albian/Cenomanian boundary.

The second large sedimentary cycle of the Cretaceous lasts up to the top Turonian boundary and in most parts slightly into the lowermost Coniacian, again not uninterrupted by smaller, secondary sea level drops, such as the Moza event.

Rudistid facies prevails throughout the Judean group, synonym to the "Judean limestone" (WELLINGS). However, LEWY AND RAAB (1976) distinguished a certain number of cephalopods.

a) The Lower Cenomanian starts with
- chalky marls of En Yorqe'am and Isfiye
- passing laterally into the Beit Meir dolomites (Figure 17)

b) The Upper Cenomanian comprises of alternations of
- marly channel facies
- limestone-dolostone platform and
- reefal facies

c) In the North, these facies are referred to as
- Deir Hanna and Sakhnin that correspond to
- Amminadav-Weradim dolomites interrupted by Acanthoceras limestone of Kefar Sha'ul in some parts of the West Bank and correspond to
- Zafit, Avnon, Tamar limestones and dolomites in the Eastern West Bank and the Negev.

d) At top Cenomanian, a slight regression takes place (LEWY, 1988). Then starts the last sedimentary cycle: Judea group ends with predominantly limestone of Turonian – Coniacian age. In Turonian to Coniacian, a wide carbonate platform was established from Lebanon to the Sinai.

Near the top boundary of the Turonian-Coniacian cycle, glauconitic sands appear and correspond to a global regression 90 Ma ago. The upper limit is erosive due to embryonic tectonic movements of the Syrian Arc system, partial emersion and successive erosion.

4.2 Names and limits

The Cenomanian – Lower Coniacian sequence contains a wide, well-established and distinguished range of lithofacies and biostratigraphy (Figure 15). A large set of formation names is found in the literature that cannot be avoided completely. In the following, a generalisation will be attempted, where it is possible without becoming unreliable or contradictory and without omitting the most important trends and differences. In addition, there continues the difference between Palestinian and Israeli terms.

As for the Upper Albian, a revised and updated chronostratigraphy of the Palestinian formations will be presented (see Figure 16)

In the West Bank, the Palestinian stratigraphy distinguishes Lower Cenomanian **Yatta** formation, Upper Cenomanian **Hebron** and **Bethlehem** formations and (mainly) Turonian **Jerusalem** formation (ROFE AND RAFFETY, 1963 ff.).

In broad terms, Yatta is considered an aquitard/aquiclude, while the rest forms the Upper Aquifer. Sometimes, middle and top Jerusalem are referred to as "Uppermost Aquifer" (see Section F: Hydrogeology).

The Israeli terminology for the area of the West Bank subdivides each, Yatta and Bethlehem into two formations each (see Table 6). The succession is: **Beit Meir** and **Moza** (for Yatta), **Amminadav** (for Hebron), **Kefar Sha'ul** and **Weradim** (for Bethlehem) and **Bi'na** (for Jerusalem).

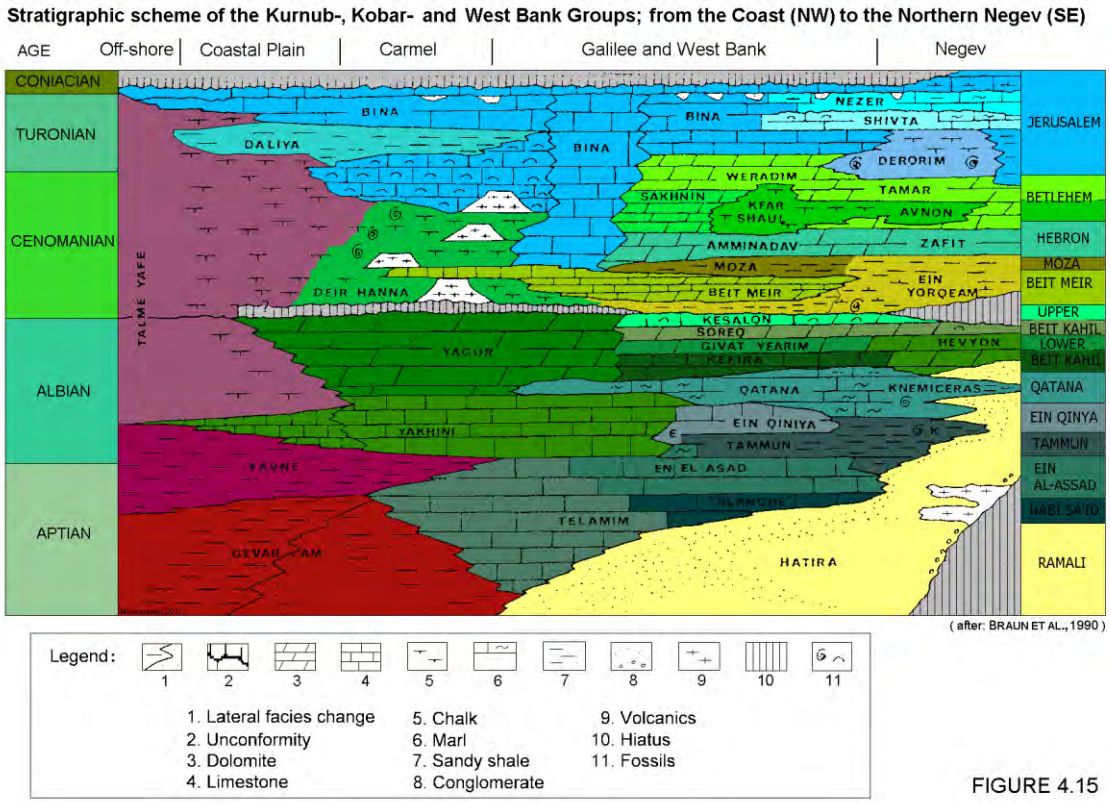


Figure 15: Stratigraphic scheme of the Kurnub, Kobar and West Bank groups.

In the eastern part of the West Bank and towards the south, conditions change. Yatta becomes one formation, called **En Yorqe'am** with Beit Meir thinning out gradually as a tongue in the middle of En Yorqe'am. Amminadav is referred to as **Zafit**, Kefar Sha'ul as **Avnon** and Weradim as **Tamar**. The unified Bi'na formation is split into three, from bottom to top, **Derorim**, **Shivta** and **Nezer**. It should be noted, that En Yorqe'am, Zafit, Avnon and Tamar are often referred to as "members" of the Cenomanian-Turonian **Hazera formation**. In the very south, **Ora** formation is used for the Turonian.

To the North and to the West, towards Galilee and Mt. Carmel, but also in some places of the Coastal plain (such as between Tulkarem and Netanya) the whole sequence is divided into three formations only.

Deir Hanna formation comprises of Yatta and Hebron and some smaller parts of Kefar Sha'ul (Lower Bethlehem), overlain by **Sakhnin** and followed finally by **Bi'na**. At the reefal complexes, Carmel, Caesarea, Helez etc. in the coastal plain, Cenomanian consists of 4

formations: **'Isfiye**, **Bet-Oren**, **Khureibe** and **Junediya**. The Turonian is referred to as **Muhraqa** and **Daliya**, or as Bi'na.

In the southern coastal plain, in the oil wells, and by the Geophysical researchers, the Cenomanian is often called **Negba** formation. Offshore, **Talme Yafe** continues to Upper Turonian or even top Turonian.

If not stated otherwise, the main sources for this chapter are KESHET AND MIMRAN (1993) and MESSERSCHMID (2000) for Ramallah area, ARKIN ET AL. (1965) for Jerusalem area, ARKIN AND BRAUN (1965) and HAMAOUI AND RAAB (1965) for the Negev, ARKIN AND HAMAOUI (1967) for the coastal plain and SASS AND BEIN (1982) for Mt. Carmel area. For general information, HIRSCH (1990) and GUIDEBOOK (1990) are important.

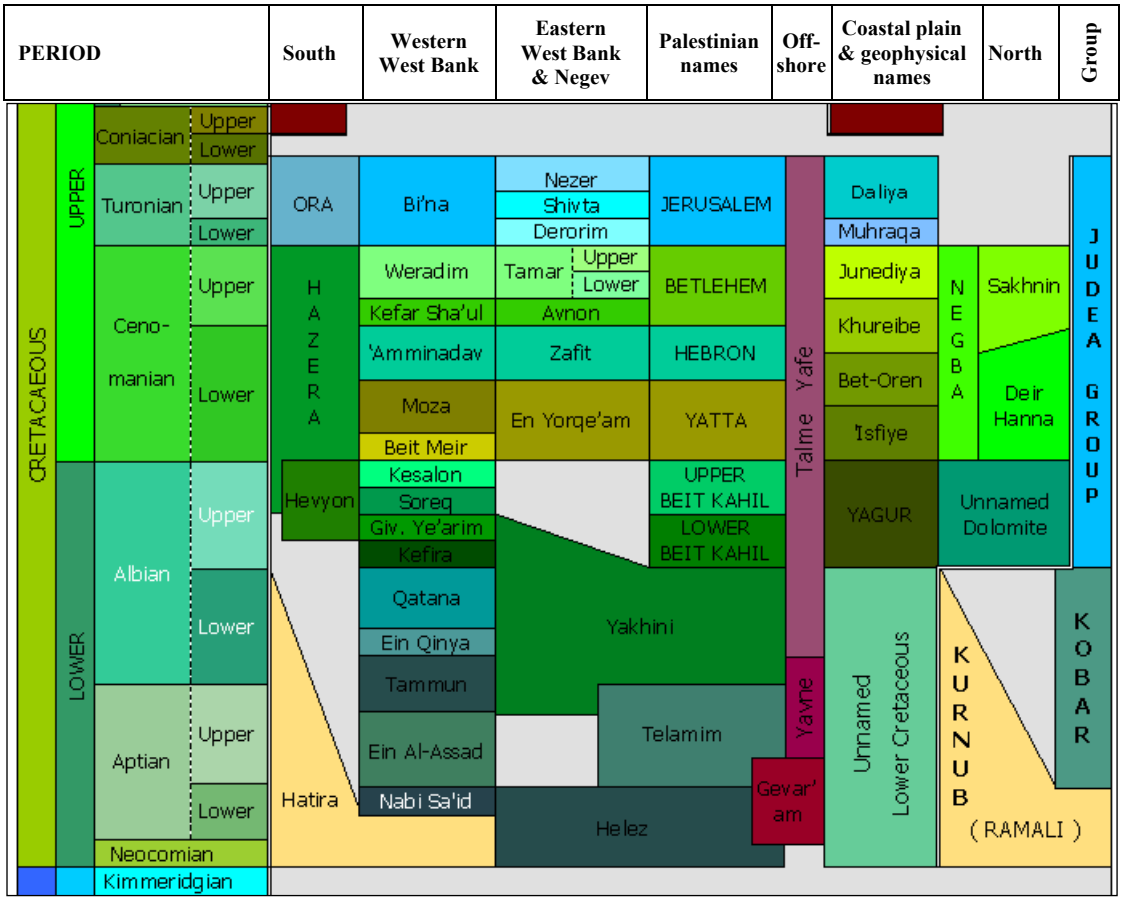


Figure 16: Stratigraphy of Ramali, Kobar and Judea groups, Cretaceous

4.3 The sedimentary sub-cycles

4.3.1. First Cycle: Lower Cenomanian
(equivalent to Yatta)

In the Negev and southern West Bank, at the base of Ein Yorqe'am formation, patches of oyster lumachelles fill scour holes and solution cavities on the surface of top Kesalon. En Yorqe'am is up to 60m thick, with prevailing chalk and limestone with bivalves, echinoids, ostracodes and Early Cenomanian ammonoids (LEWY AND RAAB, 1976). Uppermost En Yorqe'am, notably argillaceous, is known as Moza marl.

Where limestones, biostroms, and chalks of En Yorqe'am are replaced by tidal-flat dolomites, they are called Beit Meir, which may contain rudistid biostromes in its upper part.
Similar to top Kesalon, top Beit Meir is often strongly limonitized, a sign for non-deposition phases, while Moza marl and clayey limestone reflect a normal shallow marine environment, with abundant bivalves, echinoderms, ostracodes and foraminifera.

4.3.2 Second Cycle: Upper Cenomanian
(equivalent to Hebron, Bethlehem)

In the North, there are lateral facies changes between Sakhnin – with massive dolomites – and Deir Hanna – more basinal chalks and limestone – in a small area range.

In the West Bank, there is a series of three formations: Hebron and Lower Bethlehem and Upper Bethlehem, Amminadav, Kefar Sha'ul and Weradim respectively in Israeli terms. (In the Negev, this interval is referred to as Zafit, Avnon and Tamar members of Hazera formation.) The bottom and top formations, Amminadav and Weradim are more dolomitic, Kefar Sha'ul, in the middle is chalkier. At parts, Bethlehem consists of Weradim or of Kefar Sha'ul only, while the other formation wedges out.

Amminadav and Weradim reflect a normal open marine environment with rudistid reefs, as well does Sakhnin. These dolomites contain irregular lenses of limestone and quartzolite, as well as rudistid and oyster reefs. The reefs were separated by channels, in which the chalks and marls of Kefar Sha'ul facies and Deir Hanna facies respectively were deposited.

Photo 13: Sakhnin dolomite, near Nahariyya (Northern Israel, 172.5/271)

At the base of Amminadav, there is platy limestone with fossilized fishes and snakes (found in quarries of villages near Ramallah, such as Beitin and 'Ein Yabrud).
Late Cenomanian ammonoids are found in the marly chalk and platy limestone of Kefar Sha'ul.
The Upper Cenomanian thickness is up to 250m.

4.3.3 Third Cycle: Upper Cenomanian – Lower Turonian
(equivalent to lower Jerusalem)
Daliya formation or "Daliya marl" is found at Mt. Carmel with marl and shale.
In the Negev, Ora and Derorim formations contain marl, shale, chalk and limestone, with ammonoids suitable for dating. These marls hint to an anoxic event according to FLEXER ET AL. (1986)
Upper Cenomanian – Lower Turonian Derorim is the lowermost member of the triad Derorim – Shivta – Nezer, referred to as such in the central and southern West Bank and further south in

the Negev, while this Upper Cenomanian – Lower Coniacian series is a uniform formation, called Bi'na in the Northern West Bank and north and west of it. Bi'na is a well-bedded limestone.

Figure 17: Cenomanian facies map (after HIRSCH, 1990)

4.3.4 Fourth Cycle: Middle Turonian – lower Coniacian
(equivalent to upper Jerusalem)

Middle Turonian – Lower Coniacian Shivta formation consists of massive limestone, forming cliffs at parts (near Jerusalem). Vertically, it undergoes a facies change to the overlying Nezer formation, which consists generally of sub-lithographic limestone, chalk and marl and is well bedded. Nezer formation often contains a clastic sandy unit near the Turonian/Coniacian boundary of 90Ma age. This event reflects a regression, referred to as "Avnimelech event", after the first author who described it in 1950 (AVNIMELECH, 1950 and 1966)

Period		Stage	Israeli		Palestinian	
			Group Name	Formation name	Group Name	Formation name
Upper	CRETACEOUS	Senonian	Mt.Scopus Group		Abu Dis Group	
		Turonian	Judea Group	Bi'na	**West Bank Group**	**Jerusalem**
		Cenomanian		Weradim		**Upper Bethlehem**
				Kefar Sha'ul		**Lower Bethlehem**
				'Amminadav		**Hebron**
				Moza		**Upper Yatta**
				Beit Meir		**Lower Yatta**

Table 6: Simplified stratigraphic table of the West Bank formations (Israeli and Palestinian terminologies)

Since Upper Cenomanian, at the peak of the Cretaceous transgression, the entire Negev is submersed, with shallow facies in the very south (Gerofit-Ora) and more differentiated facies towards the north: Ein Yorqe'am-Nezer in the Negev; Beit Meir-Bi'na in the West Bank; Sakhnin-Bi'na in the Galilee and a reefal barrier (Muhraqa/Bi'na) extending under the Shefela plain (western foothills along the green line) and up until Mt. Carmel, where also some volcanics intercalate. The most pelagic facies extends along the coast (Negba-Daliya).

4.4 Lithofacies

4.4.1 West Bank

Northern West Bank

ROFE AND RAFFETY described the entire section of Cenomanian-Turonian in Nablus district. Tulkarem area is described by ILANI (1972) for the section of Sakhnin (Hebron, Bethlehem) upwards.

Yatta crops out in the southeast (such as Rishash), the south (Salfit) and the west of Nablus district.

The main part of Yatta is the lower member, **Beit Meir** formation. Its characteristic lithology is marly limestone interbedded with dolomitic limestone or dolomite. The dolomite and limestone usually appears in yellowish or brown colours, with a non-sugary grain fabric. Minor chert content, either nodular, lentoid or disseminated, is reported from some locations. Besides this, some chalk, chalky marl, and marl is found throughout the formation, but in high amounts at the base and the top (Moza). Like the dolomite and limestone, the marl appears in thin lamination.

This top marl allows distinguishing lower Yatta (Beit Meir, 90 – 100m) from upper Yatta (Moza, 10 - 20m), according to the Israeli terminology. South of Nablus, in Audala borehole, **Moza** formation is characterised by light to whitish limy marl and chalk as a main component and by a coloured mixture of fine-crystalline dolomite and dolomitic limestone, ranging from white, grey, greenish grey and brown to beige, red and rosé. However, the existence of Moza-formation, with its conspicuous marls and chalks has not yet been proved for the entire area. In the western part of the district, Beit Meir is not so easily discernible from Hebron, since it laterally undergoes a gradual facies change to massive dolomite facies.

It shall be mentioned already, that in the North, Yatta retains the aquicludal characteristics, found in the central and southern West Bank. However, it shows an increased development of limestone, compared with the areas further south.
The overall thickness of Yatta is about 100-120 m.

Hebron formation is more uniform than Yatta but undergoes laterally a considerable facies change. Its outcrops are extensive and its thickness lies in a range between 105m and 260m. In Israeli terminology, it is called **Amminadav**, with identical base and top boundaries.
The main lithological component is dolomite and dolomitic limestone. On the flanks of the anticline the lithology is limier, east and west of it, Hebron consists almost entirely of dolomite. The rock is hard, massive and poorly bedded. It shows sugary texture, by this a high secondary porosity and a well-developed karst in many parts of the formation. Brecciation is common throughout the formation with limestone fragments embedded in dolomitic cement. Chert nodules are also common. Occurrence of chalk and marl has been reported at some outcrops and boreholes. The dolomite is grey, brown, whitish or mottled. The limestone is light grey, pink, or red and more thinly bedded than the dolomite.

In the West and Northwest, towards Tulkarem, the formation is referred to as **Sakhnin** formation. Sakhnin reaches approximately from Hebron to Betlehem, with Sakhnin 1 as an equivalent to Hebron (Amminadav) and Sakhnin 2 and 3 equivalent to lower and upper Bethlehem (Kefar Sha'ul and Weradim). Like in the East, and unlike on the flanks of the anticline, the facies is entirely dolomitic. ILANI (1972) gives a detailed description of the outcropping upper 40m of the formation (see table 7), which consist mainly of mosaic dolosparite and towards the top also of some laminated dolomicrosparite. The dolosparite is hard and compact, with vugs, cavities and well-established joints. At times, it is porous. Some horizons show abundant fossil record, some of which are silicified. The dolomicrosparite is rugged and contains fossil fragments. The described outcrop is near Kur at the coordinates 158.2/184.0.

Bethlehem formation consists of dolomite and limestone, massively bedded with a well-developed karst. Some parts with thin-bedded limestone are used for floor tiles. The dolomite forms a rugged morphology on gentle slopes. Southwest of Nablus, the formation consists of a chalky limestone with occasional marl beds towards it's top. The formation has outcrops in the Fari'a Anticline, east of Nablus, and in the Anabta Anticline, in wadi bottoms and hill tops to the west of Nablus. Its thickness is 40 to 110 m.

Name	Ras El-Muntar	E of Shuffa	Zur Natan	Kur	Sheikh At-Taban
PGE/PGN	158.0/191.8	159.8/185.9	152.5/182.7	158.2/184.0	159.4/181.4
Upper Bi'na	40+	50+	-	60	48
Middle Bi'na	20	20+	-	13	16
Lower Bi'na	10	0	12+	21	0
Sakhnin 3 (Wer.)	15	0	29	19	30
Sakhnin 2 (K.S.)	60	35	58	45	19+
Sakhnin 1 (Am.)	12+	-	14+	40+	

Table 7: Comparison of thickness data for the Upper Cenomanian in Tulkarem area (ILANI, 1972): Hebron (Sakhnin1), Bethlehem (Sakhnin2, 3) and Jerusalem (Bi'na) formations. Fields, marked zero, mean that the formation wedges out.

According to the Israeli terminology, Bethlehem consists of 2 formations, a lower formation, Kefar Sha'ul and an upper formation Weradim. Some authors (i.e. ILANI, 1972) refer to these formations as Sakhnin2 and 3.

In the West Bank foothills and slopes east and southeast of Tulkarem, ILANI (1972) describes **Sakhnin 2** (lower Bethlehem) as again mainly dominated by dolomite (mosaic dolosparite), hard sugary and fossiliferous. However, the dolomite contains calcite grains at several layers throughout the column. At the top, the 45 m thick section is covered with 2 meters of sparry, porous and compact limestone. The bottom is only discernible from underlying Amminadav by its softer character, that continues for about 5m. **Sakhnin 3** (upper Bethlehem) is only 19m thick. The dolomite continues as a compact, rugged dolosparite at the lower part and as laminated rugged mosaic dedolomite in the upper part. Southeast of Tulkarem, Sakhnin 3 laterally wedges out and reappears again over short distances.

At the area east and southeast of Qalqiliya, Bethlehem is again described as succession of Kefar Sha'ul and Weradim. Kefar Sha'ul is more than 30m thick and consists of soft, white to yellow marl, mostly altered to caliche. It contains some dolomite and limestone. The microfacies is mostly of various types of micrite (MITTLEFEHLDT AND SNEH, 1998).

Weradim, overlying Kefar Sha'ul, and where the latter wedges out, directly over Amminadav, is up to 80m thick and consists of a variety of different facies. Fine to medium crystalline dolomite and limestone are found as well as medium to finely crystalline dolomite and limy dolomite, medium bedded, with chert and quartzolite near the top. It can also appear in a facies of sugary, partly dolomitic limestone, yellow-red-grey-brown and in places karstic.

Weradim is at times interfingered or replaced by another facies that is called Eyal facies (or Eyal formation - MITTLEFEHLDT AND SNEH, 1998). Eyal is between 0 and 80m thick and consists of platy, well bedded, white, grey, yellow or pink limestone and dolomite, fine to medium crystalline. The platy limestone alternates with medium bedded dolomite, marl and irregular rugged dolomite. In the upper part, chert beds are common.

There is a slight angular unconformity at the boundary between Weradim and Bi'na (Bethlehem and Jerusalem). This is also known from its type section in the Galilee.

In general, **Jerusalem** consists of thin-bedded limestone, fine-grained and uniform, sometimes dolomitic. It has a well-developed karst and forms a cliff morphology.
In the outcrops in the axial area of the Anabta Anticline, to the west of Nablus, and Fari'a anticline to the east of Nablus, the thickness of Jerusalem is about 50 to 120m.
Its base is characterised by 2-3 m thick massive limestone resting on pink marl. This soft and reddish nodular limestone (with ammonites) is called Mizze Ahmar and is used as a building stone.
The same name applies for the middle member, a cliff forming limestone with rudists.
Towards the top, chalk beds with occasional chert bands are common, and the formation is transitional to the facies above. However, in some areas you find an upper sugary dolomitic limestone, Mizze Helu, which is hard and an excellent building stone.

In Qalqiliya, it is called Bi'na formation and consists of three members: the lower limestone and dolomite member, the middle bioclastic limestone member ("Meleke") and the upper sublithographic limestone member (Mizze Helu).
For the area east and southeast of Tulkarem, ILANI (1972) reports the following thickness relations from outcrops (see table above).

Central West Bank - Ramallah-District

Layers of dolomite and some limy dolomite and limestone, alternating with marl horizons, build up Beit Meir formation. The layers built of dolomite have a yellowish to light-grey tone, fine-grained, dense, homogenous, with limonitic colourings, with a medium to soft hardness. In the outcrops, also layers of quartzolite and chert nodules occur.
The thickness of the formation reaches 110m.

Moza formation is composed of marly dolomites, limestones and marls, all light yellowish-brown and white; dense, of medium grain, hard and thin-layered.
The thickness of the formation in the mapping area fluctuates between 10 and 15m.

Amminadav formation appears in two facies:

a) A limy facies, in which the rock is of *Malkha* type, a white bioclastic limestone with layers of transitional rock of the *Mizze Helu* type,
b) b) a dolomitic facies with a coarse-grained dolomite rock of a greyish colour on the fresh cuts. Very thin-bedded layers in both facies interchange in tones of light and dark.

The appearance in the landscape depends on the facies: In the limy facies appears as a hard, stony rock that builds cliffs with broad lateral distribution and with conspicuous grey colour (KESHET AND MIMRAN, 1993). The dolomite facies has a dark grey appearance and is thin layered, which is very obvious and characteristic. What is missing here is the rocky and cliffy appearance of the limy facies.
There are layers built of very thin strata with interchanging light and dark tones, in those strata undeveloped joints can be found that remind on mud-cracks. The area where the rocks of the formation are exposed is very weathered and creates a stony area. The thickness of the formation is about 160m.

The **Kefar Sha'ul** formation was found to comprise of two units: The lower unit is defined by *Acanthoceras* and the upper unit by Deir Yassin-Limestone.

The lower section is built of chalk and white marl with limestone. The fine-grained and hard limestone stands out in small outcrops from within the Nari. The upper section is built of limestone of thin layering, 2-3cm thick that is used for plates for building. The limestones are fine-grained, of a yellow and red colour, the limestones appear with a chalky characteristic. In this section, chert occurs sometimes. Its appearance is layered in thin beds of 2cm thickness and its colour is brown.

The formation is impermeable to water and has a low hydraulic conductivity. The formation is part of the Upper Aquifer of the Judean group and of Upper Cenomanian-Turonian age.

In the lower unit there is Acanthoceras-Marl and in the upper unit there is Deir Yassin-Limestone. These two sections are nicely distinguished. The lower unit seems soft and uniform because of the Nari cover and the upper unit stands out because of its very good layering and because there is less Nari. The lower unit is built of chalk and white marl with limestone. The upper unit is built of thinly plated limestone (2-3 cm), which is used for building plates. The thickness of the formation reaches up to 100m. The formation crops out in limited areas in the western margins of the Ramallah anticline. In the eastern margins of the anticline, the formation is exposed in wider areas in a strip whose direction is SW-NE.

Weradim formation is composed of coarse-grained dolomite, sugary to sandy, sometimes with bioclastic coarse-grained dolomite and also with fine-grained dense dolomite. The dolomite is of dark grey colour with stains of limonite.
The thickness of the formation is about 30m.

The **Derorim** formation is not marked in the first Israeli geological map of Ramallah district (SHAKHNAI, 1969). In that work, there was no mapping of the formation, even though it was clearly identified on the ground, in very small areas in the wadis and in low areas.
The formation has a medium to low hydraulic conductivity and belongs to the Upper Aquifer of the Judean group and it is of Upper Cenomanian/Turonian age.
The thickness in outcrops was measured ~10m, with the basis of the formation unexposed. The formation is exposed in the wadis, in reduced areas at the East of Ramallah district. The age of the formation is determined by the collected fauna as Upper Cenomanian/Turonian.

In **Shivta** formation, the lithology is mainly limestone of white, yellowish, creamy colour, medium grained, hard and rich in stylolitic contacts with yellowish-marly filling and with limonite stains. There is also a white limestone horizon, very fine-grained, hard, with calcite veins and coarse porosity and there is a vuggy calcite filling.
The formation forms a cliffy landscape with many caves. On the limestone appears a patina of dark-grey and light-grey colours. The Shivta cliff is very prominent in the landscape of the wadis and rich in big rudists. At the basis of the formation there are hard limy rocks that are weathered with fractures along the bedding. They display stylolites parallel to the shape of the weathered surface and represent a collapse of blocks. The upper part is massive, with no signs of layering.
The thickness of the formation is between 20m and 40m.
The age of the formation is determined according to its stratigraphic position as Lower Turonian (BEGIN, 1972)

Nezer formation is divided into a marly unit and a limy unit. The marly unit is fine-grained and made of white chalky marl, brittle, with a number of limestone beds of creamy colour inside. Usually the unit is covered with talus. The colour of the limy unit is yellowish/white/creamy with a grey patina and includes fine stylolites, filled with calcite and limonitic stains and has medium hardness.

The formation is hard, built of straight cliffs that are the continuation of the Shivta cliffs underneath. Between both cliffs, there is a dividing soft layer, built of the marly material of the Nezer formation. The formation, particularly in its upper part, is characterised by fine bedding, 0.4 to 0.5m thick. In the upper part in most places there is a transition from cliffs to terraces. The thickness is between 100 and 150m.

Photo 14: Nezer outcrops in Beit Hanina, Neve Ya'akov, white and creamy limestone, karstic with stylolites

Western Jerusalem Mountains and foothills

Beit Meir consists of well-bedded dolomite with flint and quartzolite concretions and minor interbedded marl. At the type location, there are two members, a lower Carmila member and an upper Hamasreq member. The Carmila member is a 70m thick, partly laminated dolomite series. The dolomite is fine crystalline and contains flint concretions, quartz crystals and spherulites. The Hamasreq member is only 30m thick, again with well-bedded dolomite, but very fine crystalline. At also has flint concretions and is separated from Carmila by yellow marl. Beit Meir type location is adjacent to Kesalon type location on the upper slopes above Wadi Kesalon (153.520/132.240).

Photo 15: dm-banks in Kesalon cliff, SW of Jerusalem, at 164.2/130

Photo 16: Crystalline dolomite of Beit Meir formation, S of Beit Meir at 153.5/132

Photo 17: Beit Meir, sugary dolomite, 153/132

Photo 18: Beit Meir, quartzolite lense, 153/132

Moza consists of fossiliferous, mainly green and yellow marls and calcareous clays, with intercalations of thin bedded, fossiliferous limestone. At type location the thickness is 15m. Type location is near Zova at 126.470/132.070, 5km west of Jerusalem.

Photo 19: Moza marl, Ramallah, 168.5/141.4

Photo 20: Moza, yellow marl (153/135.4)

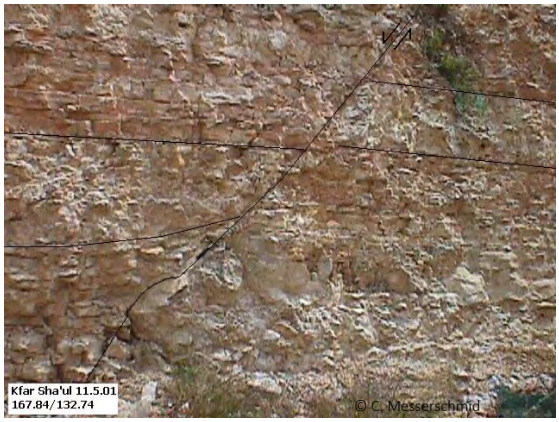
Amminadav has its type location at 163.490/129.540, east of Hadassah hospital, on the southwestern outskirts of Jerusalem. Dolomite prevails, but some limestone is found in the upper part. Therefore, two members are distinguished at the type location:
The lower dolomite member starts with 10m of blocks of dolomite. In the outcrop, the rock is very weathered (Nari). However, it resembles a conglomerate, indicator for an unconformity. The dolomite of the lower member has some fine crystalline limestone in its upper part and occasionally lenses of quartzolite. The upper member is referred to as limestone member.

The **Kefar Sha'ul** formation generally contains fossiliferous, argillaceous limestone and marl of 75m thickness at the type location in Kefar Sha'ul, on the western outskirts of Jerusalem (167.840/132.740). Two members are distinguished: The lower fossiliferous, argillaceous limestone member is thin bedded, with beds between 10-30cm. The limestone is microcrystalline and alternates with marl layers. Fossils, like molluscs, echinoids and planktonic foraminifera are commonly found in the 60m thick section. The upper member is 15m thick. Here the limestone is laminated and even more thinly bedded (10-15cm) with fossil fishes and molluscs. Argillaceous material sits between the individual laminae.

Photo 21: Amminadav, karstic dolomitic limestone

Photo 22: Calcite crystals in a vug in Amminadav dolomite

Photo 23 and 24: Kefar Shaul - yellow and red limestone in cm-bank and as red fine laminated layers at type location Kefar Shaul, West-Jerusalem, 167.8/132.7



Photos 25 and 26: Outcrop of Kefar Sha'ul formation at type location;
Kefar Sha'ul in W-Jerusalem, 167.84/132.74; Epikarst holes and faults in plated limestone

Weradim formation overlies Kefar Sha'ul in a sharp contact at the type location in Jerusalem (168.950/131.250). Here, it is only 25m thick. In the south of the Jerusalem-Bet Shemesh axis, Weradim overlies Amminadav directly (Kefar Sha'ul is missing). The formation contains well bedded to massive dolomites and limy dolomite with lenses of coarse crystalline limestone.

Bi'na formation generally consists of fine crystalline and microcrystalline fossiliferous limestone with some dolomite and dolomitic limestone at the base and with flint concretions in the middle part. Its total thickness of 160m at the type location can be divided into four members with local, Arabic names, from bottom to top: Dolomite and limestone member (Mizze Ahmar, 23m thick), detrital limestone member (Meleke, 40m thick), limestone and nari member (lower part of Mizze helu, 40m, containing the "Acteonella flint") and a sublithographic limestone member (upper part of Mizze Helu, 56m). Type location is in Wadi Dolev, near Beit Shemesh (151.370/126.650), described by ARKIN ET AL. (1965).

4.5 Summary and structure

Throughout several sedimentary cycles, platform conditions prevail in the entire area, except the Western margin, where Talme Yafe continues with its basinal and slope facies pelitic clastics.
At the end of the long Upper Cretaceous platform sedimentation, compression and tectonic conversion forms a series of asymmetric folds. This Syrian arc folding pattern follows older, Palaeozoic patterns (BAHAT, 1999): Deep faulting due to pre-Senonian crustal movements reaches down to the depths of Palaeozoic formations on the entire width of the Syrian Arc folding belt and especially on its edges, near the border between Israel and Gaza and near the Jordan Rift Valley.
The basement normal faults are reactivated into reverse faults on which the Syrian Arc folds are leaning.

5. UPPER CRETACEOUS TO RECENT

5.1 Upper Cretaceous: Coniacian and Senonian (89-65 Mio a)

It was already mentioned that the Judea Group sedimentation continues beyond the Turonian – Coniacian boundary in some areas. The following overview therefore starts with the Upper Coniacian. In the Upper Coniacian, the whole country and all its different environments undergo a drastic change to new conditions. In general, sea level rises and initial structural movements commence. By this, the Judean group is interrupted by an erosional gap in most of its areas and is overlain by a new group, referred to as **Mt.Scopus group** by the Israeli and as **Abu Dis group** (see Figure 20) in Palestinian terminology[2].

The Coniacian structural movements are the initial phase of the Syrian Arc folding system that developed during Senonian – Palaeogene as a response to the tectonic activities of the alpine phases in the Tauro-Zagrid ranges, when the Tethys ocean closed and the Arabian peninsula began to approach Eurasia in the regions of Cyprus (ophiolite obduction!), southern Turkey, Northern Syria and further to Iran in the East. The collision between the two plates on this "Northern Arabian margin" started in the Mid-late Eocene.

The initial Early Upper Coniacian movements consisted of not much more than a slight southwestward tilting in the study area, which led to submarine and sub-aerial partial erosion, especially in the Northeast. The pronounced slope to the West of the Cenomanian-Turonian platform, on which the deeper water Talme Yafe clastics had been deposited, became less pronounced and disappeared subsequently. In the same time, a supra-regional sea level rise brought most of the former carbonate platform under pelagic and neritic conditions. The gradual eustatic sea level rise continued uninterrupted and without any intermediate drop from Late Turonian to Early Senonian.

[2] The term Abu Dis is used differently. ROFE AND RAFFETY (1963) refer to it as one of the Senonian **formations** only. More recently, it is used as a **group** name, comprising all formations up to the Palaeocene in the West Bank.

Again, only the extreme southeast, near Eilat and the southern Sinai were less or even unaffected by these facies changes. However, some authors give evidence for continued Turonian-Coniacian sedimentation in restricted areas in the Western Galilee, the Judean desert (SE West Bank) and the Judean Mountains (Kafri, 1965).

5.1.1 Abu Dis Group / Mt.Scopus group

Abu Dis group or Mt.Scopus group comprise of Campanian, Senonian and Paleocene. In the terminology by Rofe and Raffety, the succession of formations in the Central West Bank is a succession of the following formations from bottom to top: **Abu Dis**, **Amman**, **Zarqa**, **Khan Al-Ahmar**. Instead of Amman, Zarqa the name **Wadi El Qilt** formation has been introduced as well (see Table 10, at the end of the chapter).

In general, the facies of Senonian (see Figure 23) is characterized by plankton-rich pelagic chalks and marls. Episodically, phosphoritic chalk, phosphorite and biogenic silica were deposited. Under the influence of early diagenesis, they were transformed to silicified chalk, chert and porcellanite. Anoxic events are indicated by bituminous chalks and dark oil shales.

Figure 23: Facies map of the Senonian (after Hirsch 1991): There is a SE-NW trend of deepening water from shallow water with chert and phosphates (Sayarim and Mishash) in the south and southeast to open pelagic chalks (Menuha-Ghareb, Ein Zeitim). At the edge of the Syrian Arc, near the Jordan Rift Valley and west of Jerusalem, Maastrichtian Ghareb series, together with overlying formations, up to Eocene age that have a high bituminous content underwent auto-metamorphosis of the self-combustion type (Hatrurim). In Mt. Carmel, Volcanism occurred.

Table 10 shows a summary table of West bank formations, as proposed by PWA in 2002. Table 11 shows a summary of thickness ranges for the West Bank formations. Table 12 shows a comparison between the different terminologies, as introduced by Rofe and Raffety, as used by the Israeli and as suggested for PWA. Figure 32 presents a geological overview map of the most important groups in the area, with a shaded relief as background.

Period	Epoch	Lithology	Formation	Sub-Formation	Group	Israeli formation names		Hydro-stratigraphy	Thick-ness
QUA-TERN ARY	Holocene		Alluvial					Local	
	Pleistocene		Lisan			Saqiye	Yafo	"Aquitard"	10-200
TERTIARY Neog.	Upper Miocene-Pliocene		Beida		-			Local aquifer	20-200
	Lower Miocene						Beit Guvrin		
Paleogene	Lower-Middle Eocene	Nummolitic reefal Limestone	Jenin	Jenin4	Jenin	Zor'a	Maresha	Aquifer	90-670
		Nummolitic bedded Limestone		Jenin3					
		Nummolitic Limestone , Chalk		Jenin2			'Adulam		
		Chalk, nummolitic Limestone		Jenin1					
	Paleocene	Marl, Chalk	Khan Al-Ahmar		Nablus	Ein Zeitim	Taqiye	Aquitard (local aquifer)	40-150
CRETACEOUS Upper	Maastrichtian-Danian	Chalk, Marl					Ghareb		
	Campanian	Main Chert, Phosphate	Wadi Al-Qilt				Mishash	Aquiclude	10-120
	Coniacian-Santonian	Chalk and Chert	Abu Dis				Menuha		0-450
Lower	Turonian	White Limestone, stilolithes	Jerusalem	Upper	Ramallah (West Bank)	Bi'na	Nezer	Upper aquifer	40-190
		Limestone , Dolomite		Middle			Shivta		
		Yellow thin bedded Limestone		Lower			Derorim		
	Cenomanian	Dolomite , soft	Bethlehem	Upper			Weradim		50-210
		Chalky Limestone , Chalk		Lower			Kefar Sha'ul		
		Karstic Dolomite	Hebron				Amminadav		65-160
	Albian	Yellow marl	Yatta	Upper			Moza	"Aquitard"	50-125
		Lime - & Dolostone , Chalk, (Clay)		Lower			Beit Meir		
		Reefal Limestone	Upper Beit Kahil	UBK2			Kesalon	Lower Aquifer	10-20
		Dolomitic Limestone , interbedded with Marl		UBK1			Soreq		60-130
		Dolomite	Lower Beit Kahil	LBK2	Kobar		G. Ye'arim		40-90
		Karstic Limestone		LBK1			Kefira		100-160
	Aptian	Marl, marly nodular Limestone	Qatana				Qatana	Aquitard	42
		Marly Limestone and Limestone	Ein Qinya				Ein Qinya	Local Aquifer	55
		Shale	Tammun				Tammun	Aquiclude	300+
		Shale and Limestone	Ein Al-Assad				Ein Al-Assad		20+
		Marly Limestone , sandy	Nabi Sa'id		Kurnub		Nabi Sa'id	Aquifer	20+
	Neocomian	Sandstone	Ramali				Hatira		70+
		Volcanics	Tayasir				Tayasir		35
Jurassic	Oxfordian		Malih	Upper Malih	-	ARAD GROUP		Aquitard	
				Lower Malih	-			Aquifer	

Table 10: Schematic new stratigraphy for the West Bank, suggested by PWA 2002
Note: New formation names are used, such as **Wadi Al-Qilt** formation for Campanian, instead of Amman/Zarqa formations. New group names have been introduced: **Jenin** group for Eocene, instead of Jenin Subseries or *'Avedat group (Israeli)*, **Nablus** group for Senonian, instead of Abu Dis group or *Mt.Scopus group*, **Ramallah** group for Upper Albian-Turonian, instead of West Bank group or *Judean group*, **Kobar** and **Kurnub** groups for Lower Cretaceous. The lithostratigraphy is extremely simplified, the Israeli formation names are incomplete and only for a broad comparison. Also the hydrostratigraphy changes from area to area and between Northern, Eastern and Western aquifer basins.

Formation	Northern West Bank		Central West Bank		Southern West Bank	
	West	Centre	Centre	East	West	East
	TULKAREM	NABLUS	RAMALLAH	JERICHO	HEBRON	DEAD SEA
Alluvial	10	-	-	-	-	-
Lisan or Pleistocene	10-200	200+	200	30 (200)	0-20	150+
Beida or Mio-Pliocene	22-70(-1000)	200+	-	-	10-40	10-30
Jenin or Eocene	0-90(-140)	490-670	-	-	250	-
Khan Al-Ahmar	30 -150	40-150	115	35 (115)	40-90	70-100
Wadi Al-Qilt (Amman Zarqa)		0-40	45-120	75 (45-120)	10-15	52-58
Abu Dis		0-450 (60-180)	55-225 (40-70)	25-80 (55-225)	70	30-112
Jerusalem	60-100	60-180	120-190	40-145	100	114-148
Bethlehem	30-80-110	30-115	90-210	50-80 (90-150)	50-165	114-274
Hebron	*105-260*	105-260	160 (130-200)	65-130 (130-200)	40-90	52-63
Yatta	*50-150*	50-150	120-125	85-120	40-75	83
Upper Beit Kahil	*110-190*	110-190	80-140	(170-250)	90-150	139+
Lower Beit Kahil	*250-290*	250-290	160-260	(160-260)	140	

Table 11: Comparison of thickness ranges in different areas of the West Bank

ROFE & RAFFETY	NEW PALESTINIAN TERMINOLOGY	ISRAELI TERMINOLOGY
Alluvial or Holocene	**Alluvial or Holocene**	Alluvial or Holocene
Lisan or Pleistocene	**Lisan or Pleistocene**	Lisan or Pleistocene
Beida or Mio- to Pliocene	**Beida or Mio- to Pliocene**	Bet Guvrin-Yafo (Saqiye group)
Jenin Subseries	**Jenin or Eocene**	‘Avedat group
Khan Al-Ahmar	**Khan Al-Ahmar**	Ghareb/Taqiye
Amman, Zarqa	**Wadi Al-Qilt**	Mishash (Chert+Phosphate member)
Abu Dis	**Abu Dis**	Menuha
Jerusalem	**Jerusalem**	Bi’na (Derorim, Shivta, Nezer)
Bethlehem	**Bethlehem**	Kefar Sha’ul, Weradim
Hebron	**Hebron**	‘Amminadav
Yatta	**Yatta**	Beit Meir, Moza
Upper Beit Kahil	**Upper Beit Kahil**	Soreq, Kesalon
Lower Beit Kahil	**Lower Beit Kahil**	Kefira, Giv’at Sha’ul
Qatana	**Qatana**	Qatana
Ein Qinya	**Ein Qinya**	Ein Qinya
“Kobar”	**Tammun**	Tammun
	Ein Al-Assad	Ein Al-Assad
	Nabi Sa’id	Nabi Sa’id
Ramali	**Ramali**	Hatira (Kurnub)
Tayasir	**Tayasir**	Tayasir
Malih	**Malih**	Beer Sheva, Haluza

Table 12: Comparison of West Bank formation names according to different terminologies (Note: The top and bottom boundaries of these formations are not always defined identically)

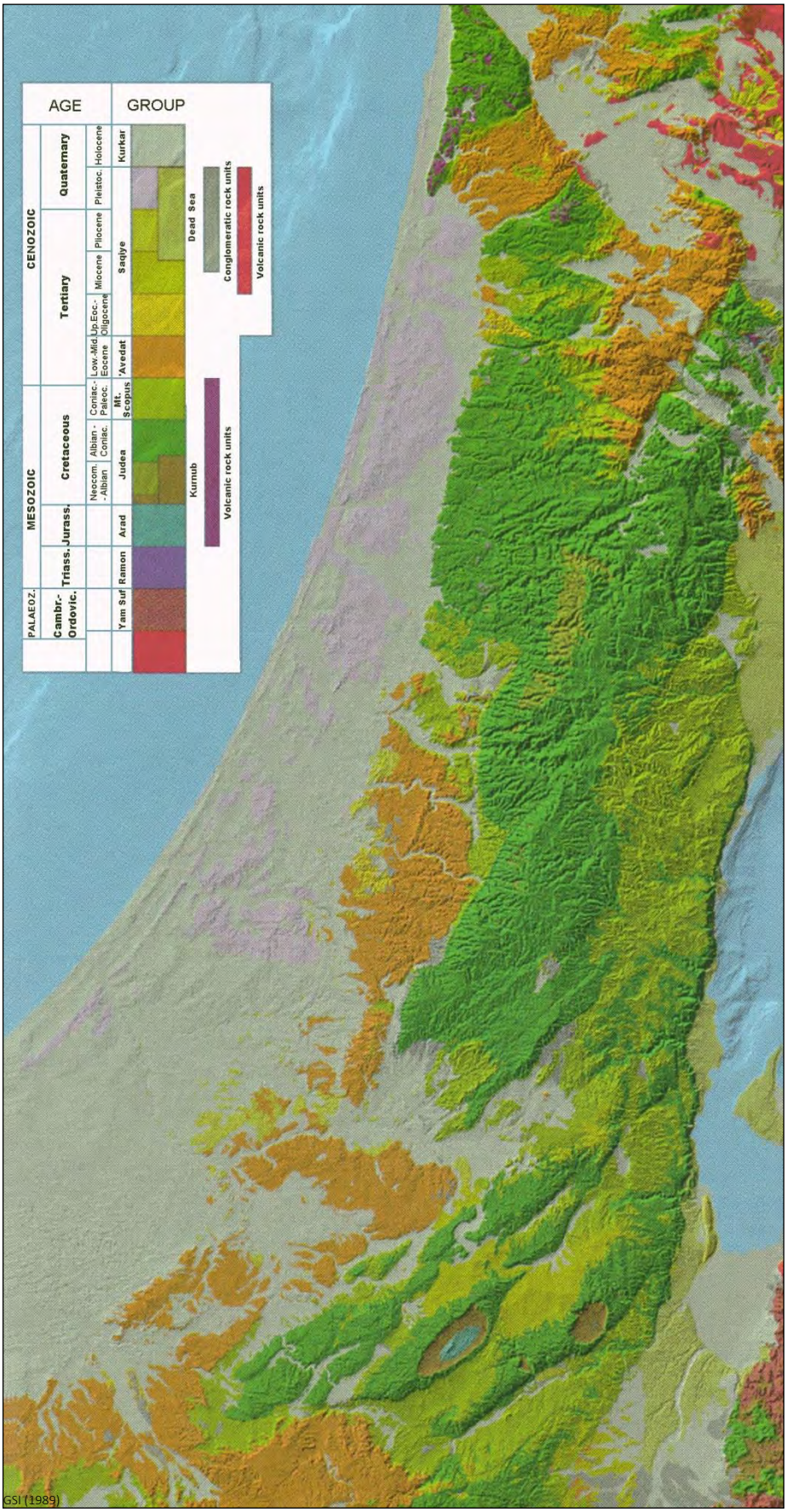


Figure 32: Shaded relief and geological map

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5.4 Structure and Summary

The following intends to give a short overview over the structural development of the area.

The typical Syrian arc pattern, with its NE-SW strike follows older, Palaeozoic patterns (BAHAT, 1999). During the Mid-Carboniferous Asturian orogenic phase the area had been uplifted and exposed to erosion. Deep faulting due to pre-Senonian crustal movements reaches down to these depths on the entire width of the Syrian Arc folding belt and especially on its edges, near the border between Israel and Gaza and near the Jordan rift valley. The phase of calm sedimentation in the Northern Negev came to an end with the tectonic inversion and southeast tilting during the late Hercynian phase. A slight folding, mainly adjacent to NE-trending faults was produced.

Late Cretaceous – Early Tertiary (90 – 40 Mio a) *[Coniacian-Eocene]*
Structural movements start in the early Upper Coniacian, they deepen and continue until approximately Eocene. As an effect of the northward movement of the Arabian plate, compression and tectonic inversion occurs. The result is a series of asymmetric blocks of the so-called "Syrian Arc System" (around 40 Ma) that are leaning on reverse faults caused by re-activation of basement normal faults. Therefore, thickness and facies changes in the overlying Senonian and Eocene sediments are controlled by the structural development. Where Cretaceous rocks were exposed on the structural highs, erosion took place. The Syrian Arc system is present with NE-SW directed faults and lineaments, as well as folds.

Early Tertiary – Recent (40 – 0 Mio a)
In the Early Tertiary, a drastic drop in the sea level occurs. Deeply incised channels develop and the folding during Oligocene is accentuated. Subsequently, the channels are filled in Late Oligocene - Early Miocene. The most prominent of these channels is the Afiq-channel between Gaza and Beer Sheva.

Initiation of the Dead Sea Graben
Extensive rifting starts and holds on during middle Miocene. The Dead Sea – Jordan valley – Wadi Araba depression is part of the many thousand kilometres long East African Rift system, from the Taurids down to Rwanda. The prominent direction of the sinistral strike slip is around 10 degrees NNE. Lineaments of this orientation are usually considered to be associated to this rift system. The Dead Sea itself is formed by a pull-apart basin, with a secondary extensional movement of around 70 degrees ENE.

Still in Miocene, starts the formation of the Levantine basin in the SE Mediterranean and of small intra-continental basins filled with conglomerates and sandstone, mainly along the future Jordan Rift Valley.

Seawards, a NE-SW step-faulting and rifting develops accompanied by a reactivation of the NW-SE faulting. Also, a widespread volcanism can be registered. Finally the Miocene – Pliocene is characterised by a recurrence of a drastic sea level fall and desiccation (evaporation) of the Mediterranean Sea in late Miocene time and subsequent rise in early Pliocene.

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Deep-seated aquicludes in a fractured carbonate environment, West Bank

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Abstract: Test results and long term operation from four new boreholes in strongly karstic and fractured carbonate aquifers in the West Bank indicate the wide range of lateral facies changes and consecutive aquifer characteristics. This paper investigates and redefines the nature of the aquicludes underlying the aquifers, based on geophysical logs, rock cuttings, TV-logs, pumping tests and a new "deflection point" method. These methods allow for defining accurately the lithological and hydrostratigraphic character as well as the position and effectiveness of the different aquicludes. It enables to track down facies changes more closely and define sub-aquifers with formations that have been assigned overall "aquicludes" in the existing literature. The findings can be used to better design and position the well filter sections. By this, common long term operation problems can be reduced.

1. INTRODUCTION

Within the framework of the "Water supply and sanitation projects, Palestine", German Technical Cooperation (GTZ) together with Jerusalem Water Undertaking Ramallah (JWU) and the Municipality of Nablus (MuNa) has drilled seven boreholes for well production and investigation purposes in the years 1995 to 1999, four of which will be discussed in this paper. They are located in the central and northern West Bank (see Fig. 1).

This paper presents the results of investigating the distribution of the so-called "aquicludes", diverse formations with aquiferal and impervious hydrostratigraphic units. These results question the traditional understanding that Yatta can be referred to as a homogenous "middle aquiclude" and Kobar as the "bottom aquiclude".

In the West Bank, Palestine, deep water wells are drilled in an environment of strongly karstic and fractured carbonates. This has posed a challenge to the geological and hydrogeological interpretation of the results of logging, coring, sampling and pump testing, mainly because the lithology of the targeted formations undergoes rapid lateral facies changes. This results in almost every new well showing a different distribution of facies sequences. As will be shown below, already small changes in facies can change the hydrogeological character of the formations. Aquifers turn into aquicludes or aquitards and vice versa.

Figure 1: Location map of the 4 new boreholes.

2. GENERAL STRATIGRAPHY

The deep wells in the West Bank generally target two aquifers, a so-called Upper Aquifer of Upper Cenomanian – Turonian age and a Lower Aquifer of Upper Albian age.

Conventional literature from both, Palestinians and Israeli sources describe two >100m thick aquicludes: one underlying the Upper Aquifer and the other the Lower Aquifer.

In Palestinian terminology, the Upper Aquifer is usually understood to comprise of Hebron, Bethlehem and Jerusalem formations. In Israeli terminology some of the formations are further sub-divided and equivalent names are 'Amminadav (for Hebron), Kfar Sha'ul and Weradim (for Bethlehem) and Bi'na or Derorim, Shivta & Nezer (for Jerusalem). The Lower Aquifer comprises of Lower Beit Kahil (LBK) and Upper Beit Kahil (UBK) formations in Palestinian terms. Israeli literature subdivides LBK into Kefira and Giv'at Ye'arim formations, and UBK into Soreq and Kesalon.

The two aquifers are separated by a rather marly or clayey "middle aquiclude", called Yatta by the Palestinians, or Beit Meir & Moza by the Israeli. The Lower Aquifer is underlain by several formations of the so-called Kobar group (Neocomian to Lower Albian). However, the nature of these "aquicludes" is not as simple as described above, as shall be shown in the following.

Description of formations

With the exception of Moza and Kesalon, most of the formations, lie in a thickness range of 80 -150m. Moza (or Upper Yatta in Palestinian terms) and Kesalon (or Upper UBK) are 20-30m thick only. Drilling starts at different stratigraphic levels. However, in the productive areas and while targeting the Lower Aquifer, the outcropping formation is in most cases Bethlehem formation or the formations above or below this unit (Jerusalem or Hebron). As a rough approximation, wells tapping the Lower Aquifer have to be drilled for more than 500m, often reaching well depths of as much as 800m below ground level (bgl). Due to the available local technology, pump tests are performed as single-hole tests and often with the bottom of the well remaining uncased ("open hole"). The Lower Aquifer water levels encountered in the boreholes are usually confined and lie in a range of depth between 200m bgl and 600m bgl.

Both, Lower and Upper aquifers consist of carbonates, limestone and dolomite. The separating formations are characterised by a higher content of marl and clay (Yatta) or shale (Kobar). As a secondary component, chalk is also encountered in the Cenomanian, especially in Bethlehem and Yatta formations. The chalk behaves as an impervious rock and reduces the aquifer potential.

Age		Formation	Literature	EinSamia # 6 [m]		Audalah [m]		EinSenia # 7 [m]		Beit Dajan [m]	
Cenomanian	Up.	'Amminadav	Upper Aquifer	Upper Aquifer	122	dry aquifer	103	not drilled		not drilled	
	Lower	Moza	Aquiclude (YATTA)		21	–	27				
		Beit Meir b			59	water level at bottom	80				
		Beit Meir a		Aquiclude	35		22				33.5+
Albian	Upper	Kesalon	Lower Aquifer	"middle" Aquifer	22	Aquifer	33			dry	18
		Soreq		Aquitard	79		76				80
		Giv.Ye'arim		Lower Aquifer	68		60	dry	43+		58.5
		Kefira			147		120	weak: no recharge	185		74
	Lower	Qatana	Bottom Aquiclude (KOBAR)	Bottom Aquiclude	48+	Bottom Aquiclude	5+	Aquiclude	52	weak: 5m fract	82.5
		Ein Qinya		-		-		weak Aquifer	72	good: 18m fract	57
Aptian		Tammun d						Aquiclude	89	weak: 14m fract	46.5
		Tammun c							86	Aquiclude	71.5
		Tammun b							43		61
		Tammun a							37		48
Neocomian		Ein Al-Assad						Aquitard	38		47+
		Nabi Sa'id						weak Aquifer	67	-	
		Hatira	Deep Aquifer						113+		

Table 1: Comparison of formation thickness and aquifer properties between literature and 4 new boreholes

Specific hydrogeological literature on Yatta and Kobar is relatively scarce. Despite geological evidence, most hydrogeological studies overly simplify both, Yatta and Kobar as homogenous overall aquicludes or sometimes also as leaky aquicludes. Yatta is thus referred to as "the middle aquiclude" and Kobar as "the bottom aquiclude" (Rofe and Raffety 1965, Shachnai 1980, Kroitoru, Mazor & Issar 1992, Weinberger et al. 1994, Aliewi et al. 1995, Guttman & Zukerman 1995, CDM/Morganti 1998, etc.).

However, drilling and test results suggest a more complicated picture: Test results and long term operation from various boreholes indicate the wide range of conditions with respect to degree of fracturing and karstification, rock lithology and aquifer parameters. As will be shown in the following, both Yatta and Kobar undergo laterally considerable facies changes and locally reach aquifer conditions suitable for well abstraction. Thus, formations that constitute aquicludes in one place can be encountered as aquifers just a few kilometres away. Therefore, the special nature of the so-called "middle aquiclude" and the "bottom aquiclude" has to be refined in the light of the new drilling results. Table 1 compares the general assignment in the literature with the actual findings in four boreholes.

3. YATTA FORMATION

Yatta formation of Lower Cenomanian age is divided into Moza and Beit Meir formation in Israeli terms. In a typical section, Moza forms a top yellow marl layer (*Moza*). *Beit Meir a*, the bottom of Yatta, is often encountered as a blue clay section. The middle of Yatta (*Beit Meir b and c*) is rather aquiferous, consisting of a cocktail of limestone and dolomite, but also chalk and chert.

However, due to lateral facies changes, either one or both of the impervious horizons can thin out or change into carbonatic lithology. Accordingly, Yatta can be part of the Upper aquifer (like in Ein Samia) or part of the Lower aquifer. It can form an independent middle aquifer (mostly perched) or be rather an overall aquitard. In some places, both of its impervious horizons at the top and bottom change to carbonate lithology, thus creating one uninterrupted aquifer, as found in Audala well, 5km SSE of Nablus.

3. a) Audala well

Audala well was drilled to 526m depth, from the lower part of the "Upper Aquifer" until the bottom of the "Lower Aquifer". The water table was encountered at 227.8m bgl, within *Beit Meir a* (bottom of Yatta). Coring was performed in this horizon, delivering a yellowish hard dolomite with karstic features. The very karstic overall nature of the drilled formations in the borehole caused complete loss of circulation while drilling. Due to this lack of samples, and since only three cores were taken, the geological interpretation relied strongly on the analysis of the geophysical logs. No sonic log technology was available at this time. Gamma-ray, Resistivity and Calliper logs were therefore the most important logs for the interpretation. The Upper and Lower Aquifer were encountered here as one unit, not sufficiently separated by Yatta. Yatta was found to be more of a carbonatic than of a marly nature. The gamma-ray log for the Yatta section shows peaks between 20 and 40 API units only (see Fig. 2). Water levels, logging and pump testing data confirm this result. The main results of the gamma-ray logs are listed in Table 2).

Besides the logs, the cores and the relatively few rock cutting samples, also the result of pumping tests showed and confirmed the above assessment that Yatta formation here does not act as an aquiclude at any horizon. The drawdown during the tests showed a uniform behaviour of the lowermost Yatta (Beit Meir a) and the underlying Upper Beit Kahil (Kesalon) formations.

On the other hand, also the upper part of Yatta was found only slightly marly. The water levels in the well were encountered unconfined and thus the Upper and Lower Aquifers are considered to act as one connected aquifer system, not sufficiently divided by incomplete aquitards of Beit Meir a and b (see Table 2).

Yatta, in Audala well, is not a separating unit but part of a combined aquifer complex of the Upper and the Lower Aquifers.

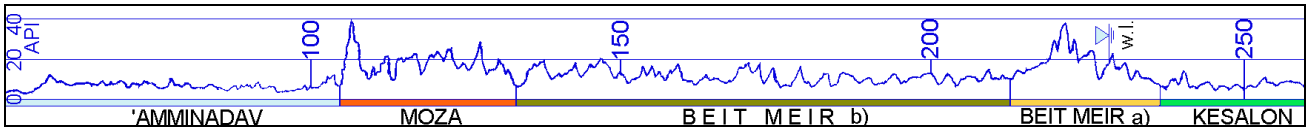

Fig.2: Gamma-ray log of Yatta formation in Audala well

Depth [m bgl]	Israeli Formation name	West Bank Formation name	Usual assignment	Actual findings	Reading (API units)	Lithologic equivalent
0-102.5	Amminadav	HEBRON	*"Upper Aquifer"*	**Combined Upper and Lower Aquifer** No measurable separation	<10	Strictly carbonatic
130	Moza	YATTA	***"Middle Aquiclude"***		15-25 (40)	Slightly marly
212.5	Beit Meir b)				± 10	Carbonatic
232.5	Beit Meir a)				15-40	Somewhat marly
264	Kesalon	UPPER BEIT KAHIL	*"Lower Aquifer"*		<10	Strictly carbonatic
353.5	Soreq				<10 (± 20)	Mainly carbonatic, marly intercalations
407	Giv'at Ye'arim	LOWER BEIT KAHIL			< 10 (>10)	Carbonatic
515.25	Kefira				<10 (>20 at bottom)	Strictly carbonatic; bottom slightly marly
523.97	Qatana	QATANA	**Bottom Aquiclude**		>30	Marly and clayey

Table 2: Litho- and hydrostratigraphy of Audala borehole (according to rock cuttings)

3. b) Ein Samia well # 6

Ein Samia well # 6, located 25km NNE of Jerusalem, penetrates part of the Upper and the entire Lower Aquifer (Fig. 3, Tab 3).

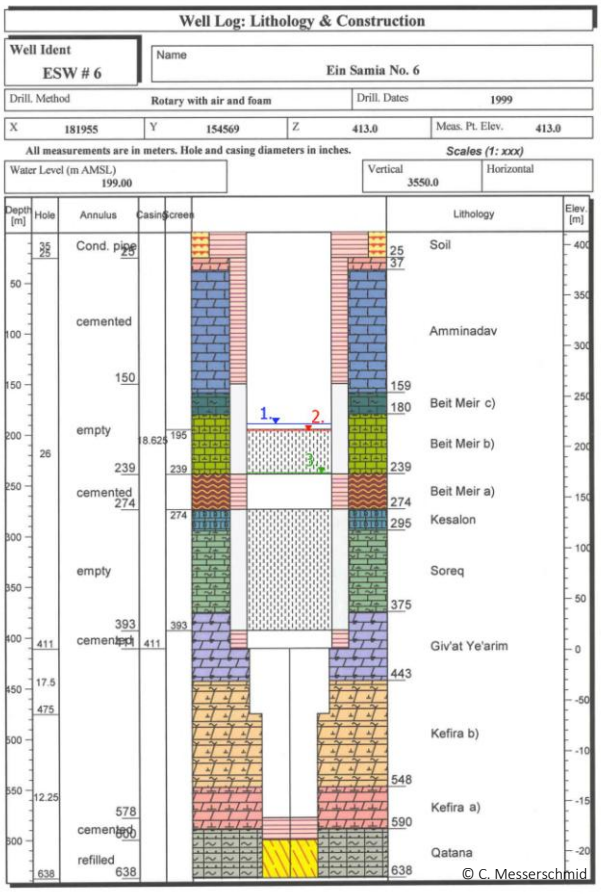

Figure 3: Design of Ein Samia well # 6

Moza, the top yellow Marl layer was encountered missing here. Yatta consists of three different members: Beit Meir a, b and c from bottom up. Beit Meir a is a prominent 35m thick layer of blue clay from 274m up to 239m depth. Beit Meir b and c consist of dolomite and limestone, somewhat marly in the upper and chalky in the lower half. They therefore form part of the Upper Aquifer and proved to be very productive in the pump tests. Figure 4 is a TV-log photograph of Beit Meir b) at 235m depth. It shows a light, solid limestone with karstic holes in abundance and some cavities in dm-size.

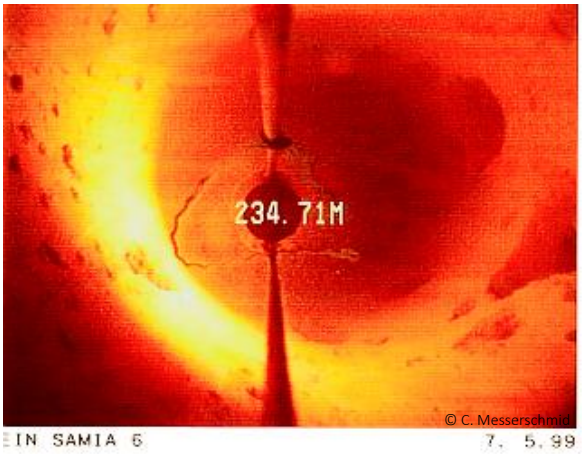

Figure 4: Beit Meir b: Karstified limestone (235m bgl)

Below Yatta lies a thin limy formation (Kesalon), underlain by 80m of chalky dolomite with rhythmic thin marl intercalations. This Soreq facies forms an aquitard and therefore the Lower Aquifer only reaches from 375 to 590m bgl.

Depth [m bgl]	**Potential**	**Formation** PALESTINIAN (Israeli)	**Lithology**
0-25	-	Recent	Soil and gravel
37	Aquifer	BETLEHEM (Avnon)	Chalky limestone
159		HEBRON (Amminadav)	Karstic dolomite and limestone
239		Upper YATTA (Beit Meir b,c)	Porous dolomite, some limestone, few marl
274	Aquiclude	Lower YATTA Beit Meir a	Limestone and blue clayey marl
295	Aquifer	Upper UBK (Kesalon)	Limestone and chalky limestone, some dolomite
375	Aquitard	Lower UBK (Soreq)	Brittle chalky dol. & limestone; thin marl
448	Aquifer	LOWER BEIT KAHIL (G.Y. Kefira)	Chalky dolomite and porous dolomite
590			Limestone & dolomite; some marly limestone
638	Aquiclude	"KOBAR" Qatana	Bituminous marly limestone and marl

Table No. 3: Geological and hydrogeological characteristics of borehole ESW # 6

Pumping tests

Pump tests were performed at three different stages of the drilling process. The borehole was first pump-tested in the Upper Aquifer alone, then in the Upper and the top of the Lower Aquifer together and finally in both aquifers together. Here, the main section of Yatta was found to be very productive and part of the phreatic upper aquifer system. Table 4 gives an overview over the three pump tests. The static water level remained almost unchanged from the first to the second test, despite the presence of the strong aquiclude of Beit Meir a. This is mainly due to the reduced thickness of Kesalon, which does not have a strong influence on the combined water level of both units in the second pump test. The static water level sank some 15m after full penetration of Soreq aquitard, that acts here as an incomplete separation unit between Upper and Lower aquifer.

	1. Test	2. Test	3. Test
Date	30.4. 99	6.5.99	1.7.99
Drill depth	254m	335m	551m
Pump setting	232m	330m	468m
Aquifer	Upper Yatta	Upper Yatta & Kesalon	Upper Yatta, Kesalon & LBK
SWL	**177.94m**	**179.6m**	**195m**
Max. DWL	**200.2m**	**200.2m**	**202m**
Maximum Drawdown (80-90m^3/h)	11.96 m	20.6m	7.7m
Transmissivity	958 m^2/day	460 m^2/day	647 m^2/day

Table 4: Summary of pump tests 1-3 in Ein Samia well # 6 (all depths in m KB)

Finally, a fourth pump test was performed after completion of the borehole (reaming and casing and acidisation) at a final drill depth of 638m bgl. All aquifers were connected in the borehole. The water level had dropped another 10m to 214m bgl. The pump used in this test was much stronger and operated for nearly 24 hours at a pumping rate between 396 and 424 m^3/h. No stabilization of drawdown was observed. Then the pumping rate was reduced to 330m^3/h and equilibrium was reached quickly at a drawdown of around 80m. The apparent transmissivity for the combined aquifers was low, between 74m^2/day (Hantush-method), 94m^2/day (Jacobs- & Theis-methods) and 97m^2/day (recovery test).

In the analysis of the recovery test, a new "Deflection point" method was used to determine and confirm the position of the bottom of the Upper aquifer (bottom *Beit Meir b*), see Fig. 5.

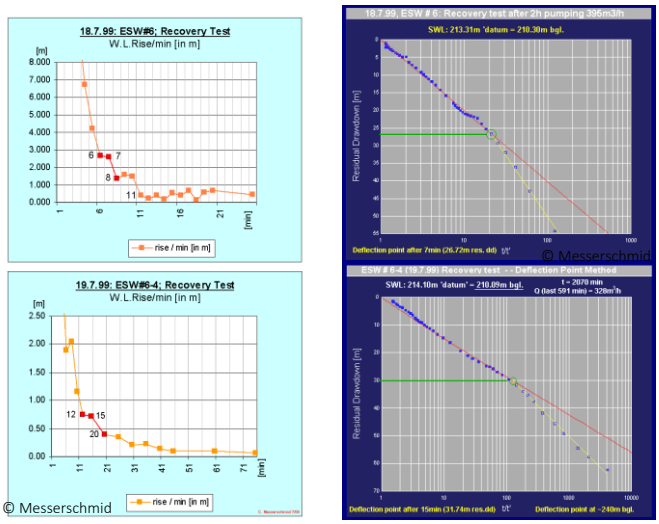

Figure 5: Water level rise (left) and Deflection point (right) in recovery tests – Ein Samia well # 6 (18.7.99 and 19.7.99)

During recovery, it was noticed that the water level rise changes its speed at a certain horizon. This was observed during both independent tests on two consecutive days (see Fig.5). The change in speed occurred after ~7 min in the first and after ~15min in the second recovery test.

This deflection point method was applied to the tests where strong pumping rates forced the dynamic water level below the mark of 239m bgl depth. This is the boundary between the Upper aquifer (Beit Meir b) and the "middle aquiclude" – Beit Meir a.

Two tests were conducted under these circumstances (17.-18.July and 18-19.July 1999; once a short test performance for the strong pump and then a 35h duration pump test). In both cases, the Lin-Log diagram shows a conspicuous deflection point at a depth of this horizon ~239m bgl. The water level rise is fast until the top of the "middle aquiclude" and then slows down abruptly. Two mechanisms account for this behaviour.

Aquiclude top: This is because until this depth both aquifers contribute to the recovery of the water level. The lowest inflow point of the Upper Aquifer into the well lies just above the aquiclude.

Differences in piezometric heads: The water level of the Lower Aquifer lies below the water level of the Upper Aquifer. This is known from adjacent boreholes (ESW# 2, 2a and 3 and 4). Up till the elevation of the lower of the two piezometric heads both aquifers contribute. But to fill up further towards the elevation of the higher piezometric level (until a combined water level is reached) can only be done by the aquifer with the higher head alone, here the Upper Aquifer. Once the water level is above this elevation, only the Upper Aquifer alone has to fill the borehole up again and in addition continuously looses some water to the Lower Aquifer which has a deeper piezometric level.

This deflection point method is suitable for well recovery tests on two different aquifers that have sufficiently different depths and piezometric heads and that are pumped together as a connected unit in the borehole. In addition the thickness of the separating layer should be sufficient to discriminate the different speeds of water level rise from other influences like preferential karstic inflow horizons within one aquifer.

On the first day (1st combined test) the deflection point was at an elevation of 237.02m bgl, on the second day at an elevation of 241.83m bgl. These four metres of difference could be interpreted as a slight (and temporal) depletion of the lower aquifer, especially during the long second combined test, which leads to a lowering of this piezometric head.

In Ein Samia well # 6, only the bottom Yatta acts as an aquiclude. Top Moza is missing and the rest of Yatta is an excellent aquifer.

3. c) General conclusions about Yatta

The hydrogeological character of Yatta varies in different wells: Its main portion can be part of the Lower or part of the Upper Aquifer, as in Ein Samia well #6. It can form a mostly perched independent middle aquifer between these two units, or it can be part of an overall and hydraulically well connected system of Upper and Lower Aquifers together, like in Audala well.

4. KOBAR GROUP

The Kobar group aquiclude is composed of 300-400m thick series of marl, clay and shale, forming a powerful bottom aquiclude of the Mountain Aquifer in the West Bank and in Israel. Two exploration wells targeted this formation (Beit Dajan well and Ein Senia well #7). Ein Senia well was drilled till the deep Ramali sandstone, with Ramali being known as Kurnub aquifer in neighbouring areas and countries.

4. a) Ein Senia well # 7

Ein Senia well, 25km N of Jerusalem was the first water exploration well in the West Bank to be drilled down to the deep Ramali sandstone aquifer. It taps Neocomian to Aptian strata of the entire Kobar group (Table 5). Rock cuttings, cores and geophysical logs were analysed to reveal the nature of the formations. The water table of the deep sandstone aquifer was encountered too deep for pump testing at 658m bgl.

The analysis shows that Kobar here is dominated by marl, clay and shale (Tab.6, Fig.7). From 228 to 280m depth, Qatana formation is characterized by confining marl and clayey marl. A 300m thick sequence of shale and clay interbedded with some marl and very little limestone was encountered from 352 to 645m. This main aquiclude is built-up by Tammun and Ein Al-Assad formations. Together with Qatana this impervious facies is 420m thick and constitutes the main confining aquiclude at the bottom of the West Bank aquifers.

Between Qatana and Tammun sits Ein Qinya formation with predominantly marly limestone from 280 to 352m depth. Ein Qinya in this region forms a local aquifer suitable for well production. However, exploitable conditions are restricted to areas where it is connected to the rainwater recharge from the surface.

The Lower Cretaceous undergoes a gradual change from shale to limestone, sandy limestone and finally sandstone at a depth between 775 and 825m, always interbedded with shale. The deep sandstone aquifer therefore starts at its top with a gradual transition from shale to limey and arenitic conditions. It was not fully penetrated and purely arenitic conditions were not reached by the borehole. Coring at 824m (Fig. 6) delivered an interbedding of dark shale (as above) and calcarenite (increasing downwards).

In other words, only Ein Qinya, Nabi Sa'id and Ramali formations were found to have a lithology that allows for some aquifer potential, however with insufficient recharge.

Figure 6: Core from 824m depth: Shale and calcarenite

Figure 7 shows a comparison of different logs in Ein Senia #7. It can be seen that within Kobar only Ein Qinya forms an aquifer. The rest of the formations are aquicludal. The high Resistivity of the formation indicates more fresh water inflow and more fractured rock conditions. The high Sonic speed shows that the rock is a more dense limestone than its neighbouring formations.
Tammun and Ein Al-Assad form the main aquiclude of Kobar group. The Calliper log shows the wash-out horizons of clay and shale, especially within Tammun b and c. The conclusion that the wide diameter in this case is attributed to fracturing can be reached through comparison with the slow Sonic speed in exactly the same depths (up to 130µs/ft and more).
In Ein Senia well # 7, only Ein Qinya formation constitutes a weak local aquifer within Kobar group. The rest of Kobar is an impermeable and powerful aquiclude.

Depth [m bgl]	**Formation**	**Usual assignment**	**Aquifer potential** (according to lithology & logging)	**Lithology**	**Resistivity Log** [ohm–metres]	**Calliper log** [qualitative]
0-228	LBK (Kefira, G. Ye'arim)	"Lower Aquifer"	Good aquifer	Dolomite, limestone, marl, some clay	>200	Narrow, smooth
280	Qatana	"**Bottom Aquiclude"** **Kobar**	Weak aquiclude	Marl and clayey marl	<80	Wider, softer
352	Ein Qinya		Weak aquifer	Marly limestone, some marl	>200	Narrow, slightly fractured or soft
441	Tammun (d)		Very strong Aquiclude	Clay & marl, some bituminous limestone	<20	Wash outs
527	Tammun (c)			Marl and marly limestone	>30	Narrow above, soft, washout below
570	Tammun (b)			Shale and clay	<20	Strong wash outs!
607	Tammun (a)			Marl, both: clayey and limy	>40	Narrow
645	Ein el Assad			Marl and marly shale	<20	Strong wash outs!
712	Nabi Said	"Deep Sandstone Aquifer"	Very weak aquifer	Limestone, some marl	>80	Narrow, hard, some fractured horizons
825	Ramali ("Kurnub")			Limestone, shale and sandstone	<30	Strong wash outs!

Table 5: Aquifer potential according to Resistivity and Calliper Logs at Ein Senia well # 7, compared with the usual assignment

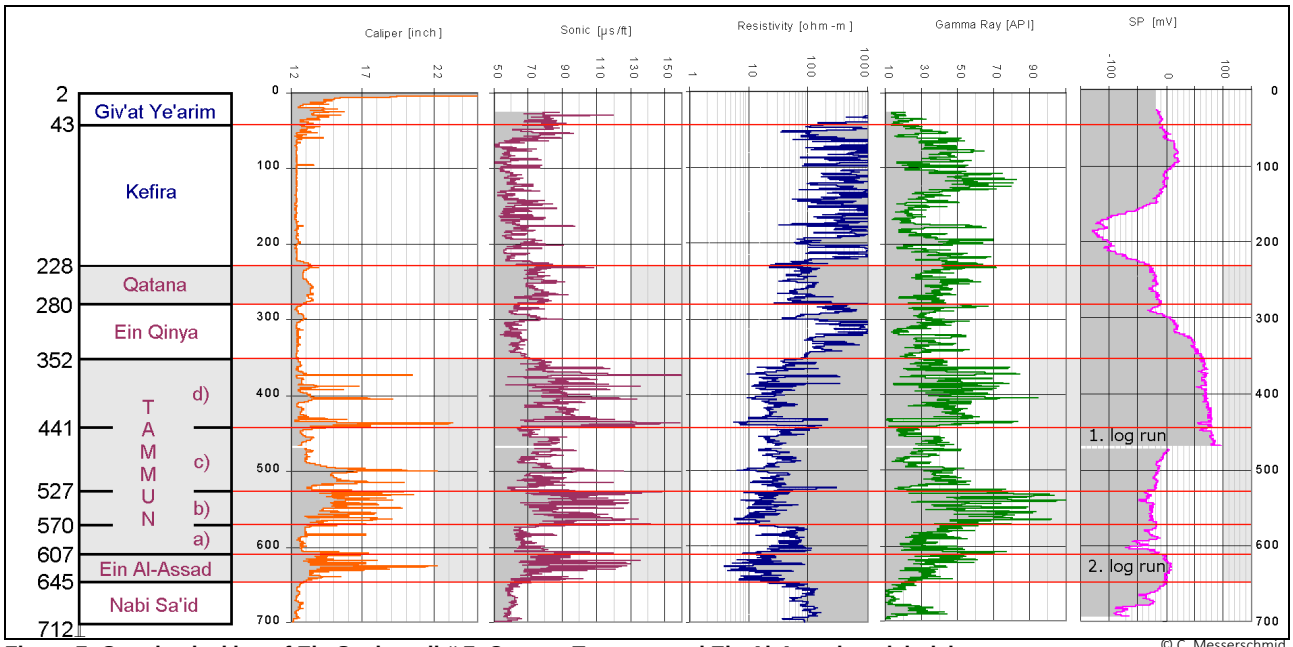

Figure 7: Geophysical log of Ein Senia well # 7: Qatana, Tammun and Ein Al-Assad aquicludal

4. b) Beit Dajan well

Beit Dajan well, 5km E of Nablus was drilled to a depth of 650m, penetrating the "Lower Aquifer" and Kobar group down Lower Albian. Here, the upper third of Kobar was found to be a composite series of aquitards and aquicludes of marl and shale, interbedded with nodular limestone horizons. These limey horizons of Qatana, Ein Qinya and upper Tammun attain an overall thickness of 200m. They contain three highly fractured sections of an accumulative thickness of 41m which provide preferential inflow to the well (Fig. 8).

A good match for the Kobar horizons indicated white in the figure can be found for Calliper, Sonic, Resistivity and Gamma-ray logs. Here, the wide diameters stem from fractures, not from wash-out horizons. This can be seen by comparison with the low sonic speed and the high Resistivity together with low gamma-ray values. Low Gamma-ray here stands for more carbonatic conditions. Therefore the low speed of the Sonic log indicates extensive fractures and the high Resistivity signal indicates more fresh water inflow than in the adjacent clay horizons.

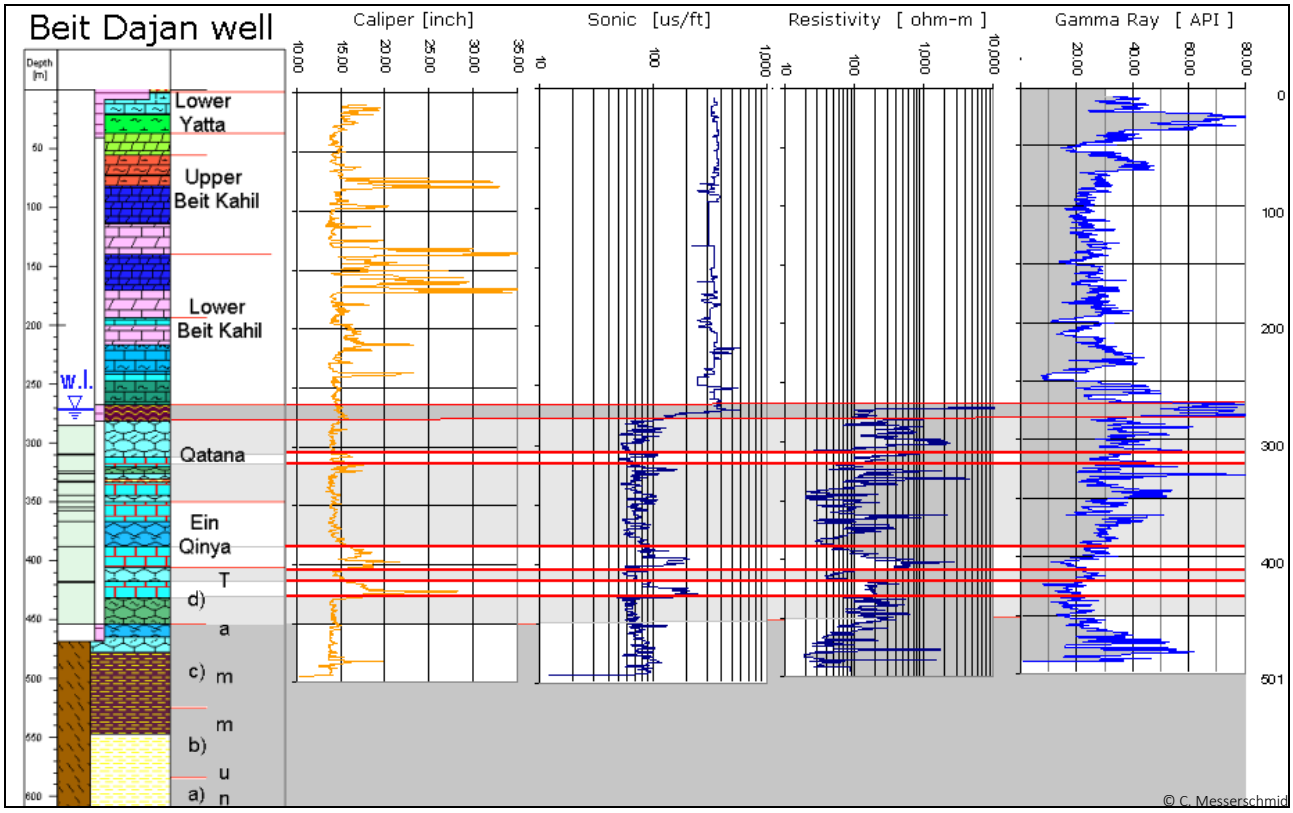

Figure 8: Comparative geophysical logs at Beit Dajan well: Kobar multilayered aquifer/aquiclude

A TV-log survey allows for a direct optical comparison of the different formations within Kobar group. At 315m depth, Qatana has a strongly fractured section. The fracture in the marly limestone is 84 degrees inclined and about 5m long (see Fig. 9).

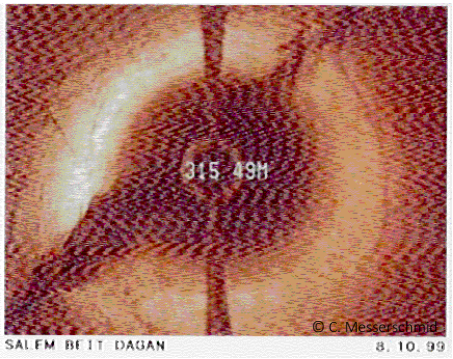

Figure 9: Fractured Qatana formation (315m bgl)

Also Tammun d has some sections of good fracturing. The rock formation in the borehole was encountered loose, forming fractures and small cavities (see Fig. 10). A very different situation is found in Tammun c at 483m bgl. Here the borehole is smooth, which confirms the shale found in cuttings and logging. Figure 11 shows a deformation of the borehole to an eye-shape. This is due to swelling of the soft clayey shale after being drilled and in addition due to formational lateral stress.

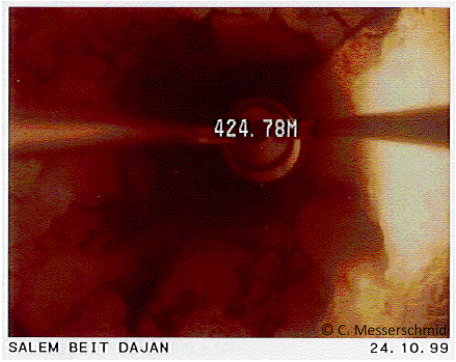

Figure 10: Fractured Tammun d) (425m bgl)

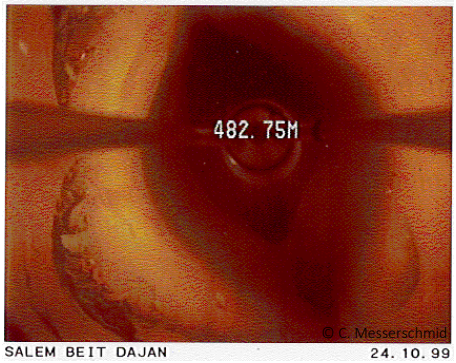

Figure 11: Deformed, but otherwise smooth shale of Tammun c) (483m bgl)

Also the pump test indicated a double porosity fractured aquifer. The static water level was slightly confined at 271m depth inside the strong aquiclude that is formed by the top Qatana clay. A long duration pump test with a pumping rate of 74m^3/h over 80 hours indicated that that the well has insufficient recharge to maintain such an abstraction rate. The dynamic water level stabilized only at a weaker rate of 60m^3/h.

The log-log and semi-log plots of the pump test curve (Fig. 12) can be compared with the "fractured dyke" aquifer according to Kruseman/De Ridder (1992). Of course, the Kobar group multilayered aquifer is not a dyke but it is equivalent to that type because the fractures provide a high secondary porosity in an aquifer of otherwise poor primary porosity. The matrix is a quite marly limestone or even marl itself.

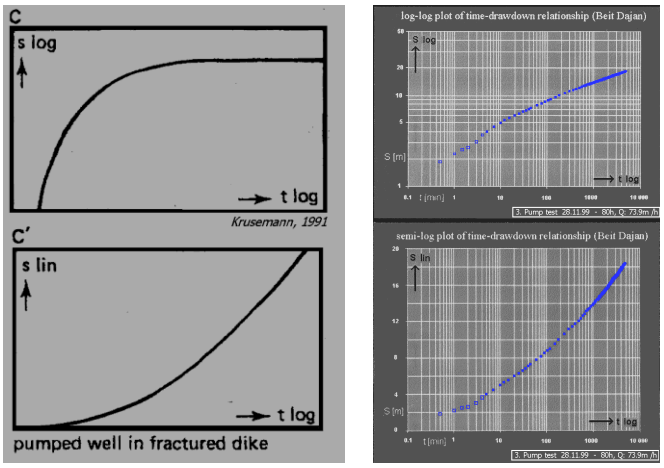

Figure 12: Kruseman curve and pump test curves of Beit Dajan well.

The graph also shows that stabilisation of the dynamic water level was not reached, because the pumping rate was too high and the "cone" of drawdown did not reach the limits of the zone of inflow of recharge to the well.

Thus, Upper Kobar here can be considered a multi-layered aquifer, albeit with restricted recharge: The well is suitable for supply on a local scale only. Hydrocarbon-age analysis and several pump test analysis methods confirm the findings of coring, sampling and logging in this double porosity fractured aquifer.

In Beit Dajan well, a multilayered aquifer was discovered in Upper Kobar, while Lower Kobar is a strong aquiclude, predominantly built-up of shale.

4. c) General conclusions about Kobar

Kobar, usually a strong aquiclude, can be aquiferous in some areas, for parts of its section. While the Ein Qinya formation was already known as a local aquifer, the new findings show that Qatana and even upper Tammun can also be locally aquiferous. The yield however, is restricted due to the lack of direct rainfall recharge in these usually deeply buried series. In other areas, Kobar undergoes a lateral facies change, and Qatana and especially Tammun are purely aquicludal as in Ein Senia well #7.

5. CONCLUSIONS

Future well drilling has to take these findings into account. Well design and the testing program must pay attention to the specific nature of the "aquicludes" in each of the different well locations. Failure to address these issues can lead to surprises in the findings, technical problems during construction and problems in the long term operation.

Tracking the facies changes and the change in hydrogeological characteristics of the "aquicludes" more closely allows for a better design and thus better results in the long term operation of the deep wells in the West Bank. Taking into account all sub-aquifers or confining layers at new well sites will result in higher yields, lasting sustainability and more effective use of the water resources that are so crucial for any development in an environment like Palestine.

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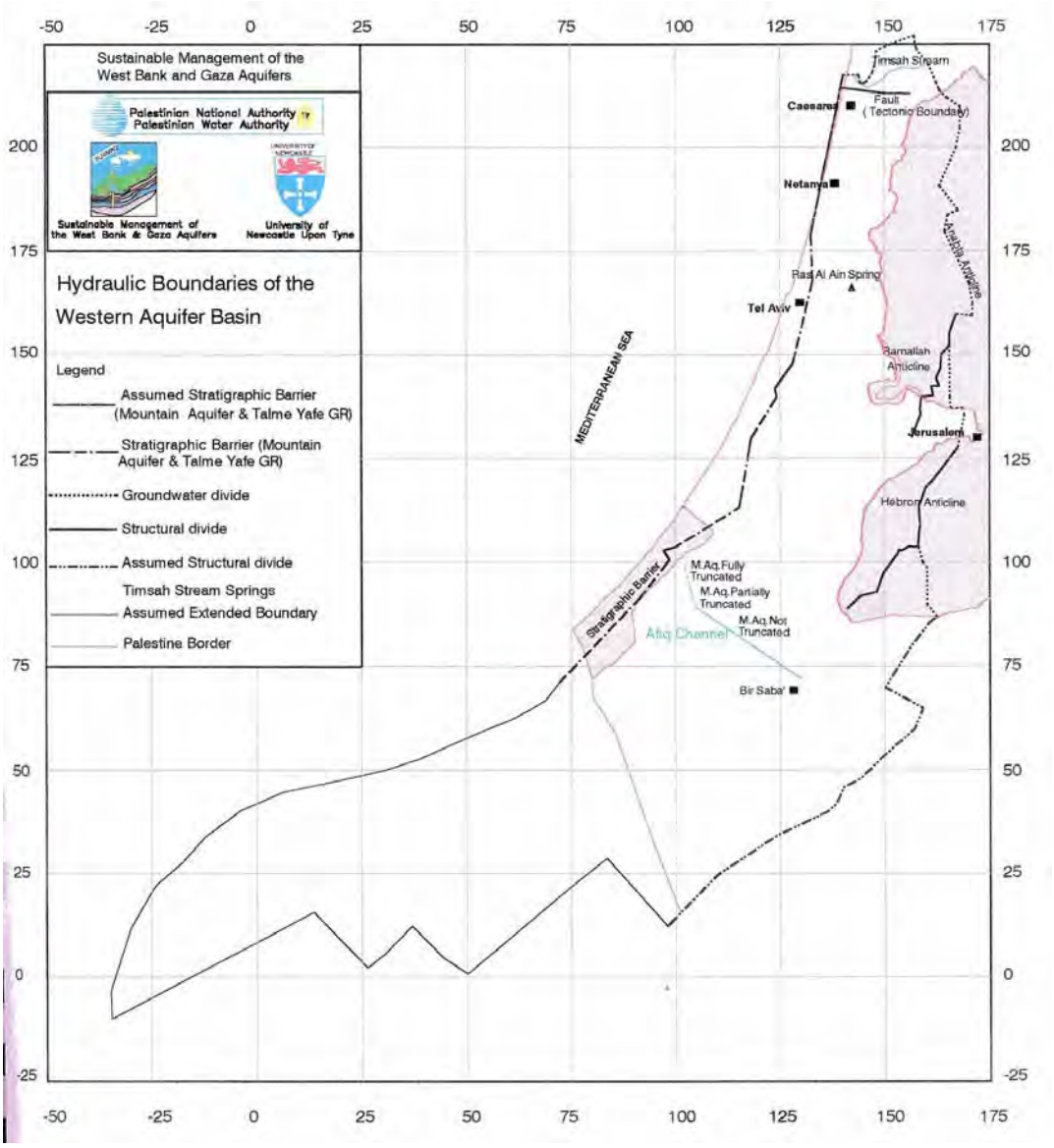
Sustainable Management of the West Bank and Gaza Aquifers

Boundaries of the Western Aquifer Basin and the Eocene Aquifer in the Northeastern Aquifer Basin

Working Report
SUSMAQ-MOD # 6.1 V1.0
Version 1.0

December 2001


Sustainable Management of the West Bank and Gaza Aquifers
Palestinian National Authority
Palestinian Water Authority
Sustainable Management of the West Bank & Gaza Aquifers
University of Newcastle Upon Tyne
Hydraulic Boundaries of the Western Aquifer Basin
Legend
Assumed Stratigraphic Barrier (Mountain Aquifer & Talme Yafe GR)
Stratigraphic Barrier (Mountain Aquifer & Talme Yafe GR)
Groundwater divide
Structural divide
Assumed Structural divide
Timsah Stream Springs
Assumed Extended Boundary
Palestine Border
Timsah Stream
Fault (Tectonic Boundary)
Caesarea
Netanya
Ras Al Ain Spring
Tel Aviv
Ramallah Anticline
Jerusalem
Hebron Anticline
MEDITERRANEAN SEA
Stratigraphic Barrier
M.Aq.Fully Truncated
M.Aq.Partially Truncated
M.Aq.Not Truncated
Afiq Channel
Bir Saba'
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Boundaries of the Western Aquifer Basin
Executive summary

The boundaries of the Western aquifer Basin, their hydrogeological nature and modelling type are summarized briefly herein and shown in the map next page.

Carmel region (N)

The Beny amina fault with up to >700m throw is a physical boundary with structural effects. It raises the aquifers under the alluvial close to the surface and lets the strongly confined water emerge at the Timsah and Taninim springs. These springs act as one of the main outlets and could be modelled as a **specified flow boundary or specified head boundary**.
Along the foothills of Mt. Carmel range, the boundary is set by the erosion of the aquifer formations and thus constitutes a **no-flow boundary**.
Further East under the Ramot Menashe Syncline, the no-flow boundary might turn into a **flow-boundary**. It would be essential to define the amount of flow towards the North that passes through this boundary. Then it could be modelled as a specified flow boundary as well. The definition of the exact extension to the North depends on more data about water levels.

NEAB limit – Northern West Bank (NE)

Along the 'Anabta anticline, Jerusalem and upper Betlehem formations crop out. The Upper aquifer is partly eroded and forms a **geo-structural divide** (no-flow boundary). The Lower aquifer is a **groundwater divide** (no-flow boundary).
In the southern part, where the Anabta anticline dies out and a 'positive zone' is indicated in structural maps, the boundary is a groundwater divide for **both aquifers** (no-flow boundary).

EAB limit – West Bank anticlinorium (E)

From the triple point of the EAB, NEAB and WAB (near Yutma), the boundary follows as a geo-structural divide, which constitutes a physical boundary. It shall be modelled as a **no flow boundary**, since the aquifers are eroded along the axis of Ramallah anticline and the bottom aquiclude (Kobar group) crops out.
Near Kobar, the boundary splits into two branches.

The Western branch follows the Ramallah anticline. The bottom aquiclude crops out here and marks a **physical boundary** (geo-structural divide) within the modelling area between the main Western Aquifer Basin and a sub-basin, which drains SW to the main basin.
The Eastern line runs West of Ramallah and Jerusalem at topographically and structurally high levels. This boundary is a **groundwater divide** that marks the boundary between the Eastern and the Western Basin. Its position is likely to shift with hydrologic stresses on the water table.
ESE of Betlehem the boundary continues on the Hebron anticline towards SSW as a **physical boundary** (geo-structural divide), until it splits again (at N 104), analogous to the above situation.
A Western thorn follows the plunging axis of the Hebron anticline to the SW and separates another sub-basin from the main WAB (**geo-structural divide**).
The Eastern line follows towards the south (along PGE 100) as a **groundwater divide** to the Harei' Anim anticline. Here it turns into a **physical boundary** (geo-structural divide) and continues SSE until it crosses the Green Line.

Northern Negev (SE)

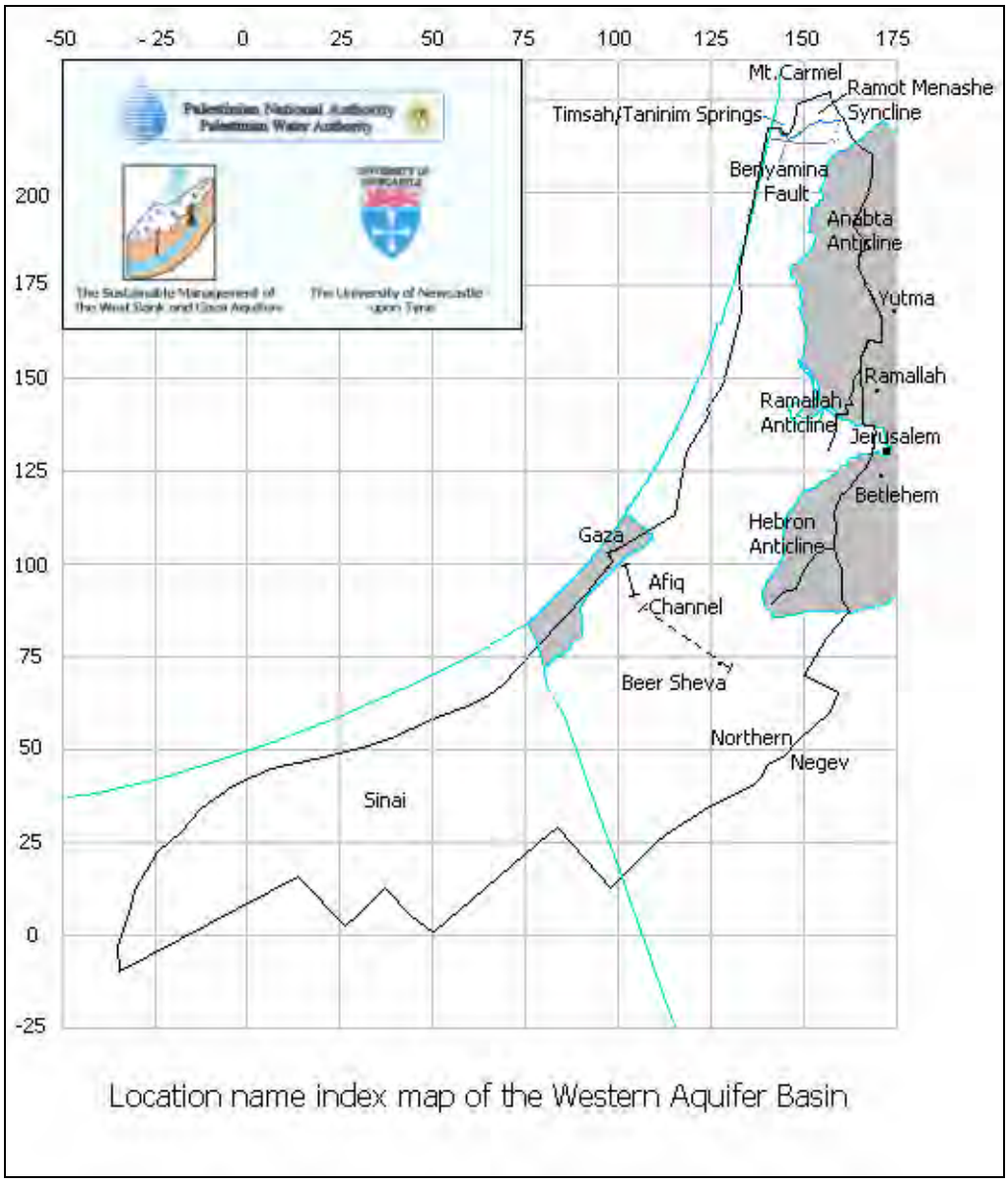
The **physical boundary**, modelled as a no flow boundary, continues along the axes of the anticlines, reproducing their en-echelon pattern. In most parts the aquifer here is dry. Upper and Lower Cretaceous thickness diminishes and at times Jurassic crops out. Strong faulting juxtaposes different structural levels and formations. This creates hydraulic connections and provides brackish inflow into the WAB from deeper aquifers (Kurnub and Arad group).

Sinai (SW)

Little activity takes place in the Sinai: Neither pumping nor recharge have been recorded, although the basin covers a large area here. The Sinai portion of the WAB can therefore be modelled as a distant corner with minimal stresses, i.e. a **distant boundary**.

Mediterranean coast line (W)

The line of facies change between Judea group and Talme Yafe formation is a **physical boundary** and acts as a barrier. It runs parallel to the coast line from the Sinai in the South until Mt. Carmel in the North.



The map indicates locations, mentioned in the executive summary.

Afiq channel between N-Gaza and Beer Sheva

The Neogene channel, filled with impervious material, fully dissects the aquifers over a length of 10.5km from Gaza towards SE and constitutes a barrier here. Further SE, the truncation is incomplete until the channel ends near Be'er Sheva'. The channel will be modelled as the end of the modelling area.
Near Gaza, it is a physical boundary (barrier). In the East, where it only partly dissects the Judea group (thus allowing flow connections to the south), it could be modelled as **specified flow boundary**.

TABLE OF CONTENTS

CHAPTER ONE

GENERAL BACKGROUND ON THE TYPES OF BOUNDARY CONDITIONS

1.1 Specified head boundaries 1
1.2 Specified flow boundaries 2
1.3 No-flow boundaries 2
1.4 Head-dependent boundaries 5

CHAPTER TWO

THE WESTERN AQUIFER BASIN BOUNDARIES BY GEOGRAPHIC REGIONS

2.1 The Northern boundary: Benyamina fault, Mt. Carmel and Ramot-Menashe syncline 7
2.1.1 Mt. Carmel 7
2.1.2 Benyamina fault 7
2.1.3 Ramot-Menashe syncline 9
2.1.4 Boundaries 9
2.1.5 Model area boundary 10
2.1.6 Cross section No.1: Yesha 1 – Carmel 1 12
2.1.7 Cross section No. 2: South of Mount Carmel and Northern Coastal plain 14

2.2 The Northeastern boundary: Northeastern West Bank (West of Jenin) 15
2.2.1 Cross sections No. 3 and 4: Deir Istiya – Turmus ʻAiya and Yutma 17

2.3 The Eastern boundary: Central and Southern West Bank Anticlinorium 21
2.3.1 Ramallah – Jerusalem area 21
2.3.1.1 Cross section No.5: West of Jerusalem 25
2.3.2 South of Betlehem 26
2.3.2.1 Cross section No. 6: Beit Guvrin – Yatta Section 26
2.3.2.2 Cross section No. 7: Wadi Duma – Yatta – Ein Gedi 30

2.4 The Southeastern boundary: Negev 31
2.4.1 Cross section No. 8: Northern Negev 33
2.4.2 Cross section No. 9: Central Negev – Revivim and Oron 34

2.5 The Southern basin boundary: Sinai 38

2.6 The Southern model boundary: Afiq channel 38
2.6.1 Cross section No. 10: Afiq channel 40

2.7 The Western boundary: The Talme-Yafe barrier 42
2.7.1 Cross section No. 11: Southern coastal plain 42

2.8 Summary table of coordinates of the Western Aquifer Basin boundary 44

CHAPTER THREE

HYDRAULIC BOUNDARIES OF THE EOCENE AQUIFER – NORTHEASTERN AQUIFER BASIN

3.1 No-flow boundary 45
3.2 Specified flow boundary 45

References 54
4.1 Geological maps 55
4.2 Topographic maps 56

5. Abbreviations 56

List of Figures, Tables and Cross Sections

List of Figures

Fig. 1: Variable specified head boundary 2
Fig. 2: Anticline with water level connections 3
Fig. 3: Anticline with permanent water level separation 3
Fig. 4: Zones of a structural boundary (geo-structural divide) 4
Fig. 5: No-flow boundary – fault type 5
Fig. 6: Mt. Carmel area – schematic map 7
Fig. 7: Timsah springs and aquifer connection along Benyamina fault 8
Fig. 8: General tectonic sketch-map of the northern West Bank 15
Fig. 9: Israeli Cross section S-N 16
Fig. 10: Israeli Cross section W-E 16
Fig. 11: Geo-structural divide and groundwater divide near Jerusalem 23
Fig. 12: Stratigraphy of Revivim sheet 36
Fig. 13: Stratigraphy of Oron sheet 37
Fig. 14: Schematic section through the Afiq channel near Gaza 37
Fig. 15: Boundary of Eocene Aquifer – Northeastern Basin 46
Fig. 16: Boundary conditions of Eocene Aquifer – Northeastern Basin 47
Fig. 17a:Geological map of the northern West Bank 48
Fig. 17b: Legend to the geological map of the northern West Bank 49
Fig. 18: Structural geology of the northern West Bank 50
Fig. 19: Extent of the Eocene aquifer – Northeastern basin 51
Fig. 20: Cross section SW-NE 52
Fig. 21: Cross section NW-SE 53

List of Tables

Table 1: Coordinates of the boundary in the Carmel / Ramot-Menashe area 9
Table 2: Coordinates of the geo-structural divide near Jerusalem 22
Table 3: Limits and middle line of assumed range of groundwater divide 23
Table 4: Thickness and elevation data of Judea group formations – Southern Hebron anticline 28
Table 5: Summary table of coordinates of the Western Aquifer Basin boundary 44

List of Cross sections

Cross section No. 1: Yesha 1 - Carmel 1 11
Cross section No. 2: South of Mt. Carmel and Northern Coastal Plain 13
Cross section No. 3: Deir Istiya – Turmus ‘Aiya 18
Cross section No. 4: Yutma 19
Cross section No. 5: West of Jerusalem 24
Cross section No. 6: Beit Guvrin – Yatta 27
Cross section No. 7: Wadi Duma – Yatta – Ein Gedi 29
Cross section No. 8: Northern Negev 32
Cross section No. 9: Central Negev – Revivim and Oron 35
Cross section No. 10: Afiq channel 40
Cross section No. 11: Southern Coastal Plain 43

CHAPTER ONE

GENERAL BACKGROUND ON THE TYPES OF BOUNDARY CONDITIONS

The selection of the boundary conditions for the Western Aquifer Basin is difficult because of the complex geology and hydrogeology of the basin itself. With regard to the Eocene Aquifer of the Northeastern Aquifer Basin, the selection of the boundaries is relatively easier as they are determined with the outcrops of the Eocene rocks. There are some areas where the Eocene is covered by Quaternary, but using the available cross sections the extent of the Eocene can be determined. Before the details of how the boundaries of WAB and Eocene were determined, it is important to provide a general introduction on the types of the boundary conditions and how they are modelled.
It is important to realise that the correct determination of boundary conditions of the modelled aquifer system plays a major role in the determination of its flow patterns.

In general, there are four types of hydrogeological boundaries:

(1) Specified head boundaries
(2) Specified flow boundaries
(3) No-flow boundaries
(4) Head-dependent flow boundaries

1.1 Specified head boundaries

These are the boundaries where the head is known. This helps numerically because the governing equations of groundwater flow are written in terms of differences in heads (derivatives); therefore, known head values will guarantee a unique solution to the partial differential equations of the flow system.

Examples of these boundaries are seas, lakes, reservoirs, rivers and sometimes springs. However, head may not be constant in some rivers and vary spatially. In this case, the boundary will be a specified-head boundary but it will vary spatially, e.g., the head will be constant at each node on the boundary but will not necessarily have the same value in each node (see Fig. 1). Springs should be dealt with very carefully. They can also be modelled as a specified-flow boundary. The problem with this is that the given flow of the spring can vary with time depending on head distribution in the aquifer. It is therefore more accurate to model springs as drains where changes in heads are taken into considerations. However, when the spring outflow is large or where a number of spring form a sort of a small or a big stream, these springs can be easily modelled as a specified flow boundary.

In terms of modelling, sometimes a high value of the storage coefficient is normally assigned to nodes with known heads in order to prevent the known head at these specified head nodes from changing during the simulation. This also reflects the fact that the specified head boundary represents for the modelled system an infinite source of water supply.

In both the WAB and Eocene systems, there are no rivers that can be simulated as specified head boundaries. The only two areas that should be studied with care in this regard are: (1) The Taninim (Timsah) spring which forms a river and the contact between the WAB and the Mediterranean; (2) The Gilboa - Bisan springs. These will be discussed in detail later. In general, these springs produce a large volume of water that leaves the aquifer through great faults and then forms what so called small rivers. In this case, it will be accurate if they are simulated as specified fluxes.

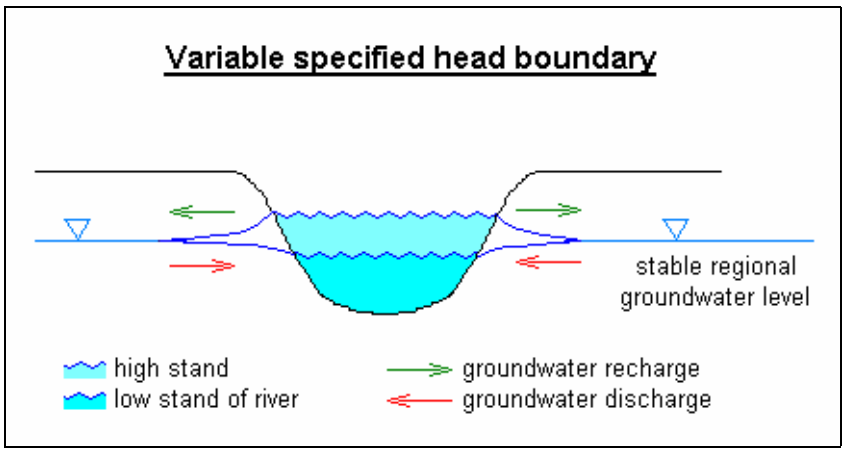


Fig. 1: Variable specified head boundary

1.2 Specified flow boundaries

Specified flow boundaries can be surface water bodies, spring flows and underflows. One example of underflow is the case when there is a hydraulic connection between aquifer basins and water moves underground from one basin to another. This is also true for seeps to or from aquifer bedrock underlying the modelled system.

In regional modelling terms, it is sometimes more accurate to model rivers as a specified flow condition rather than as a specified head boundary. Also, it is recommended to investigate whether it is more accurate to simulate injection or pumping wells at the specified flow boundaries such that the total injection or withdrawal equals the specified flow.
This type of boundary may be applicable to the Taninim (Timsah) spring and to the areas where there is an exchange of flow between the WAB and EAB on one side and between WAB and the Mediterranean on the other side (if there is an evidence to support the latter).

1.3 No-flow boundaries

Regional groundwater divides are typical examples of no-flow boundaries. They are found near topographic highs (recharge areas). This is the case for most of the eastern boundary of WAB, which represents the recharge area of the Basin. Figure 2 shows that in some cases and due to stresses of pumping and recharge the position of groundwater divide might move suggesting inflows between the two separated basins at the old location of the groundwater divide.

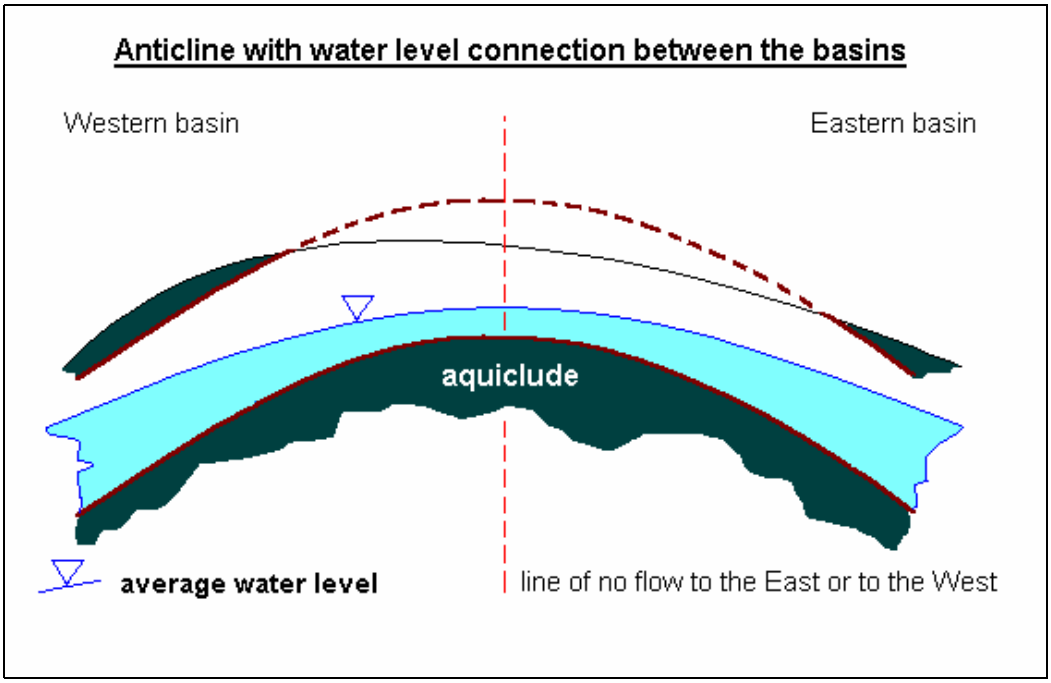


Fig. 2: Anticline with water level connections

This is also the case for structural boundaries. In anticlinal areas where the bottom of a middle aquiclude that separates two aquifers crops out (Figure 3), the Upper Aquifer formation is completely eroded and therefore limited by a structural divide.

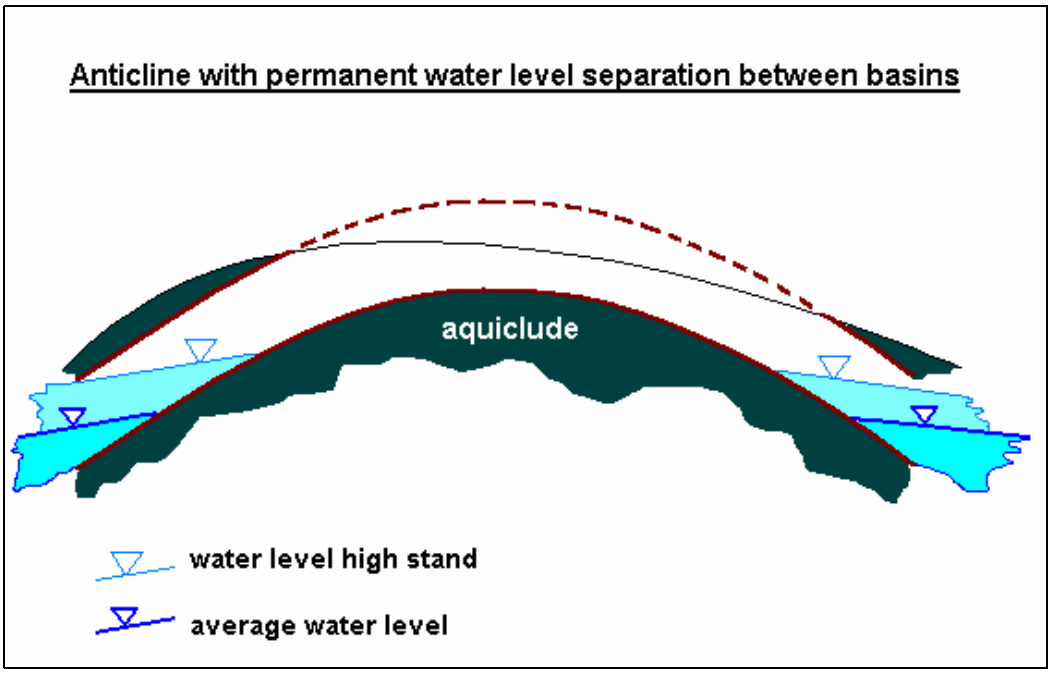


Fig. 3: Anticline with permanent water level separation

However, since there is no discontinuity in the water level of the Lower Aquifer, these areas are considered groundwater divides for the Lower Aquifer. Both, the groundwater divides and the structural divides are modelled as no-flow boundaries.

An extreme case is the situation where both aquifers have been completely eroded and the bottom aquiclude of the Lower Aquifer crops out. Such a situation is found in parts of the Ramallah anticline and in the Northe rn Negev. For the modelling of the aquif er basin, the axis of the anticline is not identical with the limit of the modelling area. Three lines (on a map) have to be differentiated (as indicated in Fig. 4):

- The axis of the anticline is a structural feature and lies in the middle between the two basins. It is often but does not have to be the topographically highest point.
- The limit of the (lithological) extension of the aquifer is the line along which the bottom of the aquifer crops out. It is a geological feature as well. However, the aquifer usually is not filled with water up to this line. Therefore this line can also be considered the limit of the dry zone of the aquifer.
- The limit of the saturated zone of the aquifer lays further inward the basin. It is a hydrological (or hydrogeological) feature that depends on the water levels an d therefore shifts its position during the meteorological seasons. As a consequence its exact position is not easy to detect and f or practical reasons a range of position shall be assumed.

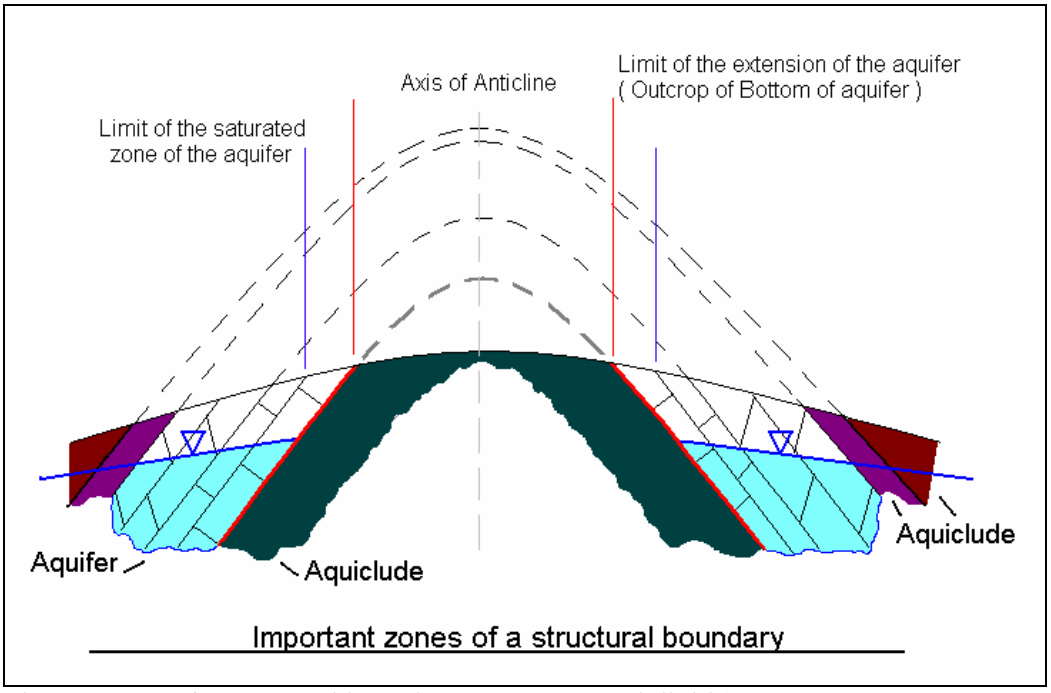


Fig. 4: Zones of a structural boundary (geo-structural divide)

Also strong faults can constitute a no-flow boundary if the vertical throw excee ds the vertical thic kness of the a quifer. Thus the aquiclude is jux taposed to the a quifer and inhibits flo w connections to the oth er block o f the fault (see Fig. 5). Th ey act as a barrier and belong to the group of the structural divides (physical boundaries).

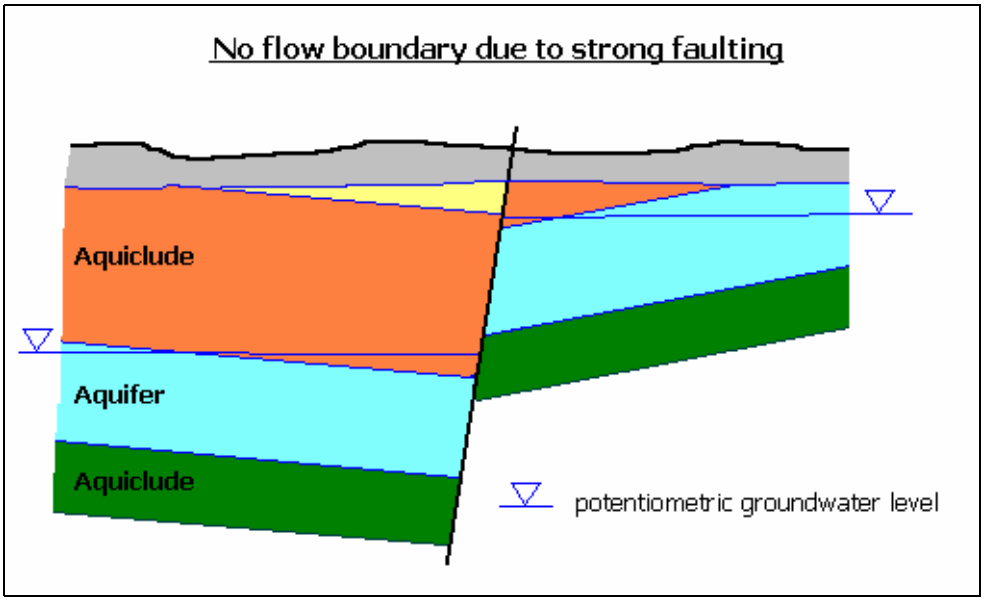


Fig. 5: No-flow boundary – fault type

Also, the litho-facies changes between the WAB and the Mediterranean constitute a no-flow boundary. It can be modelled as a barrier in the GMS.

Additionally, another no-flow boundary can be when the hydraulic properties change dramatically, e.g., normally a two order of magnitude contrast in permeability may be sufficient to justify locating a no-flow boundary (impermeable boundary). This can be the case, southeast and southwest of the Afiq channel in the domain of the WAB.

In general, a no-flow boundary may represent impermeable bedrock, an impermeable fault zone, a groundwater divide or a streamline.

In terms of modelling, no-flow boundaries are modelled by assigning zero values to the hydraulic conductivities.

1.4 Head-Dependent boundaries

Head-dependent boundaries can be in leaks from or to a river, lake or reservoir. Drains (springs) can be simulated to flow using this type of boundary. However, extra care must be taken.

CHAPTER TWO

THE WESTERN AQUIFER BASIN BOUNDARIES BY GEOGRAPHICAL REGIONS

The Western Aquifer Basin covers a large area of 9155 km^2 (including its parts in Sinai even 14,148km^2) with a wide range of different climatic, topographic, geological, hydrogeological and water use conditions. According to which the boundaries of the basin can be divided into 7 regions:

1. Northern region: Mt. Carmel and Ramot-Menashe syncline (Northern boundary)
2. Northeastern West Bank: Boundary between Northeastern Aquifer Basin and Western Aquifer Basin (Northeastern boundary)
3. Central and Southern West Bank: Jerusalem and Hebron Areas; boundary between Eastern and Western Aquifer Basins (Eastern boundary)
4. Negev (Southeastern boundary)
5. Sinai (Southern basin boundary)
6. Southern Coastal Plain: Afiq channel between Gaza and Beer Sheva (Southern study area boundary)
7. Mediterranean coast line (Western boundary)

2.1 The Northern boundary: Benyamina fault, Mt. Carmel and Ramot-Menashe syncline

2.1.1 Mt. Carmel

The Carmel Mountains at the Mediterranean coast south of Haifa are an uplifted zone, where upper and partly lower Cretaceous formations are exposed. In addition to an overall anticlinal structure, the Carmel Mountains are characterized by strong faults that extend also to the East and Southeast and lift up formations, deeply buried elsewhere in the Coastal Plain (Fig. 6).

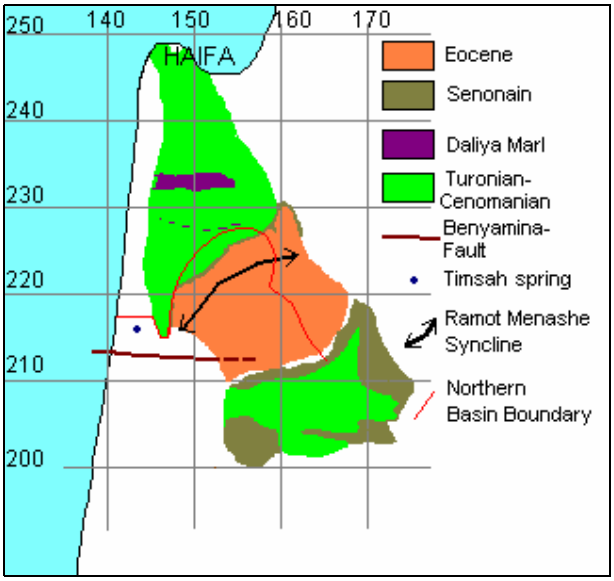


Fig. 6: Mt. Carmel area – schematic map

2.1.2 Benyamina fault

The most important of these faults is the Benyamina fault at the southern edge of Mt. Carmel area. It has a strong throw in the West and dies out to the East.
The fault extends from the Sea (WNW) land-inward (ESE) under the Ramot Menashe Syncline.

Near the coast, the northern side of this fault is uplifted more than 700 m and brings the Judea group aquifer formations close to the surface. (Fig. 7)
Further land-inward, the throw of this fault is the following:

- 450 m at the western edge of Ramot-Menashe syncline (PGE 145)
- 150 m at the western part of the syncline (PGE 147-149)
- 50 m in the middle part (PGE 149 –154)
- 20 m East of the middle part (PGE 154 –156)
- No throw (0 m) in the Eastern part (PGE 156 – 161)

Together, the Judea group and the Yakhini formation have a thickness of ~1200 m, with Judea being 875 m thick and Yakhini being 325 m thick. On the block South to the fault, the top of Judea lies at 650 m and its bottom at 1525 m below sea level. On the northern block top Judea lays at sea level (0m) and its bottom at 875 m below sea level.

Thus, 175 m of the Judea aquifers are connected along the fault plain. The groundwater in the Judea group aquifers, strongly confined at the south of the fault, is enabled to rise near the surface and to enter the shallow alluvial along the Carmel coast. As a result, the Timsah springs emerge in this area. The Timsah[1] springs form one of the two natural outlets of the entire aquifer.

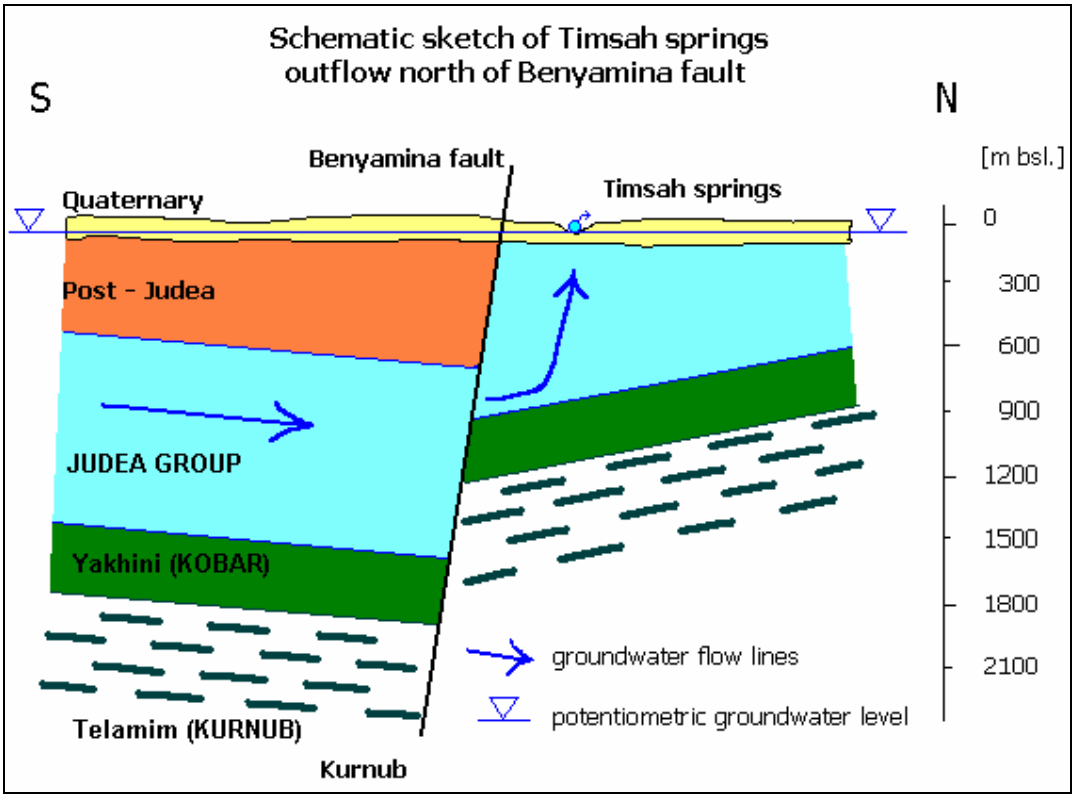


Fig. 7: Timsah springs and aquifer connection along Benyamina fault

The Carmel Mountain rises above the coastal plain further north, just 1.5 km away from the fault and forms a clearly distinct aquifer basin on its own. The shallow groundwater in the area north of the Timsah spring seems to be unaffected by the Western Aquifer basin. This is indicated by the wells in the Carmel coastline area that have an E-W groundwater flow (Guttman 1995)[2].

Former studies (i.e. Bachmat, 1995) report the existence of a so-called Daliya Marl channel that is supposed to form part of the Northern border. The Turonian Daliya formation – a marly facies equivalent to the Turonian Bi'na or Jerusalem limestone formation – has its most southern appearance at about 228PG N, in the mountain area around Um Az-Zinat (Vroman 1960), which is approximately the area of the northern WAB boundary. (See Figure 6)

[1] In the literature, there are conflicting data about the names and locations of the springs. In this study, the springs between the coast and Mt. Carmel will be referred to as Timsah springs and the springs SE of Mt. Carmel will be referred to as Taninim springs.
[2] WL in Carmel coast vary with time: +2 to +4m pre-1991; in 1991/92: +6.5 m; in 1998: +3 to +5m asl.

2.1.3 Ramot Menashe -Syncline

The Ramot-Menashe syncline lies between Mt. Carmel and the political border to the West Bank (green-line). It has approximately a square shape with the

- W corner at 148/220,
- N corner at 160/230,
- E corner at 167/220 and the
- S corner at 153/210

The syncline is flat and wide and plunges gently towards the NE. The southern margin in its western part is partly affected by the Benyamina fault. But the throw of the fault dies out towards the middle of the syncline area.

2.1.4 Boundaries

The boundary in the Carmel / Ramot-Menashe area is therefore delineated as follows (see Table 1):

PGN/PGE	PGN/PGE
150.0/224.5	
141.0/217.5	157.0/227.0
143.8/217.5	158.0/224.0
144.2/215.5	161.0/219.5
145.2/215.7	162.5/215.0
148.0/222.0	165.0 / 212.0

Table 1: Coordinates of the boundary in the Carmel / Ramot-Menashe area

The location of the boundary is based on the above structural and facies information as well as on structural contour maps of the Top Bi'na and Bottom Telamim formations (GELBERMANN E., 1993).

- The area of influence by the WAB does not reach beyond Timsah springs. At the coast, the groundwater flow north of Timsah spring is E-W. The Western Aquifer Basin does not feed the coastal strip of Mt. Carmel (up to Haifa).

- The boundary follows the southern edge of uplifted formations of Mt. Carmel.

- It then was delineated along the sea level contour line (0 m asl.) of top Bi'na formation. Where the top of the Bi' na aquifer rises above sea level (Turonian outcrops), groundwater can no longer be confined and will not emerge as springs. This is confirmed by the position of the springs from the Judea group aquifers, East of southern Mt. Carmel: The springs are mostly aligned along a line between E152 / N 219 and E 149 / N 216. (Only the Sumi springs emerge further West at E 146 / N 216). The gradient of the dip of formations on the Eastern edge of Mt. Carmel is quite steep. Therefore even a slightly higher groundwater level would shift the boundary only some hundreds of meters towards the West. Therefore, also this boundary can be considered a fixed line along the seam between the Carmel Mountains and Ramot Menashe syncline.

- The boundary bends towards the east and further towards southeast and south in the Northern part of Ramot Menashe syncline. Here, the structural contour maps only indicate an approximate position of the boundary. This is because the boundary must be considered a groundwater divide with its position depending on exact data about water levels.

- At E 158.5 / N 211.5, the northern boundary of the WAB returns to eastern directions. In this area, the WAB borders to the Umm Al-Fahm sub-basin of the Northeastern Aquifer basin (NEAB) that is described under 2.2.

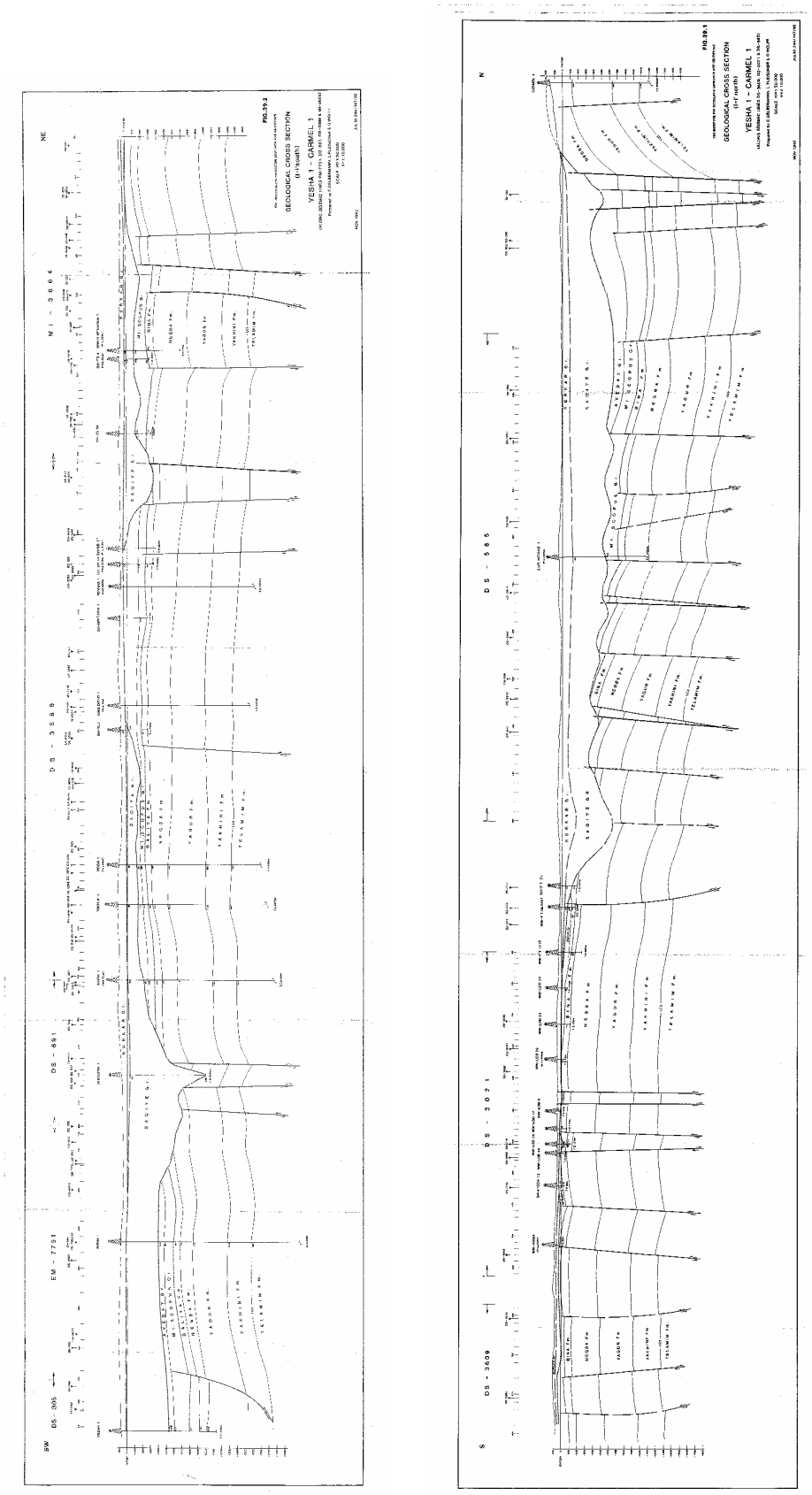
2.1.5 Model area boundary

For modelling purposes, the northern boundary of the WAB shall be considered as follows:

It is suggested to let the modelling area end at the Benyamina fault that runs from the coast through the town of Benyamina (located south of the Carmel Mountains at E 145 / N 214) and further eastwards to the Northern spur of the West bank mountain area. The Benyamina fault with a throw of up to >700 m is a physical boundary with structural effects. It raises the aquifers to the surface and lets the strongly confined water emerge at the Timsah spring. These springs are one of the main outlets of the entire basin and the fault could be modelled as a **specified flow boundary**.

Further to the East, between Benyamina and the NEAB (E 165 / N 212) the throw of the Benyamina fault diminishes and reaches zero at about PGE 160. This area, called the Ramot Menashe area is characterized by a flat and wide SW-NE trending syncline that exposes Eocene chalks (Avedat group or Jenin Subseries) at the surface. This area mediates to the division zone between WAB and NEAB. Along the Benyamina fault in this region, **some flow** towards northern directions **is possible** but does not amount to large quantities.

It would be essential to define the amount of flow towards the North that passes through this boundary. In that case it could be modelled as a **specified flow boundary** as well.



Section 1: Yesha 1- Carmel 1

2.1.6 Cross section No.1: Yesha 1 – Carmel 1

This cross section follows the coastal plain from South to North. It is reported by GELBERMANN (1993) based on findings of an Israeli geophysical survey.

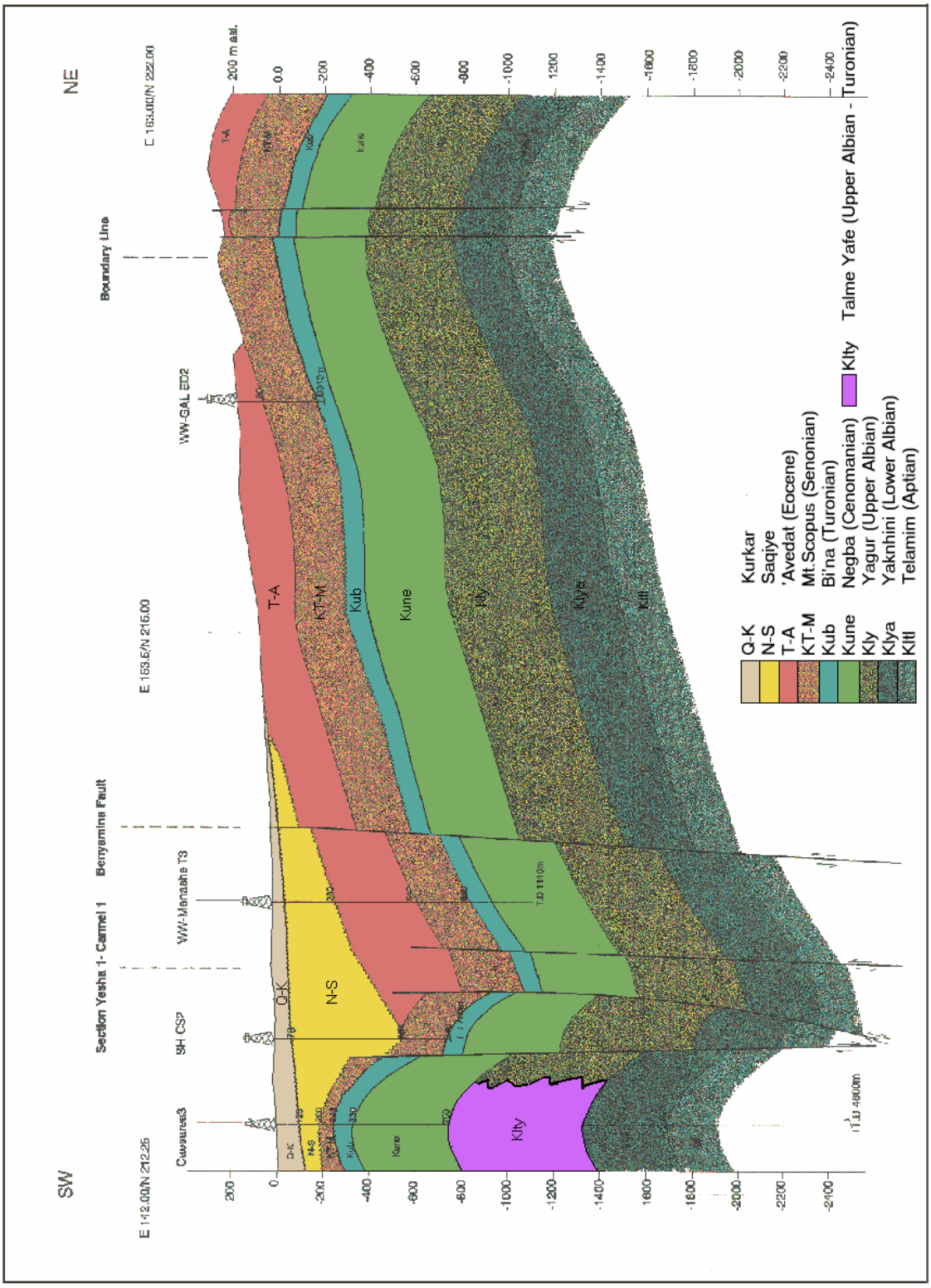
These authors use a geophysical system of stratigraphic nomenclature that subdivides the rock series in a manner, similar but not identical with the geological nomenclature. Geophysical formations names generally refer to sequences of several geological formations. The tops and bottoms of formations, according to the geophysical system are very close or identical with those of the geological system. Therefore they will be used as well to delineate the Judea group formations in this report.

The cross section shows the thickness of Bi'na, Negba and Yagur formations.
Bi'na (equivalent to Turonian Jerusalem formation in the West Bank system) is only about 80 m thick.
Negba (equivalent to Cenomanian Betlehem, Hebron and Yatta formations in the West Bank system) is about 350 m thick.
Yagur (equivalent to Upper Albian Beit Kahil formations in the West Bank system) is 400-500 m thick.
The entire Judea group has a thickness of about 880 m.

The cross section extends from the area around Ashdod (PGN 135) in the southern coastal plain until Mt. Carmel area in the North (PGN 220).
From the middle of the cross section - the area just north of Tel Aviv – and south of it, Saqiye group (Eocene – Pleistocene) becomes prominent. Where it was deposited into strongly eroded lows of the older formations (Cenomanian – Eocene) it reaches a maximum thickness of 500 m.

The northern boundary of the Western Aquifer Basin is located near the Benyamina fault in the North (PGN 215). At the cross section, the fault has a vertical throw of more than 600 m. As already described above, the throw diminishes from a maximum of 700 m in the West (PGE 141) to zero in the East (PGE 158). The Benyamina fault juxtaposes Upper Albian (Beit Kahil formations) against Upper Cretaceous (Yatta – Mt. Scopus). Upper and Lower aquifers are connected and act as one unit along the fault. The combined and strongly confined piezometric groundwater level of the composite Judea group aquifer lies near the ground surface. Since the upper aquifer formation at the Northern side of the fault is raised close to the surface, spring flow is enabled and emerges from the Timsah/Taninim spring group. However, the immediate spring outlet is located West of the cross section, where both, the structure and the topography differ slightly from the situation shown in the section.

Mt. Carmel rises to topographic elevations of more than 500 m above mean sea level. Even stronger is the (structural) uplift of formations, exposing Yagur formation (Beit Kahil) on the surface. By this, the bottom of the Judea group aquifer lies above sea level and higher than the WAB groundwater level. The Western Aquifer Basin ends at the southern part of Mt. Carmel.



Section 2: Carmel and Northern Coastal Plain

2.1.7 Cross section No.2: South of Mount Carmel and Northern Coastal Plain

This cross section starts near the Coast (SW of the town of Benyamina), continues south of the foot of Mt. Carmel towards ENE, passes the Benyamina fault and leads to the Ramot-Menashe syncline in the NE. It bends slightly towards NW at the point PGE 153.5 / PGN 215, which lies about half way between Benyamina fault and the borehole WW-GAL ED2. The section is reported from GELBERMANN (1993) and has not been modified by the SUSMAQ-project.

The cross-section shows the thickness of Judea group, composed of Turonian Bi'na formation, Cenomanian Negba formation and Upper Albian Y agur formation. The composite thickness is between 750 m and 900 m. (The maximum tapped apparent thickness amounts to 1150 m.)

Beneath the Judea group, the equivalent of the Kobar group, Yakhini and Telamim formations is shown. It is marly and clayey and forms the bottom aquiclude of the Judea group aquifers. Senonian Mt. Scopus and Eocene "Avedat groups overlie the Judea group on its top.

In the W, near the coast, the facies change to the Talme Yafe group is visible (between the wells Caesarea-3 and SH-CS2).

Benyamina fault is shown in the centre of the section. As already mentioned above, the throw of the fault diminishes towards the East. At the section it amounts to merely 140 m, as the top Bi'na horizon is at an elevation of –710 m in the southern block and of –570 m in the northern block. This throw does not suffice to bring the aquifers to the surface. They remain covered by the aquicludal Senonian and Eocene series. This means that the spring mechanism of the eastern part of the Taninim spring group (at about E 157 / N 219) is different than that of the Timsah spring near the coast.

- Artesian confined groundwater can either rise along open faults to the surface.
- However, the location of the springs suggests another mechanism. The Taninim springs are aligned along the Wadi Taninim filled with permeable gravel. The gravel beds can be fed from the Judea group aquifers further to the east, where the conditions are more favourable for such a connection: The nearest outcrops of the Turonian are about 5 km SE of the section. There, the structural elevations of the Turonian are higher and so are the elevations of the piezometric water level.

At the eastern edge of the section a culmination of the formations raises the top of the Turonian slightly above the sea level. This highest point was taken as the geo-structural boundary line for the WAB, in accordance with the structural contour maps. Exact water level measurements have not been obtained from the Israeli to this date. However, it can be assumed that the piezometric levels lie slightly above sea level. This means that an overflow over the apex will not amount to large quantities. However, as a possibility, it should be taken into consideration for the model.

2.2 The Northeastern boundary: Northeastern West Bank (West of Jenin)

Referring to the topographical, geological, structural maps, (Fig. 8) and their associated, it can be concluded that Anabta anticline is a groundwater divide at the northern part and up to 166/183 where the southern part of the anticline dies out and the out crop formations are mostly Abu Dis, Jerusalem and in some areas Hebron.

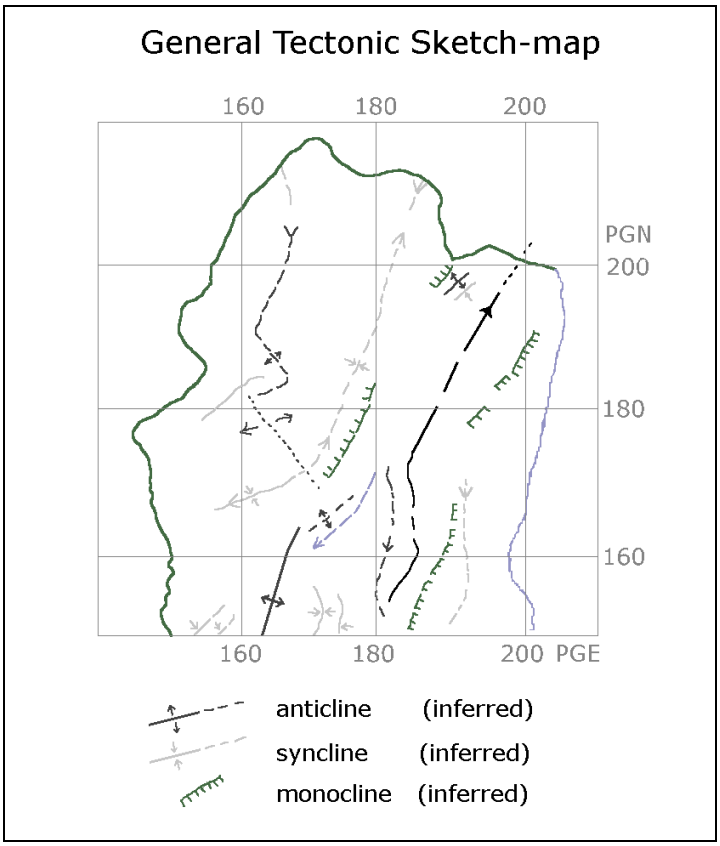


Fig. 8: General tectonic sketch-map of the northern West Bank

Al Fondoq cross section (Fig. 9) with coordinates 162.5/170-164.3/190, intersect the boundary (Anabta anticline) near the point 164.2/189 and lies nearly parallel to the divide where the southern part is higher than the northern and appears the location of the boundary is higher than the southern part of the section. Jerusalem formation is outcropping at elevation 240asl and the base of Upper Aquifer approximately at +60asl depth. Formations may be thinly saturated and a hydraulic connection at the Upper Aquifer between Western and Northeastern basin, and it considered as a Groundwater divide and modeled as no-flow boundary.
Lower Aquifer is considered as groundwater divides because its mostly saturated and modeled as no-flow boundary.
The southern part of the area and up to 164.2/180, the out crop formations are Abu Dis and Jerusalem, where Cross section Kufur Qadoum (Fig. 10) with coordinates 152/180-170/180, across the boundary at the point 164.2/180 where a main fault lowed the formations of Western Basin and formed the boundary lines between W and NE basins. According to the faults, Jerusalem formations are outcropped at elevations 380asl and Upper Yatta is located adjacent to it to the east. Hebron formation base is located at 250asl elevations depth and the water level at that area approximately +200asl which means that no hydraulic connections between Western and Northeastern basins in the Upper Aquifer and the base of lower aquifer approximately at depth –50asl and there is a hydraulic connection in the lower aquifer in the two basins. Hence it should be modelled as no-flow boundary.

Fig.9: Israeli Cross Section S-N.

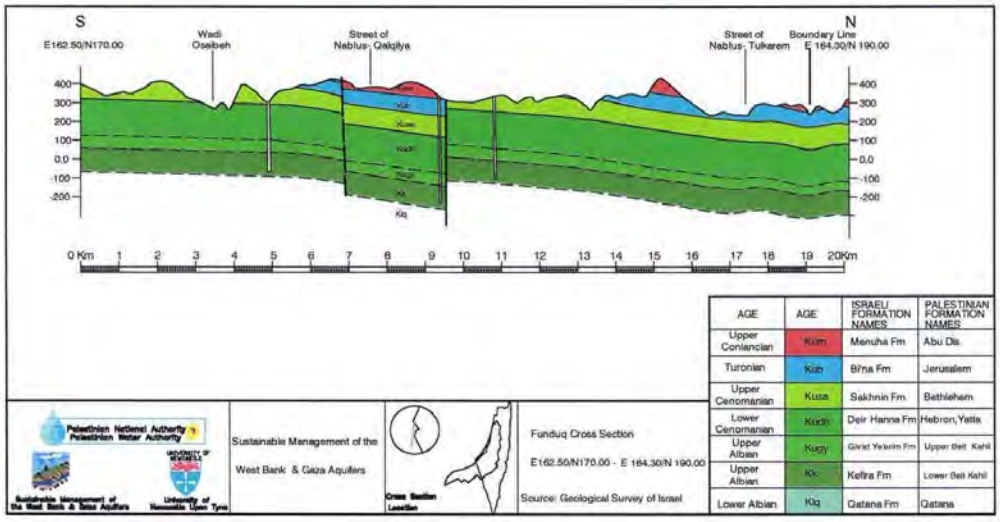
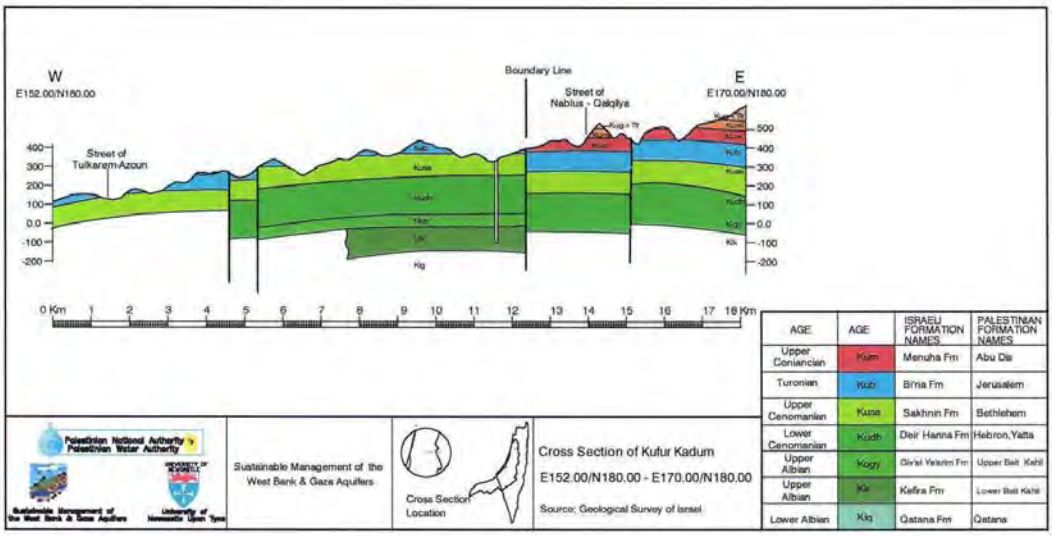


Fig.10: Israeli Cross Section W-E



To the south and up to the coordinate 170.1/167.45, the outcrop formations are mostly Abu Dis,Jerusalem,Betlehem and Hebron.

2.2.1 Cross sections No. 3 and 4: Deir Istiya – Turmus ‘Aiya and Yutma

These two cross-sections stand perpendicular to each other. They were constructed to locate the boundary in the area of the triple point between EAB, WAB and NEAB and to investigate, how the structure in the subcrop continues down to the bottom of Lower Beit Kahil (Upper Albian) formations, i.e. the Lower aquifer.
The definition of the elevation of the bottom aquifer is crucial to assess the possibilities of flow connections over the anticlinal axis.

The result of the cross-sections is, that the Lower aquifer is only partly saturated in the respective area. For this, an average water level elevation of about 400 m asl. had to be assumed. No wells penetrate these formations in the recharge area around the location. However, from other wells in the recharge areas – such as Shilo well and Ein Senia well #7 – the approximate elevation can be assumed for the Yutma surrounding. Shilo well is as much as 7 km away from the location and the static water level was found at 407 m asl. in the Lower aquifer.

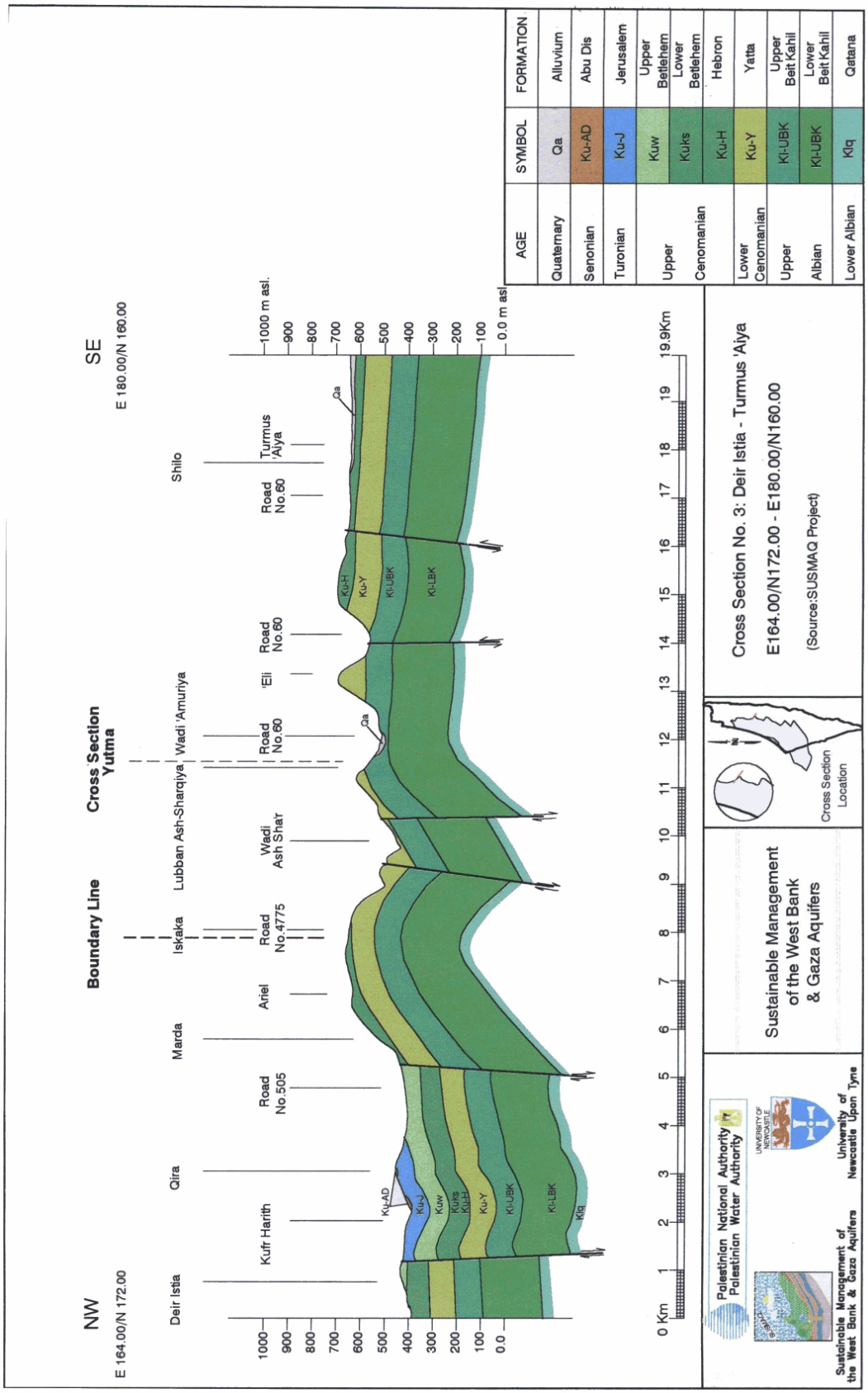
a) Cross section No.3: Deir Istiya – Turmus ‘Aiya

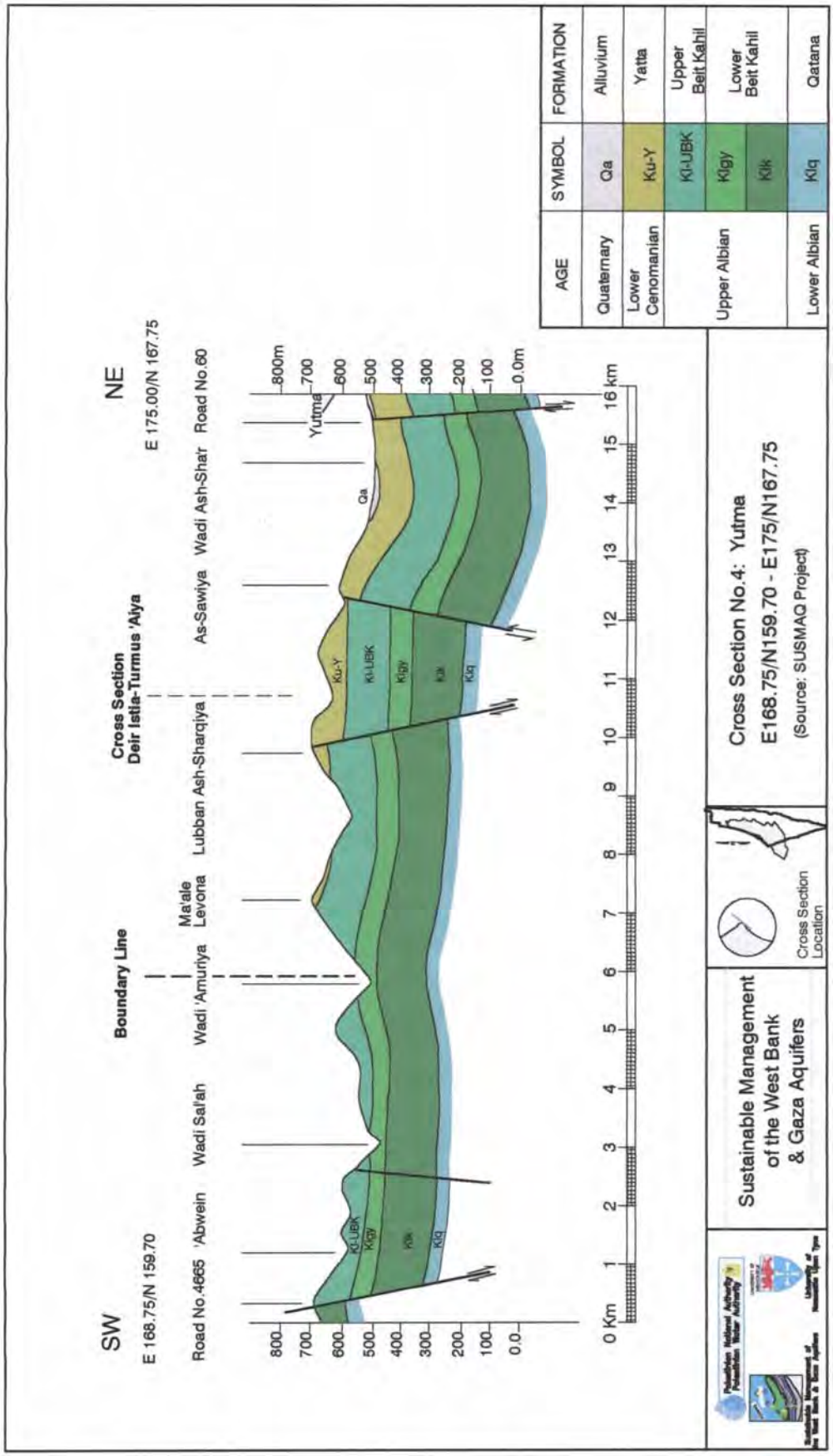
This cross section stretches from PGE164/PGN172 (NW) to PGE180/PGN160 (SE). Its central part is located close to the triple point, where the three West Bank aquifer basins (NEAB, WAB and EAB) meet.

The southeastern half of the section is located in the Eastern Aquifer Basin at ground elevations between 600 and 700 m asl. This area lies close to the surface divide (watershed) and exposes lower formations of Upper aquifer (Hebron) and uppermost formations of the Lower aquifer (Yatta).
The boundary between the NEAB and the EAB (near Wadi Ash-Sha’r) was taken from former studies that dealt with the respective basins (CH2M). It is possible that the actual location of this boundary should be shifted some 2 km to the southeast, in order to locate the boundary on the crest of the anticline where Yutma section intersects.

The Western Aquifer Basin extends from the axis of the anticline (near Iskaka) towards the northwest. This anticline is a continuation of the Ramallah anticline, although with clearly weakened features. The bottom of the Lower aquifer does not rise higher than ~200 m asl., its top lies at about 450 m asl. Since the assumed water level elevation is about 400 m asl., the Lower aquifer can be considered to be partially saturated (about 200 m).

Starting from the boundary, the ground level descends towards NW. Even steeper is the dip of the formations. By this, the stratigraphic level of outcropping formations rises towards northwest and buries the lower formations deep under ground level (and under sea level). Near Kufr Harith, the bottom of the Lower aquifer is buried as deep as >300 m bsl. and >750m below ground level. The outcrops are restricted to the Upper Aquifer formations, with rising tendency from Hebron, to Betlehem and Jerusalem. Only negligible portions of the top aquiclude (Abu Dis) have remained un-eroded in this area. Nonetheless, a rapid increase in saturated thickness, up to confining conditions can be expected. This assumption is strengthened by the fact that the Lower aquifer has sufficient outcrops in the southern surrounding of the cross section.


NW
E 164.00/N 172.00
SE
E 180.00/N 160.00
Boundary Line
Cross Section
Yutma
Deir Istia
Kufr Harith
Qira
Road No.505
Marda
Ariel
Iskaka
Road No.4775
Lubban Ash-Sharqiya
Wadi Ash Shair
Wadi 'Amuriya
Road No.60
'Eli
Road No.60
Shilo
Road No.60
Turmus 'Aiya
1000 m asl
0.0 m asl
0 Km
19.9Km
Ku-AD
Ku-J
Kuw
Kuks
Ku-H
Ku-Y
Kl-UBK
Kl-LBK
Klq
Qa
AGE
SYMBOL
FORMATION
Quaternary
Qa
Alluvium
Senonian
Ku-AD
Abu Dis
Turonian
Ku-J
Jerusalem
Upper Cenomanian
Kuw
Upper Bethlehem
Kuks
Lower Bethlehem
Ku-H
Hebron
Lower Cenomanian
Ku-Y
Yatta
Upper Albian
Kl-UBK
Upper Beit Kahil
Kl-UBK
Lower Beit Kahil
Lower Albian
Klq
Qatana
Cross Section No. 3: Deir Istia - Turmus 'Aiya
E164.00/N172.00 - E180.00/N160.00
(Source:SUSMAQ Project)
Cross Section Location
Sustainable Management of the West Bank & Gaza Aquifers
Palestinian National Authority
Palestinian Water Authority
University of Newcastle Upon Tyne
Sustainable Management of the West Bank & Gaza Aquifers


SW
E 168.75/N 159.70
NE
E 175.00/N 167.75
Cross Section
Deir Istia-Turmus 'Aiya
Boundary Line
Road No.4665
'Abwein
Wadi Sal'ah
Wadi 'Amuriya
Ma'ale Levona
Lubban Ash-Sharqiya
As-Sawiya
Wadi Ash-Shar
Road No.60
Yutma
800m
700
600
500
400
300
200
100
0.0m
0 Km
16 km
Qa
Ku-Y
Kl-UBK
Klgy
Klk
Klq
AGE
SYMBOL
FORMATION
Quaternary
Qa
Alluvium
Lower Cenomanian
Ku-Y
Yatta
Upper Albian
Kl-UBK
Upper Beit Kahil
Klgy
Lower Beit Kahil
Klk
Lower Albian
Klq
Qatana
Sustainable Management of the West Bank & Gaza Aquifers
Cross Section Location
Cross Section No.4: Yutma
E168.75/N159.70 - E175/N167.75
(Source: SUSMAQ Project)

b) Cross section No. 4: Yutma

The Yutma section extends from the prominent fault the cuts into the Ramallah anticline in the SW to the area of Yutma in NE.

The boundary between WAB and EAB crosses twice, in the SW half of the section. First, it reaches the section in the Southwest. The fault has an extremely strong vertical throw of more than 300 m. It juxtaposes the bottom aquiclude (Tammun, Ein Qinya and Qatana) against the entire section of the Lower aquifer. By this, it disconnects effectively the hydraulic connection between the two blocks of the fault.

Less pronounced is the anticline at Wadi 'Amuriya. However, it clearly marks the highest structural elevations for the main part of the section. The top of LBK is eroded in the Wadi. However it can be assumed that the top of Lower Beit Kahil reaches an elevation of 550m asl. and the top of Upper Beit Kahil, which marks the top of the Lower Aquifer, was raised to 675m asl. prior to erosion. The bottom of the Lower aquifer is lifted up to 300m asl. With the above-assumed water level of 400 m asl., the saturated thickness amounts to 100m. This is enough to create hydraulic connections between the basins and to render the boundary a ground water divide for the Lower aquifer.

The Upper aquifer is completely eroded over the entire length of the section. By this, there is no doubt, that the Upper aquifer boundary is a structural boundary in this area.

With respect to the modelling purpose, it can therefore be summarized that the Upper aquifer (eroded) marks a **geo-structural divide** and the Lower aquifer (200m saturated thickness) a **groundwater divide** along the axis of the anticline in the vicinity of the sections.

2.3 The Eastern boundary - Central and Southern West Bank Anticlinorium

The border between the EAB and the WAB is located in the heights of the West Bank that is built up by the prominent West Bank anticlinorium. The anticlinorium consists of a set of mainly N-S and NNE-SSW trending anticlines, separated in an en-echelon pattern. The dip of formations is steeper than the slope. Therefore, the lower formations are exposed at the core of the anticline, which lies near the highest elevations of the West Bank Mountains. This has two important effects:

- The formations are exposed to direct rainfall infiltration over large outcropping areas with a Mediterranean sub-humid climate, characterized by strong winter rain.
- The upper aquifer, for most of this area, is completely separated between the WAB and the EAB, as the lower aquifer formations crop out. The lower aquifer can be structurally separated as well, where the Kobar group formations of the bottom aquiclude are exposed (physical boundary). In other cases, it is separated by a groundwater divide near the axis of the anticline where we encounter an extremely restricted saturated thickness (hydraulic boundary, with no-flow conditions).

2.3.1 Ramallah – Jerusalem area

Near Jerusalem, there is a particular situation: The Ramallah anticline is the boundary between the respective basins only in its northern part, until the area of Kobar village (approximately at the coordinates PGE 165 / PGN 155). Further to the south, the boundary splits away from the Ramallah anticline (towards the East). And south of ~PGN 130, Ramallah anticline plunges low enough to enable flow connections towards the West.

Hence, the area East of the southern Ramallah anticline is a sub-basin that contributes to the WAB. It is an area with relatively high elevations of water levels (up to 489 m asl.). This allows wells to be pumped much further East, than in other areas of the Western aquifer basin (Ein Karem wells).

Therefore, two boundary lines have to be indicated: An eastern line (ground water divide) and a western line (geo-structural divide).

<u>Groundwater divide</u>

The boundary between the EAB and the WAB lies East of the intermediate high water level zone. This Eastern line is a groundwater divide and should be modelled as a no-flow boundary. Therefore, the location of the groundwater divide shifts over time, according to differential recharge and discharge ("stresses"). The approximate position of this line has been indicated by Rofe and Raffety (1961-63) and ANTEA (1998).

According to Rofe and Raffety (1961-63), this line splits from the main divide near Kobar (E166/N155). It continues southward, passes Ramallah in the West (E167/N145) and turns to SSE directions towards Jerusalem. It surrounds Jerusalem in the East (E172/N133) where it turns again to SW directions. Finally, it passes through Beit Jala

and unites with the Main divide SW of Al-Khadr (at around 164/ 123). This line is marked as "E limit of the range zone" in Figure 11.

ANTEA (1998) delineated a "subsurface watershed" south of the point PGE 165 / PGN 136. Its position is based on water levels and structural levels. According to ANTEA, NW of this point there is a dry zone, where the lower aquifer is either eroded or empty. However, there should be a connection to a recharge area further north in order to feed the locally high water levels West of Jerusalem.

Due to the lack of exact measurements, the groundwater divide can only be estimated to lie within a likely range, confined by the above-mentioned lines:

- The "underground watershed" of ANTEA (1998) is the Western limit of the zone.
- The "Groundwater divide" of Rofe & Raffety (1963) forms the Eastern limit.
- A middle line is suggested by SUSMAQ and will be subject to a sensitivity analysis at a later stage of the project.

The three lines follow the coordinates, documented in Table 3. They reunite at the northern end of Hebron anticline (PGE 165 / PGN 124.3). From here on, the boundary is a geo-structural divide, defined by the crest of the anticline or by the limit of groundwater saturation in the (lower) aquifer to the East and to the West of this anticlinal axis.

Geo-structural divide

The western line separates the sub-basin from the main WAB. This Western boundary follows the axis of the main anticline in SSW directions. It plunges southwards, until it is buried deep enough to be overflown by the groundwater. This situation is reached south of the coordinates PGE 156.45 / PGN 130.35 (see Figure 11, Table 2). The boundary of the southern branch of Ramallah anticline is a geo-structural divide.

PGE/PGN	**PGE/PGN**
168/159.9	162.95/142.6
167/159.95	161.1/142.6
165.35/155.5	161.5/140.4
165.4/152.4	158.7/140
163.55/150.3	158.35/137
163.35/149.8	158.6/135.9
163.3/147	156.45/130.35
162.2/144.5	**end**

Table 2: Coordinates of the geo-structural divide near Jerusalem

The N-S elongated lense-shaped area that is enclosed by the two divides has an outlet in the southern part (between PGN 125 and PGN 135) towards the West. It therefore contributes to the Western Aquifer basin.
Figure 11 presents the range of the zone, its Western and Eastern limit, as well as a middle line of the assumed groundwater divide. It also shows the probable area of unsaturated or eroded aquifer (dry cells in the model) and the position of the geo-structural divide on the Ramallah and Hebron anticlinal axes.

Western limit (ANTEA, 1998)	**Middle line** (SUSMAQ, 2001)	**Eastern limit** (Rofe & Raffety, 1963)
PGE / PGN	PGE / PGN	PGE / PGN
…	165.35 / 155.5	165.35 / 155.5
…	165.5 / 140.0	167.5 / 145.0
165.5 / 136.0	165.7 / 137.2	171.0 / 138.0
165.7 / 135.0	168.6 / 137.3	…
166.4 / 134.7	169.0 / 135.6	172.5 / 134.0
166.5 / 134.0	168.0 / 130.3	…
166.8 / 129.0	167.5 / 128.0	170.0 / 129.0
166.2 / 126.0	166.4 / 126.0	…
165.0 / 124.3	165.0 / 124.3	165.0 / 124.3

Table 3: Limits and middle line of assumed range of groundwater divide

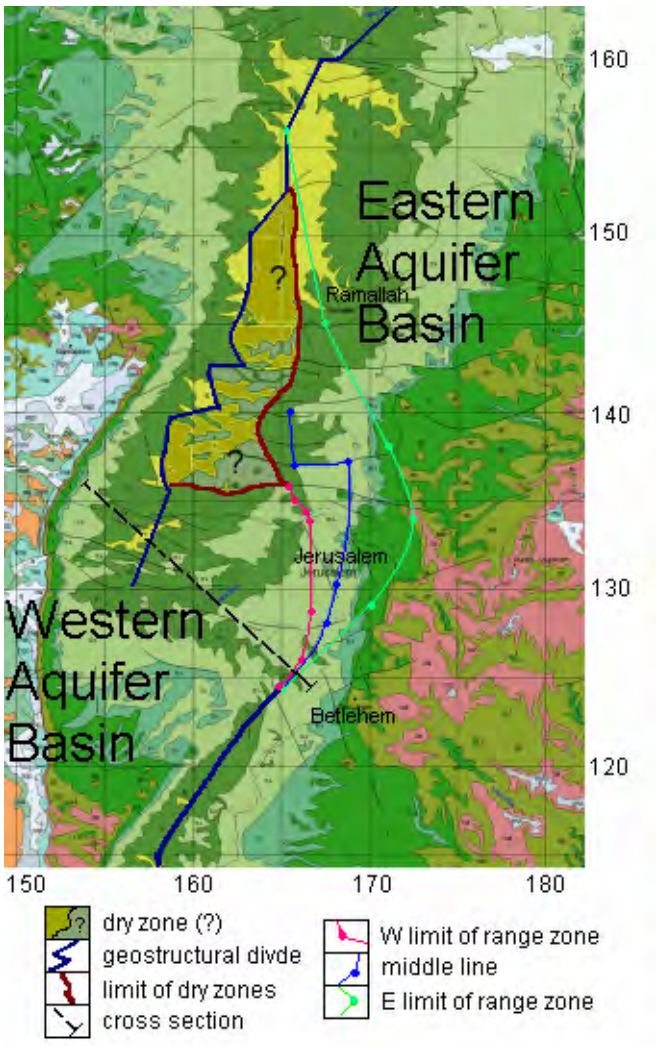
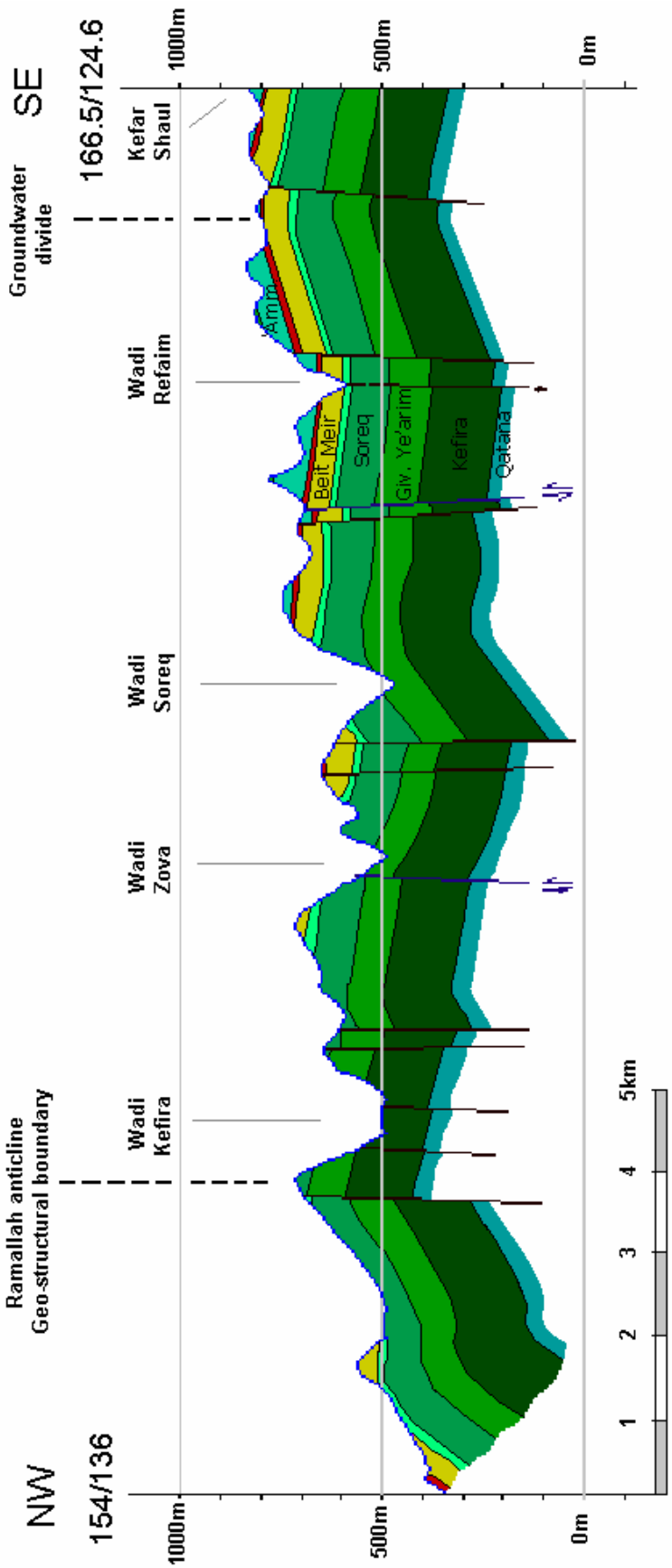


Figure 11: Geo-structural divide and groundwater divide near Jerusalem


NW
154/136
SE
166.5/124.6
Ramallah anticline
Geo-structural boundary
Groundwater divide
Wadi Kefira
Wadi Zova
Wadi Soreq
Wadi Refaim
Kefar Shaul
1000m
500m
0m
5km
Amm
Beit Meir
Soreq
Giv. Ye'arim
Kefira
Qatana

2.3.1.1 Cross section No.5: West of Jerusalem

This cross section was made to connect the southern end of the Ramallah anticline with the northern end of the Hebron anticline. The Ramallah anticline shows already weakened features in the NW part of the section (left edge) with maximum uplift around Shoresh: It has already lost the strong anticlinal features that are found further north (clear upfolding of the anticline). From the cross section southwards, the anticline plunges deeper until it finally dies out under the coastal plain sediments.

In the cross section, the Hebron anticline is more pronounced and can be found at the very SE (right) edge of the section in the area around Har Gilo settlement. Here, the bottom of the lower aquifer is raised up to 400 m above the sea level.
The objective for establishing this boundary was to connect the two anticlines that build each a geo-structural boundary further north and further south of the area. The anticlines are distributed in an en-echelon pattern, typical for the Syrian Arc structural elements.
The cross section indicates clearly that at least the lower aquifer is partly saturated with water. Near Wadi Soreq, there is an area with a pronounced low of structural elevations: The bottom of the lower aquifer reaches as deep as <100 m above sea level. This means that in the area of the section, the physical boundary is interrupted and the groundwater can flow southwestward until it joins the main basin of the Western aquifer.
It is important to emphasize that there is evidence of a regional high of groundwater levels, as tapped in Ein Karem and other well fields of the section's surrounding. Water levels reach nearly as high as 500m above sea level. This important finding indicates a recharge area north of this section.

The understanding, obtained from the compiled analysis of the cross sections, structural contour maps, geological maps and water level contour maps is the following:

- The Ramallah anticline is not the boundary of the WAB on its entire length. At the area around Kobar the boundary splits off the anticline and continues towards S and later SSE directions. It follows on the western outskirts of Jerusalem and then bends back towards SSW until it joins Hebron anticline, approximately at the area of the eastern edge of the section (Al-Khadr area).
- An intermediate zone of regionally high water levels stretches between this boundary and the southern end of Ramallah anticline towards the south.
- This intermediate zone drains towards SW and then joins the Western Aquifer Basin. The cross section documents the flow connection in the lower aquifer, approximately perpendicular to the direction of the section.
- By this, it can be stated that the intermediate zone is part, or a sub-basin of the Western Aquifer Basin. The boundary between the WAB and the EAB in its area of distribution is a groundwater divide.
- The groundwater divide shifts its position according to stresses like differential rain recharge, well and spring discharge, return flows etc.
- A range of maximum assumed distribution was delineated to describe the area of the divide.
- The western limit of this range is the line of "subsurface watershed", delineated by ANTEA (1998). Its Eastern limit is the "groundwater divide" as defined by Rofe & Raffety (1961-63). The zone enclosed is approximately 2 km wide.
- In a later stage of the project it may be possible to further assess the position of this divide with the help of the numerical model. For the time being, this range is considered the boundary area between WAB and EAB.

2.3.2 South of Betlehem

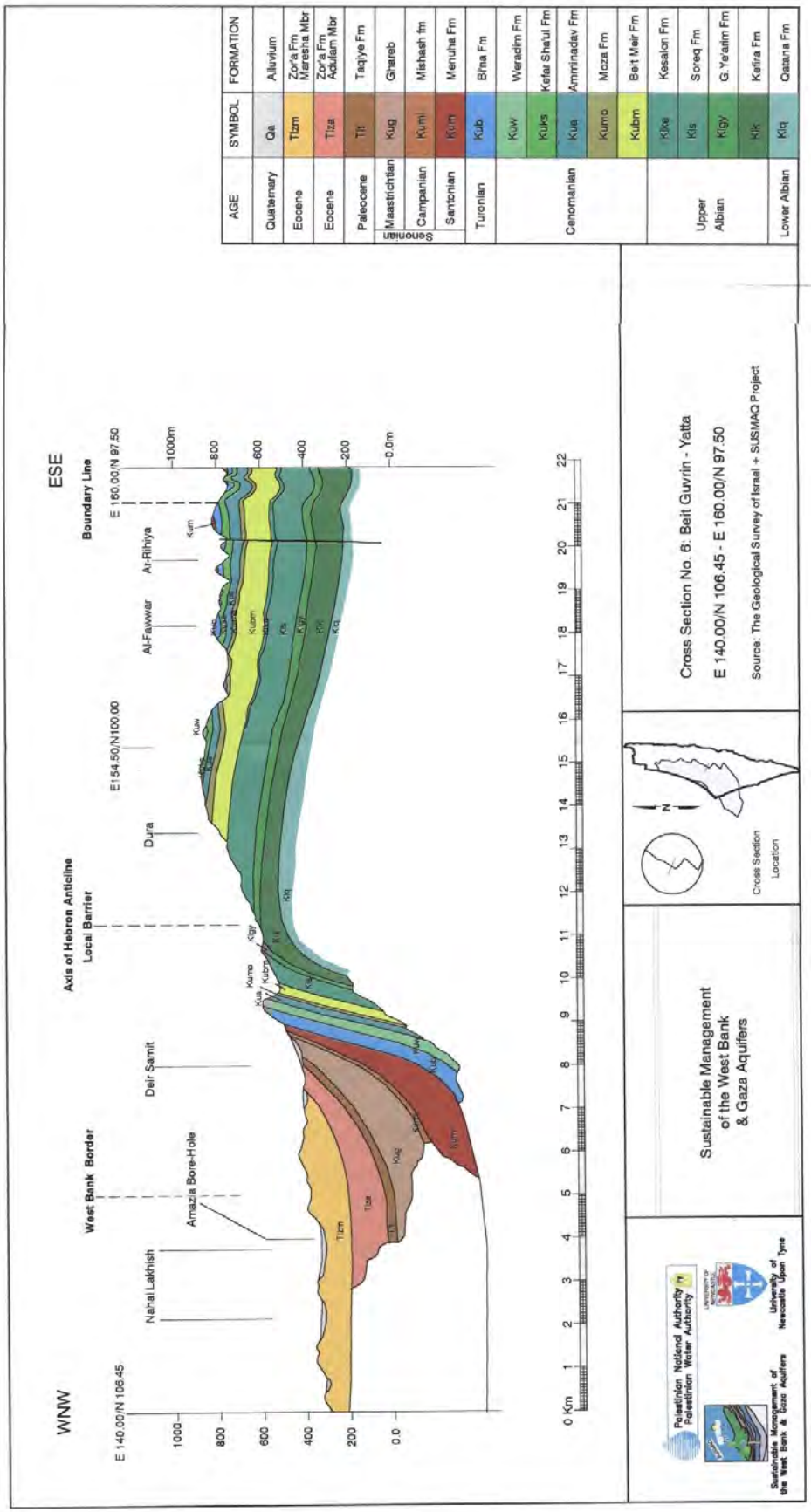
South of Betlehem, the boundary follows again the main anticline (Hebron anticline) as a structural barrier. From around PGN 105 southward, the anticline proceeds in SSW direction, but the divide splits off and continues as a groundwater divide to SSE direction towards the Horvat Karmel dome (163/92) and then till the Harei 'Anim Anticline (162/97). From here it bends towards SW and follows this anticlinal structure – again as a geo-structural divide - (via 156/80) until it leaves the West Bank (150/70) towards the northernmost Negev.

2.3.2.1 Cross-section No. 6: Beit Guvrin – Yatta

This section stretches from E 140 / N 106.45 at the Coastal plain to E 160 / N 97.5 at the West Bank Mountains (about 2 km North of Yatta).

The Lower Aquifer is more than 250 m thick and the Upper aquifer reaches a thickness of more than 200 m. The entire Judea group reaches a thickness of up to 500 m. At the coastal plain, the top of the Judea group aquifer is buried more than 400 m deep below sea level. In the foothills of the West Bank, short after passing the Green Line, the formations undergo a steep rise in elevation. Further inside the West Bank, the top Bi'na reference level is lifted to elevations of more than 900 m asl. However, in most of the area near the axis of the anticline, the top of Bi'na (Jerusalem) formation is eroded. The axis of the southern part of Hebron anticline passes the cross section near PGE 150. However, this axis does not form the boundary between WAB and EAB. Instead, the boundary is found at about PGE 159.25 as a groundwater divide. The area between the axis and the ground water divide is a sub-basin of the WAB with groundwater flow directions to the south and southwest and subsequently turning into Western directions. The situation is **analogue to the one found near Jerusalem**. The boundary of the WAB branches off the anticlinal axis at the north of the cross section and from there on only divides the main basin and the sub-basin of the WAB.

The split of the boundaries that opens an area between the structural divide along the Hebron anticline and the groundwater divide in the East creates a sub-basin with relatively high water levels. On the anticline itself, the upper aquifer is eroded in a strip of 4-8 km width. In the sub-basin, mainly the Upper Cenomanian and Turonian crops out. Shallow wells like Al-Fawwar and Ar-Rihiya tap the water level of the upper aquifer at elevations about 670-710 m asl. This water level in the upper aquifer of the sub-basin lies clearly above the regional groundwater level in the main part of the Western Aquifer Basin. Within the sub-basin, the Lower aquifer remains unused. Only some local reservoirs of perched groundwater have been tapped in the Lower Yatta and uppermost UBK formations. The water level was found very high at about 900 m asl. (only 3-4 m bgl.). However, this perched groundwater should not be considered to indicate regional water tables of the lower aquifer itself. The regional water table of the Lower aquifer can only be estimated at around 400 m asl. The top of Beit Kahil formations (Top Kesalon) lies in altitudes between 500 m and 700 m asl. and the bottom of the Lower Aquifer (bottom LBK or bottom Kefira) lies between 200 m and 500 m asl.


WNW
ESE
West Bank Border
Boundary Line
Axis of Hebron Anticline
Local Barrier
Nahal Lakhish
Amazia Bore-Hole
Deir Samit
Dura
Al-Fawwar
Ar-Rihiya
E 140.00/N 106.45
E 154.50/N100.00
E 160.00/N 97.50
1000m
800
600
400
200
0.0m
0 Km
AGE
SYMBOL
FORMATION
Quaternary
Qa
Alluvium
Eocene
Ttzm
Zor'a Fm Maresha Mbr
Eocene
Ttza
Zor'a Fm Adullam Mbr
Paleocene
Ttt
Taqiye Fm
Maastrichtian
Kug
Gharab
Campanian
Kumi
Mishash fm
Santonian
Kum
Menuha Fm
Turonian
Kub
Bina Fm
Kuw
Weradim Fm
Kuks
Kefar Shaul Fm
Kua
Amminadav Fm
Kumo
Moza Fm
Kubm
Beit Meir Fm
Kjke
Kesalon Fm
Kjs
Soreq Fm
Kjgy
G.Yearim Fm
Kjk
Kefira Fm
Kjq
Qatana Fm
Cross Section No. 6: Beit Guvrin - Yatta
E 140.00/N 106.45 - E 160.00/N 97.50
Source : The Geological Survey of Israel + SUSMAQ Project
Cross Section Location
Sustainable Management of the West Bank & Gaza Aquifers
Palestinian National Authority
Palestinian Water Authority
University of Newcastle Upon Tyne

The southwestward plunging axis of the anticline can be identified from structural contour maps (ANTEA, 1998; GSI geological maps, Sheet 11-III, 15-I, 15-II). This thorn along the axis plunges gently towards SSW until it buries the formations deep enough to be overflown at the axis. The following table (Tab. 4) shows the thickness and respective altitudes of the top Bi'na (Jerusalem), bottom Bi'na and bottom Kefira (Lower LBK) key horizons.

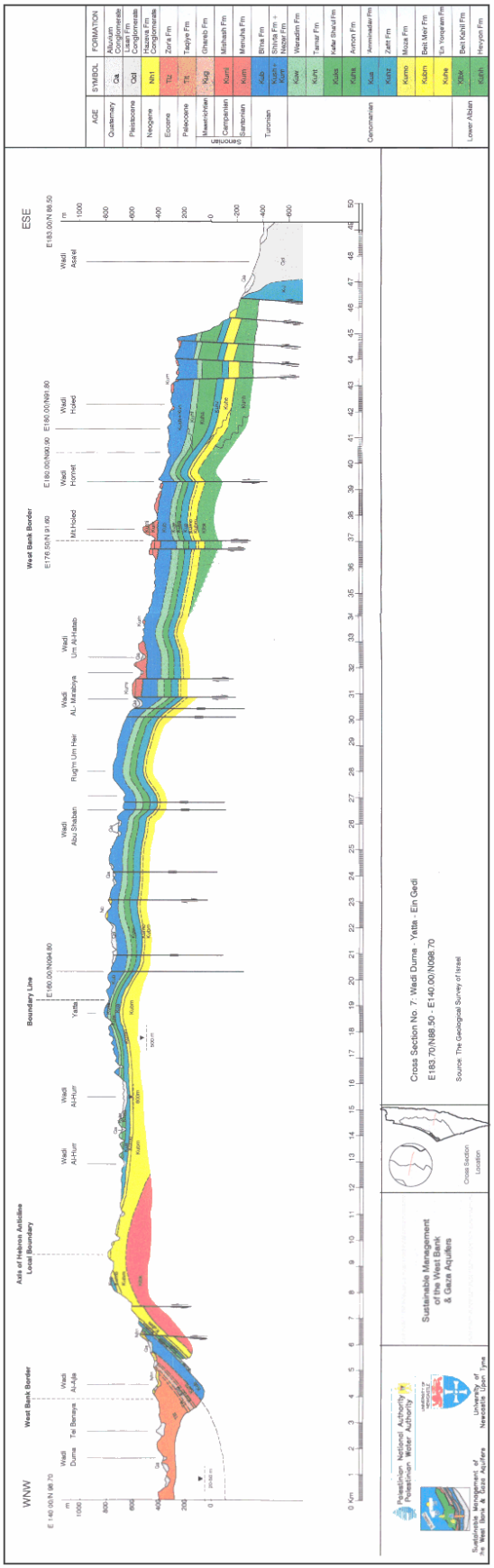
PGE/PGN	**Elevation Top Judea [m asl.]**	*Thickness Up.Aquifer+ Moza [m]*	**Elevation Base Moza [m asl.**	*Total thickness of Judea group [m]*	**Elevation Bottom LBK [m asl.]**
150/100	**1080**	*260*	**820**	*570*	**500**
150/98.2	**1000**	*230*	**770**	*600*	**400**
149.5/96.4	**900**	*200*	**700**	*650*	**250**
149.5/95	**800**	*200*	**600**	*700*	**100**
149.5/91	**700**	*200*	**500**	*700*	**± 0**

At PGE ~150; data based on structural contour maps, sheets 11-III, 15-I

Tab.4: Thickness and elevation data of Judea group formations – Southern Hebron anticline

The anticlinal axis plunges NNE-SSW, at approximately PGE 150. From the above can be concluded roughly that south of PGN 98.2 the Lower aquifer is partly to fully saturated and groundwater flow over the anticlinal axis is enabled. The Upper aquifer is partially saturated south of PGN 95, where its bottom is less than 500 m asl. However, these conclusions are based on estimated water levels and require further confirmation.

On the other hand, the groundwater divide is not a fixed location but shifts according to the stresses of addition and subtraction of groundwater in the aquifers. Both, the buried Lower aquifer and the exposed upper aquifer are partially saturated. Its approximate position was also based on structural criteria, as the data on water levels in this area are very scarce.



Section 7: Wadi Duma – Yatta – Ein Gedi

2.3.2.2 Cross-section No.7: Wadi Duma – Yatta – Ein Gedi

This cross section starts at the foothill region near Wadi Duma (at PGE 140 / PGN 98.7). The cross section crosses the western border of the West Bank at E 143.7 / N 97.85. It then passes Yatta in the north, leaves the West Bank at E 176.5 / N 91.6 and ends at the Dead Sea (E 183.7 / N 88.5).

As this cross section is compiled from cross sections of separated sheets, the section is deflected between the coordinates E 180 / N 90.9 and E 180 / N 91.8.

The cross section crosses the entire West Bank anticline and the lithofacies' of the respective formations undergo several changes on its way from W to East.

The easternmost part of the section (near the Dead Sea) generally is believed to display a lithofacies rather typical for more southern locations, such as in the Negev.

Most noticeable is the facies change within Yatta. While in the West, Yatta is composed of an upper thin marly Moza and a lower thick limy, dolomitic and somewhat chalky Beit Meir unit, in Ein Gedi in the East it is undivided and referred to as Ein Yorqe'am formation. This eastern (or southern) facies representative contains green, extremely hard clay, somewhat sandy at times.

Also Beit Kahil undergoes a change, mainly in thickness but also slightly lithofacies-wise. In the West it is subdivided into Kefira and Giv'at Ye'arim (UBK) and Soreq and Kesalon formations (LBK). In the East, it stands undivided as Hevy on formation, characterized by a strong content of clay layers, interbedded rhythmically with dolomite beds.

The Eastern equivalent of 'Amminadav (Hebron) is Zafit. Betlehem formation is divided into an upper unit Weradim and a lower unit Kefar Sha'ul in the West, while it is divided into Avnon and Tamar in the East. Especially the lower unit (Kefar Sha'ul → Avnon) thickens from 10-90 m in the West to 90-165 m in the East and becomes chalkier and less limy towards the East.

However, in order to give a comprehensive overview, the formations were unified as much as possible according to the *new compiled stratigraphic system* by SUSMAQ project.

With respect to the boundaries of the WAB, the cross section shows the situation as follows: Similar to the area further North, the formations rise steeply (though not as steep as further north) in Western part of the West Bank anticline. As before (section 6), the axis of Hebron anticline builds a local boundary between a sub-basin and the main WAB only. The axis is indicated in the cross section. Here the top of the lower aquifer clearly exceeds an elevation of 600 m asl. This is the highest recorded groundwater level. This aquifer is therefore only partially saturated.

The groundwater divide that separates the EAB hydraulically from the WAB is located further East, at E 158.75 / N 95.05. Here, only the lowermost unit of the Upper aquifer (Hebron or 'Amminadav formation) surpasses the 600m-elevation. As in the area of

section 6, the groundwater between the anticlinal axis and the groundwater divide drains to the south, southwest and then joins the main WAB.

As in other places of the West Bank, the area surrounding the anticlinal axis is the most important zone of direct rain infiltration recharge.
At the Western edge of the cross section, a groundwater level of 20 -50 m asl. is documented which indicates a complete and confined saturation of both the Upper and the Lower aquifers.

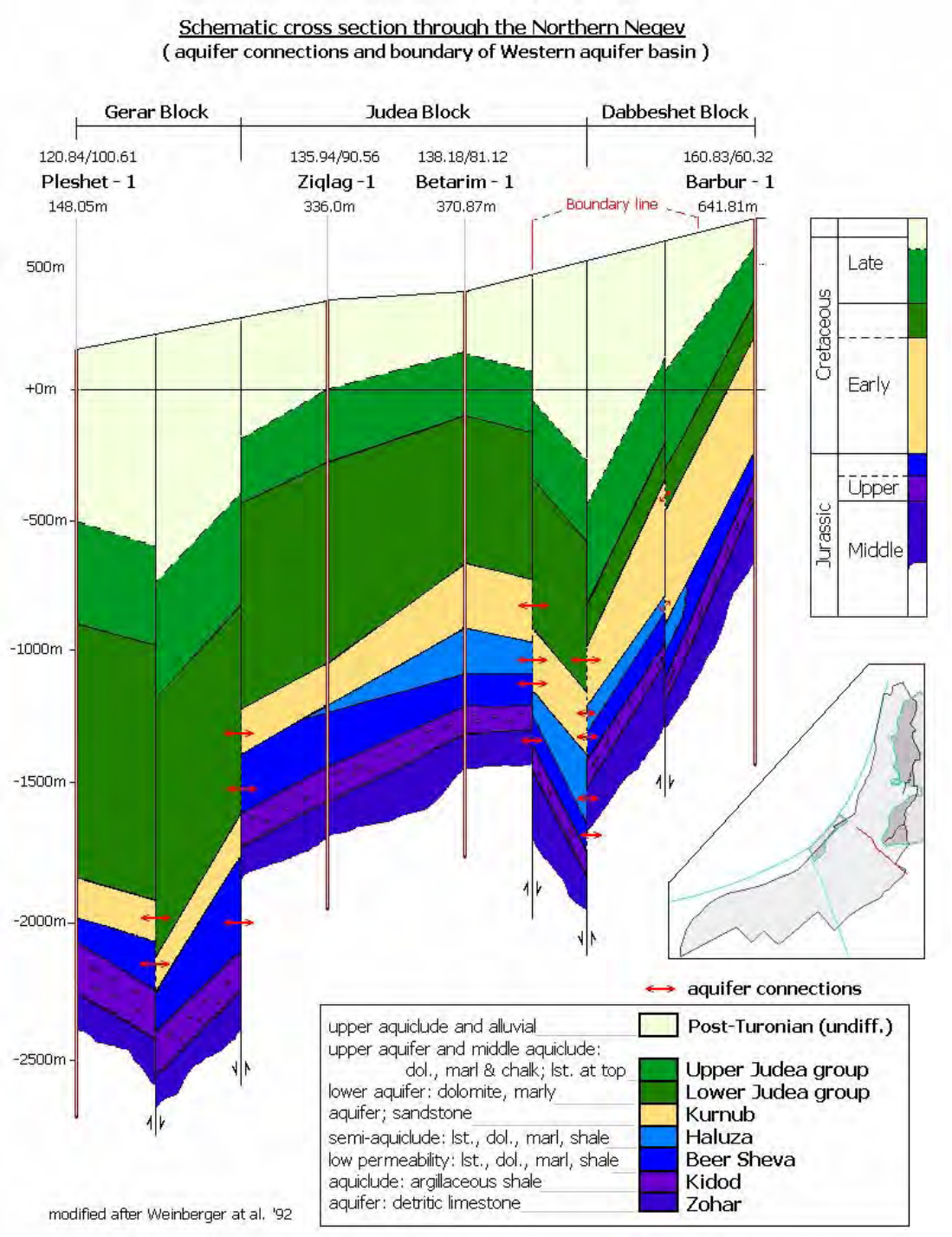
2.4 The Southeastern boundary: Negev

Towards the south, the climate undergoes a sudden and marked change: Sub-arid to fully arid climate prevails in the Northern and Central Negev. The aquifer formations do crop out, but due to the scarce rainfall, recharge from this area plays only an insignificant role, if compared to the West Bank. A set of domes and anticlines alternates with undisturbed bedding and synclines. The usual trend is of the Syrian Arc directions – NE-SW and ENE-WSW.

Again, strong faults characterize the area. But they lead to a special feature, not found further north (or to much less extent): The Lower Cretaceous aquiclude beneath the Lower aquifer is much thinner than in the North. This is a consequence of the gradual Cretaceous transgression over this fossil continental margin. During Aptian and Albian times, the sea transgressed gradually from N and NW over the southern continent. It led to thick shale and clay deposits in the North, while continental and proximate sedimentation continued in the south. As a result, the aquiclude is more than 400 m thick at the central West Bank (Kobar group) and north of that. In the Negev, only a thin aquiclude separates the Kurnub group from the Lower aquifer (marly limestone in Lower Hevyon member of Hatira formation, equivalent to bottom Lower Beit Kahil formation in the West Bank) and sometimes, even this bottom of the aquifer is not completely aquicludal. Therefore, upward leakage from the Kurnub aquifer is possible at times. More often, and more important, the hydraulic connections between the aquifers are realized by strong deep-throwing faults in the Negev. Since the Lower Cretaceous is thin, at times, even a direct lateral connection between the Lower aquifer and Jurassic (!) formations is found in the subcrops. The deep aquifers (Kurnub and Jurassic) contain brackish water. Due to this, the lower aquifer gets "salty feet" when hydraulically connected. In the Beer Sheva area, over-pumping of the aquifer is responsible for a marked increase of Cl-levels in the past decades.

The boundary of the aquifers is defined by the anticlines that expose the Upper aquifer and partly the Lower aquifer. (At two domes with differential erosion – *makhteshim*, also Kurnub and Jurassic crops out.) The Negev rises from sea level to heights of more than 600 m asl. (Mt. Raham a, Revivim-Oron section). Because of this, the saturated thickness is found very reduced in the Northeastern Negev, (the Upper aquifer is even dry at times) and a hydraulic boundary is found here.

In the area between the West Bank and the northern Negev, the boundary follows structural highs (anticlines). At 150/70 it turns to SE till 159/65. From this point on it follows constantly SW directions (159/065, 157/060, 149/053, 144/048, 140/046, 138.25/042, 136/040, 124.3/034.5, 112.75/026.8, 110/25) until it passes to the Sinai.


Schematic cross section through the Northern Negev
(aquifer connections and boundary of Western aquifer basin)
Gerar Block
Judea Block
Dabbeshet Block
120.84/100.61
Pleshet - 1
148.05m
135.94/90.56
Ziqlag -1
336.0m
138.18/81.12
Betarim - 1
370.87m
160.83/60.32
Barbur - 1
641.81m
Boundary line
500m
+0m
-500m
-1000m
-1500m
-2000m
-2500m
Cretaceous
Late
Early
Jurassic
Upper
Middle
aquifer connections
upper aquiclude and alluvial
upper aquifer and middle aquiclude:
dol., marl & chalk; lst. at top
lower aquifer: dolomite, marly
aquifer; sandstone
semi-aquiclude: lst., dol., marl, shale
low permeability: lst., dol., marl, shale
aquiclude: argillaceous shale
aquifer: detritic limestone
Post-Turonian (undiff.)
Upper Judea group
Lower Judea group
Kurnub
Haluza
Beer Sheva
Kidod
Zohar
modified after Weinberger at al. '92

2.4.1 Cross-section No.8: Northern Negev

This cross section starts in the West, halfway between Gaza and the West Bank (E120/N100), passes the southwestern tip of the West Bank and bends slightly towards the south until it reaches the area between 'Arad and Dimona in the Northern Negev (E160/N60).

The cross section is taken from Weinberger, Rosenthal and Flexer (1992). Their study improved the understanding of the aquifer connections and interactions in this area. Multistage strong faulting, partial uplift, tilting and down-throw along the faults juxtaposes Kurnub and Judea group, Arad and Kurnub group and at places even Arad and Judea group (Northwest of oil well Ziqlag-1, at E 130 / N 94).

The thickness and throw of formations is based on extensive geophysical survey data. An abrupt and dramatic thinning of Judea thickness takes place between Betarim and Barbur wells (E155 / N 72). In the West, Judea has a thickness of almost 1000 m, while in the East it reaches merely 100 m, one tenth of the western thickness. Accordingly, the Post-Turonian formations (QT-S) thicken strongly east of the above fault.

Also the other formations show great thickness variations, albeit not as strong as the former.

The whole Negev is a system of SW-NE trending blocks, separated by faults. From NW to SE these blocks are Gerar block, Judea block, Dabbeshet block and Negev Highlands.

In the cross section, the blocks appear as horsts and grabens. However, this appearance is a misperception; the sections were constructed by connecting known formations at several wells by straight lines and with an exaggerated vertical scale. In reality, a mix of germanotype (faulting) and alpinotype (folding) tectonics can be found here.

It appears clearly from the cross section, that the Judea block is uplifted, relatively to its neighbouring blocks (Gerar and Dabbeshet). This indicates the continuation of the West Bank anticlinal system with ongoing Syrian Arc directions in the Negev. However, the uplift is less pronounced than in the central West Bank. More specifically, the crest of the Judea block coincides with the (plunging) continuation of the Hebron anticline. At Betarim-1 well, top Judea lies at –150 m below sea level. 10 km NNE of the well, the top of Judea is at 700 m asl. (E141/N90).

The maximum uplift of the Judea block is 1000 m relative to the Gerar block and 700 m relative to the Dabbeshet block respectively.

Since the Judea group formations are quite thick (at least in the West) and Lower Cretaceous Kurnub group formations are very thin (unlike in the central West Bank), the faults juxtapose aquifers of different stockwerks repeatedly.

A sound understanding of the aquifer connections is of great importance as these connections hold responsible for saline inflow into the Judea group aquifers from lower

formations. It will also play an important role when water levels will be modelled and calibrated at a later stage.

As for the boundary, the cross section has to be compared with the map to avoid misperceptions. At the fault between Judea and Dabbeshet block, the boundary merely touches the cross section. It does not pass and continue to the south, but flexes to the southeast, away from the section. It then passes the cross section at the eastern edge, near Barbur-1 oil well. It was already mentioned that the cross section is somewhat schematic. Therefore it indicates a continuous rise towards Barbur-1 borehole in the SE. Unlike the geological map (Sheet 19-I, Dimona; scale 1:50.000) the cross section does not show the exact position of the anticline and its axis, which crosses the section at the coordinates E 158 / N 62.75.

The boundary is a geo-structural boundary and the aquifer is assumed to be dry. As will be shown in the next section, Lower aquifer formations of the Judea group are eroded and crop out dry as high as 600 m asl. (SE edge of the "Big crater" – *Makhtesh Ha-Gadol*[3] (E 148 / N 35)).

2.4.2 Cross-section No.9: Central Negev – Revivim and Oron

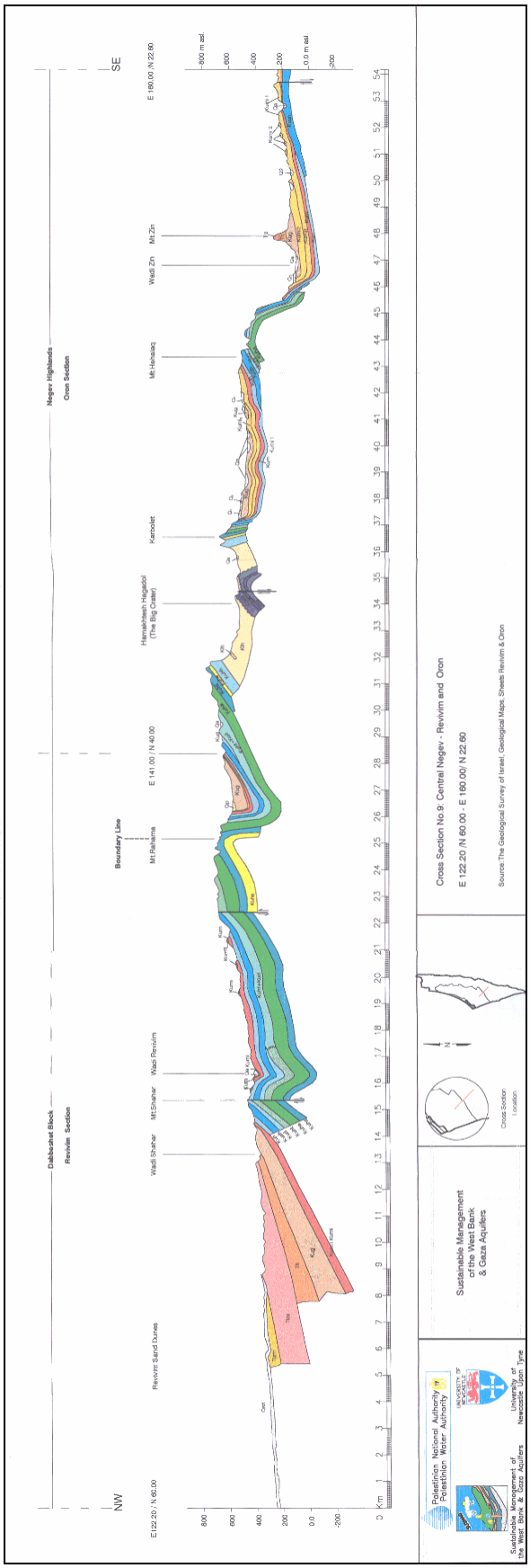
This cross section stretches from the Dabbeshet Block in the NW through the Negev Highlands in the SE. The cross sections were taken from two separate sheets of the GSI maps scale 1:50.000. In the final version of this report the stratigraphy that is now on two separate sheets, will be integrated into one new system.

The Dabbeshet Block raises both, topographically and structurally towards the SE. As a general trend, thickness diminishes from West to East, which contributes to the upcoming of the lower formations. This rise and uplift continues in the Negev highlands and reaches its maximum at the big crater where Lower Cretaceous and even uppermost Jurassic formations crop out at approximately 500 m asl.

The boundary is a geo-structural boundary. It is located at the axis of the anticline at Mt. Rahama. The Upper aquifer lies here between 500 m asl. (bottom Hebron, Zafit) and 860 m asl. (eroded Top Nezer, Upper Jerusalem).

Water levels are low and even the Lower aquifer can be considered dry at the WAB boundary. The area east of this boundary rises even higher structurally and brings Jurassic formations to the surface at the eroded domes of "the big crater" (Makhtesh Ha-Gadol). Consequently, the structurally high zone between Mt. Rahama and Mt. Hehalaq can be considered a dry zone between the Western and the Eastern Aquifer Basins.

[3] Makhtesh means mortar pot, as for grinding coffee, i.e. This name was assigned due to its crater-like morphology. Structurally, however, the Makhteshim, are neither craters nor synclines, but domes that have been eroded differentially due to the heterogeneous hardness of the up-domed formations.



Section 9: Revivim - Oron

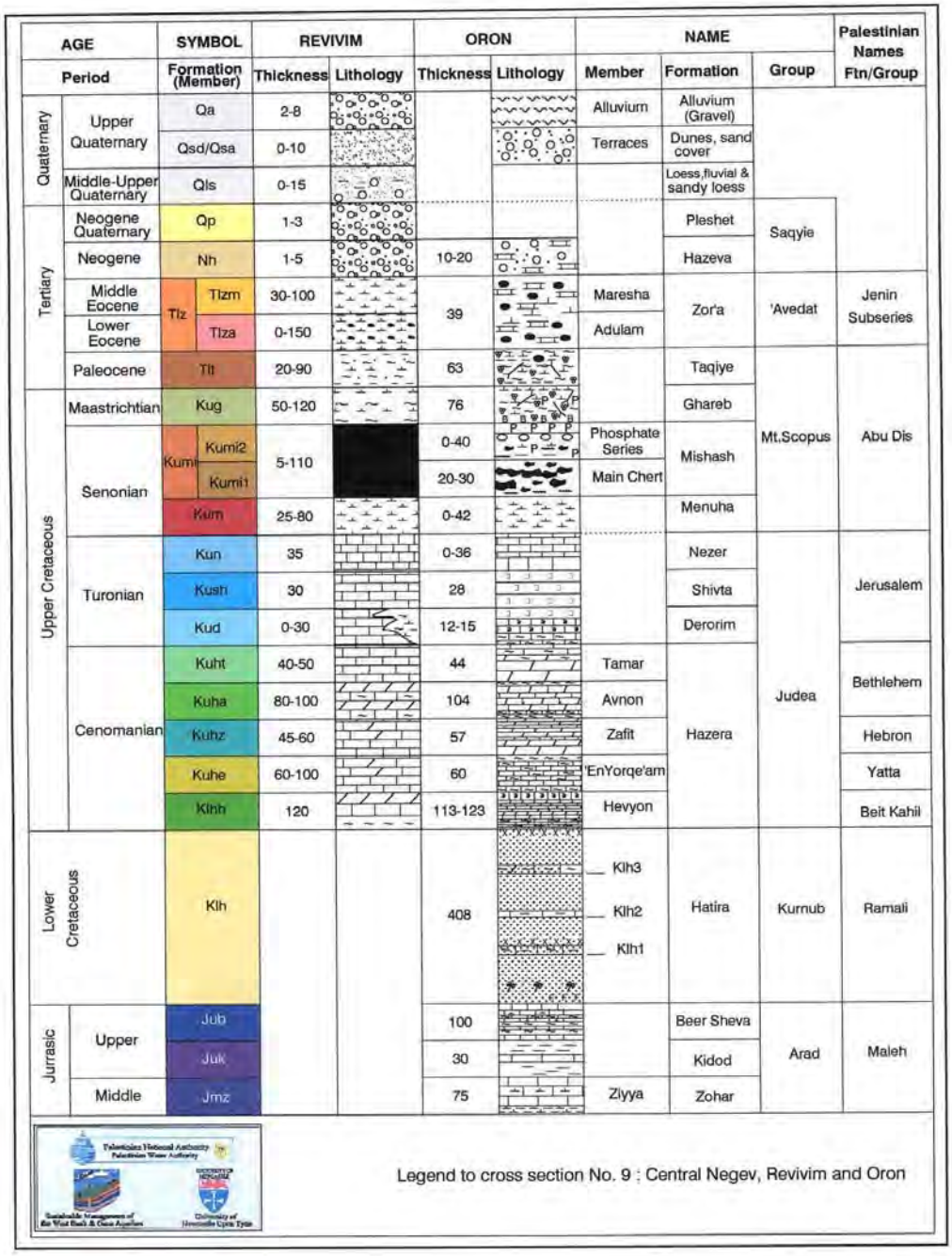


Figure 12,13: Stratigraphy to Section No. 9, Oron and Revivim sheets

2.5 The Southern basin boundary: Sinai

The large areas of the Sinai are basically a desert in climate and vegetation and the aquifer is covered for most parts by impermeable rocks of Eocene and post-Eocene age. Recharge is therefore negligible. An absence of marked anticlines and faults does not allow a clearly defined subsurface boundary. Instead, the groundwater flow diminishes gradually and finally reaches a stage where practically no-flow takes place. This boundary can be described as something like a dead zone. It will be modelled as a no-flow hydraulic boundary. According to the system of (ANDERSON/WOESSNER, 1992, pg. 102) it can be modelled and referred to as a **Distant** Boundary

2.6 The Southern model boundary: The Afiq-Channel

A Neogene erosion channel stretches NW-SE from N-Gaza to Beer Sheva. The channel cuts into the older formations and is filled with impermeable (clayey to marly) clastics. In the area near the coast, the bottom of Afiq channel is about 1100 m deep below ground surface. According to GVIRTZMAN (1968) it is here filled with about

- 175 m of calcareous marl – Early Miocene Ziqim formation
- 250-400 m of volcanics and evaporites – Middle Miocene Mavqi'im formation
- 175-700 m of calcareous shale & clay – Late Miocene to Lower Pleistocene Yafo formation.

And it is incised into all formations starting from Mid Eocene (chalky Maresha member of Zor'a formation) and as deep as the uppermost part of the Lower Cretaceous, which is here approximately the contact between the lower part of Kefira formations (Lowermost Lower Beit Kahil) and the upper part of Qatana formation (upper most Kobar group).

The subdivision of the Judea group in this area is different than that of the West Bank, according to GVIRTZMAN (1968).

a) An unnamed bottom unit of undifferentiated Dolomite
b) The Negba formation, here as a chalk and marl member
c) Turonian (and upper most Cenomanian) Daliya member as a chalk and calcareous clay unit

The Judea group is between 800 and 1000 m thick. The bottom Dolomite is 400-700m, Negba 400 m and Daliya only 100 m thick.

The Afiq channel truncates the aquifer over a short distance only. It starts in the SE part of Gaza city. Here the channel is incised into Talme Yafe group clays that are

considered an aquiclude. The contact between Talme Yafe and the eroded Judea group in the channel is at the coordinates PGE102/PGN99.5. From here until PGE104/PGN92 the aquifer is fully truncated (eroded) and filled with impermeable Neogene and Quaternary alluvial (Fig. 14). The impermeable clastics overlie Lower Cretaceous sediments that are part of the aquiclude below Judea group. Therefore it is an effective barrier that stops groundwater flow towards the South and Southwest. This barrier zone stretches for about 7.5 km towards SSE. Beyond PGE104/PGN92, the channel continues with partial truncation of the aquiferous bottom Dolomite of Judea group over a length of about 3 km till the coordinates PGE105/PGN89.1. In this area, groundwater flow is reduced but not fully impeded.

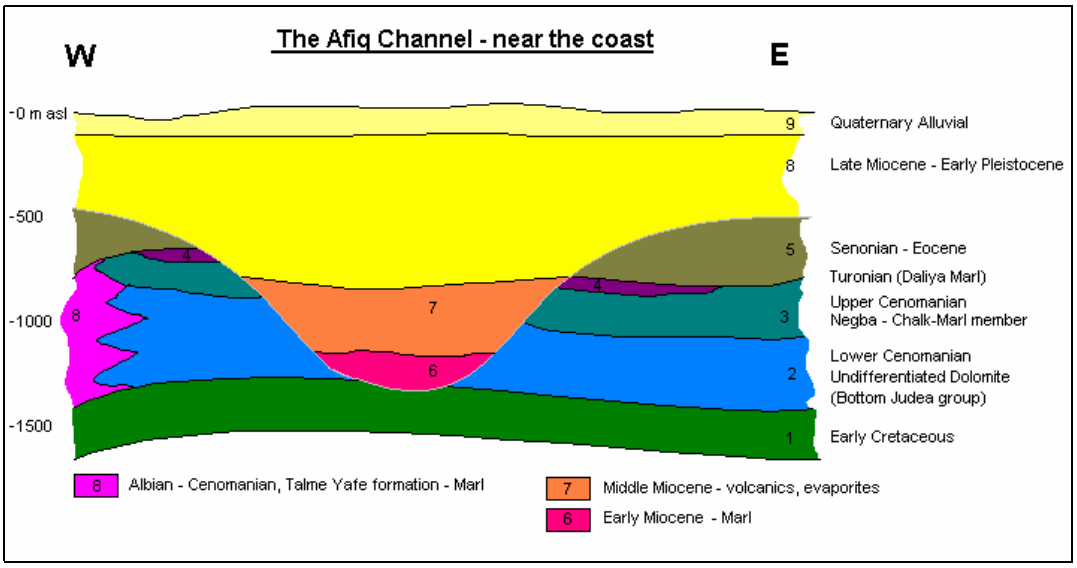


Figure 14: Schematic section through the Afiq channel near Gaza

The channel continues towards ESE to Beer Sheva (PGE130/PGN72), although its erosional bottom does not reach Judea group anymore. Only for the last 10 km before Beer Sheva, Judea group again is partially eroded, but it can be assumed that this erosion only truncates the upper non-aquiferous part and thus does not affect groundwater movement.

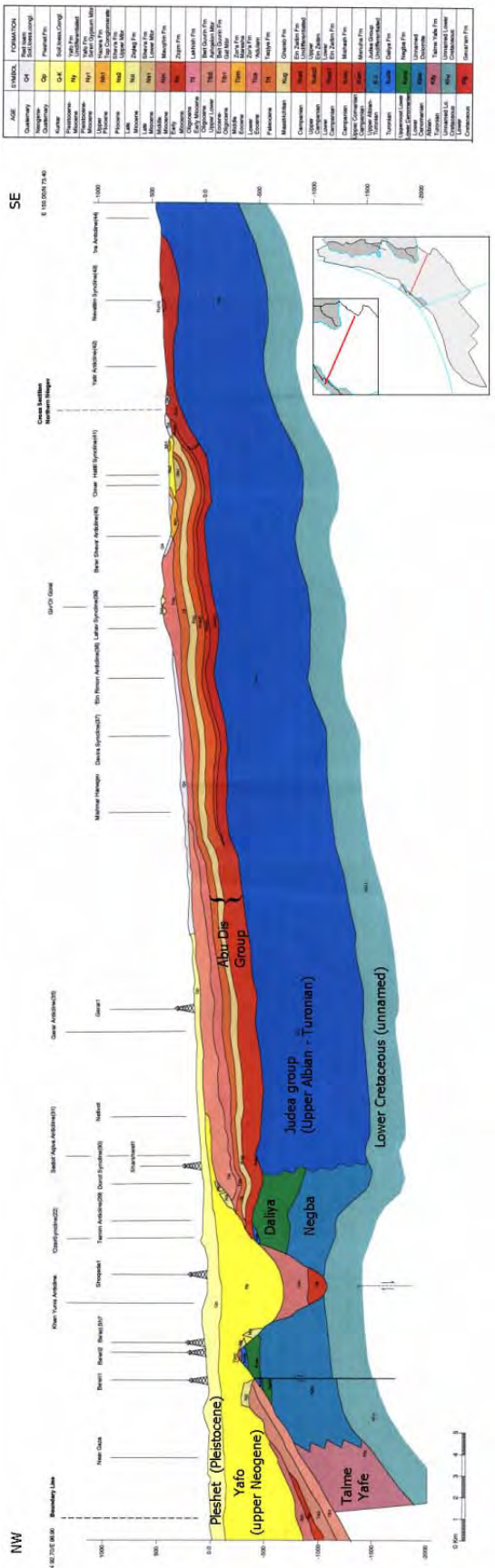
From the above follows that only a reduced portion of the Judea group aquifer has been incised and is disrupted in its hydraulic connection towards the Sinai in the South.

- Near the coast, the impervious channel fill of the Afiq erosion channel effectively blocks the flow over a length of 7.5 km.
- As the channel extends southeast another 3 km land-inwards towards Beer Sheva, it becomes less and less deeply incised (immature river channel) until it finally ceases to exist and the Judea group aquifers remain undisturbed.
- However, it is important to note that, towards the East, the hydraulic properties decrease in flow, potential, saturated thickness, recharge, conductivity and the like. Therefore, the undisturbed area, East and SE of Beer Sheva does not contribute significantly to the hydraulic activity of the Western Aquifer basin.

It can be summarized that the Afiq channel acts as a barrier to the flow in southern directions only over a distance of 10.5 km. The areas south of the channel are almost completely un-utilized and no recharge takes place there. These areas will be modelled with decreasing permeabilities as a dark background corner of the basin.

The Afiq channel is a no-flow boundary in parts, where it is completely incised into the upper and lower aquifers. It is a flow-boundary, where it is partly or not at all incised into these formations and will be modelled as a specified flow boundary.

Effectively and practically, the Afiq-Channel will be considered the southern margin of the model area.



Section 10: Afiq-Channel

2.6.1 Cross section No. 10: Afiq channel

This cross section shows the situation in the southern Coastal Plain and Northern Negev. It extends from the southeastern part of Gaza (city) in the WNW to the area E of Be'er Sheva' in the ESE. The cross section is based on the works of Gvirtzman (1968).

In most parts of the section, the Judea group is generalized and undifferentiated. Only in the environs of the Afiq channel, it is divided into its Turonian part (Daliya formation, equivalent to Jerusalem and Bi'na in the North), its Cenomanian units (Negba formation, equivalent to Yatta, Hebron and Betlehem formations in the West Bank) and a lower unit of "Unnamed Dolomite" (equivalent to Beit Kahil formations in the West Bank and to Hevyon members in the Negev).

It should be reminded on the fact, that the lower part of Judea group is diachronous from Northwest to Southeast. Marine sedimentation started already in the Aptian in the North, while this transgression was not fully established before the Lower Cenomanian in the South. This is why the (chronostratigraphical) ages of the Unnamed Dolomite is not identical to that of its northern equivalents (Beit Kahil etc.).

Petrographically, the aquifer is mainly formed by the Dolomite, while the upper parts are of more aquicludal lithologies like chalk, marl and calcareous clay.

Contrast to the Judea group, the younger formations are differentiated quite specifically: Mt.Scopus, 'Avedat and Saqiye groups overlie Judea. They dip generally towards the west and therefore crop out subsequently towards the east. The Quaternary alluvial (Kurkar and Pleshet) thickens towards the coast.

Most importantly the cross section shows the truncation of the Afiq channel near the Gaza strip. The channel is of Post-Eocene age and it is filled with Neogene clastic and evaporitic sediments. The Middle Eocene Mavqi'im formation can also be represented by volcanics. In the area of the cross section the channel intersects the entire Judea group to a depth of bout 1200 m below sea level. Since its filling is hydrologically impermeable, it builds a barrier for the groundwater flow that is directed SSW. As already mentioned above, the channel acts as a barrier over a length of about 10.5km. Further SE, its erosional cut into the Judea group is incomplete and allows groundwater flow towards the Sinai.

Another important feature shown in the section is the facies change of Judea group in the westernmost part of the section. All along the present coastline, Talme Yafe group with its impermeable marl and clay replaces the carbonatic platform sediments of Judea group. By this, it builds a powerful barrier that inhibits groundwater flow towards the sea and leads to a backwater rise and confinement of the groundwater levels in the coastal plain.

2.7 The Western boundary: The Talme Yafe barrier

The Western boundary of the WAB stretches approximately along the coastal plain, somewhat land-inward from the recent coastline. It is also referred to as a hinge line. The Upper Cretaceous carbonates of a stable platform were bordering the continental margin during deposition. West of this line, deep-sea clays and other impermeable sediments were sedimented over a long period. They are referred to as the undifferentiated Talme Yafe group. This formation creates a strong contrast in facies. It is impermeable and thus an aquiclude. It is modelled as a no-flow boundary.

However, the facies change is not an exact line (and this "line" dips towards the west in addition). It is therefore not a line on the map, but rather a strip of some 100 m to a few kilometres width.

The facies barrier of the Talme Yafe group is responsible for the formerly very strong springs in the coastal plain – Ras El-Ein and Timsah/Taninim springs. The springs created swamps and even a river in the past. The swamps have been drained and the river (Yarkon or Al-Auja) diminished to a fraction of its former flow.

As a summary of the above, the boundary is a **barrier** and shall be modelled as a **no-flow boundary.**

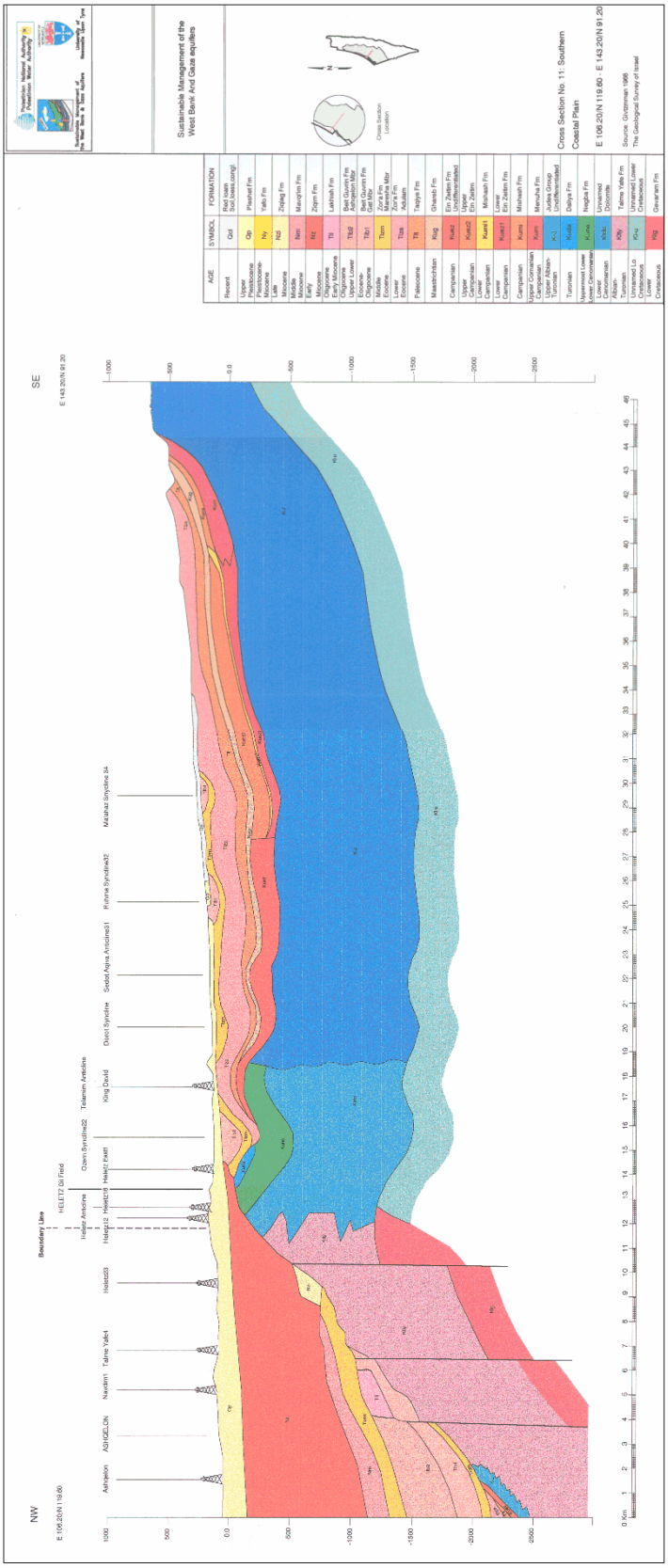
2.7.1 Cross section No. 11: Southern Coastal Plain

This cross section lies almost parallel to the Afiq channel section. It reaches from the coast near Ashqelon (NW) to the foothill area of the West Bank Mountains near Dhahariya (SE). It is based on Gvirtzman (1968).

Again, Judea group is largely undifferentiated, while the Senonian, Tertiary and Quaternary formations are subdivided meticulously. At the eastern margin of the cross section, the steep western flank of West Bank anticlinorium (Hebron anticline) is visible.

The truncation and replacement of the Judea group by the Talme Yafe group is obvious in the area of the Heletz oil field. Near the contact between Judea and Talme Yafe, the aquifer of the Unnamed Dolomite is not overlain by Upper Cenomanian or Senonian formations. Here, an erosional gap extends till the Early Miocene Ziqim formation. However, since the Ziqim formation is of marly facies, it acts equivalent to the Talme Yafe group: As a barrier to the groundwater flow within the Judea group aquifers.

It shall be emphasized, that the hinge line, the facies change between Judea and Talme Yafe is not a vertical contact, but rather an interfingering zone of gradual lithological change. When mapped in a detailed scale, it creates a strip along the coast, rather than a sharp and distinct line. It can also be seen from the section, that the hinge line does not always match with the actual coastline. Therefore, the exact position of this barrier was mapped according to the structural contour maps by Gelbermann (1993).



Section 11: Southern Coastal Plain

2.8 Summary table of coordinates of the Western Aquifer Basin boundary

The following table summarizes the coordinates of the Western Aquifer boundary line from North to South. Where the boundary splits to form sub-basins (as under 4. and 6.), two columns of coordinates represent the respective limits of the sub-basin.

1. Mt. Carmel
141.0/217.5
143.8/217.5
144.2/215.5
145.2/215.7
145.7/216
147/218
147.7/220
147.9/222
148/223.2
150/224.5
157/227
157.5/224
160.5/220
162.2/216
163/214
165/212

2. NE-West Bank
168/210
168/205
167/200
163/191
167.5/185
165/184
164.2/180
170.1/167.45
171/162.5
170.85/159.7
168/159.9
167/159.95

4. Central West Bank	
E branch Gw-divide	W branch Structural divide
165.35 / 155.5	165.35/155.5
165.5 / 140.0	165.4/152.4
165.7 / 137.2	163.55/150.3
168.6 / 137.3	163.35/149.8
169.0 / 135.6	163.3/147
168.0 / 130.3	162.2/144.5
167.5 / 128.0	162.95/142.6
166.4 / 126.0	161.1/142.6
165.0 / 124.3	161.5/140.4
	158.7/140
	158.35/137
	158.6/135.9
	156.45/130.35

5. Hebron anticline
161.5/120
159.7/118.2
158/114
158.4/109
158.05/107
157.95/104

6. Southern West Bank	
E Branch Gw-divide	W Branch Structural divide
159/100	157/103.8
160/99	155.7/104
160/90	154.4/103
162.3/87.1	154/102.9
	153.2/103.1
	153/102.3
	149.6/97.5
	148/93
	144/92
	141/89

7. Negev
160.5/85.5
159.0/83.6
156.2/80.4
150/070
159/065
157/060
149/053
144/048
140/046
138.25/042
136/040
124.3/034.5
112.75/026.8
110/25

8. Afiq channel	
102/99.5	
104/92	Fully truncated
105/89.1	Partially truncated
130/72	Not truncated

3. Talme Yafe Barrier
157/212.8
139.7/214.5
132.3/179
132.8/168
128/148
123.8/142
124.2/140
118/130
115.2/113.3
100/103.9
97/103
98.5/100.8
91.3/91.5
91.3/90.5

Table 5: Summary table of coordinates of the Western Aquifer Basin boundary

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4.1 GEOLOGICAL MAPS

Sheet	Area	Year	Author	Publisher	Scale
1-IV	Nahariyya	1972	U. Kafri	GSI	1:50.000
2-II	Tel Odem	1987	D. Mor	GSI	1:50.000
2-III	Zefat	2001	D. Levitte	GSI	1:50.000
2-IV	Kazrin	1987	D. Mor	GSI	1:50.000
3-II	Shefar'am	1983	Y. Levy	GSI	1:50.000
3-IV (a)	Nazareth (part Tiv'on)	1983	J. Guttman	Tahal/OEI	1:50.000
4-II	Gamla	1985	H. Michelson, D. Mor	GSI	1:50.000
5-I H	adera	1996	A. Sneh et.al.	GSI	1:50.000
5-III	Netanya	1985	S. Ilani	GSI	1:50.000
5-IV N	ablus	2000	P. Cook	GSI	1:50.000
6-I, II	Bet She'an	2000	Y.H. Hatzor	GSI	1:50.000
8-I	Kefar Sava	1993	N.Hildebrand-Mittlefehldt	GSI	1:50.000
8-II	Salfit	1997	A. Sneh	GSI	1:50.000
8-III	Lod	1997	Y. Yechieli	GSI	1:50.000
8-IV	Ramallah	2000	E. Shachnai	GSI	1:50.000
9-I,II	Ma'ale Ephraim	1997	A. Sneh	GSI	1:50.000
9-III,IV	Jericho	1997	Z.B. Begin	GSI	1:50.000
11-I	Beit Shemesh	1967	Y. Arkin	GSI	1:50.000
11-II Jer	usalem	1976	Y. Arkin	GSI	1:50.000
11-III	Beit Guvrin	1983	F. Hirsch	GSI	1:50.000
11-IV H	ebron	1972	J. Kolton	GSI	1:50.000
12-I	Wadi El-Qilt	1973	I. Roth	GSI	1:50.000
12-III	Mizpe Shalem	2000	U. Mor, A. Burg	GSI	1:50.000
15-I	Eshtemoa	1977	A. Gilat	GSI	1:50.000
15-II	Har Hezron	1987	A. Gilat	GSI	1:50.000
16-I	En Gedi	1986	E. Raz	GSI	1:50.000
17-II, 18-I	Rehovot Ba-Negev, Holot 'Agur	1984	E. Zilberman	GSI	1:50.000
17-IV N	izzana	2001	E. Zilberman	GSI	1:50.000
18-II	Revivim	1984	A. Starinsky et.al.	GSI	1:50.000
19-I D	imona	1996	R. Roded	GSI	1:50.000
19-II H	a-Makhtesh Ha-Qatan	1995	F. Hirsch	GSI	1:50.000
19-III O	ron	1978	R. Roded	GSI	1:50.000
19-IV, 20-III	Neot Hakikar	1994	Y. Yechieli et.al. G	SI	1:50.000
21-III	Har Loz	2001	Y. Avni	GSI	1:50.000
25-II Y	otvata	1994	H. Ginat	GSI	1:50.000
25-III	Har Seguv	2000	A. Segev et.al.	GSI	1:50.000

Sheet	Area	Year	Author	Publisher	Scale
5	Netanya	1994	A. Sneh & M. Rosensaft	GSI	1:100.000
5, 6	Northern Samaria	1997	A. Sneh et. al.		
7, 8	Tel Aviv - Yafo	1994	A. Sneh & M. Rosensaft	GSI	1:100.000
7, 8, 9	Southern Samaria		A. Sneh et. al.		
10 A	shqelon	1994	A. Sneh & M. Rosensaft	GSI	1:100.000
14 N	irim	1994	A. Sneh & M. Rosensaft	GSI	1:100.000
17 N	izzana	1961	Y.K. Bentor & A. Vroman	GSI	1:100.000
18 A	vedat	1951	-	GSI	1:100.000
19	Arava Valley	1957	Y.K. Bentor	GSI	1:100.000
24	Yahel	1997	H. Ginat & A Sneh	GSI	1:100.000
26 Ei	lat	2000	Z. Garfunkel et.al.	GSI	1:100.000

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4.2 TOPOGRAPHIC MAPS

Sheet	Area	Year	Publisher	Scale
5-II	Umm El -Fahm	1992	Surv. Isr.	1:50.000
5-IV N	ablus	1998	Surv. Isr.	1:50.000
6-I,II	Beit She'an	1994	Surv. Isr.	1:50.000
6-III,IV	Beqa'ot	1992	Surv. Isr.	1:50.000
8-II	Salfit	1996	Surv. Isr.	1:50.000
8-III L	od	1995	Surv. Isr.	1:50.000
8-IV	Ramallah	1996	Surv. Isr.	1:50.000
9-I,II	Ma'ale Ephraim	1996	Surv. Isr.	1:50.000
9-III,IV	Jericho	1993	Surv. Isr.	1:50.000
11-I	Bet Shemesh	1995	Surv. Isr.	1:50.000
11-II	Jerusalem	1996	Surv. Isr.	1:50.000
11-III B	et Guvrin	1989	Surv. Isr.	1:50.000
11-IV	Hebron	1993	Surv. Isr.	1:50.000
12-I,II Q	aliya	1993	Surv. Isr.	1:50.000
12-III,IV	Mizpe Shalem	1991	Surv. Isr.	1:50.000
15-I Es	htemoa	1993	Surv. Isr.	1:50.000
15-II H	ar Hezron	1993	Surv. Isr.	1:50.000
16-I,II	En Gedi	1993	Surv. Isr.	1:50.000

5. Abbreviations

WAB	Western Aquifer Basin
EAB	Northeastern Aquifer Basin
NEAB	Eastern Aquifer Basin
PGN (N)	Palestinian grid - North
PGE (E)	Palestinian grid - South
WB West	Bank
asl.	Above sea level
bsl.	Below sea level
bgl.	Below ground level
gw Groundw	ater
N North	
W West	
S South	
E East	
UBK	Upper Beit Kahil
LBK	Lower Beit Kahil
SUSMAQ	The Sustainable Management of the West Bank and Gaza Aquifers
PWA	Palestinian Water Authority

Chapter 19

Western Aquifer Basin

INVENTORY OF
SHARED WATER RESOURCES IN WESTERN ASIA (ONLINE VERSION)

german cooperation
DEUTSCHE ZUSAMMENARBEIT

BGR Bundesanstalt für Geowissenschaften und Rohstoffe

ESCWA
United Nations Economic and Social Commission for Western Asia

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Western Aquifer Basin

EXECUTIVE SUMMARY

The Western Aquifer Basin is the most productive water basin in Israel and Palestine, yielding the highest-quality water in the area. The aquifer formation extends from the western slopes of the West Bank, through large parts of Israel to the north of the Sinai Peninsula. The aquifer's water resources and groundwater flow are concentrated to the north of the mostly impermeable Afiq Channel and its extention running along a line from the city of Gaza via Be'er Sheva in Israel to the southern limits of the West Bank.

Average annual abstraction over recent decades exceeds the estimated long-term average annual recharge, which means the aquifer is gradually being depleted. Israel currently controls 100% of the aquifer and abstracts 94% of its water, while Palestinians abstract only 6%. Egyptian use of the aquifer is negligible.

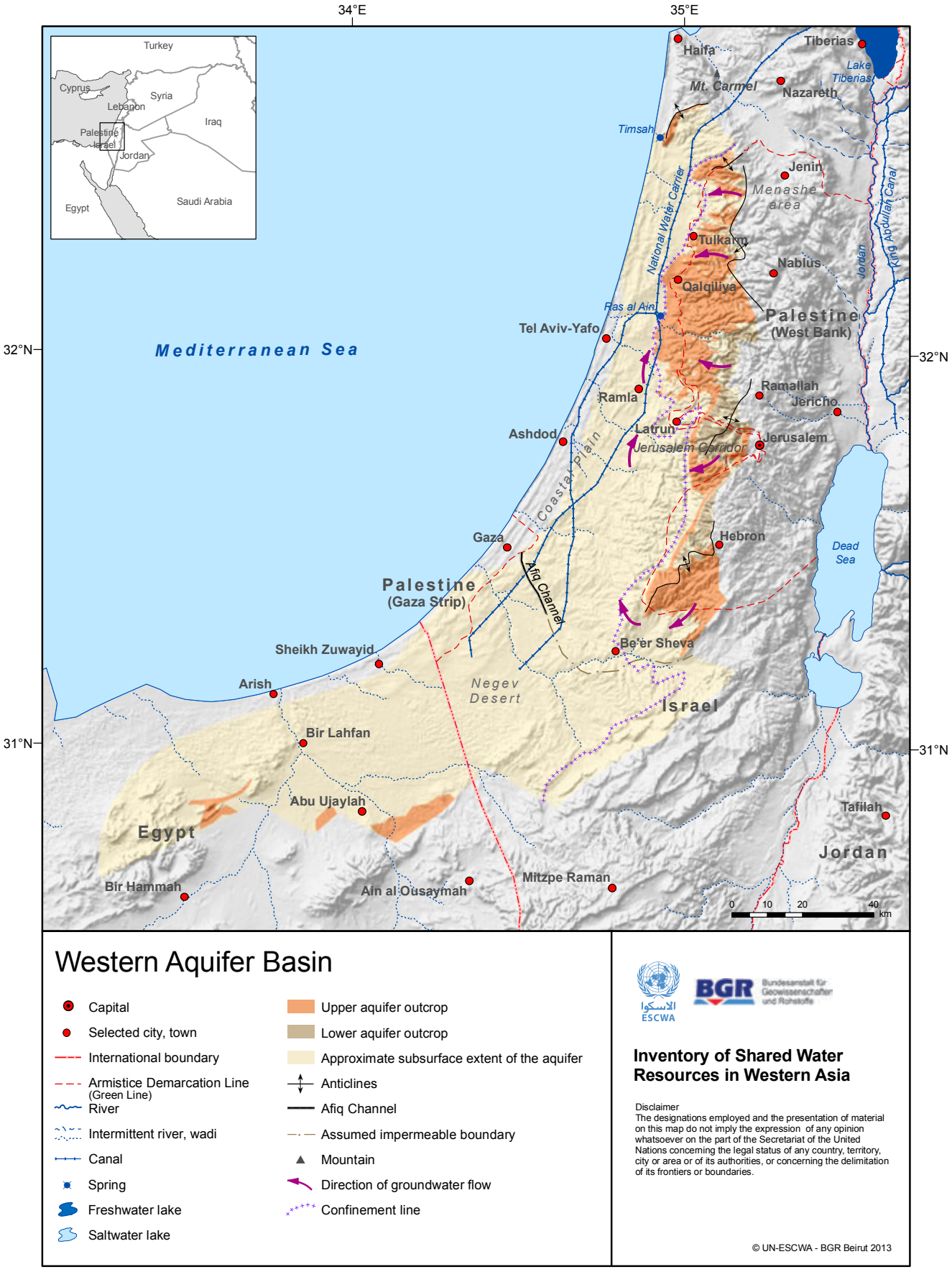
Riparian cooperation on water resources management in the Western Aquifer Basin is largely related to the Israeli-Palestinian conflict. While there is no basin-wide agreement between the three riparians, Israel and PLO have signed two temporary bilateral agreements (Oslo I and II) that both include articles on water resources in the aquifer basin. In particular, the 1995 Oslo II agreement established a Joint Water Committee (JWC), which is responsible for regulating water resources use in the West Bank, including licensing of wells and changes in water allocations. However, in practice the committee has had limited impact and the complicated licensing procedures form a major obstacle to the development of Palestinian infrastructure in the basin. Since the Oslo II agreement, no high-level technical or political negotiations on water-related issues have taken place.

As a productive aquifer with high-quality water, the Western Aquifer Basin is considered a key resource by Israelis and Palestinians. It will therefore form an important point of discussion during final peace negotiations between the two parties.

BASIN FACTS

RIPARIAN COUNTRIES	Egypt, Israel, Palestine
ALTERNATIVE NAMES	Palestine: Western Mountain Aquifer, Ras al Ain-Timsah Aquifer Israel: Yarkon-Taninim Aquifer
RENEWABILITY	Low to medium (2-100 mm/yr)
HYDRAULIC LINKAGE WITH SURFACE WATER	Groundwater from the basin used to discharge through two major springs in Israel and Palestine
ROCK TYPE	Fractured, karstic carbonates
AQUIFER TYPE	East (recharge area): unconfined Centre and west: confined
EXTENT	Total: 9,000-14,167 km^2 Hydrologically most active: 6,035-6,250 km^2
AGE	Middle to Late Cretaceous (Albian to Turonian)
LITHOLOGY	Limestone and dolomite, some marl and chalk
THICKNESS	600-1,000 m
AVERAGE ANNUAL ABSTRACTION	Total: ~390 MCM Israel: 368.7 MCM (1970-2008) Palestine: 23.7 MCM (1995-2011)
STORAGE	..
WATER QUALITY	Very good
WATER USE	Agricultural, domestic and industrial
AGREEMENTS	Israel-Palestine (PLO) 1993 - Oslo I 1995 - Oslo II
SUSTAINABILITY	Over-abstraction; infiltration of untreated sewage

OVERVIEW MAP



Western Aquifer Basin

- Capital
- Selected city, town
- International boundary
- Armistice Demarcation Line (Green Line)
- River
- Intermittent river, wadi
- Canal
- Spring
- Freshwater lake
- Saltwater lake
- Upper aquifer outcrop
- Lower aquifer outcrop
- Approximate subsurface extent of the aquifer
- Anticlines
- Afiq Channel
- Assumed impermeable boundary
- Mountain
- Direction of groundwater flow
- Confinement line

ESCWA

BGR Bundesanstalt für Geowissenschaften und Rohstoffe

Inventory of Shared Water Resources in Western Asia

Disclaimer
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CONTENTS

INTRODUCTION 466

Location 466
Area 466
Climate 466
Population 466
Other aquifers in the area 466
Information sources 466

HYDROGEOLOGY - AQUIFER CHARACTERISTICS 467

Aquifer configuration 467
Stratigraphy 467
Aquifer thickness 468
Aquifer type 468
Aquifer parameters 468

HYDROGEOLOGY - GROUNDWATER 469

Recharge 469
Flow regime 470
Storage 470
Discharge 470
Water quality 471
Exploitability 472

GROUNDWATER USE 473

Groundwater abstraction and use 473
Groundwater quality issues 474
Sustainability issues 475

AGREEMENTS, COOPERATION & OUTLOOK 476

Agreements 476
Cooperation 477
Outlook 478

NOTES 479

BIBLIOGRAPHY 482

FIGURES

FIGURE 1.	Hydrogeological diagram of the Western Aquifer Basin	468
FIGURE 2.	Aquifer productivity in the Lower and Upper Western Aquifer	470
FIGURE 3.	(a) Annual discharge of the Timsah and Ras al Ain Springs and average annual precipitation in the Western Aquifer Basin area (1970-2007); (b) annual water level fluctuations of different groundwater cells in the Israeli part of the basin (1970-2007)	471
FIGURE 4.	Groundwater salinity map - Western Aquifer Basin	472
FIGURE 5.	Palestinian abstractions from wells from the Western Aquifer Basin (1995-2011)	473
FIGURE 6.	Israeli abstractions from wells in the Western Aquifer Basin (1970-2008)	474
FIGURE 7.	Licensing water projects through the Joint Water Committee	477

TABLES

TABLE 1.	Lithostratigraphy of the Western Aquifer Basin	467
TABLE 2.	Recharge estimates for the Western Aquifer Basin	469
TABLE 3.	Groundwater use from wells and springs with differing salinity values in the Western Aquifer Basin (1994-2007)	474

BOXES

BOX 1.	Palestinian Access to Water in the West Bank	475
BOX 2.	The Western Aquifer Basin in the Oslo II Agreement	476

Introduction

LOCATION

The Western Aquifer Basin is the most productive aquifer basin in Israel and Palestine, yielding the highest-quality water in the area. The aquifer basin stretches from the West Bank mountain tops in the east, down the western slopes to the Coastal Plain and the Mediterranean Sea in the west. From north to south it extends from the Mount Carmel foothills to the northern Sinai Peninsula. The Western Aquifer Basin is also referred to as the Western Mountain Aquifer or named after its principal historic outlets, the Ras al Ain Spring[1] north-east of Tel Aviv-Yafo and the Timsah Spring[2] south of Mount Carmel.

AREA

The Western Aquifer Basin covers a total area of 9,000 to 14,167 km^2, depending on the definition of the aquifer's southern boundary in the Sinai Peninsula.[3] This chapter focuses on the area north of the Afiq Channel (see section on Hydrogeology below), which is the more productive part of the aquifer. Different studies estimate the surface area of this part of the basin between 6,035 and 6,250 km^2,[4] of which approximately 70% lies in Israel and 30% in the West Bank.

CLIMATE

The Western Aquifer Basin is characterized by a semi-arid climate. The West Bank mountains cause orographic lifting, which results in precipitation from moisture-laden clouds drifting in from the Mediterranean Sea. Average annual precipitation lies between 550 and 700 mm, with rain- and snowfall occurring mainly between October and March. On the Coastal Plain, average annual precipitation ranges from around 600 mm in the north to 250 mm in the south, while the arid Sinai Peninsula receives no more than 50 mm.

POPULATION

The total population within the most hydrologically active part of the basin north of the Afiq Channel is estimated at around 4.6 million. Around 1 million people live in the Palestinian part of the basin, including populations in the governorates of Bethlehem, Qalqiliya, Salfit and Tulkarm, and part of the governorates of Hebron and Ramallah/Al Bireh.[5] The number of Israeli settlers in the Western Hills was estimated at 148,000.[6] Around 3.4 million people live in the Israeli part of the basin, including populations in the Central District, and parts of the districts of Tel Aviv, Haifa (Hadera Sub-district), Jerusalem (Bet Shemesh), as well as the Southern District (Ashkelon and Be'er Sheva Sub-districts).[7]

OTHER AQUIFERS IN THE AREA

The Western Aquifer Basin is surrounded by seven aquifers, with which it stands in partial flow contact.[8] In the north, it is bounded by the Carmel Coastal, the Western Galilee and the North-Eastern Aquifer Basins. To the west, it is overlain by the Coastal Aquifer Basin (see Chap. 20), while to the east it is bounded by the Eastern Aquifer Basin. To the south, the Western Aquifer Basin is in contact with the Negev Aquifers, the shallow Coastal Aquifer and the deep Kurnub Aquifers in the Sinai Peninsula.

INFORMATION SOURCES

This chapter focuses on the parts of the Western Aquifer Basin that are located in Israel and the West Bank and draws on data published in scientific studies, official government documents and organization reports as listed in the bibliography. Certain data (e.g. spring discharge, well abstractions) was obtained directly through the Inventory's Country Consultation process. Very little information was available for the part of the aquifer located in the Sinai Peninsula. The Overview Map was delineated based on local and regional references.[9]

Al Khadr, South Hebron Hills, West Bank, 2010. Source: EWASH.

Hydrogeology - Aquifer Characteristics

AQUIFER CONFIGURATION

On a local and sub-regional scale, the Western Aquifer Basin contains two aquifer horizons (a lower and an upper), which act as a single combined aquifer unit on a regional and basin-wide scale.[10]

The lower aquifer crops out along the crest of the West Bank Anticlinorium,[11] predominantly within the West Bank, but occasionally also in Israel (e.g. the Jerusalem Corridor) and dips with increasing steepness towards the coast in the west. Similarly, the upper aquifer crops out in the middle and lower slopes of the West Bank, with small outcrop areas to the west of the Green Line.[12] Both series plunge deep beneath thick impermeable Neogene series in the Coastal Plain and in most of the Sinai Peninsula.[13]

The aquifer outcrops, which cover a total area of about 1,976 km^2, mainly occur in the mountains and foothills of the West Bank. Based on the total aquifer extent, the West Bank contains 65% of the total combined outcrop area (1,276 km^2), while 25% of the outcrops occur in Israel and 10% in the Sinai Peninsula.[14]

In the mountainous regions, the aquifer strata dip more steeply than the slopes and expose the deepest formations – the core of the anticline – at the mountain tops. That means that the aquifer is receptive to direct rainfall recharge in the mountains and foothills, especially in the eastern part of the aquifer basin. Here, active epikarst systems develop with wide fractures, cracks, channels and even caves that allow for rapid, deep infiltration of the percolating waters and remarkably high recharge rates (up to 57% of rainfall).[15]

The lateral boundaries of the aquifer (see Overview Map) have been discussed at length in the literature.[16] Of particular importance for the aquifer configuration is the Afiq Channel, which stretches from Be'er Sheva in the east to northern Gaza in the west.[17] This buried erosion channel is filled with impermeable series (evaporites, fine clastics etc.) that deeply bisect the aquifer basin into a northern, hydrologically active aquifer and a southern part, which barely contributes to the active flow system. The section to the east of the Afiq Channel (east and south-east of Be'er Sheva) does not contribute significantly to the hydraulic system of the Western Aquifer Basin, due to lower flow, saturated thickness, recharge and conductivities.[18]

STRATIGRAPHY

The Western Aquifer Basin is composed of Upper Cretaceous (Upper Albian, Cenomanian and Turonian) carbonatic sediments, layers of limestone and dolomite,[19] alternating with confining layers of marl and some chalk. On a local and supra-local scale two aquifer horizons (lower and upper) can be identified, which act as one combined aquifer system on a regional and basin-wide level.[20] Parts of the aquifer are strongly karstified, which explains high local productivity rates.

Table 1. Lithostratigraphy of the Western Aquifer Basin

AGE	FORMATION		LITHOLOGY		HYDROSTRATIGRAPHY	
Senonian	Abu Dees		Chalk, chert, marl		Aquitard	
Turonian	Daliya	Jerusalem	Chalky marl	Limestone	Aquitard	Upper aquifer
Cenomanian	Undifferentiated Talme Yafe	Bethlehem		Dolomite, limestone, marl, chalk.		
		Hebron				
		Yatta		Chalk, marl, limestone.		Aquitard
Albian		Beit Kahel		Dolomite, limestone, marl.		Lower aquifer
		Qattana		Marl, clay.		Aquitard

Source: Compiled by ESCWA-BGR based on Abusaada, 2011, p. 46, fig 2.3 (modified after PWA and UNuT, 2004 and Weinberger and Rosenthal, 1994).

The aquifer basin is underlain by the Qattana Formation,[21] an aquitard of the Aptian and Lower Albian Kobar Group sediments, which consists of a 300-500 m-thick succession of mostly impermeable marl, clay and shale with thinner intercalations of carbonates.[22]

In the Coastal Plain in Israel and most of the Sinai Peninsula, the aquifer basin is overlain by thick sequences of impervious younger sediments, such as the Senonian Mount Scopus and Neogene Saqiye Groups.[23]

AQUIFER THICKNESS

The upper and lower aquifers have a combined thickness of 600-900 m.[24] On average, the upper and lower aquifers each have a thickness of around 350 m. The layers are incompletely separated by less permeable and impermeable marly and chalky series with a thickness of 100-150 m. This results in an overall thickness of 700-1,000 m for the entire aquifer system.[25]

AQUIFER TYPE

The aquifer system is generally unconfined in the mountain and slope areas in the eastern part of the basin.[26] Saturation increases gradually towards the west, first in the lower and then the upper aquifer. West of the confinement line – which runs roughly along the Green Line – the aquifer system experiences strongly confined hydraulic (in the past even artesian) pressure, which brings water levels in bore-holes in the Coastal Plain up to a few dozen metres below ground level and feeds the (now partially dried up) Ras al Ain and Timsah Springs.

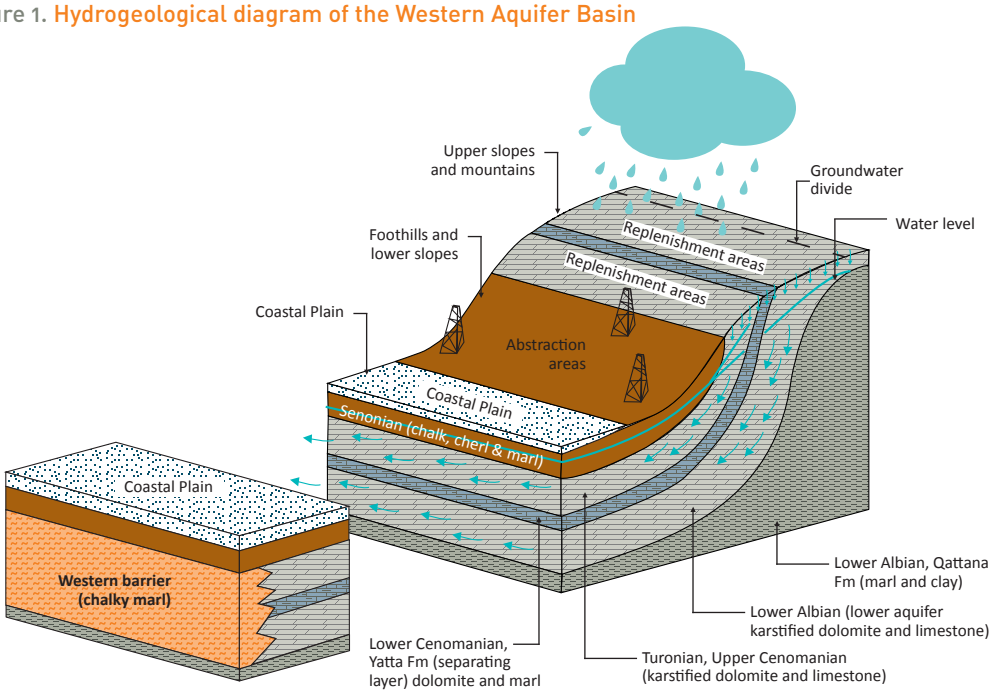
AQUIFER PARAMETERS

Aquifer parameters in karst aquifers are generally highly variable. Annual well discharges range from less than $1x10^{-1}$ MCM to more than 7.5 MCM. Specific yield was found to vary between 1% and 8%,[27] while storativity in the confined areas ranges between 10^{-6} and 10^{-4}.[28]

In the confined areas in the Coastal Plain, transmissivities of between $1.7x10^{-1}$ and $4.63x10^{-1}$ m^2/s have been reported, while they only reach several hundred square metres per day in the unconfined area near the margins of the aquifer basin.[29] In the most productive wells transmissivity can reach up to 1.16 m^2/s. Transmissivity values derived from groundwater model calibrations were sometimes double or triple the values measured in specific wells,[30] which may confirm the double continuum system in the aquifer basin, with diffuse and conduit flow systems.

Horizontal conductivities for the upper and lower aquifer are considered mostly similar, except in the mountain areas where the values increase along the flow path from less than 1-10 m/d (Hebron, Jerusalem, Ramallah) to 5-15 m/d (Tulkarm), 85-160 m/d (Timsah) and 85-600 m/d in the most productive, central parts of the Coastal Plain.[31] The vertical conductivities in the aquifer are estimated to be much lower,[32] ranging between $1.3x10^{-6}$ and $2.2x10^{-4}$ m/d.[33] Conductivities in the aquitard between the upper and lower aquifers can be as low as $7.9x10^{-3}$ m/d.[34]

Figure 1. Hydrogeological diagram of the Western Aquifer Basin



Source: Redrawn by ESCWA-BGR based on Abusaada, 2011, p. 44, fig 2.1.

Hydrogeology - Groundwater

RECHARGE

Recharge in the Western Aquifer Basin is mainly natural from direct infiltration along the karstified outcrops in the mountainous and sloped areas in the eastern part of the aquifer system. Around 73% of recharge to the aquifer takes place in the West Bank.[35] In Israel, recharge mainly takes place in the northern part of the basin (Menashe area) and in the Jerusalem Corridor. Sparse aquifer outcrops and low average annual rainfall in the Negev (Al Naqab) Desert in Israel and the Sinai Peninsula allow for only negligible recharge amounting to less than 1 MCM/yr.

A wide range of values for annual recharge is reported in the literature, from 318 to 430 MCM (Table 2). This Inventory uses the results of a recent study, which estimated a long-term average annual recharge value of 385 MCM for the period 1970-2006.[36] However, pronounced inter-annual variations in recharge are the norm and annual recharge values can range from 212 to 864 MCM, depending on precipitation and other meteorological factors.[37]

Other, smaller sources of recharge to the aquifer system include network losses, agricultural and wastewater return flows, infiltration from wadis, seawater intrusion[38] and artificial recharge through deep-injection wells. Limited agricultural development and water use in the West Bank means that the sources of recharge are less important than direct infiltration from precipitation. In Israel, where the Western Aquifer Basin is mainly confined hundreds of metres below ground, both precipitation and return flows infiltrate the overlying Coastal Aquifer.

Table 2. Recharge estimates for the Western Aquifer Basin

SOURCE	RECHARGE (MCM/yr)	COMMENT
Goldschmidt and Jacobs, 1955, p. 8.	318	Mass balance, based on low outflows from the main springs: Ras al Ain and Timsah.
Bachmat, 1995.	330, 332	Coastal Plain flow model (Goldschmidt/ Jacobs).
Assaf et al., 1993, in Hughes et al., 2008, p. 848.	350	-
Sabbah and Miller, 2012.	350	Based on the 10-year (2001-2010) average.
HSI, 2008, p. 221.	358	Estimate for the period 1970-2007.
Israel and the PLO, 1995.	362	So-called "aquifer potential"; method not specified.
HSI, 1999, in Hughes et al., 2008, p. 4.	366	Rainfall recharge over outcrops.
EXACT, 1998, p. 22.	366	Sum of outflows.
Abusaada, 2011.	385	Estimate for the period 1970-2006 based on water-level fluctuation/storage change.
Messerschmid, 2008, p. 20.	389	Water-level fluctuation, mass balance calculation.
PWA and UNuT, 2004, p. 16.	408	Maximum perennial yield (calibrated steady state and transient models).
PWA and UNuT, 2003b, p. 86.	410	Water budget calculation for Steady State Model.
Hughes et al., 2008, p. 853.	430	Modelled with wetting threshold and soil moisture deficit.

Source: Compiled by ESCWA-BGR.

FLOW REGIME

The flow in the Western Aquifer Basin is generally from east to west in the mountains and turns gradually from south to north in the Coastal Plain. South of the Afiq Channel, the flow is very limited under natural flow conditions.[39] Steep gradients in the elevated recharge and accumulation zone are followed by gentle gradients in the foothills and the lower-lying productive zone. In the recharge zone, water levels generally lie at 300-600 m asl. A gradual increase in saturation occurs in the accumulation zone, and water levels in the lower aquifer drop from 300 to 60 m asl in an east-west direction. In the foothills, water levels lie below 50 m asl, while in the Coastal Plain, a very gentle gradient slopes from more than 30 m asl in the south (Be'er Sheva), to less than 20 m asl in the centre (Ras al Ain Spring) and 5 m asl in the north (Timsah Spring).

Most of the flow is transboundary from the West Bank into Israel. Average annual inflow from the West Bank to Israel amounts to 212 MCM, of which 87% comes from the northern West Bank.[40] Locally, large-scale abstraction from Israeli wells has altered flow lines considerably, for example near Latrun. Flow from and to Egypt is negligible. The aquifer's most productive and exploitable zone lies in the Coastal Plain along the border with the West Bank (Figure 2).

The shallow Carmel Coastal Aquifer and the Coastal Aquifer Basin receive inflow from the Timsah Springs in the northern part of the Western Aquifer Basin. The Coastal Aquifer directly overlies the Western Aquifer near Qalqiliya, with modest recharge.[41]

The North-Eastern Aquifer Basin and the Western Aquifer Basin share a flow boundary in the northern sections of the West Bank mountains. The Eastern Aquifer Basin only has minor flow boundaries with the Western Aquifer Basin; most of the boundary is no-flow or even a structurally divided erosion zone between the basins along the axis of the West Bank Anticlinorium. The Negev Aquifers in the south receive some groundwater from both the Eastern and the Western Aquifer Basins.[42] Occasionally, deep-seated upward leakage along faults occurs from the Jurassic Aquifers below.[43]

STORAGE

Information on groundwater storage was not available.

DISCHARGE

Before the large-scale development of the aquifer in the 1950s, natural discharge occurred almost exclusively from the two principal spring groups, the Ras al Ain and Timsah Springs, which had an average historic discharge of 220 MCM/yr and 100 MCM/yr respectively.[44]

Since the 1950s, spring discharge has decreased sharply due to groundwater abstractions from Israeli and Palestinian wells, resulting in the drying up of the Ras al Ain Spring in the 1960s. The average discharge of the Timsah Spring also dropped to 40 MCM/yr after 1970 (Figure 3).[45] The time series shows that the springs respond quickly to wet years, underlining the highly karstic nature and interconnectivity of the aquifer.[46] After the very wet year in 1991/92, the Ras al Ain Spring started flowing again and discharge from the Timsah Spring increased significantly. However, the increase only lasted a few years and the overall discharge trend continues to be negative, due to sustained over-abstraction from the aquifer.

Figure 2. Aquifer productivity in the Lower and Upper Western Aquifer

Source: Compiled by ESCWA-BGR based on Messerschmid and Abu-Sadah, 2009.

Groundwater levels exhibit similar behaviour (Figure 3) for selected groundwater cells located in the lower, coastal part of the basin.

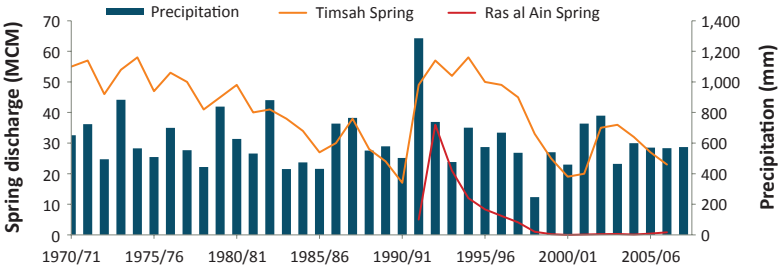
WATER QUALITY

Groundwater in the West Bank is generally fresh with chloride (Cl^-) levels mostly below 100 mg/L.[47] In Israel water is fresh in the vicinity of the Green Line, but becomes slightly brackish (250-600 mg/L) to the west (Figure 4). In the western part of the central Coastal Plain, salty and sulphate-rich leakage from overlying aquifers (e.g. the Eocene Avedat Group) is a local source of additional salt. Farther to the west, groundwater is brackish to highly brackish (600-1,000 mg/L).

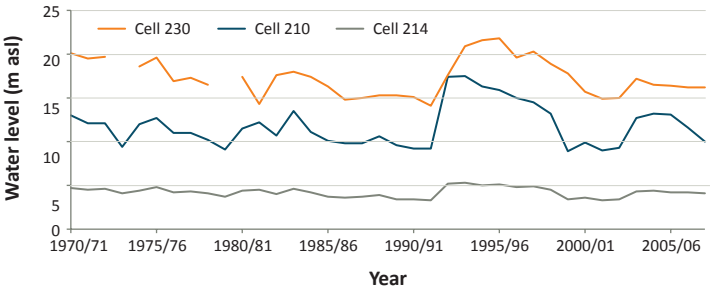
In the north-western part of the basin near the Timsah Springs, seawater intrusions of 3.5-3.9 MCM/yr[48] occur alongside deep saline water bodies at the bottom of the aquifer (>1,000 mg/L). In the area south of the Afiq Channel, most groundwater can be assumed to be strongly brackish to saline (up to approx. 2,000 mg/L), making it unfit for human consumption.

Figure 3. (a) Annual discharge of the Timsah and Ras al Ain Springs and average annual precipitation in the Western Aquifer Basin area (1970-2007); (b) annual water level fluctuations of different groundwater cells in the Israeli part of the basin (1970-2007)

a)



b)



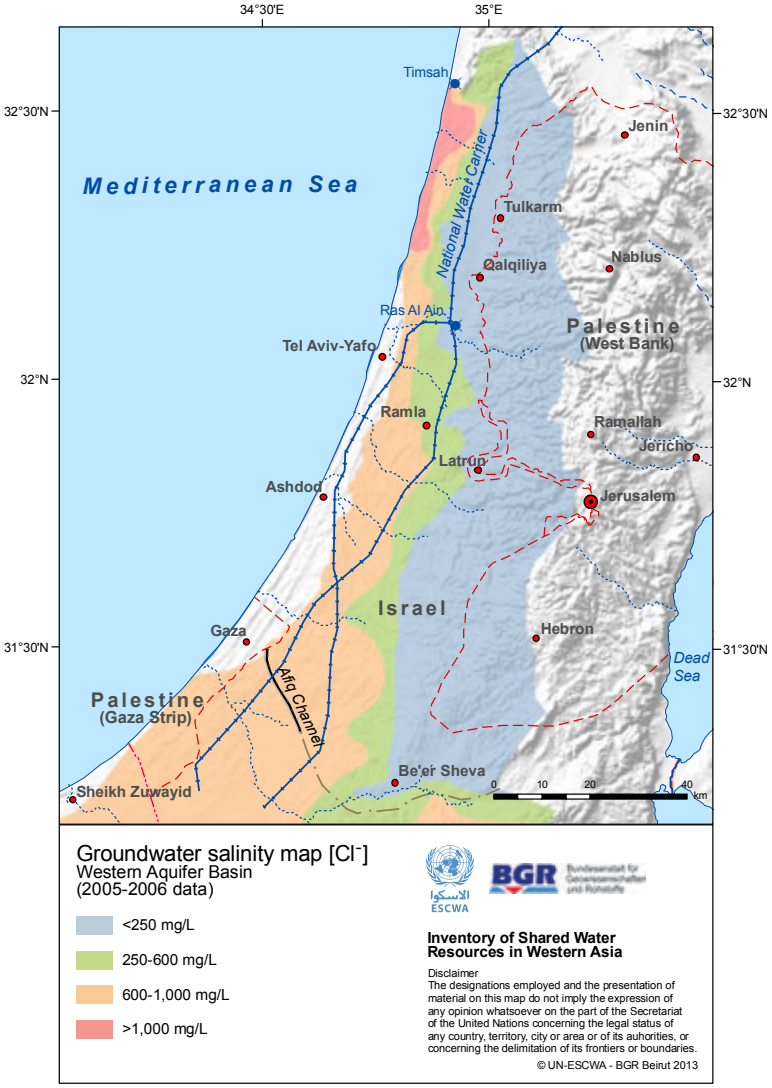
Source: Compiled by ESCWA-BGR based on PWA, 2012a.

South Hebron Hills, West Bank, 2010. Source: Adam Groffman.

EXPLOITABILITY

According to the standardized exclusion criteria used to assess exploitability in this Inventory,[49] the aquifer basin can be classified as theoretically exploitable across most of its extent, with the possible exception of the recharge zone near the eastern margin due to limited saturation and the depth of the groundwater table. More detailed studies of the renewable and intensively developed aquifer basin were found in the literature. Figure 2 shows the productivity for the upper and lower aquifer in the basin. The main productive zone of the aquifer lies near the Green Line and in the Coastal Plain in Israel, and hence constitutes only a relatively small part of the overall basin.

Figure 4. Groundwater salinity map - Western Aquifer Basin



Source: Compiled by ESCWA-BGR based on Messerschmid, 2011 with data from HSI 2008, p. 211, 231.

Groundwater Use

GROUNDWATER ABSTRACTION AND USE

Palestine (West Bank)

Local farmers, villagers and city dwellers used the Ras al Ain and Timsah Springs together with the water of small local springs. Abstractions from the Western Aquifer through bore-holes started only during the British Mandate period.[50] During the period from the early 1960s to 1967 when Jordan controlled the West Bank, abstraction from private wells with depths up to 150 m amounted to around 20 MCM/yr.[51] The water was mainly used for agricultural purposes.

Since the Israeli occupation of the West Bank in 1967, Palestinian water use in the Western Aquifer Basin has not substantially increased due to Israeli restrictions (Box 1). There are around 140 operational Palestinian wells[52] in the Western Aquifer Basin. Average annual abstraction for the period 1980-1999 was around 21.3 MCM, of which 15.5 MCM was for agricultural use and 4.7 MCM for municipal use.[53]

The Israeli-Palestinian Interim Agreement on the West Bank and the Gaza Strip (also known as the Oslo II Accords), which was signed in 1995 to cover a five-year period until 1999, allocated Palestinians in the Western Aquifer Basin an annual 22 MCM.[54]

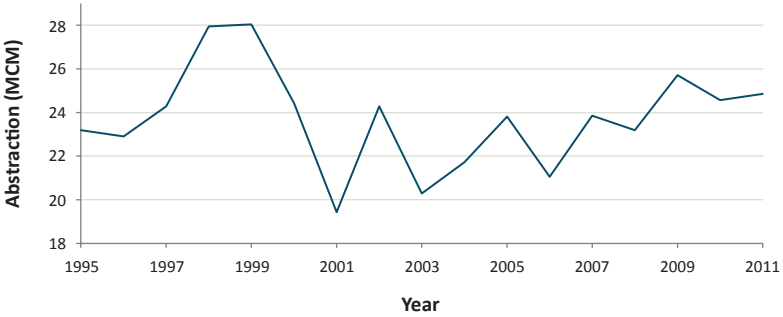
During the period between 1995 and 2011, the annual average Palestinian abstraction from wells was 23.7 MCM, exceeding the value outlined in the Oslo II agreement by 1.7 MCM/yr, or 8% (Figure 5).[55] On average, Palestinian abstractions account for approximately 6% of total abstractions from the Western Aquifer Basin.

Additional abstractions from the Western Aquifer Basin in the West Bank include around 2 MCM/yr from five Israeli operated wells.[56]

Most of the shallow private wells and the few small springs (from intermediate perched aquifer horizons) with discharges of less than $1x10^{-1}$ MCM/yr (1 L/s) are used for small-scale irrigation or to provide supplementary domestic supply during the dry summer months. In 2009, the combined discharge from those small springs was about 2.4 MCM.[57]

In the entire West Bank, local water production in 2010 amounted to 98.3 MCM, of which 71.5 MCM were pumped from around 250 wells and 26.8 MCM were produced in springs.[58] Agriculture accounted for approximately 70% of local water use in the West Bank. An additional 55.5 MCM were purchased from Israel's national water company Mekorot in 2010, mostly for domestic use.[59]

Figure 5. Palestinian abstractions from wells from the Western Aquifer Basin (1995-2011)



Source: Compiled by ESCWA-BGR based on PWA, 2012a.

South Hebron Hills, West Bank, 2010. Source: Adam Groffman.

Israel

Groundwater development in Israel experienced rapid and sustained growth in the early 1950s.[60] Exploitation of the Western Aquifer Basin in the Coastal Plain accelerated after 1958, mainly from Mekorot wells. Today around 500 wells abstract water from the Israeli part of the Western Aquifer Basin.[61] Most Israeli wells are situated in the productive zone of the aquifer and individual well yields are far higher than Palestinian well yields in the West Bank, which are generally older and shallower.

From 1970 to 2008, average annual pumping from the Western Aquifer Basin in Israel was 368.7 MCM (Figure 6)[62] or 94% of total abstractions from the aquifer basin.[63] Israel also has exclusive access to a number of large springs which discharge an annual average of 43.9 MCM, bringing the total average yield from the aquifer basin in Israel to 412.6 MCM.[64]

Israeli abstractions have remained high since 1970, without a clear trend. Annual abstractions vary with rainfall, and the maximum and minimum annual abstractions of 245 MCM (1991/92) and 576 MCM (1998/99) are inversely correlated to the years of highest (1991/92) and lowest (1998/99) rainfall (Figures 3 and 6).

The Oslo II Accords allocated Israel a temporary share of 340 MCM from the Western Aquifer Basin.[65] Figure 6 shows that Israel's average annual abstraction from wells in the basin reached 393.3 MCM for the period 1995-2008, 53.3 MCM or around 15% more than the volume outlined in the agreement. In addition, if full use of spring discharge is taken into account, Israel's total annual average use after 1995 amounts to 429.3 MCM, which represents 89.3 MCM or 26% more than the amount stipulated in the Oslo II agreement.[66]

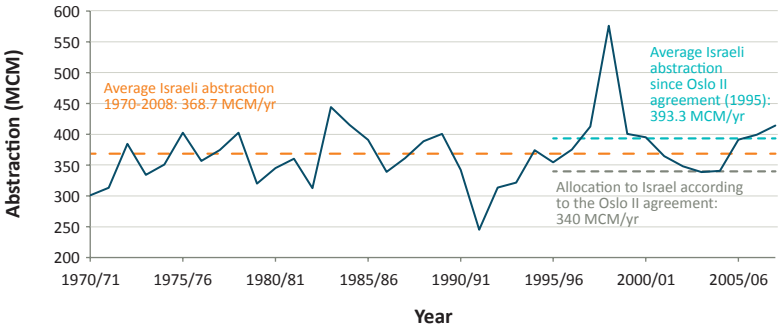
Israeli over-abstraction has led to continuously dropping water levels, which in turn increases salinity problems, particularly in the north of the aquifer basin.[67] Spring flow has also sharply diminished (see section on Discharge above). Israel has used the deep aquifer to compensate for reduced surface water availability from the Jordan River and Lake Tiberias, especially after successive dry winters.[68] Artificial recharge of the Western Aquifer in Israel was introduced early on, reaching 55 MCM/yr in the mid-1970s. After 1995, this figure dropped to 3 MCM/yr.[69]

No information is available on the sectoral allocation of Israeli abstractions in the basin. Most Israeli wells in the Western Aquifer Basin are connected to and feed centrally into Israel's National Water Carrier system,[70] which distributes water from different sources across the country for municipal and agricultural use. It is therefore difficult to trace where the water that is abstracted from the Western Aquifer Basin in Israel is used and for which purposes. Figures from 2010 show the following sectoral allocation of total available water sources in Israel: 57% was used in agriculture, 36% for domestic purposes and 7% in the industrial sector.[71]

Egypt

A few bore-holes have been drilled into the Cenomanian series of the Western Aquifer Basin in the Sinai Peninsula. However, no data is available on abstractions and use in Egypt.

Figure 6. Israeli abstractions from wells in the Western Aquifer Basin (1970-2008)



Source: Compiled by ESCWA-BGR based on PWA, 2012a, similar to Zeitoun et al., 2009.

Table 3. Groundwater use from wells and springs with differing salinity values in the Western Aquifer Basin (1994-2007)

SOURCE	SALINITY		GROUNDWATER USE (MCM)		
	Type	Cl (mg/L)	Israel	Palestine	Total
Well abstraction	Very fresh	0-99	132	19	151
	Fresh-brackish	100-399	225	7	232
	Brackish-saline	>400	7	—	7
	TOTAL		364	26	390
Spring flow	Very fresh	<50	0.07	1.95	2.02
	Fresh-brackish	50-399	1.42	..	1.42
	Brackish-saline	>400	37.16	..	37.16
	TOTAL		38.6	2	40.6

Source: Compiled by ESCWA-BGR based on HSI, 2008; PWA, 2010.

GROUNDWATER QUALITY ISSUES

As shown above, only 7 MCM/yr (<2%) of all abstractions from the Western Aquifer Basin are brackish-saline (Table 3). The sustained over-abstraction of the aquifer has increased the risk of salinization in the aquifer.[72] Spring outflow has declined drastically and groundwater levels have dropped substantially, which increases the risk of saline water being drawn into the northern and western part of the aquifer.

Pollution by untreated sewage is another threat in the outcrop and recharge areas, both in Israel[73] and the West Bank, where domestic wastewater from Palestinian towns and villages and Israeli settlements is released into the environment without treatment.[74] This raw sewage flows through wadi beds and seeps into the aquifer below. Over 2 million people live in outcrop and recharge areas in the eastern part of the aquifer basin in Israel and the West Bank. The lack of adequate wastewater treatment facilities and the absence of sound agricultural

practices mean that nitrate levels locally exceed the World Health Organization guidelines. While few wells have been affected to date, nitrate levels reach 100-145 mg/L in the area of Tulkarm and Qalqiliya and 60-80 mg/L in the Hebron area.[75]

SUSTAINABILITY ISSUES

The water resources in the Western Aquifer Basin have come under increasing pressure since the 1950s, with abstraction rates rising close to and beyond sustainable levels. It is beyond the scope of this Inventory to provide a reliable and detailed water balance estimate, but a simple comparison of long-term annual averages may be indicative of the over-abstraction of groundwater that has taken place in the Western Aquifer Basin.[76]

In the period 1970-2006, average annual outflows reached 434 MCM, while average annual recharge from rain amounted to 385 MCM. The injection of 15 MCM/yr of water into the aquifer has made up for part of the overdraft, but leaves a 34 MCM deficit, which is equal to nearly 9% of natural recharge.[77]

There are pronounced variations in annual recharge and abstractions however, and while available data points to over-abstraction, the aquifer partially and/or locally recovers in particularly wet years, as reflected in spring and groundwater levels (Figure 3).[78] It is important to note that the data series mostly refer to locations in the western part of the basin, which is the confined and productive zone. The effects of over-abstraction may be felt quite differently in the eastern part of the West Bank, where groundwater is located at greater depth, is partly unconfined and undergoes more pronounced fluctuations. A more detailed study on sustainability in the Western Aquifer Basin, covering a longer time period and taking into account spatial and temporal variations as well as cyclical climate patterns, was not available during the preparation of this Inventory.

Finally, it is important to point out that the current use pattern in the aquifer basin and the respective abstractions by the two main riparians take place within the context of the ongoing Israeli-Palestinian conflict. Since the Israeli occupation of the West Bank in 1967, Palestinians have been unable to freely access, use or develop water resources in the West Bank, including the Western Aquifer Basin (Box 1). Thus in addition to unsustainable use of the aquifer, the issue of inequitable use of the Western Aquifer Basin also needs to be addressed.

BOX 1 Palestinian Access to Water in the West Bank

Since the start of the Israeli occupation of the West Bank in 1967, the Palestinian population living in the Western Aquifer Basin area has been unable to further develop or at times maintain its water infrastructure. A series of military orders issued by the Israeli authorities in the late 1960s requires Palestinians to obtain different permits and authorizations for all water-related projects including the drilling of new wells, increasing abstraction from existing wells or carrying out maintenance work on supply and distribution networks. The military orders remain in force today.[a]

As a result, Palestinians have not been authorized to drill a single well in the Western Aquifer since 1967.[b] Networks, reservoirs and pumping stations no longer meet current needs and are often severely run down, while the Israeli army regularly destroys private household rainwater harvesting cisterns if they lack proper permits.[c]

The multiple restrictions mean that Palestinians in the West Bank suffer from chronic water scarcity. Overall, average actual domestic availability and consumption for Palestinians in the West Bank is estimated at about 50 L/cap./d, with many households consuming as little as 20 L/cap./d.[d] The extremely low levels of consumption place most West Bank communities well below accepted international standards.[e]

In addition, many areas in the relatively water-rich West Bank experience annual supply shortages and interruptions during the dry summer months, with inhabitants in parts of Hebron Governorate consuming 10-15 L/cap./d, and receiving water only every 40 days.[f] Many communities have to transport water by tanker from filling points to their village. However, the supply is unreliable, partly because of checkpoints and the Israeli regulation of the operation of filling points. It is also much more expensive than water from the municipal network. Water availability is further restricted by the fact that permit applications for well repair are regularly rejected (Figure 7).

Overall, Israeli restrictions on Palestinian water development projects mean that water supply from Palestinian-controlled wells and springs in the West Bank no longer meets the demands of the growing population. While average abstraction from wells has remained nearly constant at around 61-62 MCM/yr over the past 30 years, average discharge of Palestinian-controlled springs has dropped from an average of 64 MCM/yr in the period 1980-1999 to 40 MCM/yr in the period 1999-2010, a 40% decrease.[g] Overall, average groundwater availability for Palestinians in the West Bank dropped from 126 MCM/yr in 1980-1999 to 101 MCM/yr in 1999-2010, a 20% decrease. In combination with high population growth rates, the gradual reduction in access to water sources strains per capita water availability.[h] As a result, Palestinians in the West Bank are increasingly dependent on water from the Israeli water company Mekorot and purchased an estimated 55.5 MCM for domestic use in 2010.[i]

(a) Officially only in Area C, de facto in Areas A and B.
(b) ECHO, 2009.
(c) Amnesty International, 2009, p. 12.
(d) World Bank, 2009, p. 107.
(e) The World Health Organization (WHO) recommends a standard of 100 L/cap./d for optimal water supply.
(f) World Bank, 2009, p. 16.
(g) For the period 1980-1999, average annual values are available in PWA and UNuT, 2001b: abstraction from Palestinian wells in the West Bank was 62 MCM and discharge of Palestinian springs amounted to 64 MCM, giving a total annual water yield of 126 MCM. For the years 1999-2010, annual averages were calculated based on water statistics in the Palestinian Territory Annual Reports 2000-2012: abstraction from wells was 60.9 MCM and spring discharge amounted to 39.6 MCM, giving a total water yield of 100.5 MCM.
(h) According to official censuses, the Palestinian population in the West Bank grew from 1.87 million in 1997 to 2.35 million in 2007, a 26% increase.
(i) PWA, 2012b, p. 17.

Agreements, Cooperation & Outlook

AGREEMENTS

Riparian cooperation on water resources management in the Western Aquifer Basin is inextricably linked to the Israeli-Palestinian conflict. There is no agreement in place for the aquifer basin as a whole, which is shared between Egypt, Israel and Palestine.

However, Israel and the Palestine Liberation Organization (PLO) have signed two bilateral agreements regarding the use, protection and allocation of water resources in the Western Aquifer Basin. Officially referred to as the Declaration of Principles on Interim Self-Government Arrangements (DOP), the 1993 Oslo Accords between Israel and PLO were the result of extensive negotiations in the aftermath of the Madrid Conference.[79] The agreement dedicates a short paragraph to water, outlining principles of cooperation, joint management, water rights and equitable use.[80]

The Oslo Accords were followed in 1995 by the Israeli-Palestinian Interim Agreement on the West Bank and the Gaza Strip or Oslo II, which addressed the topic of water and sewage in Article 40 of the Protocol on Civil Affairs

BOX 2 The Western Aquifer Basin in the Oslo II Agreement

A section of the Oslo II agreement emphasized the importance of safeguarding the existing use of the Western Aquifer Basin in Israel and the West Bank. Schedule 10, entitled "Data Concerning Aquifers", stipulated "existing extraction, utilization and estimated potential" and, where applicable, the "remaining quantities" for each of the Eastern, North-Eastern and Western Aquifers. The exact nature, origin and relationship of the numbers provided were not specified. Schedule 8 of the agreement stated that the
"...average annual quantities (...) shall constitute the basis and guidelines for the operations and decisions of the JWC".[a] The decisions included the licensing and drilling of wells, increases in extraction, etc.

For the Western Aquifer Basin, an annual average of 362 MCM/yr was given, based on estimates of Israeli and Palestinian "existing utilization" (or shares) of 340 MCM/yr and 22 MCM/yr, respectively, and there were no remaining quantities. The Joint Water Committee (see section on Cooperation) has not approved further development of the Western Aquifer Basin in the West Bank.

Using the data from this Inventory, existing use in the Western Aquifer Basin prior to 1995 was 426 MCM, 64.5 MCM or nearly 18% more than the figure stated in the Oslo II agreement.[b] Other sources published similar findings[c] and recent average annual recharge estimates for the basin are also higher (Table 2).

(a) Joint Water Committee.
(b) For the period from 1970-1995, Israeli average annual abstractions were 355.8 MCM and spring discharge amounted to 47.7 MCM (PWA, 2012a). Assuming a Palestinian abstraction of 23 MCM, the total pre-Oslo yield was 426.5 MCM.
(c) HSI, 2008, p. 221 calculated total outflows from the Western Aquifer Basin before 1995 at 404 MCM/yr, representing 42 MCM/yr or 12% more than the existing use according to Oslo II.

Timsah Spring, Israel, 2012. Source: Adi Faran.

(Annex III) and which was intended to cover the five-year period 1995-1999. The agreement recognized Palestinian water rights in the West Bank, which are to be negotiated in permanent status negotiations.[81] It also acknowledged the need to develop additional water resources[82] for various uses and the importance of safeguarding existing use (Box 2).

Other topics covered in Oslo II include the mutual avoidance of harm and protection of the aquifer from over-abstraction and pollution. Water purchases at full cost and mutual cooperation in studies and future projects, training, research and knowledge transfer, emergency situations and data exchange were also addressed in the agreement.[83] Furthermore, the Interim Agreement made provisions for the parties to establish a permanent Joint Water Committee (JWC) for the interim period. The body was charged with regulating water resources use in the West Bank.[84]

In Israel, the Oslo II agreement is widely seen as a turning point that shifted responsibility for the Palestinian water sector to the Palestinian Authority. Yet in practice it did not change the scope of Israeli control,[85] and all Palestinian abstractions and water resources development projects in the Western Aquifer Basin remain subject to Israeli approval.

COOPERATION

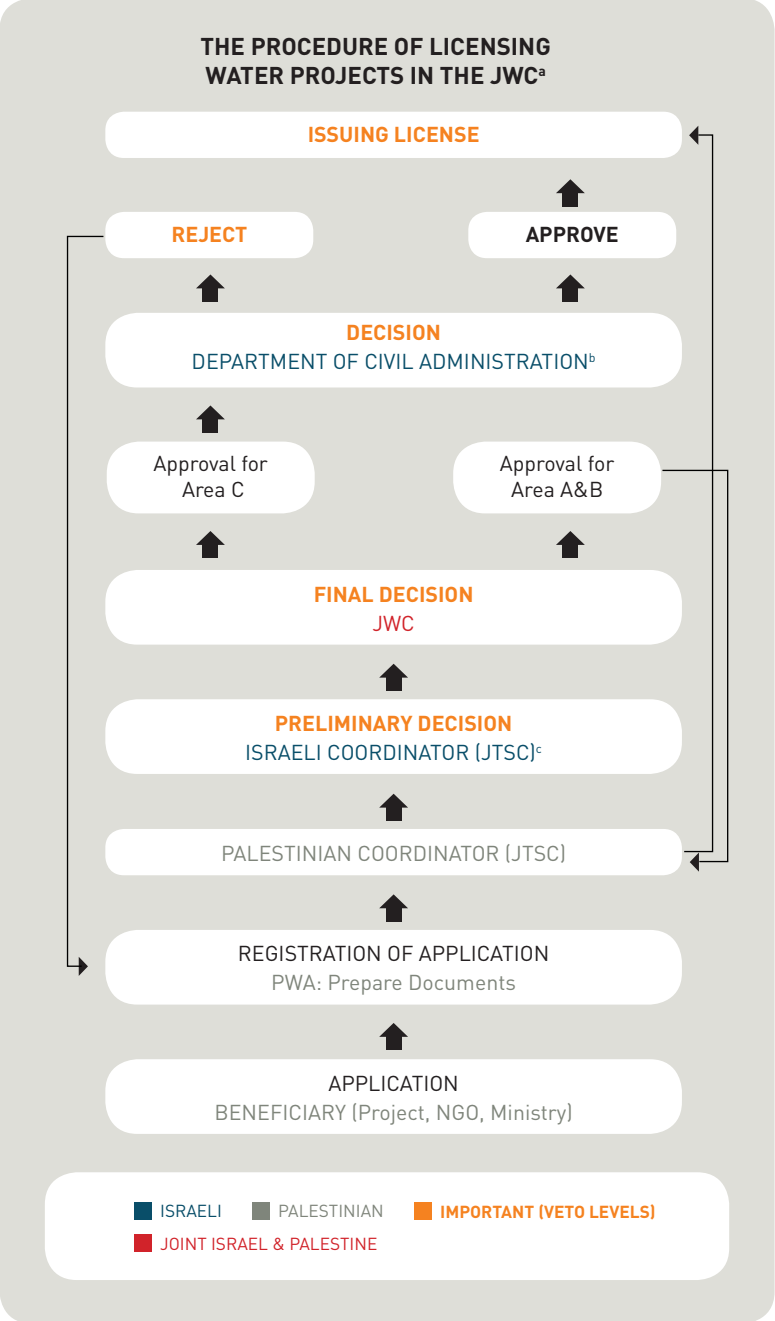
In 1994, in accordance with the Interim Agreement, the parties established the Joint Water Committee (JWC), which comprises an equal number of Israeli and Palestinian representatives.[86] According to the agreement, JWC was established to discuss and decide upon the licensing and drilling of new wells, increasing extractions, development of water resources and systems, allocation of additional water, and changes in allocations. In addition, JWC was given the responsibility to establish and annually update a schedule of extraction quotas based on existing licences and permits.[87]

Although it was hailed as success story for Israeli-Palestinian cooperation, the committee's work has had limited impact.[88] Critics have described JWC as ineffective and as a means of "dressing up domination as cooperation".[89]

While both parties have full veto power over development activities in the section of the Western Aquifer Basin that is located in the West Bank, Israel's water resources development projects are concentrated in the aquifer's main production zone in the Coastal Plain in Israel, over which JWC has no mandate. As a result, Palestinians have no say over Israeli water development projects in the Western Aquifer Basin, while Israel regularly exercises its veto right to obstruct Palestinian plans to build new water infrastructure or carry out maintenance work on existing structures.[90]

The Israeli minister of the environment and the Palestinian minister of water conceded in December 2011[91] that JWC was ineffective. While they disagreed on how it could be remedied, they both called for the re-examination of the committee's structure and operational mechanism.[92]

Figure 7. Licensing water projects through the Joint Water Committee



Source: Redrawn by ESCWA-BGR based on Attili, 2007.
(a) JWC: Joint Water Committee.
(b) The Department of Civil Administration (DCA) is part of the Israeli Army, established to manage local governance issues and security operations in the West Bank and Gaza. Following the Oslo process, the DCA retains this role in Area C (World Bank, 2009).
(c) JTSC: Joint Technical Sub-Committee.

The licensing of Palestinian water projects, including gaining approval for the drilling of a well, remains a long process that is often obstructed by complicated procedures as shown in Figure 7. After registration of the application needed for the licence, it is submitted to the Palestinian coordinator of the Joint Technical Sub-Committee (JTSC), and then to the Israeli coordinator who takes a preliminary decision before submitting it to JWC. The final decision is taken by JWC and at this stage both the Palestinian and Israeli side have a veto right. For projects approved in Area A and B[93], the project approval is re-submitted the Palestinian coordinator of JTSC, which is responsible for issuing the licence. Projects approved in Area C require a second approval by the civil administration which has the right to reject the application. More than half of the West Bank remains under the control of the Israeli military (Area C), further restricting Palestinian water infrastructure development.

OUTLOOK

Final status negotiations and agreements have stalled since 1996 and the five-year interim period outlined in the Oslo II agreement elapsed more than a decade ago. In addition, no high-level technical negotiations on water-related issues have taken place in the intervening period.[94]

From a Palestinian perspective, the inequitable distribution of water resources from the Western Aquifer Basin and the issue of water rights form the crux of the conflict. In addition, the JWC licensing procedure continues to form a key obstacle to the development of Palestinian infrastructure in the basin. Israel, on the other hand, maintains pressure on Palestinians to improve wastewater treatment in recharge areas in the West Bank, and also claims that in contradiction of the agreement, Palestinians have drilled several hundred unauthorized wells in the West Bank, and are not developing new water sources such as reuse of treated wastewater or desalination.[95]

Palestinian negotiators have developed a position based on the principles of international water law with the aim of ensuring long-term sustainable and equitable use of the basin's water resources.[96] However, given that the wider Israeli-Palestinian conflict remains unresolved, the inequitable distribution of water resources from the Western Aquifer Basin is unlikely to be addressed in the foreseeable future.

Potential future land swaps[97] and their relevance to recharge zones and/or productive abstraction zones in the aquifer basin are also likely to play an important role in future negotiations.[98]

Yarkon Spring (Ras al Ain Spring), Israel, 2009. Source: Ian W. Scott.

Notes

1. Referred to as the Yarkon Spring in Hebrew.
2. Referred to as the Taninim Spring in Hebrew.
3. PWA, 2012a estimates the Western Aquifer Basin area at 11,862 km^2 with Egyptian, Israeli and Palestinian basin shares of 19%, 62% and 19%, respectively. Abusaada, 2011 estimates the total area at 9,000 km^2, while Messerschmid, 2008, p. 25 indicates an area of 14,167 km^2. Generally, the depth of extension of the aquifer basin into the Sinai Peninsula is a matter of contention: Sheffer et al., 2010 quote an area of 13,000 km^2. Dafny et al., 2010, p. 2 just provide a lower limit of >10,500 km^2; Guttman and Zukeman, 1995 discuss different Israeli models such as Shakhnai, 1980 who extends the basin in the Sinai Peninsula "towards Jabal Hilal and further to El-Arish" while Guttman, 1988 is quoted to have "shifted the boundary from the Boqer Anticline to the structure of the Shalid El-Arish fields" (Guttman and Zukerman, 1995, p. 2) and the basin area is quoted as 10,481 km^2 (Guttman and Zukerman, 1995, p. 14). SUSMAQ reports mostly assume the maximum area size quoted here, but also a slightly smaller area of 14,148 km^2 (PWA and UNuT, 2003b, p. 6). Weinberger et al., 1994, p. 233 extend the area into the Sinai Peninsula as well, but without giving a value for area size.
4. Messerschmid, 2008, and Abusaada, 2011 respectively.
5. The population estimate for the area of the basin situated in Palestine is based on a 2007 population census by PCBS, 2009.
6. PCBS, 2011.
7. The population estimate for the area of the basin situated in Israel is based on a 2008 census by Central Bureau of Statistics in Israel, 2009.
8. Messerschmid, 2010, p. 6.
9. Abusaada, 2011; Messerschmid, 2010, PWA and UNuT, 2001a.
10. PWA and UNuT, 2005, p. 37. See also Avisar et al., 1997. On a local scale, however, many more subdivisions are noticeable (Dafny et al., 2010, p. 6; PWA and UNuT, 2003b; PWA and UNuT, 2003a).
11. The West Bank Anticlinorium is composed of the Anabta Anticline (in the north), the Ramallah Anticline (in the centre) and the Hebron Anticline (in the south). See Overview Map.
12. The Green Line was delineated in the 1949 Armistice Agreements after the 1948 Arab-Israeli war and refers to the demarcation line between Israel and neighbouring countries. The line was maintained as a boundary until 1967, when Israel occupied the Jordanian-controlled West Bank and East Jerusalem, as well as the Egyptian-held Gaza Strip and the Syrian Golan Heights. Today, the part of the Green Line that runs between Israel and the West Bank is used to differentiate between areas administered by the Israeli government and those under the authority of the Israeli military or the Palestinian National Authority.
13. PWA and UNuT, 2002, p. 178.
14. Outcrop calculations by Messerschmid, 2011. Other authors reach similar figures (PWA and UNuT, 2003a; Weinberger et al., 1994).
15. Abusaada, 2011, p. 82.
16. Such as Weinberger et al., 1994; PWA and UNuT, 2001a; Messerschmid, 2010; Abusaada, 2011.
17. PWA and UNuT, 2001a, p. 37.
18. PWA and UNuT, 2001a.
19. PWA and UNuT, 2001a, p. 113.
20. PWA and UNuT, 2005, p. 37. Also see Avisar et al., 1997.
21. Abusaada, 2011.
22. Messerschmid, 2003, p. 6. In the Israeli petroleum industry and the domain of geophysical stratigraphy, the aquitard is also referred to as Yakhini.
23. PWA and UNuT, 2002, p. 178.
24. Ibid., p. 166.
25. PWA and UNuT, 2002.
26. Confined conditions may also be observed locally in the eastern part of the basin, according to PWA, 2012a.
27. Zukerman, 1999 estimates a specific yield range of 1.8% to 8%, while recent model calibrations (Abusaada, 2011) suggest a range of 1% to 7.5%.
28. Guttman and Zukerman, 1995 found storativity to be within a range of 10^{-5} to 10^{-4}. Based on model calibrations, Abusaada, 2011 reports a different range of 10^{-6} to 10^{-5}.
29. Guttman and Zukerman, 1995, p. 19.
30. Dafny et al., 2010; Abusaada, 2011.
31. Ibid. The estimates are based on model calibrations and largely confirm earlier assessments. See Guttman and Zukerman, 1995; Zukerman, 1999 and PWA and UNuT, 2002.
32. Abusaada, 2011.
33. Weiss and Gvirtzman, 2007.
34. Dafny et al., 2010, p. 12, fig.10.
35. PWA, 2011.
36. Abusaada, 2011 reviewed a number of recharge methods and concluded that the method using water level, fluctuation and storage change provides the best estimate for yearly groundwater recharge. The method was used to calculate the long-term annual recharge of 385.2 MCM for the period 1970-2006.
37. Guttman and Zukerman, 1995, in PWA and UNuT, 2003a, p. 49.
38. Water discharging from the Timsah Springs is a mixture of freshwater and seawater. More than 3 MCM/yr of seawater is estimated to discharge from the springs (Paster et al., 2006).
39. Near Be'er Sheva intensive abstraction has altered natural flow lines (PWA and UNuT, 2001a, p. 39).
40. Messerschmid and Abu-Sadah, 2009. The areas of Baqa, Qalqiliya, Rantis and Tulkarm.
41. Messerschmid, 2010.
42. Ibid.
43. Weinberger and Rosenthal, 1994.
44. HSI, 2004 in Paster et al., 2006, p. 157. The values refer to pre-1950s spring discharge.
45. HSI, 2008, p. 221.
46. See also Abusaada, 2011, p. 136.
47. HSI, 2008, p. 211.
48. Paster et al., 2006, p. 164,166.
49. The following criteria are used to assess exploitability in this Inventory: drilling depth/depth to top of aquifer; groundwater level; and water quality/salinity. For more information on the approach, see 'Overview & Methodology: Groundwater' chapter. See Figure 4 for information on water quality. Depth to top of aquifer was determined using the Middle East Geological Map (MEG-Maps), sheet "Cretaceous": the deepest part of the basin reaches 800 m, while the area north of the Afiq Channel is less than 600 m deep. Groundwater level data was not available (see section on Flow regime).

50. Harpaz and Schwarz, 1967, p. 83.
51. According to PWA and UNuT, 2001c.
52. Most sources only provide well numbers for the entire West Bank. Many of the shallow, older production wells have low productivities or are no longer operational and due to Israeli restrictions, only a few have been rehabilitated. PWA and UNuT, 2001b states an average of 144 Palestinian production wells in the Western Aquifer Basin for the period 1980-1999. PWA, 2011 states 137 in 2009.
53. All figures from PWA and UNuT, 2001b. The total figure of 21.3 MCM includes an additional abstraction of around 1.1 MCM by the West Bank Water Department. Palestinian Statistics count domestic and industrial use under municipal supply.
54. According to Schedule 10 of the agreement, the Palestinian allocation of 22 MCM/yr in the Western Aquifer Basin includes 20 MCM/yr of unspecified origin and 2 MCM/yr from springs near Nablus.
55. This assumes that the Palestinian abstraction figures presented in Figure 5 include the spring abstractions near Nablus mentioned in the Oslo II agreement. Otherwise average Palestinian abstractions of 23.7 MCM/yr represent an excess of 3.7 MCM/yr or 18% of the Oslo II value of 20 MCM/yr.
56. According to PWA and UNuT, 2001b there were four Israeli wells with an average annual abstraction of 2.1 MCM in the period 1980-1999. PWA, 2011 stated that Israel absracted 2 MCM annually from five wells in the West Bank.
57. PWA, 2011.
58. PWA, 2012b, p. 22, 81.
59. Ibid., p. 17, 23. According to IWA, 2012 a slightly lower quantity of 52.6 MCM was provided to the Palestinian Authority in the West Bank in 2010; Palestinian water purchases from Mekorot have risen steadily from 27.9 MCM in 1995.
60. Zeitoun et al., 2009.
61. PWA, 2011. More than 500 Israeli wells according to PWA and UNuT, 2001c.
62. Data on Israeli abstractions was provided by PWA, 2012a and is based on records of the Hydrological Service of Israel for the various groundwater cells in the Western Aquifer Basin. Some doubt remains as to whether the data sets represent Israeli abstractions only as Palestinian sources affirm. The data sets may also include Palestinian abstractions in the West Bank, though it is not clear which level of abstraction is assumed. In the latter case, all Israeli values in the text need to be corrected (reduced) accordingly.
63. Assuming Palestinian abstractions of 23 MCM/yr; PWA, 2011 states the same percentage.
64. Data on spring discharge in Israel provided by PWA, 2012a.
65. The Israeli allocation of 340 MCM in Schedule 10 of the agreement does not specify the origin of utilized water (i.e. from wells or springs). It is, however, specified for the Eastern and North-Eastern Aquifer Basins which are also covered in Schedule 10.
66. All water use figures in this paragraph are from the data set provided by PWA, 2012a. See note 62 as well. If the data sets include Palestinian abstractions in the West Bank, Israel's average annual abstraction since 1995 would have to be corrected (reduced) accordingly.
67. HSI, 2008.
68. Zeitoun et al., 2009.
69. HSI, 2008, p. 221.
70. Israel's National Water Carrier is a 200 km conduit that conveys water from Lake Tiberias in the Jordan River Basin to urban centres along the Israeli coast and further south to the Negev (Al Naqab). See Chap. 6 for more information.
71. Central Bureau of Statistics in Israel, 2012. See Chap. 6 for more information on sectoral water use in Israel.
72. Zeitoun et al., 2009.
73. Particularly the sewage from Jerusalem. For 40 years, untreated sewage has flowed into the streambed of Nahal Soreq, located west of Jerusalem in the Western Aquifer Basin recharge area (Haaretz, 2008).
74. FoEME, 2004.
75. Ibid.
76. In the following approximation, average annual outflows are composed of Israeli and Palestinian abstractions and discharge of major springs. Israeli abstractions (366.5 MCM) and spring discharge (44.4 MCM) for the period from 1970-2006 were calculated from the data set provided by PWA, 2012a as presented in figures 3a and 6. Due to the lack of data prior to 1995, Palestinian abstractions were assumed to be 23 MCM/yr throughout, giving a total average outflow of 433.9 MCM/yr. Inflows considered in the approximation include recharge from rain, which amounted to 385.2 MCM/yr on average for the period 1970-2006 according to Abusaada, 2011. An additional average inflow of 14.5 MCM/yr for the same period stems from artificial groundwater injection to groundwater cells 210 and 211 as listed in the data set provided by PWA, 2012a. The remaining deficit amounts to 34.2 MCM.
77. The deficit is only a rough approximation and may even represent a serious over-estimation as Israeli abstractions in the PWA, 2012a data set may already include unspecified Palestinian abstractions in the West Bank (see note 62 above), in which case Palestinian abstractions would have been counted twice as outflows. If a correction of 23 MCM is made, the remaining overall deficit amounts to only 11 MCM/yr or 3% of recharge. Given the uncertainties and errors inherent in all of those estimates, a 3% gap may not be sufficient to conclude that there is over-abstraction from the aquifer.
78. PWA, 2012a provided water level data for groundwater cells 210, 211, 212, 214, 220 and 230 for the period 1964-2007. While a falling trend due to over-abstraction can be observed throughout much of the observation period, water levels rose after the wet winters of 1991/92 and 2002/03.
79. The Madrid Conference, which was held in Spain in October 1991, was led by the United States of America and jointly sponsored by the Soviet Union. Its aim was to initiate a negotiated peace process involving Israel and Palestinians, as well as other Arab countries, including Jordan, Lebanon and Syria. The conference comprised negotiations on various issues, including shared water resources and is considered the catalyst for the later Oslo Accords (Hiro, 2003; MERIP, 2012).
80. Israel and the PLO, 1993, Annex III, partly focuses on cooperation in the field of water and mentions the joint establishment of a water development programme as a basis for cooperation on water management, water rights and the equitable use of joint water resources.
81. Israel and the PLO, 1995, Annex III, Article 40.
82. The additional quantities of water described in the agreement are: 28.6 MCM/yr, to be made available immediately and 70-80 MCM/yr to be made available over the interim period until 1999/2000 (Israel and the PLO, 1995, Annex III, Article 40, Paragraph 7).

83. Israel and the PLO, 1995, Annex III, Article 40, Schedule 11.
84. Israel and the PLO, 1995, Annex III, Article 40, Schedule 8.
85. Zeitoun, 2008.
86. Israel and the PLO, 1995, Annex III, Article 40, Schedule 8.
87. Ibid.
88. Rouyer, 2000.
89. Selby, 2003. Similarly, Amnesty International, 2009 refered to JWC as a pretence of cooperation.
90. World Bank, 2009.
91. The discussion took place as part of the panel "Cross-Border Waters and Regional Sustainability" moderated by Gidon Bromberg, Israeli Director of Friends of the Earth Middle East. The Palestinians have suspended their participation in JWC since September 2011, arguing that the committee is unable to effectively address any water-related issue. A number of sub-committees are still active but the main decision- making body is not working.
92. According to Bromberg's conclusion of the meeting. See EMWIS, 2012.
93. Following the Oslo II agreement, the West Bank was split into three Areas A, B, and C, with different security and administrative arrangements and authorities (Israel and the PLO, 1995, Article 11) Area C is under full control of the Israeli military for both security and civilian affairs related to territory, including land administration and planning. See Chap. 6, Box 11 for more information.
94. In Camp David (July 2000), water negotiations did not reach the level of specific technical discussions on allocations. At Annapolis (2008/09), only exploratory negotiations in the domain of water were initiated.
95. IWA, 2012. However, most of the wells are located outside the Western Aquifer Basin.
96. Phillips et al., 2007, p. 250.
97. Rothem, 2008. In the context of future negotiations towards a final status agreement, Israel has proposed land swap deals to compensate Palestinian loss of land in the West Bank as a result of settlement activity.
98. Israel's separation barrier, constructed mainly in the West Bank, east of the 1967 Green Line, further diminishes Palestinian access to the productive zone of the aquifer. See Messerschmid and Abu-Sadah, 2009, p. 16.

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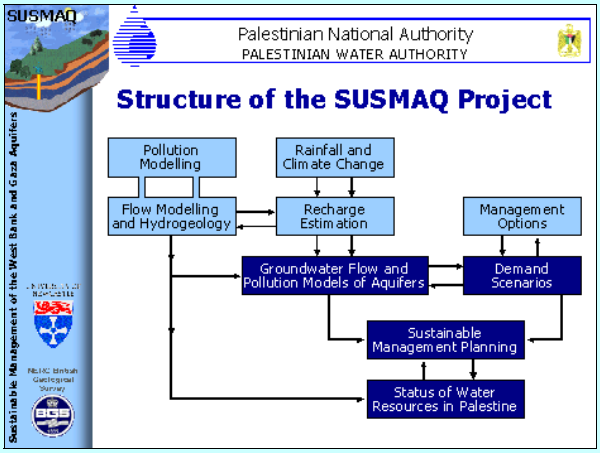
Abstract

The Flow model is created in 2 steps. First a conceptual model assesses stratigraphy, lithofacies and structure of the basin, the distribution, connections and parameters of aquifers and the cell size, boundaries and geometry of the model. In a second step, when the conceptual model is transformed into a numerical model set-up, a steady state run is executed and calibrated for various parameters, most of all the aquifer properties, but also the recharge and water levels. This numerical model uses Geo-Modelling-Software (GMS) and serves as a basis of subsequent transient conditions models.



Introduction

The SUSMAQ project on the Sustainable Management of the West Bank and Gaza Aquifers for the first time assesses this basin. Due to the severe restrictions to Palestinian water use from this basin, the Palestinians have never thoroughly investigated its geology and hydrogeology.

Flow Modelling in the Western Aquifer Basin is crucial for future water supply of the Palestinians, since this basin is a shared groundwater basin between Palestine and Israel, the largest and most productive groundwater basin in both, Israel and Palestine and therefore will play a key role in future water negotiations.

In addition, Management Options used to develop several demand scenarios that then are integrated together with the results from the Flow Model create a Sustainable Management Planning platform for the water resources in the Western Aquifer Basin.

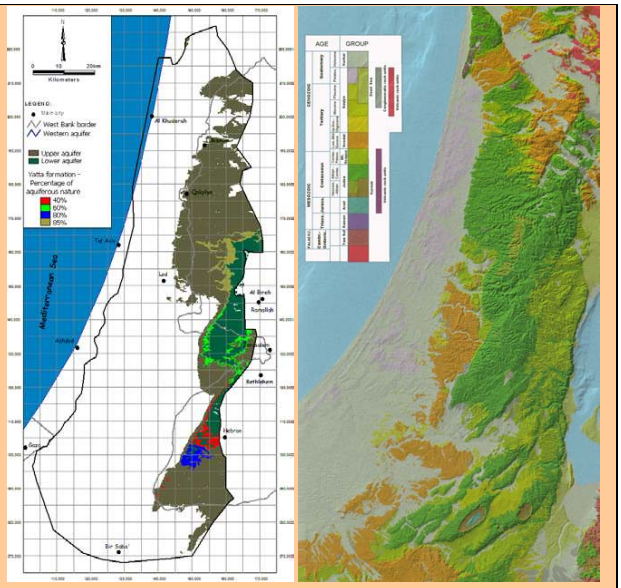
Geology

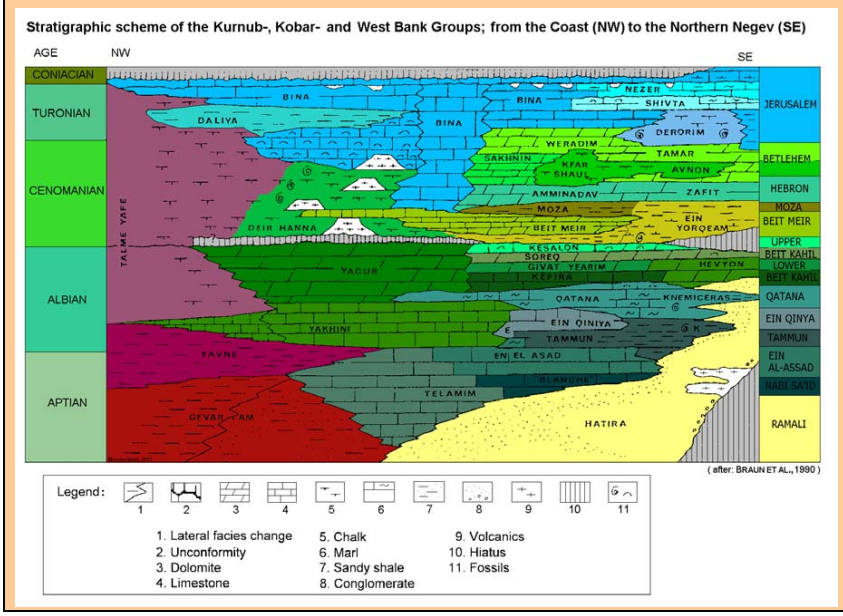
The basin consists of carbonates form the Upper Albian (Lower Aquifer) and Middle Cenomanian to Turonian (Upper aquifer), separated by Lower Cenomanian clays and marls of tens to hundreds of metres thickness. The oldest formations crop out in the Ramallah and Hebron anticlines along the Eastern border, Cenomanian outcrops are concentrated in the foothills region and parts of the Negev, while in the Coastal Plain the aquifer system is covered and partly truncated by 100's of metres of Senonian and Eocene chalks and Neogene to Quaternary pelitic clastics (Saqiye group).

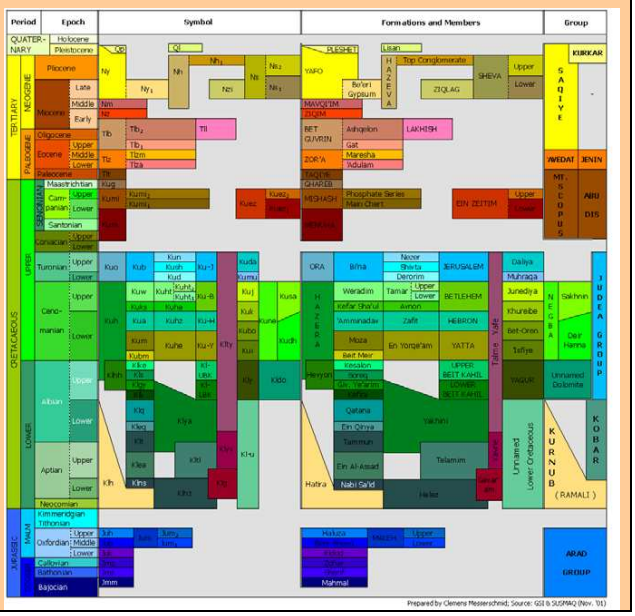
Aquifer formation	Outcrop size	Aquitard formation	Outcrop size
Upper Albian	292.4 km^2	Lower Cenomanian	165.7 km^2
Middle Cenomanian - Turonian	1366 km^2	Senonian – Quaternary	4210.5 km^2

In more detail, the actual situation is a complicated pattern of different lithofacies types and terminologies that up till now have not been unified completely (see diagrams below).

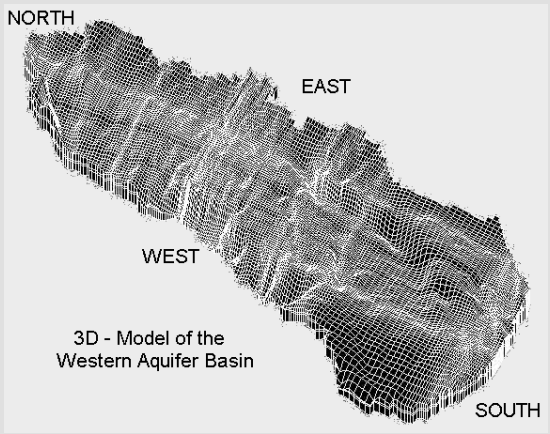
The middle aquiclude Yatta formation (or Beit Meir / Moza formations) crops out in moderate elevations (300-500m) in the West Bank and West of Jerusalem. Not all of Yatta is an aquitard, though. Therefore, zones of different aquifer potential were differentiated to quantify possible rainfall recharge over this formation (see right).





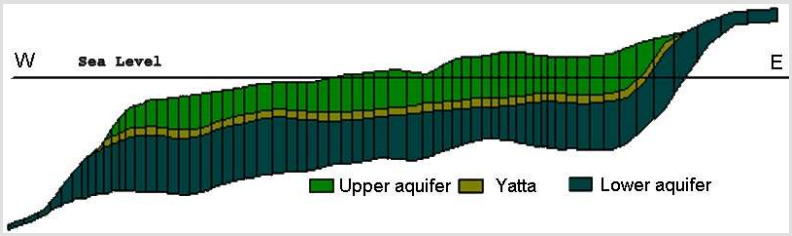


C. Messerschmid, A. Aliewi, A. Kalbouneh, R. Yasin, M. Abu Sadah – Ramallah, 2001

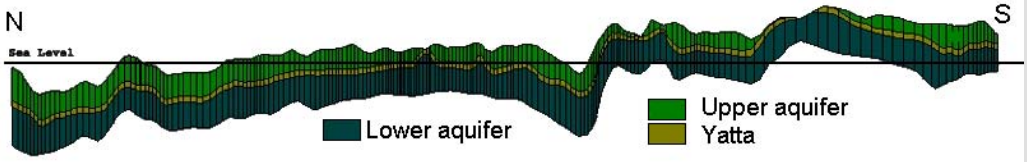


Basin geometry

Top and Bottom of the aquifers were constructed by structural contour maps. Over 16000 data points were chosen and inserted to give a reliable geometry. The middle aquitard, so far was inserted at known locations (well logs, etc.) and interpolated in between. Major faults yet have to be included in the model set-up.



The average aquifer thickness is around 800m, including some 100m of the middle aquitard. In the south, the thickness is reduced to only 500m. Under the coastal plain and due to the truncation by the Saqiye group, the thickness is also reduced, sometimes strongly

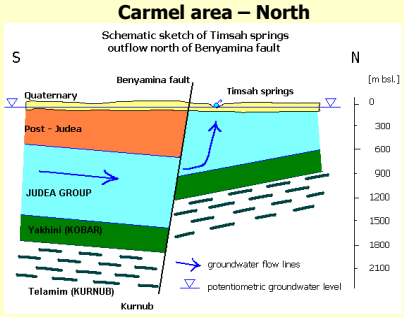


Boundaries

Detailed studies were executed to assess position and type of the aquifer boundaries. In addition to geological map and field experience, geological cross-sections were constructed at different areas. The variety of boundary types reflects the structural and lithological diversity of the area.

- GW divides: In the North, Northeast and parts of the Jerusalem and Hebron anticlines
- Most of the 2 anticlines (E) and presumably the Negev area (SE) are structural divides
- The West is bounded by Talme Yafe stratigraphic divide
- The Southern end of the Model area is built by Afiq Channel
- The strongly throwing Benyamina fault (700m) constitutes an internal tectonic boundary near the Northern natural outlet – Taninim (Timsah) springs (see right)

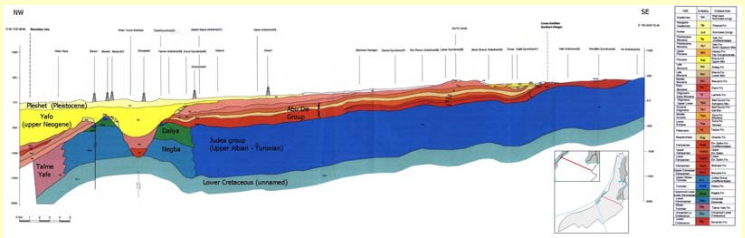
Carmel area – North



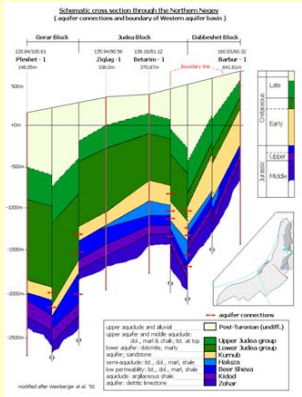
Benyamina fault creates aquifer connections to the Pleistocene and subsequent outflow in low areas

Afiq-Channel – South

This Neogene erosion channel, filled with impervious clastics and evaporites dissects the aquifer completely over 10.5 km length and partly for another 20 km. It is modelled therefore as specified flow boundary



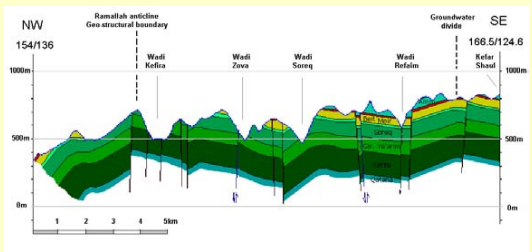
Negev – Southeast



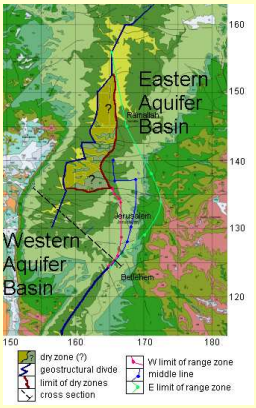
In parts of the Negev, due to over-pumping, Aquifer connections to the Lower Cretaceous Sandstone and partly Jurassic aquifers lead to saltwater intrusion hazards. (→)

Jerusalem area – East

The cross section shows, that SW flow is enabled, assuming water levels not below 400m asl (as in Ein Kerem well field).

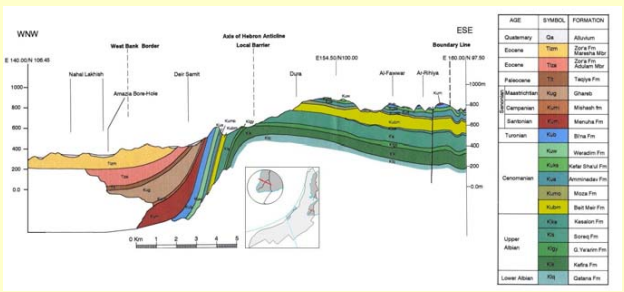


A sub-basin within the Western Aquifer opens in the area between the boundary to the Eastern Aquifer and the southern continuation of the Ramallah anticline to its West. (→)

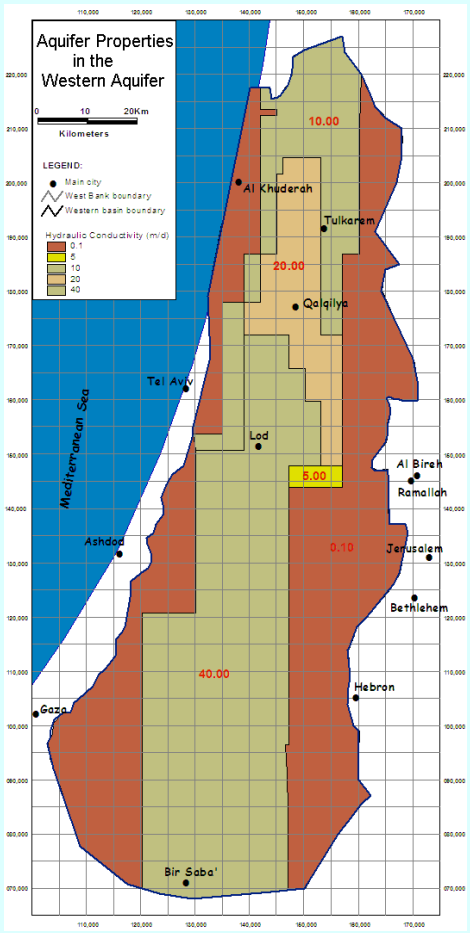


Hebron area – East

Analogue situation in the southern Hebron area, where the apex of the anticline, a SW-directed thorn, constitutes the western boundary of a sub-basin within the Western Aquifer. The main boundary lies further east.



C. Messerschmid, A. Aliewi, A. Kalbouneh, R. Yasin, M. Abu Sadah – Ramallah, 2001



Aquifer characteristics

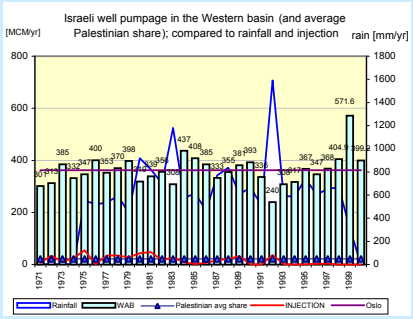
Aquifer properties have not yet but coarsely been estimated. As a next step, the steady state model calibration will target on porosity, transmissivity and storativity.

← Hydraulic Conductivity

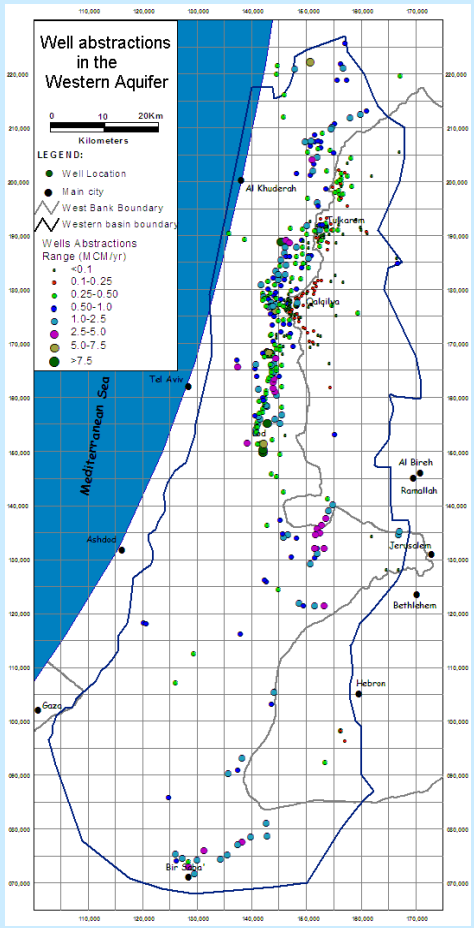
Horizontal and vertical Conductivity was defined according to existing studies and own estimates. Horizontal conductivity is locally increased around the main springs (Yarkon or *Al-'Auja* and Taninim or *Timsah*). It is regionally decreased in the West Bank Mountains recharge area and along the coastal Talme Yafe facies barrier.

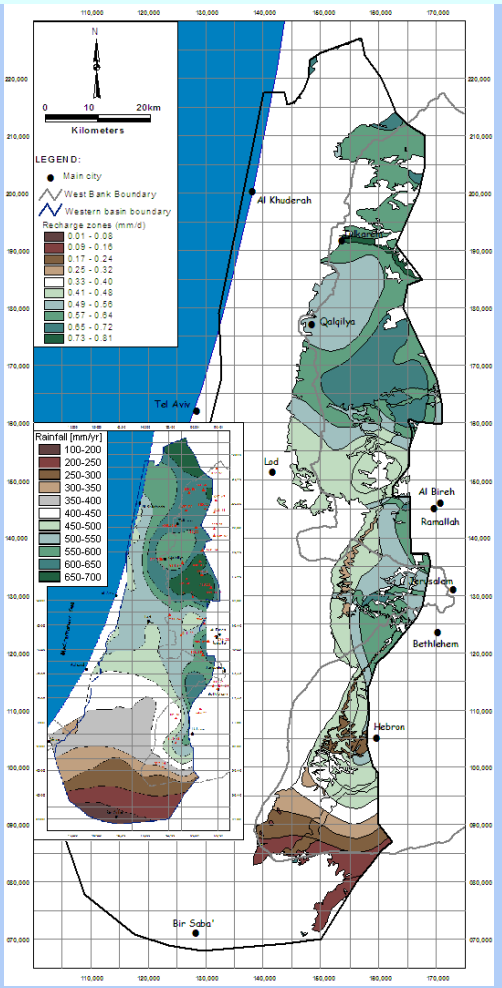
Well files

Historical well abstractions increased drastically in the 1950s and '60s and still rise (1999: 572 MCM). Conversely, natural spring flow has dropped to a small fraction of its natural flow, i.e. from over 300 MCM/yr to now less than 50 MCM/yr.



Over 90% of the pumpage stems from Israeli controlled wells. The abstraction rates and their spatial distribution are crucial for running a transient flow model. The map shows the pumping rates of 1996.

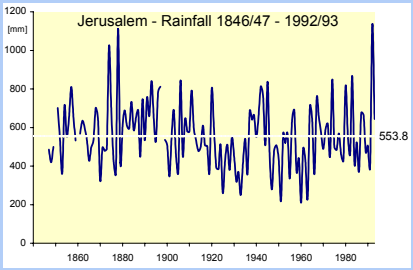




Time series data

Rainfall and recharge

Rainfall (small map) has a clear distribution, with its maximum (>600mm) in the central and northern West Bank. Towards the S, SW and W rain heights sink to small portions (<200mm).



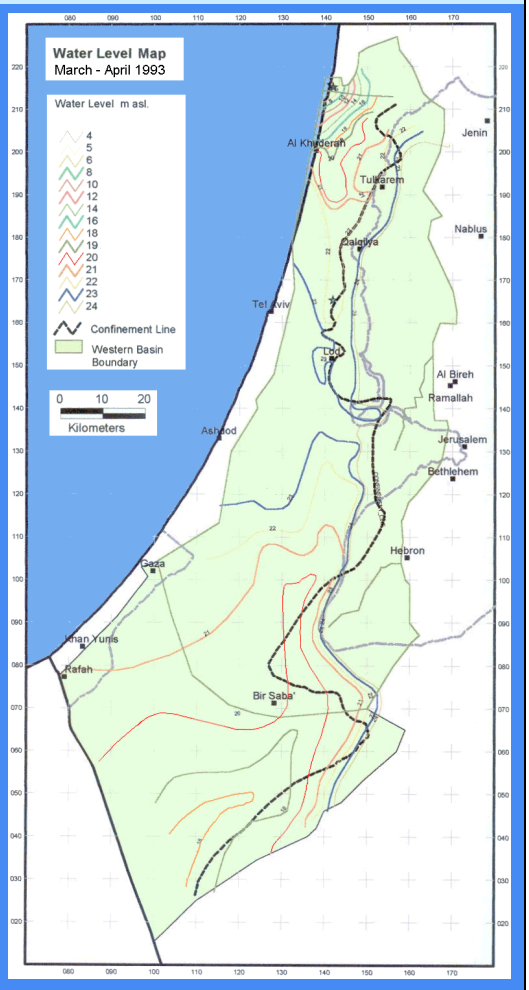
Recharge strongly correlates to the amount of rainfall.

In addition, intensity and duration of rain events are taken into consideration. Also, the lithology of the outcropping formation, soil and vegetation cover and land use are important factors. Slopes rule the run-off. Less important factors are the distribution of temperature and other climate factors, because rain almost exclusively occurs in the cold season and direct rain infiltration recharge occurs in areas with similar winter climate conditions.

Infiltration over Yatta aquitard was divided into different rates, according to its aquifer potential. The Upper and Lower aquifers mainly crop out in the West Bank, where >90% of recharge take place as direct rainfall recharge.

Water levels

Time series data on water levels will be studied for the transient run numerical model. The water levels will have to be differentiated to the Upper and Lower aquifers respectively. For this, a better understanding of the aquifer connections is required. Therefore, the target of the steady state calibration will include the aquifer connections, by vertical conductivity and fault connections, besides the above mentioned aquifer parameters.



C. Messerschmid, A. Aliewi, A. Kalbouneh, R. Yasin, M. Abu Sadah – Ramallah, 2001

Appendices of chapter 3

Wadi Natuf – Hydrogeological Frame

3.1 Field measurement campaign (SUSMAQ # 48)

3.2 Perched springs (SUSMAQ # 65)

Palestinian National Authority
Palestinian Water Authority

السلطة الوطنية الفلسطينية
سلطة المياه الفلسطينية

Sustainable Management of the West Bank and Gaza

UNIVERSITY OF NEWCASTLE

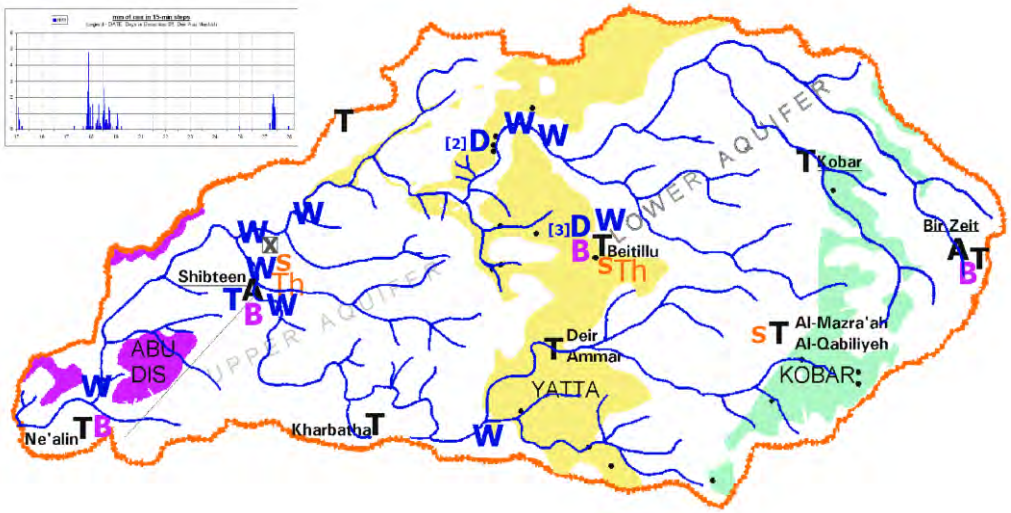
NERC British Geological Survey

Department for International Development

DFID

Field Measurement Campaign for Wadi Natuf Recharge Estimation:

Field Observations



Final Report
SUSMAQ-NAT # 48 V 0.3

Prepared by:

SUSMAQ TEAM

Palestinian Water Authority, Palestine
Water Resource Systems Research Laboratory
University of Newcastle upon Tyne, UK

August 2003

Disclaimer

This work report is an output from the Natuf Recharge Estimation Component, part of the SUSMAQ project.

Work reports are designed to present and to communicate the results of work on the SUSMAQ Project without delay. The findings, interpretations and conclusions expressed are those of the authors (the team) and should not be attributed to other collaborators on the SUSMAQ project.

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The SUSMAQ Project

The aim of the project is to increase understanding of the sustainable yield of the West Bank and Gaza aquifers under a range of future economic, demographic and land use scenarios, and evaluate alternative groundwater management options. The project is interdisciplinary, bringing together Hydrogeologists and groundwater modelers with economists and policy experts. In this way, hydrogeological understanding can inform, and be informed by, insights from the social sciences. The results of the study will provide support to decision-making at all levels in relation to the sustainable yield of the West Bank and Gaza aquifers.

The project runs from November 1999 to October 2004, and is a partnership between the Palestinian Water Authority, University of Newcastle and British Geological Survey. The project is funded by the United Kingdom's Department for International Development (DFID).

Recharge Estimation in Wadi Natuf

The Recharge Estimation in Wadi Natuf catchment area is part of the SUSMAQ project.
The Recharge Assessment focuses on a catchment stretching East of Birzeit down to the Green Line.
It aims at a better understanding of the mechanisms that control recharge as well as its quantities. A Field Measurement Campaign produces primary data, covering meteorological data such as rainfall and evaporation, surface water data such as run-off, groundwater data such as spring discharge, water levels and water quality of surface, groundwater and other hydrogeological data such as karst features, aquifer characteristics and vulnerability.
The report documents the background, objectives, design and work plan for the measurement campaign in winter 2003/2004.

Bibliographical Reference

This report should be referenced as SUSMAQ (2003). Conceptual Model of Wadi Natuf Groundwater Recharge. Working Report No.: **SUSMAQ-NAT #64 V0.3.** Sustainable Management for the West Bank and Gaza Aquifers, Palestinian Water Authority (Palestine) and University of Newcastle upon Tyne (UK).

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– Excerpts –

Table of Contents

page

1. Scope and objectives **1**

2. Hydrogeological background of the Natuf catchment **2**

2.1 Location 2
2.2 Rainfall and runoff 2
2.3 Geology and aquifer system 2
2.4 Typical land forms of formations in the study area 5
2.5 Wells 8
2.6 Springs 9

3. Methodology **11**

3.1 Desk Study 11
3.2 Field investigations 11
3.2.1 Topography and land use investigations 11
3.2.2 Geological investigations 12
3.2.3 Hydrological investigations 12
3.2.4 Hydrogeological investigations 13
3.3 Methods of analysis 14

4. Work plan and staff (*not included here*) **14**

5. Literature **14**

List of Tables

Table 1: Comparison of Israeli and Palestinian formation names 4
Table 2: Literature data on springs in Wadi Natuf (from Summary of Palestinian Hydrologic Data 2000, PWA) 11

List of Figures

Figure 1: Drainage of Wadi Natuf 1
Figure 2: Ground elevations in Wadi Natuf 2
Figure 3: Dirt road after high intensity rain (March 19, 2003) in Wadi Shabbabeh 3
Figure 4: Simplified geological map of Wadi Natuf 5
Figure 5: Low. LBK (Kefira) in Ein Arik; karstified and massive bedding 6
Figure 6: Up. LBK (Giv'at Ye'arim), low. UBK (Soreq) at top of hill (W Kobar) 6
Figure 7: Yatta (Beit Meir/Moza), Hebron (N Deir 'Ammar) 6
Figure 8: Lower Yatta (Beit Meir) (NE Deir 'Ammar); Natural terraces 6
Figure 9: Lower Bethlehem (Kefar Sha'ul) over Hebron (NE of Nili, SE Shibteen 7
Figure 10: Hebron karst (3km E Jammala) Soil pockets between isolated rocks 7
Figure 11: Hebron, Bethlehem (Kefar Sha'ul/ Weradim) (View at Nili road) 7
Figure 12: Upper Bethlehem (Weradim) over Hebron; Wadi Hammameh [Wadi Zarqa] 7
Figure 13: Lower lower Bethlehem (Lower Kefar Sha'ul) W of Deir Nizam 7
Figure 14: Upper Bethlehem (Weradim) at Nili settlement; Barren, karstic slopes 8
Figure 15: Hebron, Upper Bethlehem (Weradim), Jerusalem at top; Wadi Hammameh 8
Figure 16: Upper Bethlehem (Weradim), top of hill: Jerusalem (NW of Shibteen) 8
Figure 17: Overview map of different landforms, typical for geologic formations 9
Figure 18: Springs in Harat Al-Wad (Beitillu) 10
Figure 19: Springs in Wadi Zarqa 10
Figure 20: Measurement location map 12

(*not all figures included here*)

1. Scope and Objectives

The Sustainable Management of the West Bank and Gaza Aquifers (SUSMAQ) Project includes a major component called, "Recharge Estimation". The objective of this component is to provide estimates of groundwater recharge to the West Bank aquifers and vertical flows between aquifer units. Recharge is a key element in the modelling of the groundwater system of the Western Aquifer Basin and without it the model will lack accuracy. Recharge estimation plays a vital role for the understanding and quantification of groundwater resources. In the karstified series of the outcropping formations of the Western Aquifer Basin (WAB), a highly complex pattern of recharge is to be expected. Lack of reliable data from the literature makes it necessary to further investigate this component in modelling the groundwater system of the WAB. Intensive fieldwork in a chosen study area will provide primary data on the factors that govern recharge.

Up to this time, there is no comprehensive assessment of recharge in Palestine that is based on fieldwork and primary data. The available literature on recharge provides broad assumptions that recharge as just a percentage of rainfall. Recharge fieldwork is still missing. Therefore, this document is about generating primary data (e.g., field data) about recharge in the West Bank aquifers.

In the light of the above, the importance of carrying out fieldwork for recharge estimation can be summarised as follows:

- The flow and pollution models of SUSMAQ will not produce accurate results if the recharge estimation is not based on primary data generated in the field;
- The primary data generated from this research will help validate the Recharge Model that will be developed by the BGS.

This research is about undertaking fieldwork for recharge estimation in an experimental catchment in the Western Aquifer Basin (called the Natuf catchment). The idea is to instrument a Wadi within the Natuf catchment near Ramallah (see Figure 2) as a means of collecting good primary data for use in recharge estimation. The political unrest in the West Bank has made it difficult to travel freely in the West Bank and Israel in order to carry out work in the Western Aquifer Basin as a whole. Therefore, the relatively easy access to the Natuf catchment in addition to diverse hydrogeological features was behind choosing this catchment. The salient points about this catchment include:

- Relatively small in area (~100 km^2),
- Presence of outcrops of the upper and lower aquifers and the dividing "aquitard" (Yatta formation), and of some outcrops of the under- and overlying aquicludes (Kobar and Abu Dis groups),
- One production well and two monitoring wells (with monthly level and pumpage data),
- Several hundreds of small springs and groundwater outlets,
- Relatively easy and quick access from Ramallah,
- Populated by 19 Palestinian villages and 7 illegal Israeli settlements.

It is realised that the recharge estimation for the Natuf Catchment of the Western Aquifer Basin will provide a good understanding about recharge in this basin. This understanding will be used within a GIS framework to extrapolate the results across the WAB. However, the findings of this work should encourage more recharge fieldwork in other catchments of WAB so that the results can be integrated to provide a comprehensive recharge map for the whole basin.

The objectives of the Natuf catchment study are:

- To instrument Wadi Natuf catchment near Ramallah as a means of collecting good primary data for use in recharge estimation;
- To use the results from the field programme in order to provide insight into the recharge processes
- To provide data for the Recharge Model under development by the BGS;
- To train the involved PWA staff in both the fieldwork and in how to analyse the primary data in order to estimate recharge.

2. Hydrogeological background of the Natuf Catchment

2.1 Location

The proposed study area is called Wadi Natuf (Figure 1). It is a sub-catchment of the Western Aquifer Basin (WAB or 'Auja-Tamasih aquifer), with its most eastern mountainous part already belonging to the Eastern Aquifer basin (EAB). The catchment is located north-west of Ramallah and within the western surface drainage area of the West Bank. The drainage of Wadi Natuf is split into a northern branch and a southern branch, each with several minor tributaries. The branches meet near the Shibteen well field (Figure 1).

The surface of the study area (upstream of the Shibteen wells) is around 100 km^2. The catchment lies at an elevation between 138m asl at the outflow of Wadi Natuf and 816m asl at the Birzeit University – New Campus on the Eastern border of the catchment (Figure 3).

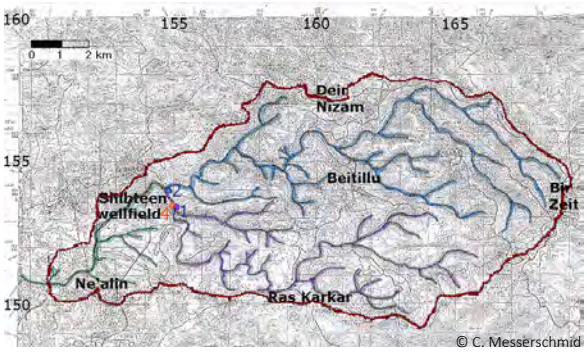


Figure 1: Drainage of Wadi Natuf (coordinates in Palestinian grid PGE/PGN)

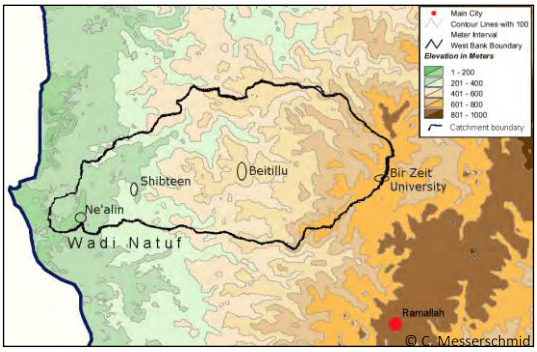


Figure 2: Ground elevations in Wadi Natuf

2.2 Rainfall and Runoff

The climate is typically Mediterranean with hot dry summers and moderate to cool rainy winters. The precipitation reaches remarkable amounts and intensities during the rainy season. In addition, rainfall exhibits a strong spatial variation. Both result in a high spatial and temporal variability of runoff and Wadi flow. Field evidence shows that a certain threshold of soil saturation has to be surpassed to trigger runoff in the Wadi, which occurs a few days per season as storm runoff and floods, at times reaching violent flow regimes. Figure 3 shows a strong flow after torrential rain in Wadi Dilb (Shabbabeh) in March 2003. This Wadi is located 1km south of the catchment.

Figure 3: Dirt road washed after rain of high intensity (March 19, 2003) in Wadi Shabbabeh

In other Wadis, like Wadi Zarqa, flow is sometimes supported by spring flow from local springs. Many ephemeral and permanent springs emerge from the outcropping aquiferous formations, especially the lower part of Yatta (*Beit Meir*) and the upper part of Upper Beit Kahil (*Kesalon*) formations. These springs are fed by infiltrating rainwater that does not percolate to the regional water table of the aquifer system due to impermeable substrata (mainly yellow marl) or due to increased permeabilities along karstic fractures, channels and pistons). Only few springs are measured occasionally but no springs have been measured regularly in Wadi Natuf so far.

In addition to the rainfall distribution, lithology and karst development, other factors play a decisive rule in runoff generation, such as soil type and thickness, slopes and terraces, land use and sealing of surface etc.

2.3 Geology and Aquifer System

The study area is located within the Mountain Aquifer system (partly WAB and EAB), which is composed of thick sequences of layered limestone, dolomite, chalk and marl. The main outcrop formations belong to formations of the Albian to Turonian age (Figure 4).

In general, the Western Mountain Aquifer formations crop out on the western flanks of the major anticlinal structure that builds up the West Bank. The dip of the formations is steeper than the average slopes, and the stratigraphically lower formations at the axis of the anticline outcrop at the highest elevations, near the crest of the West Bank. Two major aquifer systems can be differentiated, divided by series of impermeable and aquitardal lithologies, such as marl, clay and chalk (Table 1).

Both aquifers, but especially the Lower Aquifer, display strong features of karstification in both the outcrops and subcrops, such as schratten and karren, karstic channels and caves, sinkholes, etc.; although, the nature of the karst – active or paleokarst as well as its degree - remains to be investigated.

Below is a brief description of the formations encountered in the Natuf catchment – see also Table 1 (normal font style for Palestinian formation names, *italic font* style for Israeli formation names).

- **Lower Beit Kahil** (*Kefira* and *Giv'at Ye'arim* formations): Around 240 m thick karstified carbonates with about 70 m brown hard dolomite in its upper part and measured 166 m thick hard limestone and dolomite, with an increase of somewhat marly layers towards the bottom in the lower part of the formation.
- The **Upper Beit Kahil** (*Soreq* and *Kesalon* formations): The lower section is a 100 m thick rhythmic sequence of mainly soft yellowish dolomite in dm- to m- thick banks, intercalated by cm- to dm- thick marly layers. The upper portion (about 20 m) of the formation is very hard dolomite of reefal origin that forms a prominent cliff in the landscape. Upper and Lower Beit Kahil together form the Lower Aquifer complex. However, the Soreq formation (or lower Upper Beit Kahil) is considered an aquitard, due to its marly intercalation. Accordingly, many springs emerge within the outcrop (recharge) area of the aquifer, fed by a perched water table, within upper UBK (*Kesalon*) formation that gives rise to springs at its bottom, where it is underlain by yellow marls of the rhythmic marl-dolomite alternation that characterizes lower UBK formation (*Soreq*). Beit Kahil stands almost entirely in the Albian. Some doubts remain as of the age of Upper UBK (*Kesalon*), while the above following Lower Yatta (*Beit Meir*) formation (which forms the main body of Yatta formation) is of Early Cenomanian age, at some places uppermost Albian to Cenomanian.

Table 1: Comparison of Israeli and Palestinian formation names in the Natuf area

Palestinian name	Israeli symbol		Israeli name
Abu Dis Group	Kum		Mt. Scopus Group
Jerusalem	Kub	Kub I Kub II	Bi'na
Bethlehem	Kuw		Weradim
	Kuks	Kuks b) Kuks a)	Kefar Sha'ul
Hebron	Kua		'Amminadav
Yatta	Kumo		Moza
	Kubm		Beit Meir
Upper Beit Kahil	Kuke		Kesalon
	Kus		Soreq
Lower Beit Kahil	Kugy		Giv'at Ye'arim
	Klk		Kefira
Qatana	Klq		Qatana
Ein Qinya	Kleq		Ein Qinya
Tammun	Klt		Tammun

- **Yatta** (*Beit Meir* and *Moza* formations) is generally considered the regional aquitard that separates the Lower Aquifer from the Upper Aquifer. Its upper 10 to 15 m thick yellowish marls and sometimes clays (*Moza*) form the aquiclude. The colourful facies of the main, up to 110 m thick part (*Beit Meir*), consisting of dolomite, limestone, marl, chalk, quartzolite and chert, gives rise together with *Kesalon*, to many perched springs and therefore must be considered an aquifer rather than an aquitard on the local scale.
- **Hebron** ('*Amminadav*) and **Bethlehem** (*Kefar Sha'ul* and *Weradim*) formations are sometimes difficult to distinguish in the field, for several reasons:
  - The 160 m thick Hebron formation appears in two different facies, as hard, grey, cliff-building bioclastic limestone and as dark-grey, thin-layered dolomite facies. Hebron often develops strong karstification, especially its limy facies.
  - The middle unit – Lower Bethlehem (*Kefar Sha'ul*) is missing at times or can reach up to 180 m thickness. It comprises of 2 units: a lower marly and chalky unit with limestone and a Nari

cover, and an upper, thin-layered unit of yellow and red limestone that is used as plates for plastering.

- The upper part (*Weradim*) is composed of 30 m dark, mainly coarse grained, sometimes bioclastic dolomite. Where Lower Bethlehem (*Kefar Sha'ul*) is missing and Hebron is overlain directly by upper Bethlehem (*Weradim*), the formations are difficult to be distinguished. Hebron is part of the Upper Aquifer where the Lower Bethlehem (*Kefar Sha'ul*) is either missing, or is standing in a limy facies or is sufficiently jointed and fractured. Otherwise, upper Bethlehem builds the lower part of the Upper Aquifer.

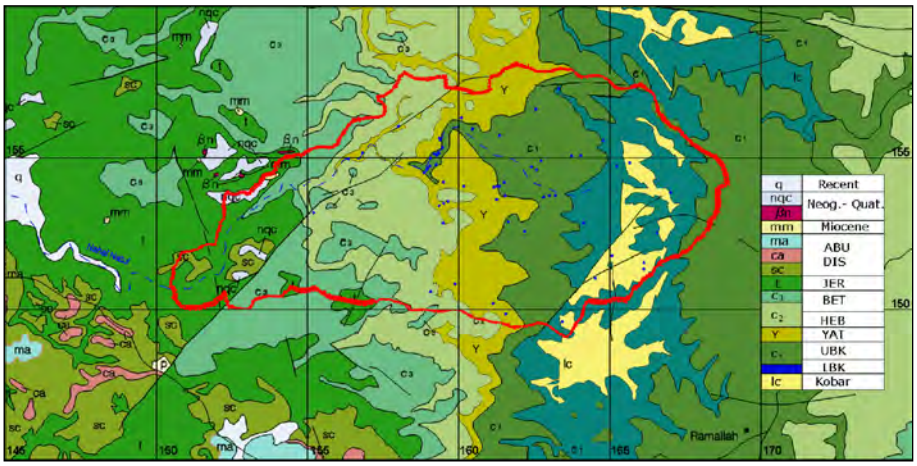


Figure 4: Simplified geological map of Wadi Natuf

- **Jerusalem** (*Bi'na* formation): Cliff-forming, hard, often stilolithic, white and creamy limestone is characterised by fine bedding (0.4 –0.5 m). The rock, that is used for building (Jerusalem-stone) is highly karstified and thus has an excellent hydraulic conductivity. It reaches between 100 m and 150 m thickness and is of Turonian age. It forms the upper part of the Upper aquifer and is overlain by the Senonian impermeable chalks of the **Abu Dis** (*Mount Scopus*) Group.

2.4 Typical land forms of formations in the study area

The assessment and categorization of different landforms (also known as land use and land cover types - LU/LC) and their attribution to geological formations, where possible, is an important step towards better understanding the recharge mechanisms and quantities in the study area. This is because landform and land use is one of the most important factors that rule the initial percolation of rainwater into the ground (surface/subsurface processes). Landforms in Wadi Natuf are of very high variety. Therefore, and for the purpose of attributing landforms to formations, a simplification of the different landforms is necessary and the description below should be considered tentative only. However, it is useful to assign different typical landforms to the formations (Figure 17) since this factor has strong effects on the recharge processes and consequently recharge quantities. In addition, it should be noted, that the "typical landforms" assigned here to the geological formations are valid and verified only for the Natuf study area and cannot be transposed and applied to the entire West Bank.

Lower LBK (*Kefira*) is a karstic carbonate, often with solution holes in abundance on the outcrop (Figure 5). This reduces its quality as agricultural land somewhat because percolating rain water is led rapidly into depths not reachable for plants and trees. However, in some areas, terracing with olive trees still exists, as around Kobar.

Upper LBK (*Giv'at Ye'arim*) is more favourable to terracing and extensive olive groves are found on the slopes of its outcrops (Figure 6). Two types of bedding are observed: Massive bedding that makes terracing more difficult and bedding in the decimetre-scale that tends to create "natural terraces" on the slopes.

Figure 5: Lower LBK (*Kefira*) in Ein Arik; karstified and massive bedding

Figure 6: Up. LBK (*Giv'at Ye'arim*), Lower UBK (*Soreq*) at top of hill (W Kobar) – excellent terraces

Lower Upper Beit Kahil (*Soreq*) with its marl-dolomite alternation is the most terrace-forming formation of the entire sequence. Abundant terraces are found on its slopes and in the plains, also agricultural crops are planted on this formation.
Upper Upper Beit Kahil (*Kesalon*) is a thin formation that builds a well discernible cliff between the softer formations above and below. Due to its reduced outcrops and the cliff, it cannot be considered a predominant farming area. However, since many springs emerge from its horizon, farming and small irrigated gardens are found on this formation.
Lower Yatta (*Beit Meir*) due to its colourful facies with alternations of soft and hard layers creates a natural tendency of terracing (Figures 7, 8). In the past, during Ottoman and British mandate times, this formation was used extensively for rain fed agriculture, as for example around Beitillu. Nowadays, only remnants of these terraces are found. Agricultural use now, is either restricted to some olive groves or to gardens near the springs.

Figure 7: Yatta (*Beit Meir/Moza*), Hebron (N Deir 'Ammar); Beit Meir with Moza flat and greener, Hebron karstic

Figure 8: Lower Yatta (*Beit Meir*) (NE Deir 'Ammar); Natural terraces

Upper Yatta (*Moza*) the very soft thin marl layer almost always builds a plain or a step on the slopes (Figure 7). This is because it erodes faster due to its softness. The steps and plains are used and form fields when possible. It is believed that due to the more marly nature of Upper Yatta (*Moza*), its soils and subsoils have a higher retention capacity for infiltrating rainwater and thus enhances farming.

Hebron formation (*'Amminadav*) is characterised by massive (or layered) well karstified carbonates (Figure 9). As is the case with lower LBK (*Kefira*), this typical karst landscape is characterised by abundant isolated rocks on the surface, separated by only small pockets of soil (Figure 10). Land use here requires an immense effort of reclamation and still, water disposition to the soils will remain reduced. Therefore, Hebron is found with almost no land use except extensive grazing. The typical landform is a rocky, relatively steep slope without any terraces (Figure 11).

Bethlehem formation here consists of either upper Bethlehem of the lower Bethlehem formations (both *Kefar Sha'ul* and *Weradim*). Lower Bethlehem has somewhat a tendency to become thinner towards the West, and near Shibteen, it is missing and upper Bethlehem (*Weradim*) overlies Hebron directly (Figure 12). Conversely, upper Bethlehem (coarse grained dolomite) thins out towards the East and near Kufr Na'ameh and SW of Deir Ammar, *Kefar Sha'ul* is directly overlain by Jerusalem formation. As mentioned above, lower Bethlehem can be further subdivided into a lower softer member of chalk or marl and an upper harder thin-bedded limestone member.

Figure 9: Lower Bethlehem (*Kefar Sha'ul*) over Hebron (NE of Nili, SE Shibteen); Lower Bethlehem is layered, Hebron is massive and karstic

Figure 10: Hebron karst (3km E Jammala) Soil pockets between isolated rocks

Figure 11: Hebron, Bethlehem (*Kefar Sha'ul/ Weradim*) (View at Nili road towards N to E; left: Shibteen); Bethlehem is barren and Hebron has olives or fields only in the plains

Figure 12: Upper Bethlehem (*Weradim*) (thin bedding) over Hebron (thick bedding); Wadi Hammameh [Wadi Zarqa]

Figure 13: Lower lower Bethlehem (*Lower Kefar Sha'ul*) W of Deir Nizam; Thin bedded red platy limestone

Lower Bethlehem (*Kefar Sha'ul*) along the northern border (Figure 13) of the catchment area has some agricultural activity like fields or olive groves, as near Deir Nizam. But for the rest of the catchment, the centre and middle of the lower slopes, no fields and no active terraces are encountered (Figure 11, 15). Lower Bethlehem here is barren rock with some grass and low bushes.

Figure 14: Up-Bethlehem (Weradim) at Nili settlement; Barren, karstic slopes

Figure 15: Hebron, Up-Bethlehem (*Weradim*), Jerusalem at top (Wadi Hammameh/Zarqa, NE Shibteen)

Also Upper Bethlehem (*Weradim*) is void of agriculture, terraces or fields (Figure 14). It is more intensely karstified and therefore resembles Hebron more than lower Bethlehem. In other words, Lower Bethlehem can be discerned as a somewhat stratified unit between the massive and karstic Hebron and upper Bethlehem formations, where all three are present.

The main outcrops of Jerusalem (*Bi'na*) lie on the foothills and build very gentle slopes or plains. In the plains, both, fields and olives are found while on its slopes, Jerusalem again is a karstic landform with small soil pockets between isolated rocks (Figure 16).

Figure 16: Upper Bethlehem (*Weradim*), top of hill: Jerusalem (NW of Shibteen) - barren hills with different degrees of karstification

2.5 Wells

There are only three wells within the catchment area. They are located on the western margin of the study area and tap the Lower Aquifer. One of the wells is a production well; the other two wells are used as monitoring wells. Note: *Boreholes in Wadi Natuf turned out not to be usable for recharge analysis – they were either not accessible or were to be broken and thus are not further documented in this Appendix (however, the sub-chapter is available at the website of www.HWE.ps.org).*

Figure 17: Overview map of different landforms, typical for geologic formations

2.6 Springs

Wadi Natuf has no major springs. All of the springs are expected to lie below 1 l/sec and most even below 0.1l/sec discharge rate. However, there are a large number of perched springs in the study area, especially around the lower Yatta and upper UBK outcrops near Beitillu, Deir ‘Ammar and Jammala (Figures 18, 19). Beitillu alone owns 102 springs. Another hundred springs is expected in the rest of the catchment, summing up to more than 200 springs.

No spring hydrographs for springs in the study area are available. Only a few of the springs have already been measured for discharge and quality. The PWA publication “Summary of Palestinian Hydrologic Data 2000” lists 11 springs (Table 2) in the catchment area but does not provide the records for them. According to available maps, several dozen of springs discharge in the study area.

Also, the spring type remains to be investigated in most of the cases. However, the abundance of springs (predominantly lower Yatta and upper UBK) suggests the existence of a more than purely local perched aquifer. The regional water table near the axis of the anticline was found around 465m asl (in a depth of 135m bgl) in a borehole slightly to the east of the study area (Ein Sinya well No.7).

More springs, groundwater outlets and “wet points” have to be mapped in a field survey. Upon conclusion of the survey, and a simple measurement of the springs, it shall be decided, which springs will be examined more thoroughly during the wet season. A close investigation of the quantities and quality of these chosen springs will then be carried out. The data shall be compared to the rainfall events and runoff results. This will help to better understand the mechanisms of recharge, estimate the pattern and quantities of subsurface runoff and eventually of ground water recharge *sensu strictu*. The total amount of perched groundwater will have to be estimated to be deducted from the total infiltration in order to reach conclusions about the total recharge to the non-perched regional groundwater tables.

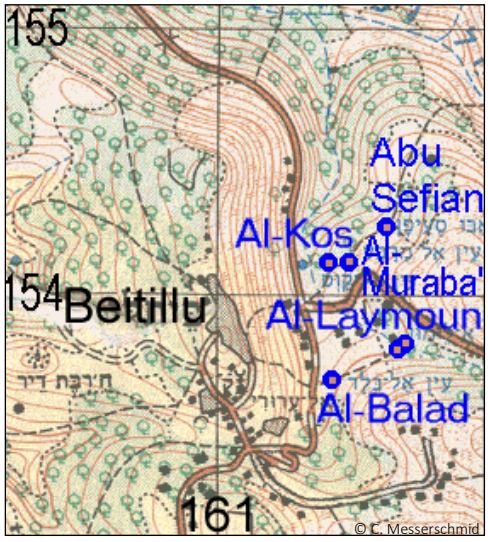


Figure 18: Springs in Harat Al-Wad (Beitillu)

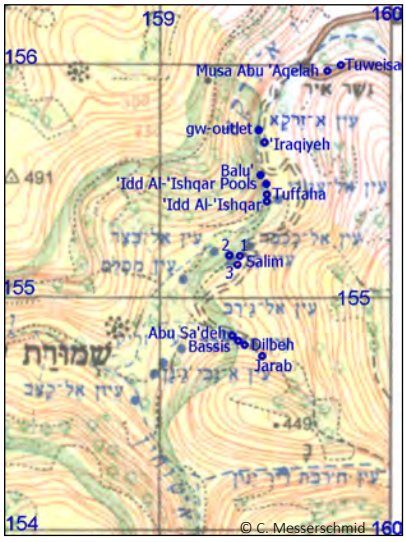


Figure 19: Springs in Wadi Zarqa

Table 2: Literature data on springs in Wadi Natuf (from PWA, 2000)

Name	Location	ID	PGE/PGN	Discharge	Chloride
El-'Abharah	Jibiya	BA/150	-	-	-
Kobar	Kobar	BA/151	-	X	-
Az-Zarqa	Beitillu	BA/155	157.5/155.3	X	-
Az-Zarqa at-Tahta	Beitillu	BA/155A	152.5/155.3	X	-
Al-Qwaiqbah	Beitillu	BA/156	-	X	-
'Akkari	Beitillu	BA/157	-	X	-
Al-Balad	Beitillu	BA/158	-	X	X
Al-Qos	Beitillu	BA/159	-	X	-
Shakhareek	Deir 'Ammar	BA/160	-	X	X
Deir 'Ammar	Deir 'Ammar	BA/161	-	X	X
Al-Balad	Jammala	BA/162	-	x	-

3. Methodology

3.1 Desk Study

Collection of secondary data from literature including maps was carried out. Not many studies have been published about Wadi Natuf yet. Of great value are the publications of the joint German - Palestinian – Israeli project for the investigation of the impact of urbanization on the water resources West of Ramallah. It should be noted however, that the efforts of that project concentrate mainly on an area south of the SUSMAQ project study area.

Israeli texts are mostly in Hebrew and therefore only of limited use.

3.2 Field investigations

It was therefore important first of all to make a thorough field assessment of the main features of Wadi Natuf, its topography and geology, its drainage, wadis and springs, the land use and accessibility to the field. The results of these field investigations were documented in a series of SUSMAQ field trip reports (SUSMAQ, 2003a) and presented in various SUSMAQ workshops (SUSMAQ, 2003b).

Planning of the recharge study, the applied methods and the chosen locations (Figure 20) rests on these field investigations.

3.2.1 Topography and Land use Investigations

The main target is to get an overview of the main features of Wadi Natuf, its relief, landforms and land use. A summary of the results has been given in the paragraphs 2.1, 2.3 and 2.4 of this report, as described below.

3.2.2 Geological Investigations

One of the objectives of the field measurement programme is to generate primary data on geological recharge parameters (Figure 20):

- Karst mapping activity: Differentiation between recent karst and palaeokarst, types and intensity of karst, joints and fractures, drainage pattern, aerial photography and Landsat imagery. This activity could be carried out by BGS staff, based on detailed aerial photographs of the catchment. This point was discussed in the June 2003 workshop of SUSMAQ. It was not decided upon yet.
- Geological mapping, cross-sections and structural geology are important factors in the recharge process determination and quantification. Fields visits were useful to familiarize with the rich set of different formations, their possible impact on water resources and their changing facies. Some of the results have already been applied and used for setting up the recharge model of the West Bank (BGS activity). Formation dip still has to be measured.
- Geological investigations are especially of importance for determining spring types and the perched groundwater system, for assessing the possibility of wadi loss recharge and for the overall application of point data (measurements at chosen sites) to larger spatial extents (categorization for and into typical formations as units with distinct recharge characteristics).
- Some of the investigations remain to be carried out yet. For example, in order to delineate the base of wadi gravels, a bagger should dig into the wadi gravels at chosen sites

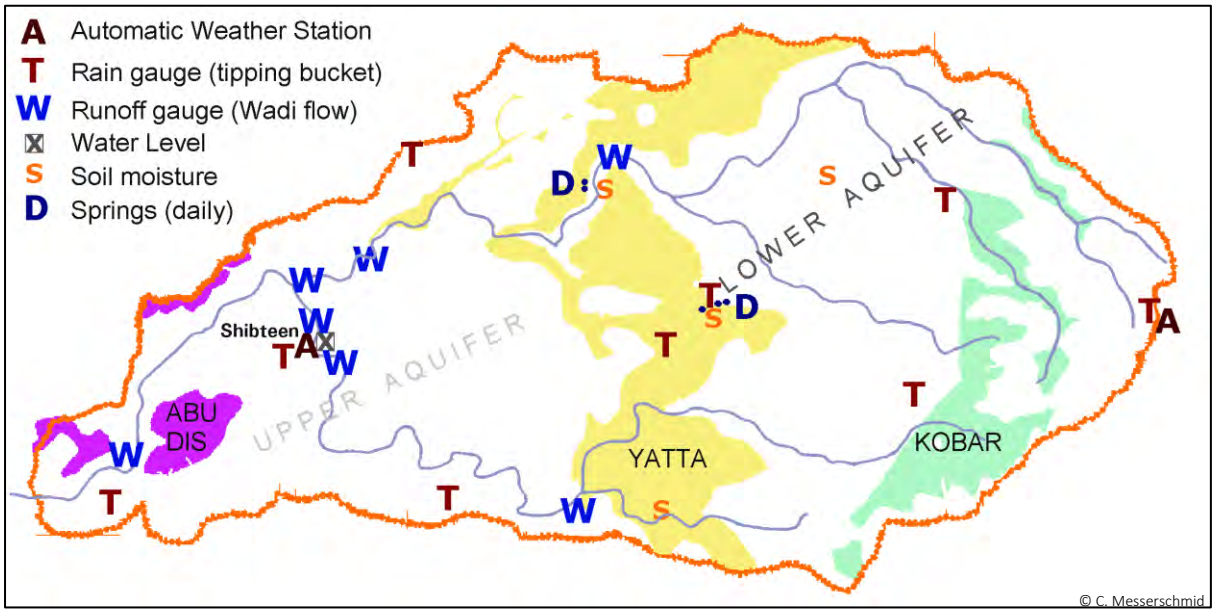


Figure 20: Measurement location map (*updated*)

3.2.3 Hydrological investigations

- Recharge as a factor of the hydrological cycle depends basically on the rainfall as well as on the losses through runoff and evaporation (in-situ direct recharge) or on the Wadi recharge and re-infiltrated recharge of water generated from other areas (perched spring discharge, wadi runoff, return-flow etc.). The spatial distribution of the rainfall and its temporal variation

can have a significant effect on the amount of recharge and its recharge area. These factors should be determined.

- A rainfall-runoff model on Wadi Natuf catchment will be a powerful tool to help recharge estimation in the Natuf catchment. This model will require comprehensive data on the distribution of rainfall, the amounts and intensities of their respective events as well as on wadi flow gauge data. Evaporation pans and Wadi gauges will also need to be deployed and infiltrometer tests will also provide insight into recharge potential.
- The results of the measurements will allow for:
  - Mapping of potential areas with infiltration capacity depending on soil type, land use and vegetation cover (field programme, mapping and sampling)
  - Determination of infiltration capacity and runoff generation depending on morphology (slopes and terraces) and lithology.
- Two Automatic Weather Stations (AWS) including tipping bucket rain gauges will be installed in the catchment on the highland and in the low area. The AWS are also equipped to measure all Penman factors (wind, radiation, etc.) and will include Class-A-Pan evaporation pans for potential evaporation. In addition, seven Tipping-Buckets (TB) will be stationed inside the wadis, in the flat areas and on the slopes. Also rain water quality will be sampled and analysed several times in each station.
- Runoff recording must cover initial Hortonian flow on slopes and terraces by field experiments such as double ring infiltrometer tests and small scale sprinkler tests. Otherwise, Wadi flow shall be gauged up- and downstream within the catchment. Five Wadi flow gauging sites will be equipped with different instruments to measure normal runoff and peak runoff, respectively.
- At selected stations, soil moisture will be continuously recorded by soil moisture sensors, installed at different depths. At other locations, soil moisture content development during the rainy season at different soil depths will require steady soil sampling and lab analysis throughout the rainy season.

3.2.4 Hydrogeological Investigations

The springs will be investigated by a monitoring programme.

- A spring survey is under way. The first step is to complete the list of all springs in Wadi Natuf, mainly in the central study area, near Deir ‘Ammar and Beitillu. This survey includes a rough estimation of the total base spring flow in the summer season, based on field measurements where possible and on other sources if necessary (oral information by the spring owners etc.).
- Based on this survey, a handful of springs will be chosen for more detailed investigation of flow rate and water quality throughout the rainy season. Hydrograph analysis and natural tracers will enable the team to determine the spring characteristics, the recharge area of the concerned springs and possible contamination sources, as well as conclusions about the recharge mechanism, speed and rate.
- Automatic discharge recorders for springs will have to be installed where feasible. Water quality can partly be recorded in the field and partly sampled and assessed in the laboratory. However, this might be difficult.

- Investigation of typical spring water composition (and natural tracers) and its variation over time will make extended sampling necessary, however, not in all but only the chosen springs in the catchment.

3.3 Methods of Analysis

The field investigations described in the above sections will provide primary data and details to use the following methods of analysis:

- Hydrograph analysis - springs
- Understanding of the groundwater system in perched aquifers
- Rainfall-runoff analysis including wadi flows
- Use of distributed time variant recharge model (developed by BGS)
- Soil moisture balance analysis
- Evaporation survey (potential) and calculation (actual)

4. Work plan and Staff (*not included here*)

5. Literature

PWA (2000): Summary of Palestinian Hydrologic Data 2000 - Vol. 1: West Bank. *Palestinian Water Authority (PWA) & USAID*, Ramallah, Palestine, 321 pp.

SUSMAQ (2003a): Field trips to the springs in Wadi Natuf, Final Report – SUSMAQ-NAT # 65 V 0.1. The Sustainable Management for the West Bank and Gaza Aquifers, *Palestinian Water Authority* (Palestine) and *University of Newcastle upon Tyne* (UK), Ramallah, July 2003, 21 pp., available at: http://hwe.org.ps/Projects/SUSMAQ_Reports/Wadi%20Natuf%20catchment%20area/Field%20trips%20to%20the%20springs%20in%20Wadi%20Natuf-full.pdf.

SUSMAQ (2003b): Recharge and Flow Modelling. Report on the SUSMAQ Workshop, 1-4 June 2003, Larnaca, Cyprus, *unpubl. report, PWA & SUSMAQ*, Ramallah, October 2003, 8pp.

Palestinian National Authority
Palestinian Water Authority

السلطة الوطنية الفلسطينية
سلطة المياه الفلسطينية

Sustainable Management of the West Bank and Gaza Aquifers

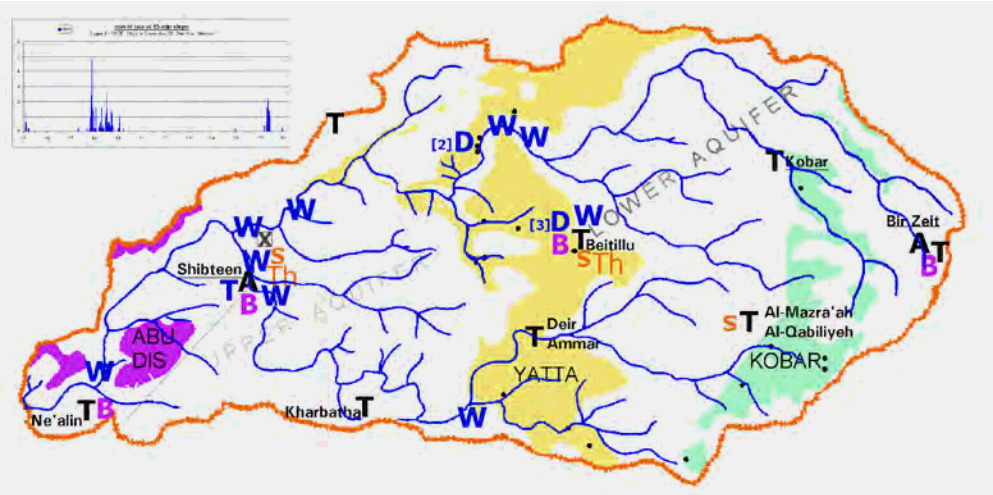
UNIVERSITY OF NEWCASTLE

NERC British Geological Survey

Department for International Development

DFID

Field trips to the springs in Wadi Natuf



Working Report
SUSMAQ-NAT # 65 V 0.1

Prepared by:
SUSMAQ TEAM

Palestinian Water Authority, Palestine
Water Resource Systems Research Laboratory
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July 2003

Disclaimer

This work report is an output from the Natuf Recharge Estimation Team, part of the SUSMAQ project.

Work reports are designed to present and to communicate the results of work on the SUSMAQ Project without delay. The findings, interpretations and conclusions expressed are those of the authors (the team) and should not be attributed to other collaborators on the SUSMAQ project.

The project does not guarantee the accuracy of the data included in this publication. Information shown in maps, figures, tables and the text does not imply any judgment on legal status of territory or the endorsement of boundaries. The typescript of this paper has not been prepared in accordance with procedures appropriate to formal printed texts, and the partners and funding agency accept no responsibility for errors.

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The SUSMAQ Project

The aim of the project is to increase understanding of the sustainable yield of the West Bank and Gaza aquifers under a range of future economic, demographic and land use scenarios, and evaluate alternative groundwater management options. The project is interdisciplinary, bringing together Hydrogeologists and groundwater modellers with economists and policy experts. In this way, hydrogeological understanding can inform, and be informed by, insights from the social sciences. The results of the study will provide support to decision-making at all levels in relation to the sustainable yield of the West Bank and Gaza aquifers.

The project runs from November 1999 to October 2004, and is a partnership between the Palestinian Water Authority, University of Newcastle and British Geological Survey. The project is funded by the United Kingdom's Department for International Development (DFID).

Recharge estimation in Wadi Natuf

The Recharge estimation in Wadi Natuf catchment area is part of the SUSMAQ project.

The recharge assessment focuses on a catchment east of Birzeit down to the Green Line.
It aims to get a better understanding of the mechanisms that control recharge and its quantities.

Primary data have to be produced, covering meteorological data such as rainfall and evaporation, surface water data such as run-off, groundwater data such as spring discharge, water levels and water quality of surface and groundwater and other hydrogeological data such as karst features, aquifer characteristics and vulnerability.

Bibliographical Reference

SUSMAQ-NAT #65 V0.1. Field trips to the springs in Wadi Natuf. Sustainable. Management for the West Bank and Gaza Aquifers, Palestinian Water Authority (Palestine) and University of Newcastle upon Tyne (UK).

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Feedback

This is Version 0.1 of a brief summary report on the findings of three field trips to the springs in Wadi Natuf, as part of the preparation of a field measurement campaign for the estimation of natural groundwater recharge in this catchment in the winter season 2003/04.
The author and the contributors welcome any feedback, both positive and negative! Please, tell us what you think about the ideas and issues raised in this report by contacting the team at one of the addresses above. Your feedback will be appreciated and will help correct possible insufficiencies in planning and setting up the field campaign.

- E X C E R P T S -

Field trip to Kobar, Wadi Zarqa and Beitillu – 13.7. 2003

The field trip began with a drive to Kobar and went on to the most western points that can be reached by car on the tracks from Kobar (and before Halamish settlement): They are Heit Ad-Daba' 163.4/156.7 and Deir Al-Jazaneh 163.5/155.8. From the two points, one can look down to Wadi At-Tlayb and towards Beitillu and Upper Wadi Zarqa' (or upper Wadi Natuf). The springs of Ein At-Tlayb (162.7/156.8) and Ein Jesta (164/156.8) are not accessible (exposed to Halamish). Ein At-Tlayb lies on west-dipping slopes and thus receives its water from the Kobar slopes (as should be expected). Ein Jesta lies between the Kobar hill-chain and the Jibiya hill-chain, however, on the slopes of Jibiya, thus receiving its waters from that little sub-catchment. Both emerge from the Upper LBK formation (*Giv'at Ye'arim*). The spring mechanism remains unclear, but it can be assumed that the springs are contact springs emerging between more permeable/less permeable or more fractured / less fractured layers within Upper LBK (*Giv'at Ye'arim*). The springs belong to the smaller springs that do not spend water around the year.

In Heit Ad-Daba', some slightly marly dolomite banks of m-thickness could be observed in the outcrops, which is typical for the lower LBK formation (*Soreq*) cropping out there. Wadi Zarqa was accessed by the road via 'Atarah and Halamish (but blocked by the army already a few hours later).

By this time of the year, there is of course no more flow in Wadi Zarqa at the crossing with the road. But thick and fresh vegetation and some wetness of the soil indicate that either some water is still left under the gravels or some invisible spring or groundwater blank emerges here and is still yielding water in July. The springs of Wadi Zarqa are still productive but have not been measured yet. The dirt road from Wadi Zarqa up to the western outskirts of Beitillu is only accessible by 4-wheel drive cars.

Figure 1: Wadi Natuf topographic map

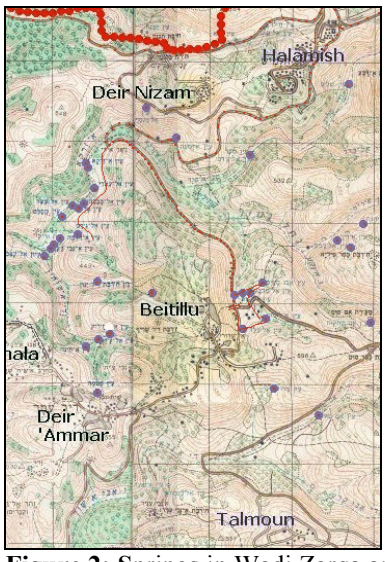


Figure 2: Springs in Wadi Zarqa and Beitillu, central Wadi Natuf

The springs visited in Beitillu are (a) Ein Al-Balad - measurable; the water flows into a cistern in a private garden and is used as drinking water, flowing around the year with a peak around February or March; (b) Ein Al-Laymoun (upper and lower spring outlets, some 30 m away from each other). The water seems to stand still in the pool and is thus not easily measurable. The water is used for irrigation. The springs are classified as strong springs by the owners/farmers. (c) Ein Abu Sa'efan –is mainly used for irrigation, but also known for its good drinking water quality. According to the farmer, people come from Ramallah and even Jerusalem in order to fill some bottles of this water. The spring issues a small

quantity of water. A 1m high cavern was dug some 3 m into the rock. The portion that flows in a small channel is easily measurable; however, there might be some quantities of water that will not be included by using this measurement method.

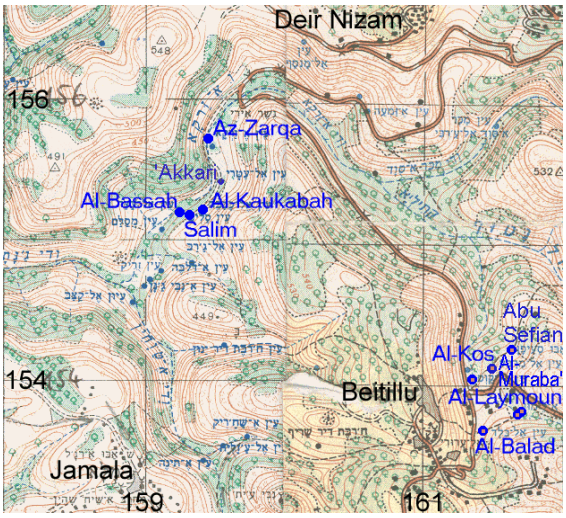


Figure 3: Detailed spring location map of Wadi Zarqa / Beitillu areas

(d) Ein Al-Muraba' issues from the foot of a massive 2.5m thick bank of limestone. A little pipe sticks out from the outcrop with a small quantity flowing out of it. However, it seems very probable that more water emerges directly into the pool at the foot of the bank through fissures and cracks under water. Water is again drinkable but mainly used for irrigation. (e) Ein Al-Kos ("*Al-Qaws*") is well measurable. It flows through a cemented "nose" into the big pool near some houses. The pool is relatively well maintained but full of litter. It is also full of bees that come from their bee hives (boxes) some 10 m above the spring.

All of the springs, with the exception of Abu Sa'efan, emerge from upper UBK formation (*Kesalon*). Abu Sa'efan lies in the outcrops of lower UBK formation (*Soreq*). Ein Al-Balad lies just on the border between upper UBK (*Kesalon*) and lower Yatta (*Beit Meir*) formations. This shows that upper UBK (*Kesalon*) is a perched spring aquifer in this area, underlain by more impermeable rocks of lower UBK (*Soreq*) formation. This "aquitard" is typically a rhythmic alternation of dm-dolomite with cm-marl. However, also within lower UBK or *Soreq*, aquiferous layers are found that feed small perched springs like Ein Abu Sa'efan or many springs in other areas. Also, lower Yatta (*Beit Meir*), above upper UBK (*Kesalon*) is not just an aquitard, but contains quite productive aquifer horizons. This is indicated on the one hand by the strong springs in Wadi Zarqa, and on the other hand by the Spring Ein Al-Balad that emerges from the boundary between lower Yatta (*Beit Meir*) and underlying upper UBK (*Kesalon*). In addition, it can be said that the outcrops of upper UBK (*Kesalon*) alone can never be enough to recharge all the springs listed above. So, a connection with rainfall recharge above, or in other words a considerable rate of downward leakage from lower Yatta (*Beit Meir*) must exist to explain the relatively large spring flow rates.

The maps below show the probable catchment of these springs (including Ein Al-Balad). The delineation of the catchment is based on geological as well as topographic considerations. The outcrop of the bottom of upper UBK (*Kesalon*) formation is a limit to the lateral extension of the catchment and the elevation of the lowermost spring of this spring group is a limit of this extension. In other words, it is assumed that in this environment of layer geometry, groundwater cannot pass from a stratigraphically lower to an upper formation. And, of course, that water does not flow upward. The springs lie between 480 and 500 m asl. So, the groundwater catchment must not be less than 500 m above sea level or above that value. All springs emerge from ~ upper UBK (*Kesalon*) formation. So the rainfall recharge can only take place on upper UBK (*Kesalon*) itself or stratigraphically higher formations. It should be added that the prevalent dip of formations is almost exactly to the west.

Hence, the groundwater recharge area of the formations is not larger than the area delineated in red in the geological map below = ~0.9 km^2 (as a maximum and if Ein Al-Balad is included). Lowest elevations and formations of possible recharge for the springs are shown in Figures 4a, 4b.

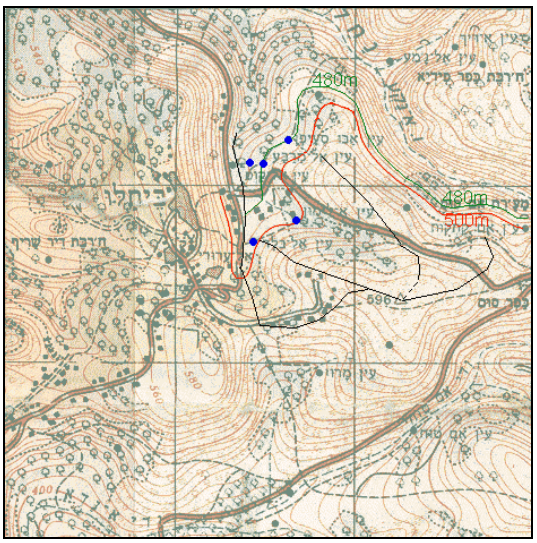


Fig. 4a: 500m elevation, springs and water divide in Harat Al-Wad

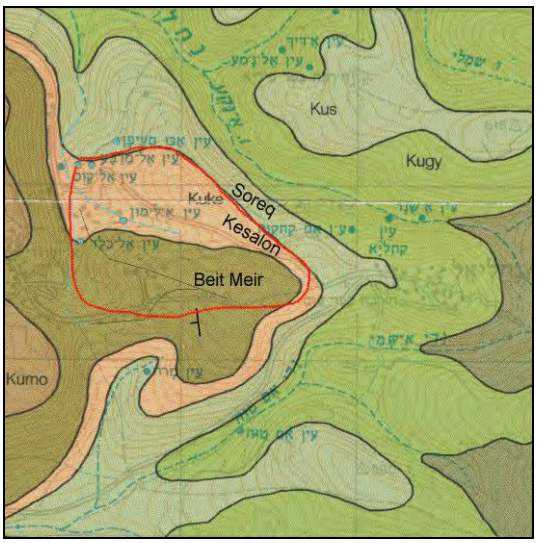


Fig. 4b: Groundwater recharge catchment area of Harat Al-Wad (including Ein Al-Balad)

No water balance estimation to evaluate roughly this analysis has been done so far. For this and as a next step, the approximate spring flow has to be measured and compared to an estimate of ~30% of recharge coefficient from area rainfall[1]. However, spring discharge should appear too small or the recharge area or coefficient too large in this approach, at least if Ein Al-Balad and lower Yatta (*Beit Meir*) outcrops are included. In addition it has to be clarified whether all groundwater recharged in this sub-catchment discharges in the springs, or whether an unknown quantity continues to flow westward towards the springs west of Beitillu.

Natuf field trip to Beitillu springs - 19.7. 2003

Springs were visited in Beitillu district. The field trip began at ~12:00 (field time). The list of springs visited is listed in the table below:

The first springs visited were the two springs along the tar road before (south of) the entry to Wadi Zarqa. They are called Ein At-Tuweisa and Ein Musa Abu ‘Aqelah and are two small contact springs that emerge from the base of upper Upper Beit Kahil or ”*u-UBK”* (*Kesalon*) formation where the reefal limestone cliff overlies thin- and medium-bedded yellow marl with red iron stains (Fe), typical for lower Upper Beit Kahil or “*l-UBK*” (*Soreq*) formation . The springs are part of a spring group that lies to both sides of the street. At least 5 spring water outlets (maybe more) belong to this group in an area of a few hundred square metres.

The springs discharge small quantities (<< 0.1 l/sec) around the year. They receive their water from the hill slopes south of the road. It can be assumed with certainty that lower Yatta or l-Yat (*Beit Meir*) belongs to the aquifer system of the perched aquifer together with u-UBK (*Kesalon*). This is because the outcrop area of the 20m thick Kesalon sequence is only some tens of metres wide (<100m) on these relatively steep slopes. Hence, recharge from u-UBK alone could not be enough for these springs, as will be shown also in the examples of the springs described below.

[1] 600 mm/yr rain on 0.9 km^2 = 540,000 m^3/yr of rain. 30% of which is equal to 162,000 m^3/yr. Distributed evenly on 5 springs this equals 32,400 m^3/yr in each spring or 88.77 m^3/d or 1.027 l/s in each spring.

At-Tuweisa emerges from the bottom of the cliff, located behind a thick cordon of bushes. However, this spring is a point-spring and therefore more easy to measure than Musa Abu ‘Aqelah, which emerges in small droplets from the cliff in a line of more than 10m length. Not all of the line is accessible due to the dense vegetation.

SPRING NAME	COMMENT
Ein Abu Qar’ana 1	Seen from street – photo 1 (lost)
Ein Abu Qar’ana 2	Seen from street – photo 1 (lost)
Ein Abu Qar’ana 3	Seen from street – photo 1 (lost)
Ein Abu Shehadeh 1	Seen from street
Ein Abu Shehadeh 2	Seen from street
Ein Ash-Sha’eb	Seen from street – photo 2 (lost)
Ein Jaheer Abu Al-Haj	Seen from street – photo 2 (lost)
Ein Dhiayb 1	Seen from street
Ein Dhiayb 2	Seen from street
Ein At-Tahar	Seen from street
Ein As-Sadeq	Seen from street
Ein At-Tuweisa (E159.8/N156.05)	Visited – photo 1
Ein Musa Abu ‘Aqelah 1	Visited – photo 2 + 3
Ein Musa Abu ‘Aqelah 2	Not visited (below street)
Ein Musa Abu ‘Aqelah 3	Not visited (below street)
Ein Musa Abu ‘Aqelah 4	Not visited (below street)
Ein Musa 1	Seen above street
Ein Musa 2	Seen above street
Ein Musa 3	Seen above street
Ein Zarqa	Only in map
Ein Al ‘Iraqiyeh	Visited (in wadi)
“Miah Jariyeh”	Visited (in wadi) “groundwater outlet”
Ein Balu’ (canyon)	Visited – photo 4, 5 + 6
‘Idd Al-‘Ishqar pools	Visited – photo 7
Ein Tuffaha spring	Visited
Ein ‘Id Al-‘Ishqar	Visited – photo 8, 9, 10 + 11
Ein Al-‘Akari	Not found
Ein Salem 1	Visited (with pools – 2 inch pipe)
Ein Salem 2	Visited (with pools – 2 inch pipe)
Ein Salem 3	Visited (with pools – dirty from litter)
Ein Deir Nanoun	(behind the hill “Jabal Kalkaleh”)
Ein Al-Jarab	Visited – pool since 4 years 35m above old location
Ein Abu Sa’deh	Visited – 1 ¼ inch pipe
Ein Bassis	Visited – 2 inch pipe
Ein Ad-Dilbeh – main (old)	Visited –photo 12 + 13
Ein Ad-Dilbeh – new (captured last year)	Visited –photo 14 (not yet connected to irrigation)
Ein Al-Qatab	Not visited (700m from Ad-Dilbeh, from same formation.)

Photo 1 shows the point outlet of Ein At-Tuweisa. At-Tuweisa will have to be measured the next time. Photo 2 and 3 very nicely portray the setting of the hard cliff above the soft yellow marls (also hanging thinly from the cliff’s underside) and by that forming an abrupt washout depth of more than one meter.

Photo 1: Ein At-Tuweisa

Photo 2: Ein Musa Abu ‘Aqelah

Photo 3: Ein Musa Abu ‘Aqelah

After visiting the two above springs, Wadi Zarqa was entered. Wadi Zarqa is the area with the highest density of springs in the entire catchment. This is due to the special geology and relief of this area.
The drainage channel of Wadi Zarqa deeply incises the l-Yat (*Beit Meir*) and u-UBK (*Kesalon*) formations. Even l-UBK (*Soreq*) formation crops out, just at the bottom of the Wadi in many places (or covered by Alluvial of the Wadi fill). Therefore contact springs at the outcrops of bottom u-UBK (*Kesalon*) have to emerge. In addition, the prevalent dip is towards the East. Some exceptions with eastern dip as in the north-western bank of Wadi Zarqa at around PGE 159.4/PGN 155.3) only „prove this rule“.
Since the prevalent dip is westwards and Wadi Zarqa surrounds the hills with extensive Yatta and u-UBK outcrops to the west, it receives the bulk of the perched groundwater flow.
Springs on the eastern slopes of the hills between Beitillu and Wadi Zarqa are rare and ephemeral.

30 m into Wadi Zarqa, springs emerge from the wadi floor or adjacent to the wadi channel. The springs are surrounded by thick vegetation and therefore are not easy to access.
Ein Zarqa, the only spring found in the literature, could not be found in the wadi. Its waters were registered though after leaving the vegetated surrounding of the spring. The wadi floor here is covered with outcropping limestone banks, which have seen many floods, because they are deeply incised (dm deep). Therefore, it can be concluded that the carving into the limestone is not a consequence of increase of runoff and recently appearing flash floods due to urbanisation but the effect of long-

standing denudation. The absence of gravel should be considered a natural state. In addition, also upstream, gravel is found in the wadi (for example east to the tar road).

The other spring in the vicinity is Wadi Al-'Iraqiyeh and could be found and approached as near as <10 m from the spring point. The flow is not large but should not be neglected and it shall be kept in mind that here already quite a portion of the spring flow might have been consumed by the vegetation.

50 m downstream Ein Al-Iraqiyeh lays the little canyon of Balu'. It is a channel incised into the bed rock deeper than 2 m, as can be seen on photos 4-6. Now, in July, only a small stream is flowing (photo 5). But after strong rain, a very large flow rate should be expected.
This point could be a good point for installation of a wadi gauge. The channel should be measured carefully and then a simple level indicator could be painted on the wall of the channel. This level would then have to be read by people from this area (the next house is merely 60m away from this spot).

Unfortunately, directly after Balu' canyon, the water of the wadi (standing or very gently flowing in a natural pool) is extremely contaminated. A motor rests on the left bank of the wadi and all its diesel fuel is spilled, contaminating both soil and water in the surrounding area (see Photo 7). Rehabilitation of this contamination is highly indicated! Water quality measurements downstream this point will not make sense, other than assessing the damage of the diesel spill.

Photo 4: Balu' pools

Photo 5: Balu' pools

Photo 6: Balu' pools

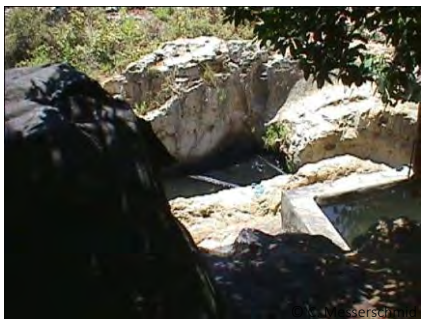


Photo 7: 'Idd Al-'Ishqar spring pools

Ein 'Idd Al-'Ishqar (photos 8-11) lies 10 m away from the main wadi and around 2m above the wadi floor. It is another example for a bottom u-UBK /top l-UBK (*Kesalon*/top *Soreq*) contact spring. The yellow marl can be clearly discerned on Photos 8 and 9.

The cliff above the marl is shown on photo 10 and 11. These two photos show two adjacent small pools built under the cliff to collect as much water as possible from this alignment spring over an entire length of around 10 m. A concentration of flow with a pipe capturing it is shown in Photo 11. This spring is another spring that could be interesting for measurements and maybe even hydrographs. It is well accessible and kept in good shape by the owner.

Photo 8: Ein ‘Idd Al-‘Ishqar

Photo 9: Ein ‘Idd Al-‘Ishqar

Photo 10: Ein ‘Idd Al-‘Ishqar

Photo 11: Ein ‘Idd Al-‘Ishqar

Not all springs of Wadi Zarqa could be visited in this short trip. But the springs of Salim, Ein Salim No.1, 2 and 3, were visited and they showed the highest flow rate (2 inch pipes), yet to be measured. The springs are leading to a large collection pool with a high renewal rate and good possibility to measure the flow. Water sampling should, however, take place at the spring outlets themselves.

The last spring group visited was further downstream at the interception with a tributary coming from Beitillu and running in SE-NW direction. These springs are Ein Al-Jarab, Ein Abu Sa’deh, Ein Bassis, Ein Ad-Dilbeh – main spring (old) and Ein Ad-Dilbeh – new spring pool (captured last year). The group lies along the bottom u-UBK (bottom *Kesalon*) outcrops at E 159.4-159.5 / N 154.8 – 154.9. Photos 12-14 show the u-UBK (*Kesalon*) cliff at some of the springs. The biggest of the springs are Ein Ad-Dilbeh and Ein Al-Jarab. Measurements of these springs are not easy because the flow is actually completely disperse along the outcrop line of the Kesalon cliff and thus even the division of this flow into 4 individual springs by the local farmer seems somewhat arbitrary. However, an attempt should be made to measure and estimate as good as possible the sum of the flow. The farmer says that the flow reaches its maximum relatively late, after (or towards) the end of the rainy season in around May to June. This delay in flow is another hint to a larger catchment, clearly exceeding u-UBK (*Kesalon*) and including most if not all of l-Yat (*Beit Meir*) formation.

The Beit Meir formation should be referred to as a cocktail of different lithologies. This makes it more difficult to predict groundwater flow within the formation. However, most of the indicators in the field point to the idea that Beit Meir is an aquifer with no sufficiently impermeable layers to force out groundwater springs from within this formation. In addition, Beit Meir should be seen as hydraulically connected to Kesalon in this area (unlike in other West Bank areas). It is possible that interlayering with less permeable units inside Beit Meir exists. The farmers tell about “wet points” higher up in the hill slopes and mostly in connection to intra-formational cliffs of l-Yat (*Beit Meir*). Also, around the cliffs the vegetation becomes denser and slightly fresher in its green colour than at the rest of the slopes. There is no way to include measurements of this portion of flow. It can be either ignored in the overall spring water balance or estimated very roughly only.

Photo 12: Ein Ad-Dilbeh – old

Photo 13: Ein Ad-Dilbeh – old

Photo 14: Ein Ad-Dilbeh – new

Photo 15: Hill west of Beitillu – 160/152.2; Hard Hebron on steep slopes; soft Moza is flat

Photo 16: From Beitillu towards East (Ein Al-Balad and Al-Kos and hill 596m)

The next task will be to delineate the spring catchment of the Ein-Al Balad spring group and assess the suitability for making a detailed study on these springs.

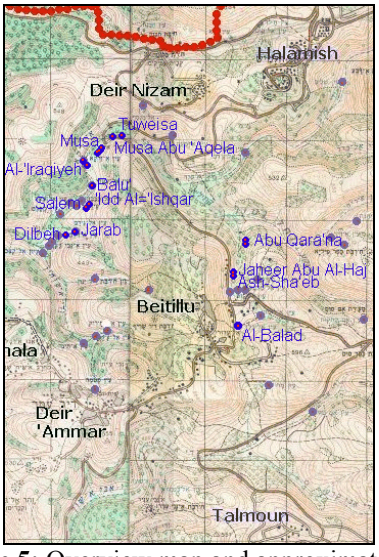


Figure 5: Overview map and approximate spring locations

Figure 6: Exact spring locations

Field Trip to Wadi Natuf – 23.7. 2003

The following springs and locations were visited in two areas in central Wadi Natuf, Beitillu – Harat Al-Wad area and Wadi Zarqa area:

In Harat Al-Wad (lower Beitillu)	**In Wadi Zarqa**
- Ein Al-Balad	- Al-Balu' pools
- Ein Al-Laymoun Al-Fauqa & At-Tahta	- Ein 'Idd Al-'Ishqar 1 and 2
- Ein Zayd	- Ein Salim 1, 2 and 3
- Ein Abu Sa'efan	- Ein Ad-Dilbeh old and new
- Ein Al-Bibi	- Ein Al-Jarab (new pool)
- Ein Al-Kos	

This brief report describes each of the springs visited, the method of investigation of the spring flow and lists the measurements in the following table. Most springs were measured by simple means, with a bucket or a pipe, by bailing and by observing the flow rate in a channel of estimated section area (Table 1). The following locations were visited and measured:

Table 1: Overview over spring flow measurements in Beitillu and Wadi Zarqa

Name	Time	Method	Reading	note	l/min	Avg l/min
Al-Balad	11:00	„*black bucket*" ([1]) under pipe, cistern	8.5l/63.44 sec 8l/60 sec 8l/60 sec		8.04 8 8	**8.01**
Al-Laymoun (Fauqa)	11:30	dirt cloud running in channel 2 cm*4 cm with ½ cm per sec			0.24	**0.24**
Al-Laymoun (Tahta)	11:45	n. m., empty pool then measure in outlet pipe	-			**-**
Zayd	12:00	measured in rock channel before pool (6.5*4.9*4.8*4.2 m diagonal 7.6 m)	0.5l/10 sec 0.5l/9 sec 0.5l/8.25 sec	60-70% 60-70% 90%	4.62 5.13 4.04	**4.59**
Abu Sa'efan	12:42	bailing from little pool, 3l measure recovery until flow goes out of little pool	3l/66 sec 3l/65 sec 3l/60 sec		2.73 2.77 3	**2.83**
Al Bibi	12:58	„*red bucket*" ([2]) under pipe in the cliff (direct)	0.5l/14 sec 0.5l/15 sec 0.5l/15 sec		2.14 2 2	**2.05**
Al-Kos	13:20	direct red and black bucket under cement nose	0.5l/3.6 sec 0.5l/3.6 sec 5l/33 sec 5l/34 sec		8.33 8.33 9.09 8.82	**8.65**
Balu' pools	13:00	Zarqa & 'Iraqiyeh flows (wadi loss & evaporation)	0.5l/0.52 sec 0.5l/0.55 sec 0.5l/0.5 sec		57.69 54.55 60	**57.41**
Idd Al-'Ishqar 1(pipe)	14:15	red bucket under outlet pipe	0.5l/5.81 sec 0.5l/5.59 sec 0.5l/5.72 sec		5.16 5.37 5.24	**5.26**
Idd Al-'Ishqar 2(pool)	14:17	grey pipe in channel with clay around; red bucket	0.5l/3.7 sec 0.5l/3.7 sec 0.5l/3.6 sec		8.11 8.11 8.33	**8.18**
Salim 1 (upper)	14:30	black bucket under outlet pipe of pool, unscrewed (correct because pool was empty)	9l/13 sec 5l/7.3 sec 9l/13.8 sec 5l/8 sec		41.54 41.10 39.13 37.50	**39.82**
Dilbeh	14:55	can only be measured by emptying and refilling of the two pools (measure recovery time) old: 18.1 * 2.7m and 18.1 * 2.6 m (0.3-1 m deep) new: 2.7 * 15 m and 2.3 * 15 m (0.5-0.85 m deep)				**-**
Al-Jarab	15:25	at new pool (upstream) black bucket at tap	5l/18sec 5l/18.5sec 5l/18.2sec		16.67 16.22 16.48	**16.46**

The total flow of all the springs measured on this day is around 150 l/min (or 9.2m^3/h or 80,575m^3/yr.

([1]) The „black bucket" is a 9 litre container

([2]) The red bucket is a small half-litre container

Appendices of chapter 4

Design, Setup and Instrumentation

4.1 Preparatory work for the conceptual model (SUSMAQ # 64) . 277

4.2 Development of a conceptual recharge model (IAH, 2004) . . 297

4.3 Purchase and installation of field equipment (SUSMAQ # 68) . 303

4.4 Wadi Natuf field measurement campaign 2003/04 (SUSMAQ) 321

Palestinian National Authority
Palestinian Water Authority

السلطة الوطنية الفلسطينية
سلطة المياه الفلسطينية

Sustainable Management of the West Bank and Gaza Aquifers

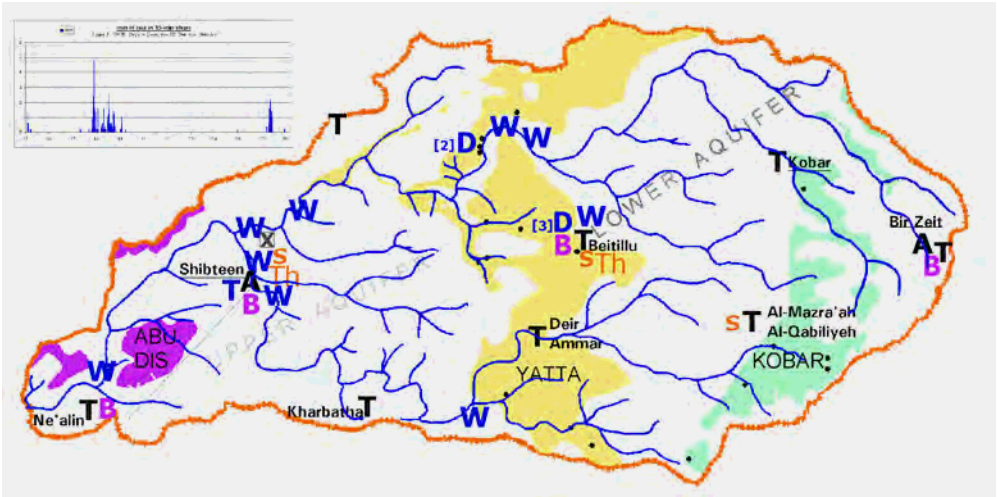
UNIVERSITY OF NEWCASTLE

NERC British Geological Survey

Department for International Development

DFID

Conceptual Model of Wadi Natuf Groundwater Recharge



Final Report
SUSMAQ-NAT # 64 V 0.3

Prepared by:
SUSMAQ TEAM

Palestinian Water Authority, Palestine
Water Resource Systems Research Laboratory
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November 2003

Disclaimer

This work report is an output from the Natuf Recharge Estimation Team, part of the SUSMAQ project.

Work reports are designed to present and to communicate the results of work on the SUSMAQ Project without delay. The findings, interpretations and conclusions expressed are those of the authors (the team) and should not be attributed to other collaborators on the SUSMAQ project.

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The SUSMAQ Project

The aim of the project is to increase understanding of the sustainable yield of the West Bank and Gaza aquifers under a range of future economic, demographic and land use scenarios, and evaluate alternative groundwater management options. The project is interdisciplinary, bringing together Hydrogeologists and groundwater modellers with economists and policy experts. In this way, hydrogeological understanding can inform, and be informed by, insights from the social sciences. The results of the study will provide support to decision-making at al levels in relation to the sustainable yield of the West Bank and Gaza aquifers.

The project runs from November 1999 to October 2004, and is a partnership between the Palestinian Water Authority, University of Newcastle and British Geological Survey. The project is funded by the United Kingdom"s Department for International Development (DFID).

Recharge estimation in Wadi Natuf

The Recharge estimation in Wadi Natuf catchment area is part of the SUSMAQ project.

The recharge assessment focuses on a catchment east of Bir Zeit down to the Green Line.
It aims to get a better understanding of the mechanisms that control recharge and its quantities.

Primary data have to produced, covering meteorological data such as rainfall and evaporation, surface water data such as run-off, groundwater data such as spring discharge, water levels and water quality of surface and groundwater and other hydrogeological data such as karst features, aquifer characteristics and vulnerability..

Bibliographical Reference

SUSMAQ-NAT #64 V0.1. Conceptual Model of Wadi Natuf Groundwater Recharge

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Feedback

This is Version 0.1 of a brief Conceptual Model on groundwater recharge in Wadi Natuf, which serves as a basis for planning the field measurement campaign during the winter season 2003/04. The author and the contributors welcome any feedback, both positive and negative! Please, tell us what you think about the ideas and issues raised in this report by contacting the team at one of the addresses above. Your feedback will be appreciated and will help correct possible insufficiencies in planning and setting up the field campaign.

Table of Contents

	page
1. Topography	1
2. Hydrostratigraphic units	1
3. Boundaries	3
4. Flow Budget	5
5. Landforms:	6
6. Recharge mechanisms:	7
7. Conceptual approach	11
8. Measurement programme	12
9. References	16

List of Figures

Figure 1: Geological overview map	2
Figure 2: Detail map of Kobar group outcrops	2
Figure 3: Main hydrostratigraphic units	3
Figure 4: Schematic section of positions of different boundary types	4
Figure 5: Structural contour map of Wadi Natuf and groundwater basin boundaries	5
Figure 6: Sub-catchments for wadi flow measurements	6
Figure 7: Landforms in Wadi Natuf	8
Figure 8: Recharge potential ranking for formations	9
Figure 9: Shibteen well No.1 hydrograph and casing depth	10

List of Tables

Table 1: Summary table on geology, slopes, soil and land use of formations	1
Table 2. Potential for recharge in West Bank	7
Table 3: Overview over measurements, data type and evaluation methods	14
Table 4: Itemized list of individual field measurements	15

Sound estimates of natural rainfall replenishment of the West Bank aquifers are crucial for a sustainable management of the groundwater resources and for successful negotiations between Israeli and Palestinians. Despite its importance, no major field based recharge investigations have been performed so far, for either the West Bank portion or the entire Western Aquifer Basin (WAB). Current figures of recharge to the WAB are based mainly on coarse comparison between pre-use spring flow (from the two main spring outlets of the basin in the Coastal Plain: Yarkon [Ras Al-Ain] and Taninim [Timsah] springs), well pumpage and rainfall heights (GOLDSCHMIDT, 1958), sometimes somewhat refined by flow modelling with simplified flow models (GUTTMAN & ZUKERMAN, 1995).

Wadi Natuf field measurement campaign attempts to start closing this gap through extensive meteorological, hydrological and hydrogeological measurements. Its results will be also used for a first West Bank-wide recharge model by BGS.

1. Topography

The size of Wadi Natuf is ~100km^2. It is located between the coordinates PGE 150.5-169 and the North coordinates PGN 149-158. The catchment lies at an elevation between 135m asl at the outflow of Wadi Natuf and 815m asl at the Bir-Zeit University – New Campus on the Eastern border of the catchment.

2. Hydrostratigraphic units

The geology has been described in the background, design and instrumentation report (SUSMAQ 2003, #48). Therefore, here, only a summary table on geology, slopes, soil and land use shall be presented (Fig. 1, 2, 3). The geology, slope, soil and land-use figures are based on field work.

Table 1: Summary table on geology, slopes, soil and land use of formations

Formation Name			Geology	Thick-ness	Slope	Soil	Land use
Palestinian	Israeli						
Jerusalem	Nezer	Bi'ra	Hard limestone (karstic)		Terraces or stone pavement	Terra Rosa	Agriculture in foothills (west) Karst collapse
	Shivta		Hard limestone (karstic)		Cliff	Terra Rossa	
	Derorim		More clastic or clay, but thin			Terra Rossa	
Bethlehem	Weradim		Dolomite/Limestone, less clear bedding, variable thickness	30	Massive		More vegetation
	Kefar Sha"ul		Marly or chalky limestone		Well bedded (massive or thinly) but only gentle terracing		
Hebron	„Amminadav		Dolomite or dolomitic limestone (karstic)	160 m	Bedding eliminated due to karst	Terra Rossa	Some restriction due to rocky fields; olives
Yatta	Moza		Yellow marl	10 to 15 m	Soft marl slumps	Thick soils gradual soil to rock	Not very well used (erosion)
	Beit Meir		Cocktail of limestone, dolomite and chalk; Bottom 30m: Blue clay		Can form good terraces, bedded		Good vegetation
Upper Beit Kahil	Kesalon		Reefal limestone, limestone banks and yellow marl at base	20m	Cliff	?Terra Rossa (or Brown Rendzina?)	Olives and crops
	Soreq		Repeated interbedding of dolomite and marl	60 to 120m	Strong terraces (often built and maintained)	Terra Rossa medium to good thickness	Intensive agriculture; olives and crops
Lower Beit Kahil	Giv"at Ye"arim		Dolomite, fractured; massive or interbedded (karstic)	70m	Strongly stepped	?Terra Rossa	Olives
	Kefira		Limestone (karstic), marly at base	165m	Medium stepped, bedding eliminated by karstic	Terra Rossa, not too thick, except in pockets	Limited agriculture, some olives, few field
Qatana	Qatana		Marl	40 – 60m			

5 main hydrostratigraphic units (Fig. 3) have to be differentiated, two of which constitute the Mountain aquifer. The units are from top to bottom (and from West to East)

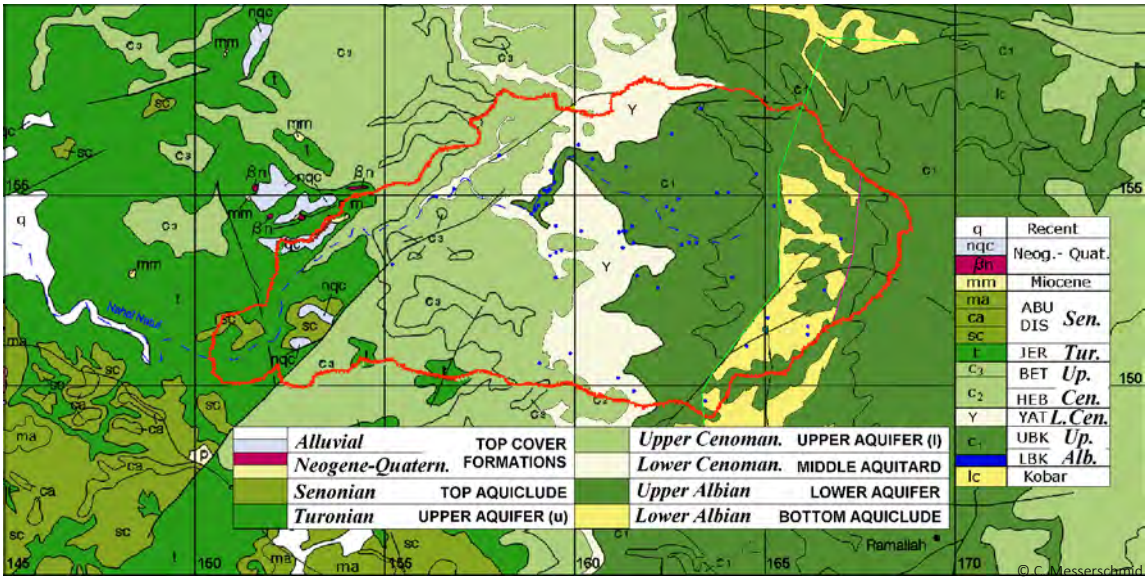

Figure 1: Geological overview map

-Top Aquiclude, above the Upper Aquifer. It consists of Senonian and younger impermeable formations, mainly chalk.
- Upper Aquifer. It consists of Jerusalem/Bethlehem and Hebron formations and is composed mainly of Limestone and Dolomite, however with some portions of marl and also chalk, especially in Bethlehem formation.
- "Middle aquitard", consisting of Yatta formation. The name aquitard is only applicable on the regional level. In reality and on the local scale, perched aquifers are found within this less permeable series.
- Lower aquifer made of Lower and Upper Beit Kahil formations. All Lower Beit Kahil is very limy or dolomitic and thus an excellent aquifer. However, the main, lower part of Upper Beit Kahil (Soreq) has marly intercalations that act on the local level as aquitard and forces contact springs to emerge on its top, where it is overlain by the thin but porous cliff-forming formation of upper Upper Beit Kahil (Kesalon).

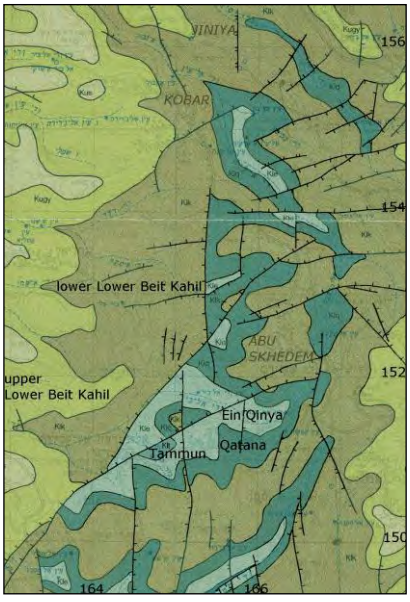

Figure 2: Detail map of Kobar group outcrops

- Bottom Aquiclude of the Mountain aquifer. It consists of different formations of the Kobar group (Fig.2). The uppermost part of Kobar, called Qatana formation can be considered an effective aquiclude to the Lower Aquifer. However below Qatana, a local aquifer forming formation crops out in the centre of the anticline – called Ein Qinya formation. It is perceptive to recharge but this recharge does not connect hydrogeologically to the groundwater reservoirs of the Mountain Aquifer (LBK).

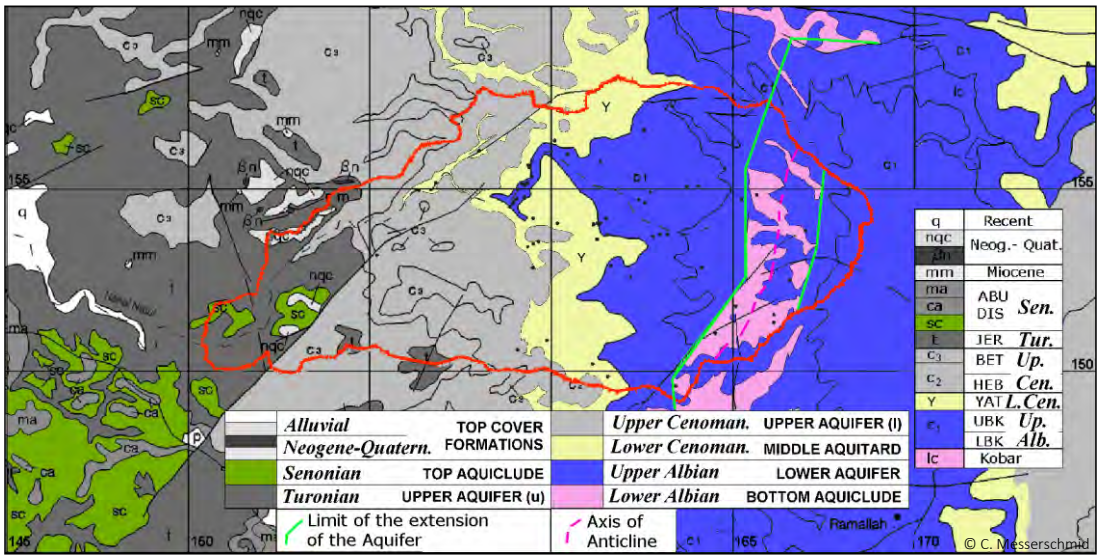

Figure 3: Main hydrostratigraphic units

3. Boundaries

The general groundwater boundaries of the WAB were described in the boundaries report of SUSMAQ (2002, #21). The boundary between the Western and Eastern Mountain Aquifer basins runs through Wadi Natuf (Fig.5). It is located at the axis of the overall anticline that forms the West Bank mountains. On the smaller scale, in Wadi Natuf, the situation is further complicated by the fact that the bottom aquiclude (Kobar Group) of the Mountain aquifer crops out. The strip of these outcrops can not be attributed to neither groundwater basin. It is a third zone between the two basins. Within these outcrops there exists another aquifer of local nature. It belongs to the Ein Qinya formation, which is known for its springs and even served for well production in small scale for Ramallah city in the past.

So, the recharge from rainfall to Ein Qinya formation has to be taken in account. It does not belong to the recharge to the Western mountain Aquifer basin. However, spring discharge can flow out and run to the outcrops of the Lower aquifer of the Mountain aquifer (LBK, UBK). It thus can contribute indirectly to the Mountain aquifer recharge.

A schematic differentiation between different types of groundwater boundaries was also discussed already in the boundary conditions report (SUSMAQ 2002, #21).

The schematic sections shows the different zones of the boundary:

- In the middle, the axis of the Anticline (pink interrupted line in Figure 4) is a structural feature and does not have to coincide with the highest elevation of the areas (surface catchment boundary). In the case of Wadi Natuf, the axis runs southwards from Ateret (northern border) to Abu Shkhedem, where it splits and continues in S, SSW directions respectively. The highest point of the catchment is found further East, at Bir Zeit University.
- To the east and to the west of this axis, lies the geological contact between Lower aquifer (LBK) and Bottom Aquiclude (Kobar) formations (green line in the figure).
- The third line of actual groundwater division (blue lines) cannot be drawn accurately because of lack of monitoring boreholes in this area. It is the line of beginning

saturation of the aquifer. Therefore, the two water bodies in the EAB, the WAB respectively, are actually separated by a strip of several km‟s width. However, it is assumed that the start of partial saturation of the Lower aquifer in the Eastern basin lies outside the catchment of Wadi Natuf. This is assumed due to the partial saturation encountered in this aquifer, 5km East of the catchment boundary (Ein Sinya well). Also the main part of Wadi Natuf, the WAB has a lack of observation wells, except for Shibteen well field. In Shibteen, the Lower Aquifer is confined; the Upper Aquifer is presumably unconfined – evidence for this are the abundant outcrops of the Upper Aquifer with almost no springs and some well features in Shibteen well #1.

- The surface catchment boundary, however can easily be delineated according to topographic maps.

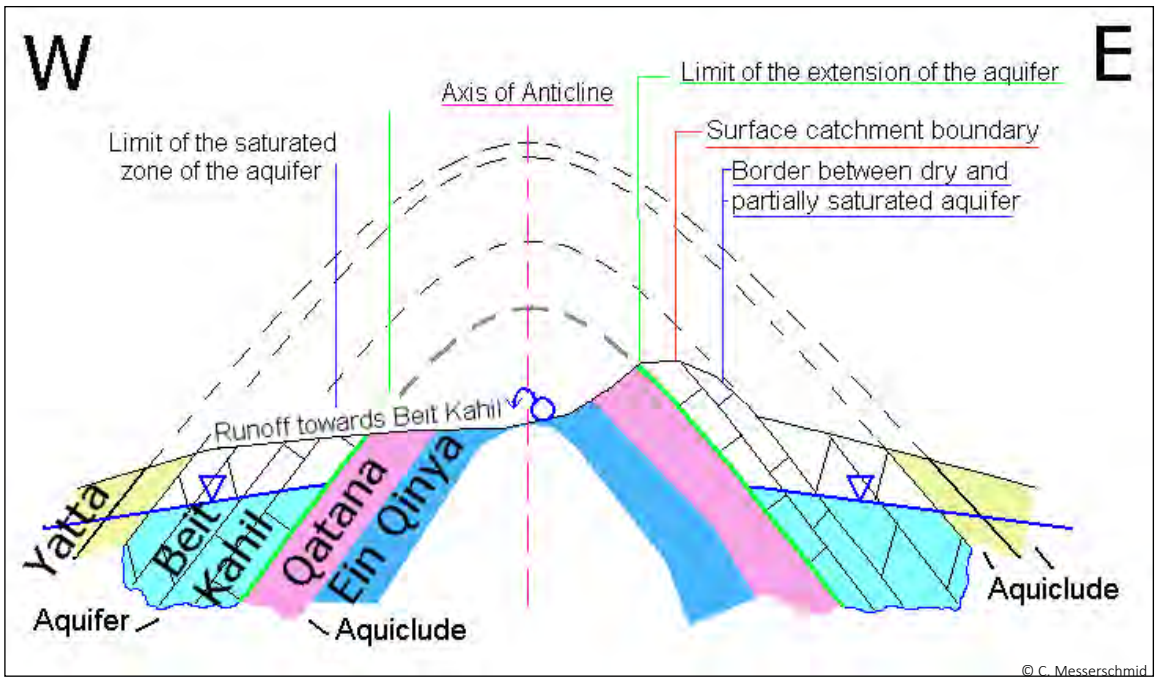

Figure 4: Schematic section of positions of different boundary types

Another problem for the boundaries is the definition of Northern and Southern groundwater boundaries of Wadi Natuf area. It is clear, that these boundaries will only roughly coincide with the catchments‟ N and S borders. It is not possible to accurately draw these boundaries unless exact information of the flow regimes (the flow lines) can be obtained. Conceptually, it can be assumed that these boundaries are belonging to the type of stream boundaries (defined only by parallel flow line). A certain improvement of the boundaries could be achieved according to the completed flow models: More insight has been gained, how the flow directions are oriented under natural and stress conditions.

Another important factor is the presence of the Ein Kerem sub-basin (Fig.5), which has its northernmost part inside Wadi Natuf. Though this area is small, conceptually it has to be taken into account. Ein Kerem sub-basin forms part of the Western Aquifer Basin. However, it is separated from the main basin by Ramallah anticline, which passes in NNE-SSW direction through Wadi Natuf. Ein Kerem sub-basin is characterized by high water levels inside the Lower Aquifer, and used by wells not far to the west of Jerusalem.

The point where the sub-basin splits off the main basin is around Abu Shkhedem, a few km west of Bir Zeit. Ramallah anticline continues in SSW direction, while the boundary between the sub-Basin and the Eastern Aquifer Basin passes in southern direction.

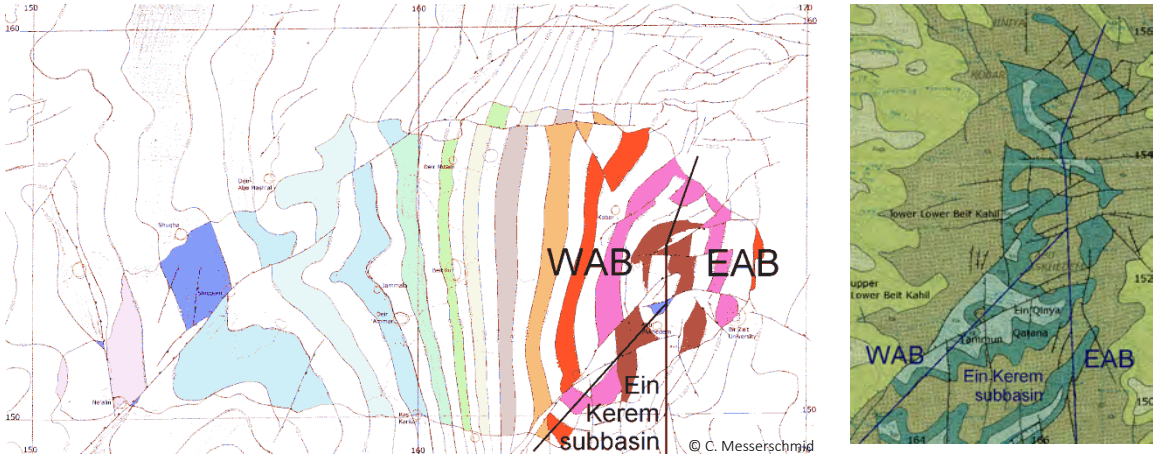

Figure 5: Structural contour map of Wadi Natuf with key Horizon: Top Turonian (modified after Fleischer, 2002 & GSI-map) and groundwater basin boundaries

Ein Kerem Subbasin adds to the overall water of the WAB but does not feed the wells in Shibteen downstream Wadi Natuf. The recharge in the Eastern basin, in the area between Abu Shkhedem and Bir Zeit has to be deducted from the overall Wadi Natuf recharge, in order to obtain values for the Western Basin.

4. Flow Budget

The flow in Wadi Natuf consists of the inflow components (rain, groundwater from adjacent areas, agricultural losses and network losses) and outflow components (groundwater outflow, evaporation, wadi flows and springs).

Inflows

- Rain: This is the largest factor. In a first rough approximation, it can be estimated, that in average 40 to 50 Mcm of rain annually precipitate over the area (100 km^2 catchment area with an average rainfall height of <0.4 - >0.5 m of rain per year).
- Inflows from irrigation are at an insignificant quantity. Irrigation does take place but the vast majority of its water stems from internal basin spring-flow form the perched aquifers. It is therefore not defined as inflow from outside.
- Network losses are also not a very large quantity. If a population of 35.000 people is assumed to live in the area, the average supply is only 60 l/d/c (=22 cu-m/yr/c) and high physical network losses of 30 % are assumed, then the total of the network losses into the ground will amount to 0.23 Mcm/yr only.
- Inflows of groundwater from adjacent areas are also not a very large component. It cannot be ascertained that the groundwater flow is directed exactly E-W, but the deviation from this direction should not be more than 20 degrees. As a very rough approximation, it shall be assumed here, that the flow is relatively evenly distributed. This allows the conclusion that along the Northern and Southern catchment boundaries, lateral groundwater-inflows will be in the same range as the lateral outflows. Thus the balance is assumed zero here.

Outflows:

- Lateral groundwater flow has been discussed above. The main portion of outflows however, should be the normal E-W directed groundwater flow, coming form the recharge areas and flowing towards the pumping areas in the Coastal plain and foothills. The overall balance of existing formulas will lead to an approximate assumption of 25-30 Mcm of groundwater flow, generated in Wadi Natuf. Most of which flows out of the area. A small portion of it belongs to the perched system, feeding springs that are used and thus transformed in different ways of “flow”. The estimated total spring flow in Wadi Natuf is expected to be around 0.5 Mcm/yr.

- Evaporation is not "flow" *sensu strictu*. However, for the water balance it is one of the most important factors. More than 50% of actual evaporation can be assumed with certainty. More exact figures will require calculations or measurements after the winter.
- Wadi runoff only occurs after high intensities. Therefore, the pattern is even more unpredictable than the total rainfall quantities and fluctuates strongly from zero flow in certain years to several Mcm/a in other years. Exact numbers have not yet been found. It should only be estimated, that wadi run-off will lie in an order of up to 10Mcm/yr in strong and high intensity rainfall winter seasons.
- Some of the wadi flow will not leave the catchment but infiltrate as wadi losses into the ground again and thus contribute to the groundwater flow. Measurement of wadi flow in different sections of the wadi will make it possible to differentiate between different sub-catchments (see Figure 6) and thus estimate wadi losses.

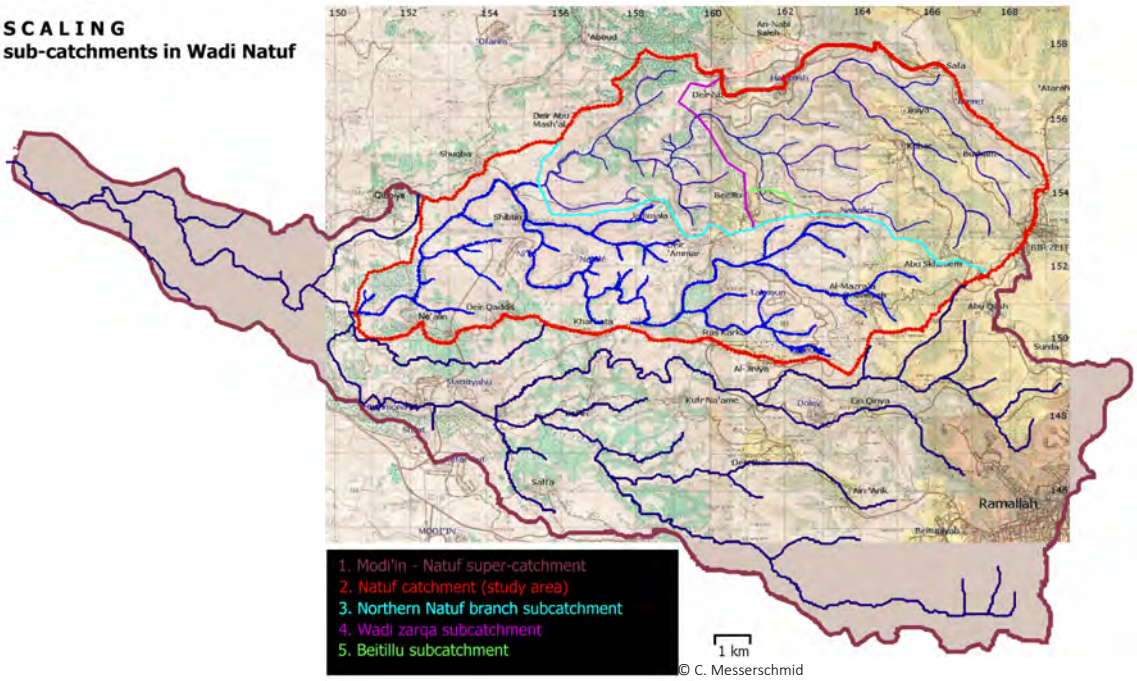

Figure 6: Sub-catchments for wadi flow measurements

5. Landforms:

The different landform types (Fig. 7) have already been described in detail in the design and background report (SUSMAQ #48). Therefore only a short summary is given here.

The outcrop area of the Lower Aquifer has strong terracing, mostly with olive trees.
Lower Yatta has remainders of terraces formerly used for non-irrigated small scale wheat production and now used only locally; in lower Wadi Zarqa area, some terraces with olive trees can be found. Upper Yatta, due to its soft marl, steps back in the slopes and thus creates plains, suitable for agriculture.

On the Upper Aquifer in Wadi Natuf there are no terraces. Many rocks are standing out with only small pockets of soil between them (rugged karstic landform).It is used only for grazing.

It can be roughly summarized:

- The Lower aquifer is characterized by low runoff, high infiltration rates and also important soil moisture mechanisms.
- The middle "aquitard", Yatta, has diverse runoff features, medium to high infiltration rates (perched springs) and the soil moisture content here is of great importance.
- The Upper aquifer has a higher runoff and also high infiltration rates; the soil moisture content is relatively unimportant and less transpiration from plants should be expected.

6. Recharge mechanisms:

The approach chosen for the catchment was based on the observation that different geological observations not only occur in specific elevations and climatic conditions but can also be attributed different typical relief, land cover and land use forms. These features together constitute the main factors of recharge. It was therefore possible to introduce a ranking (weighing) of different formations as to their specific recharge potential. These assumptions will be further assessed and confirmed by the quantitative field measurement campaign during the rainy season 2003/04.

The recharge coefficient of each geological formation will be a basis for a large scale West Bank recharge model.

A preliminary ranking of the different formations is given below (Table 2, Figure 8).

Table 2: Potential for recharge in different formations

Formation name		Potential for recharge	Perched springs	Potential for aquifer	Ranking	Notes
Palestinian	**Israeli**					
JERUSALEM	Bi"na	+++	NO	+++	1	Eastern aquifer forms two aquifer systems
Upper **BETHLEHEM**	Weradim	+	YES (forced out by Kefar Sha"ul)	+	2	Dry in Eastern Aquifer as WT too low
Lower	Kefar Sha"ul	+-	NO (possible)	+-/-	3	Poor aquifer/aquitard
HEBRON	Amminadav	++	NO	+++	1	
Upper **YATTA** Lower	Moza	--	NO	--	4	Not always present
	Bet Meir	+-	YES	-/+	3	Normally aquitard, but can be a good aquifer
Upper **UPPER BEIT KAHIL** Lower	Kesalon	+	YES (few)	+-	2	Not always top Lower but locally intermediate aquifer.
	Soreq	+/+-	YES	+-	2	Horizontal layers of Marls inhibit vertical movement and produced perched system
Upper **LOWER BEIT KAHIL** Lower	Giv"at Ye"arim	++/+++	NO	++	1	Dependant on fractures
	Kefira	+++	NO	+++	1	Fractured, but always produces good flow from wells
QATANA	Qatana	-	NO	-	4	Aquitard
EIN QINYA	Ein Qinya	++	YES	++	4	Good local aquifer, but does not feed main aquifers

Key to symbols: +++ (excellent), ++ (very good), + (good), ± (middle), - (weak), -- (very weak)

It is expected, that runoff behaviour is formation-dependent. Different geological formations react different to rainfall with respect to their recharge quantities.

- Four thick karstic aquifer formations are likely to be the main recharge areas:
  - Lower part of LBK (Kefira) and upper part of LBK (Giv"at Ye"arim)
  - Hebron and
  - Jerusalem
- Two formations are considered aquitards and no receptive for recharge:
  - Qatana formation (bottom aquiclude of the Lower aquifer)
  - Upper part of Yatta (Moza marl) formation.
- Other formations are expected to have an intermediate recharge potential
  - Bethlehem formation (upper and lower parts)
  - Lower part of UBK formation
- Finally, some formations predominantly recharge local or perched aquifers – with an unknown quantity of groundwater losses to the main regional groundwater system.
  - Lower part of Yatta formation
  - Upper part of UBK formation
  - Ein Qinya formation

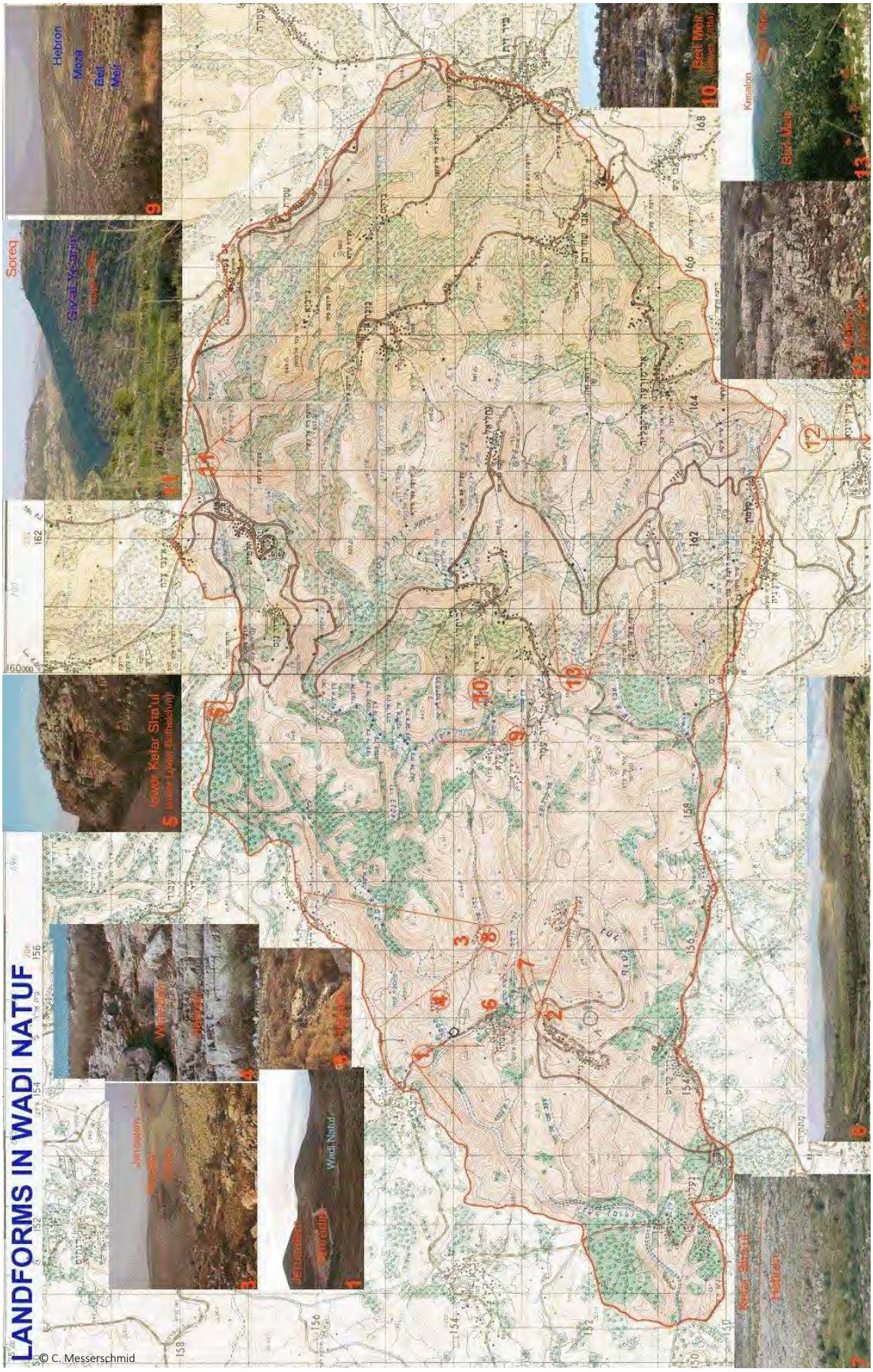

Figure 7: Landforms in Wadi Natuf

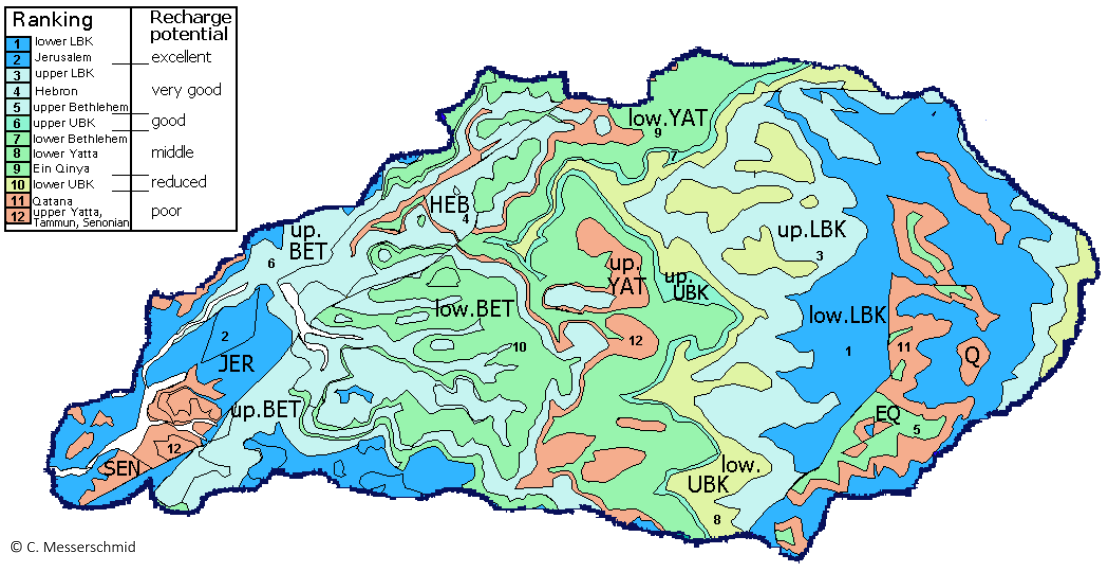

Figure 8: Recharge potential ranking for formations

The main form of recharge is direct rainfall recharge over aquifer outcrops.
Forms of indirect recharge are:

- Wadi losses – runoff in Wadis infiltrates into formations downstream the runoff generating outcrops.
- Irrigation and network losses returns in very low quantities, as mentioned above
- Groundwater throughput from aquifers adjacent to the catchment
- Inter-aquifer connections

The main mechanism as stated above is direct rainfall recharge by *in-situ* infiltration and it accounts for the bulk of the total recharge. The direct infiltration over the aquifer outcrops is slowed down and reduced where thicker soils develop. However, no thick soils (2m thick) have been encountered in the catchment. Rainfall recharge and direct infiltration also depends on the rain intensity. Very high intensities lead to preferential runoff rates and LANGE (2003) calculated runoff rates of up to 85% (of the rain) in very high simulated rainfall performed in sprinkler tests adjacent to Wadi Natuf. While such high runoff rates remain somewhat doubtful, field evidence proved the existence of flash floods after heavy storms, strong enough to wash away roads.

Hortonian overland flow (as opposed to wadi runoff) can also infiltrate directly – while not in-situ – into the outcropping formations, however down-slope the location of the respective rainfall itself.

A second factor of recharge is indirect recharge through losses of runoff in Wadi beds. Again, here the underlying geology plays an important role as could be seen in the field, when Wadi losses were encountered on aquifer formations but not on aquitard formations. Here also the composition of the gravel plays a role in addition to the underlying formations: Two trenches dug through the wadis near Shibteen showed a thickness of only 30cm of coarse sorted gravel. This gravel of course has an extremely high porosity. But below 30cm depth, the alluvial became rapidly more unsorted, combining coarse and fine gravel, sand and silt. This drastically reduces the porosity and hence the recharge potential of the wadis.

Spring discharge stems from perched aquifers in Yatta and uppermost Beit Kahil. The quantities are reduced (<<0.5Mcm/a) and in addition, most of this water is directly used by farmers or for drinking water. Hence only a very small portion adds to the Wadi runoff and then indirectly to the recharge. However, one prominent case can be found in Wadi Zarqa, where springs emerge in and near the Wadi bed throughout the year. In summer however, when flow is reduced, most of this water can be expected to get lost through evaporation and transpiration.

Network losses have also only a very reduced share in the water balance. This is due to the scarce population and in addition their very low water use due to a severe supply crisis in the Palestinian villages of the area. The illegal Israeli settlements are supplied in abundance but the number of settlers is even more marginal than that of the Palestinian population. The only exception to the above statement is of course Bir Zeit with a population of >10.000 inhabitants, many non-resident students and a clearly higher per-capita supply.

Waste water is not treated but disappears in septic tanks or is dumped into the area by tankers. While this fact gives reason to serious concern for the water *quality*, it does not affect the water *quantity* significantly.

Aquifer connections along faults (for example near Shibteen) have not been assessed yet. Anyway, they will mainly affect the ratio between the different aquifer"s recharge, but not the overall area recharge to the aquifers.

Connections between different formation in the sub-crop can lead to indirect recharge in a few cases (i.e. where strong faults juxtapose different formations, like near Shibteen. A special case in this respect is well Shibteen # 1, tapping the lower aquifer and originally sealed in the Upper Aquifer: A TV-log performed in October 2003 showed that the cementation in the annulus of the blank casing is not sealing off groundwater flow any more. This leads to constant losses from the Upper Aquifer into the lower Aquifer. This also explains the behaviour of the well hydrograph, especially in very wet seasons, when the water levels rises by almost 100m. Thus the water level reaches up to as little as a depth of 100m bgl., which is within the Upper Aquifer elevations (see Figure 9). By this, up to more than 60m of the blank casing are filled with water in years of extreme rainfall.

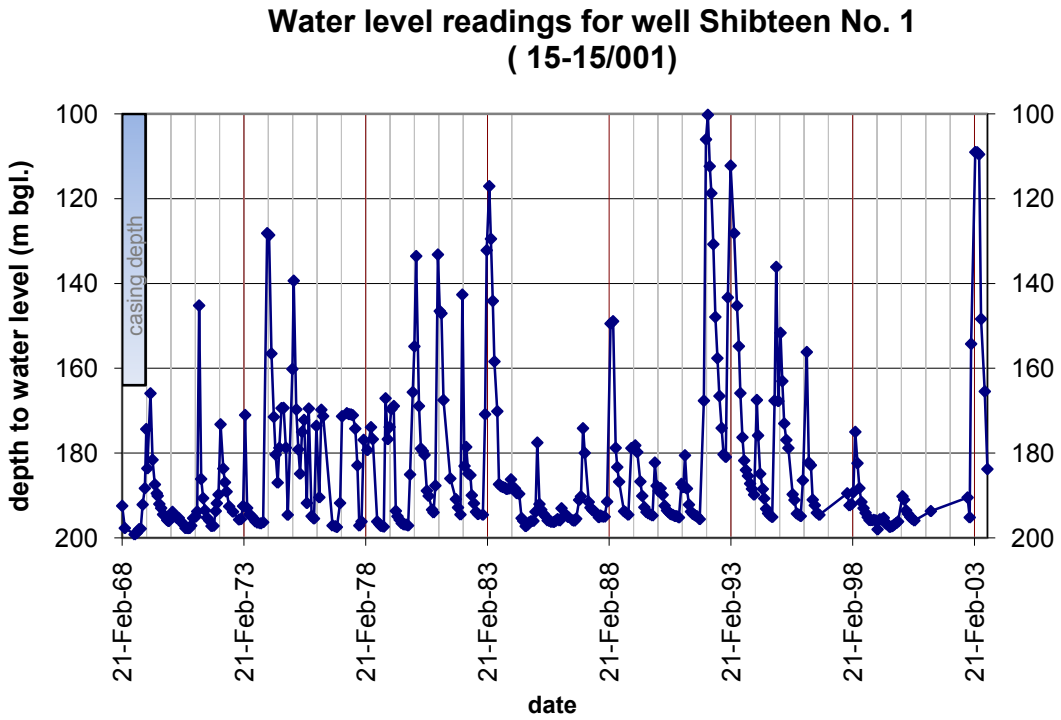

Figure 9: Shibteen well No. 1 hydrograph and casing depth

7. Conceptual approach

Recharge assessment constitutes a challenge in an environment of two very thick karstified and towards the west increasingly buried carbonate aquifers, due to the lack of observation wells in and near the recharge areas, because of the large size of the basin and its complicated geology and structural setting.

Field measurements will be performed for recharge estimation, based on a water balance approach. To enable such an approach is the main objective of the Natuf field measurement campaign (Table 3).

The water balance approach will be used, mainly because other typical methods are not applicable, and it is difficult to find a reliable method for this investigation:

- Hydrograph analysis cannot easily be applied since there is only one deep production well and one functioning monitoring well in the catchment, both tapping only the Lower of the two regional aquifers.
- Spring hydrograph analysis is obstructed by the fact that almost all springs solely emerge from local perched aquifers.
- Chloride balance is also restricted due to the lack of groundwater sampling points in the area.
- Pure soil moisture balance approaches would be misleading since large areas of the catchment significantly or entirely lack a continuous soil cover.
- The similarity of the chemism of the different hydrostratigraphic units makes chemistry based or isotope analysis impossible.

Therefore an overall water balance approach was chosen for estimating the natural replenishment due to rainfall and wadi bed infiltration. The water balance encompasses climatic features such as rainfall, potential and actual evaporation, hydrological factors as soil saturation and runoff in the form of Hortonian overland flow or wadi flow and hydrogeological components such as well water levels and spring discharge.

The basic formula for the surface water cycle is
Total Rain = Evaporation + Runoff + Infiltration
This applies to the surface processes only. And only surface water has clear boundaries.

Groundwater processes are more complicated:
Total infiltration = well abstractions + spring flow + throughput to adjacent areas
But we do not know the exact areas of groundwater recharge and their boundaries as for example for Shibteen well. Also the amount of lateral groundwater throughput to downstream areas of Wadi Natuf is not known.

A third factor is groundwater – surface water interaction, for example:

- some wadi runoff also infiltrates,
- some spring water adds to runoff, of which some again infiltrates,
- leakage between aquifers...

Only part of these features will be measurable, as shown in the following.

Conceptually, it shall be noted that an important component of the conceptual model is the scaling factor – the range form point and local to medium and regional scale and the interrelation between the different scales.

- Upper Albian age formations are differentiated;
- They are in most of the study dipping monotonously westwards, but faulted on a medium and local scale;
- Groundwater inflow to the wells comes from regional to medium scale groundwater catchments;

- Fracture trace analysis from aerial photographs had previously been executed on a medium to large scale. Relief and landform classification is done on a local to medium scale;
- Wadi flow is observed on local, medium and large scale;
- Perched springs emerge from local to medium scale groundwater bodies;
- Field investigation on outcrops and pits dug into the wadi gravels takes place on a point and small scale;
- Soil infiltration tests and soil moisture measurements first only deliver point source information (that then requires regionalisation).

8. Measurement programme

The measurement campaign is expected to generate solid data about
- rain (AWS + 7 TB)
- potential evaporation (2 AWS)
- well pumpage (and w.l.) from one well

medium quality data on
- spring flow (five springs)
- wadi runoff (8 sites)

low quality data (only estimates/calculations) on
- actual evaporation (calculated from 2 AWS)
- soil moisture balance: point values only (depends on number of sampling spots and number of samples taken) – 2 theta probes and as many collection sites as desired.

SUSMAQ will measure and calculate the climatic factors such as rain, potential evaporation and the hydrological factor of runoff for each aquifer outcrop unit. High dependency on geology (lithology, which influences land use) is expected. But each formation is also distinctly characterized by morphology and climate inside Natuf.

Actual evaporation will be calculated from potential evaporation. And from this, infiltration for each formation (and for the whole Wadi) can be derived.

Wadi losses will be estimated (sub-catchment approach).

All springs have been measured once in summer and will be measured again in winter. Five springs will be monitored closely for hydrograph analysis (continuous measurement with read-out on a daily basis). Overall spring discharge (from the perched aquifers) will be deducted from overall recharge.

Soil moisture will be sampled and monitored with theta probes and by direct soil sampling (weekly).

Points for discussion:

a) Evaluation of the measurements and findings.

There will be a large factor of inaccuracy, especially in actual evapo-transpiration (up to >50% of total rain!). Therefore, the question is, which method allows for evaluating and cross-checking whether the calculated results are on the correct side or not.

In the Lower Yatta formation (perched aquifer), a small scale catchment response of spring flow can be compared to the calculated values.

For the Lower aquifer an attempt could be made to compare the calculated values to the water level in Shibteen wells. However, this approach requires knowledge about the

groundwater catchment area and hydraulic properties of the aquifer (like porosity, permeability, storage etc.), which are difficult to define in a deep, fractured and even karstic aquifer.

For the Upper aquifer there is no control inside Natuf. The only possible way would be to compare the calculated values to water levels in wells inside Israel (and outside the study area).

b) Chloride method

The Chloride method should be applied. However, the results will be very inexact, since there is only one well tapping the Lower Aquifer in Wadi Natuf.

c) Isotopes

Another question concerns the use of isotopes, the estimation of travel time, geological recharge province, etc. Again, the lack of groundwater sampling points and the large distance of the one well (Shibteen #1) from the recharge area tapped by the well (Lower Aquifer outcrops in the Western, Upper Wadi Natuf) creates a problem.,

d) Soil moisture balance

In addition soil moisture balance methods could be applied. But in Wadi Natuf, key areas of recharge are the abundant areas of direct rock outcrops (no soil cover) and the few point data from theta probes and soil samples will hardly allow for a reliable soil moisture model.

Other approaches shall still be looked for and considered.

Progress on field investigation and instrumentation

To date, the following works have been carried out and complete unless stated otherwise.

- Field survey
- Field reconnaissance (geology, landuse, wadis etc.)
- Literature review (one Hebrew publication partly translated)
- Aerial photographs on Wadi Natuf; DTM and geology for upper Natuf
- Data collection from PWA (not complete)
- Mapping
- GIS generation of maps (not complete)
- Spring survey – summer
- Spring survey – winter (continuing)
- Soil infiltration test survey
- TV-log in well Shibteen 1 (annulus leaks from Upper into Lower Aquifer)
- Built and installed 7 boxes for wadi flow (Ne‘alin, Shibteen, W.Zarqa)
- One tipping bucket (TB) in Shibteen well station
- Schools for TB and AWS identified and permits from Ministry of education obtained
- Clean-up of wadis
- Construction of small retention walls to channel the flow towards the culverts (completed in Wadi Shibteen but not yet in WadiZarqa)
- 2 water quality hand measurement devices (physical parameters of spring water)

Table 3 lists the different instruments used in the field measurement campaign, the type of data they produce (directly measured or indirectly calculated) as well as possible means and methods to evaluate these measurements.

Table 3: Overview over measurements, data type and evaluation methods

Experiment Instrument	Data measured	Data produced (calculated)	Final recharge evaluation
TB, Totalizers and AWS	Rain intensities (continuous)	Rain intensities and amounts	Total rainfall and intensities over all the area and each formation
AWS	Humid., temp, wind, radiation (Penman)	(Penman formula)	Potential Evaporation
Class A-Pan	Direct evaporation	Evaporation Pan reading	Potential Evaporation
Thermometers and humidity measurements	Together with rain:	Haude, Schendel, Thorntwaite formulas	Calculation of actual evapotranspiration
Springs	Flow at 5 springs twice a day	Hydrograph analysis	Spring characteristics, discharge, catchment area
Springs	Quality (not suggested yet)		
Soil sampling	At three depths for soil moisture contents	Development of soil moisture in the season	Soil saturation point (and date)
Soil theta probes	Continuous reading	Development of soil moisture in the season	Soil saturation point (and date)
Wadi runoff in culverts	Water levels and hand measurements	Manning formula or hand calibration	Wadi flow and losses
Wadi runoff in natural wadis (gravel)	Water levels and hand measurements	Manning formula or hand calibration	Wadi flow and losses
Water level	Pressure probe	hydrograph	Delay time, maybe correlation to recharge

It can be summarized that it will be necessary to perform the following measurements:

A) Wadi Flow: Expected 10 visits to the wadis in which run-off is measured. This requires extensive calibration, measurements, read outs, observation (and maybe repair) – in Ne'alin, Shibteen 1 +2, Wadi Zarqa, Beitillu and near Ras Karkar[1]. If the rain is similar to the one in the season 2002/2003, then five days of flow in the wadis can be expected. Experience tells that in order to encounter these five days, it is necessary to go and check at least ten times (when strong rain occurs) – optimistically spoken.
B) In the beginning the well logger should be read 2-weekly, later on a monthly basis.
C) Theta probes shall be checked 2-weekly[2] as an absolute minimum.
D) Soil sample collection (dry, before rain, partly and fully saturated) should be performed around 20-30 times[3] at 3 locations.

[1] BGS suggested more sites in order not only to monitor run-off but actually understand and quantify water losses in the wadis (infiltration of run-off water in the wadis). However, it is not sure that such an intense presence and work plan can be maintained throughout the season.
[2] This entails actually a great risk. Other projects here (Israeli as well as Palestinian projects) read and check the theta probes on a DAILY basis. The probes are very vulnerable to destruction from people and from animals.
[3] Let's calculate with a value of 25 [times]

E) 7 TB have to be read 2-weekly in the beginning, then monthly
F) 2 AWS shall be read weekly and later on a 2-week basis[4]
G) Regularly supervise, help and advise the people who perform daily read-out of the spring flow (weekly visit at the springs and with the readers).

This amounts to 358 individual measurements (as listed in the table at the end).

Table 4 gives an overview over the field measurements, itemized and listed to estimate the work load. It quantifies and differentiates between the rate of *monthly* visits in the first measurement period (Dec, Jan) and the second period of the rainy season (Feb, Mar, Apr). This is based on the assumption that it will take around two months to become familiar with the instruments and reach a stage of routine in the field work. The last column of the table shows the total number of visits throughout the season. Naturally, this quantification is an estimate and will be subject to changes due to the actual situation in the field.

Table 4: Itemized list of individual field measurements

Place	Measurement	DecJan Sum		FebMarApr Sum		Total
		monthly		monthly		
Shibteen	Wadi1 culvert	2	*4*	2	*6*	**10**
	Wadi1 gravel	2	*4*	2	*6*	**10**
	Wadi2 culvert	2	*4*	2	*6*	**10**
	Wadi2 gravel	2	*4*	2	*6*	**10**
	AWS	4	*8*	2	*6*	**14**
	Soil	6	*12*	6	*18*	**30**
	Well	2	*4*	1	*3*	**7**
Beitillu	spring1	4	*8*	2	*6*	**14**
	spring2	4	*8*	2	*6*	**14**
	spring3	4	*8*	2	*6*	**14**
	Wadi	2	*4*	2	*6*	**10**
	Theta probes	2	*4*	2	*6*	**10**
	Soil	6	*12*	6	*18*	**30**
	TB	2	*4*	1	*3*	**7**
Ne'alin	Wadi	2	*4*	2	*6*	**10**
Ne'alin	TB	2	*4*	1	*3*	**7**
Kharbatha	TB	2	*4*	1	*3*	**7**
Deir Abu Mash'al	TB	2	*4*	1	*3*	**7**
Deir 'Ammar	TB	2	*4*	1	*3*	**7**
Bir Zeit	TB	2	*4*	1	*3*	**7**
Mazra'a Al-Qabiliyeh	TB	2	*4*	1	*3*	**7**
Mazra'a Al-Qabiliyeh	Soil	6	*12*	6	*18*	**30**
Kobar	AWS	4	*8*	2	*6*	**14**
Ras Karkar	Wadi	2	*4*	2	*6*	**10**
Wadi Zarqa	Wadi culvert	2	*4*	2	*6*	**10**
	Wadi gravel	2	*4*	2	*6*	**10**
	spring1	4	*8*	2	*6*	**14**
	spring2	4	*8*	2	*6*	**14**
	spring3	4	*8*	2	*6*	**14**
						358

[4] Assuming that during the 1st period, no major complications occur. Only then can we loosen control.

The field work requires *two teams* to work in the field on Wadi Natuf, starting *from now* and whenever necessary during the wet season!

Actually three teams would be necessary to cover all instruments in the whole wadi in ONE day:

A) BirZeit, Kobar and Mazraʿa Al-Qabiliyeh
B) Beitillu and W.Zarqa (including Ein Ayoub, Kahrbatha and Deir Ammar),
C) Shibteen/Neʿalin area (including Shuqbah and Deir Abu Mashʿal)

However, two teams are the minimum for successfully monitoring the area and control all measurement devices closely in order to avoid considerable loss of data. Any further delays in field preparation and instrumentation will considerably harm the results of Wadi Natuf recharge assessment study.

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Extended Abstract

DEVELOPMENT OF A CONCEPTUAL RECHARGE MODEL OF WADI NATUF CATCHMENT, PALESTINE

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Abstract. Recharge assessment is crucial for a sustainable management and sharing of intensely disputed groundwater resources in Israel and Palestine. For the first time, a field measurement campaign of such scale and intensity has been carried out in a 100km^2 surface catchment, called Wadi Natuf. Climate, runoff, soil moisture, springs and wells have been monitored during several consecutive seasons. The data analysis is based on a conceptual model that focuses on direct methods and a water balance for two regional and one local perched carbonate aquifer of Upper Albian to Turonian age. The conceptual model takes into consideration the different types of land forms, differentiated by the outcropping formation, its lithology and karstification, soil thickness and soil-rock ratio, vegetation type and density, morphology, relief, elevation and climate. Ranking of the recharge potential of the different formations makes it possible to up-scale point and local measurements and to apply these local data to a numerical recharge model of the Natuf area and, in a later stage, to a model of the entire West Bank.

Resumen. El gravamen de la recarga de la agua subterránea es crucial para una administracion sostenible y para compartir los recursos intensivamente disputados entre Israel y Palestina. En un campaña, primeramente emprendida en tal escala, en una captación superficial de 100km^2 de terreno - Wadi Natuf - el clima, la salida, la humedad del suelo, las fuentes y los pozos se supervisan durante varias estaciones consecutivas. El análisis de los datos será basado en un modelo conceptual que se centre en métodos directos y una balance del agua para dos acuíferos regionales y un aquifero *perched* local del carbonato de Albian Superior a la edad de Turonian. El modelo conceptual toma en la consideración los diversos tipos de formas de la tierra, de que es distinguido por la formación afloramiendo, su lithología y karstfication, grueso del suelo y cociente de la suelo-roca, tipo y densidad de la vegetación, morfología, tipo de la cuesta, elevación y clima. La graduación del potencial de la recarga de las diferentes formaciones permite las medidas del local y del punto del para arriba-escalamiento y su uso para un modelo numérico de la recarga de la captación de Natuf y en un paso más último el banco del oeste entero.

Resumo. A avaliação do recharge do groundwater é crucial para uma gerência e compartilhar sustainable de recursos intensively disputados em Israel e em Palestina. Em um first-ever em tal campanha empreendida escala da medida de campo 100km2 em um catchment de superfície - barranco Natuf - o clima, as molas e os poços da umidade do solo do runoff é monitorado durante diversas estações consecutivas. A análise dos dados será baseada em um modelo conceptual que focalize em métodos e no contrapeso diretos da água para dois aquifer perched regionais e um locais do carbonato de albian superior à idade de Turonian. O modelo conceptual faz exame na consideração dos tipos diferentes de formulários da terra, aquele é diferenciado pela formação outcropping, seu lithologia e karstfication, espessura do solo e relação da solo-rocha, tipo e densidade da vegetação, morfologia, relevo, elevação e clima. O ranking do potencial do recharge das formações permite medidas do local e do ponto do acima-up-scaling e sua aplicação para um modelo numérico do recharge do catchment de Natuf e em uma etapa mais atrasada o banco ocidental inteiro.

Keywords: *Recharge, water balance, up-scaling, landforms, ranking*

Sound estimates of natural rainfall replenishment of the West Bank aquifers are crucial for a sustainable management of the groundwater resources and for successful negotiations between Israel and Palestine. The Oslo-II Interim Peace Accords from 1995 were based on unscientific and politically biased numbers that consequently continued to restrict Palestinian development of the groundwater resources in the West Bank.

Despite its importance, no major field based recharge investigations have been performed so far. Conventional figures of recharge are based mainly on indirect methods such as coarse comparisons between pre-use spring flow (from the two main spring outlets of the basin), well pumpage and rainfall heights, sometimes somewhat refined by flow modeling with simplified flow models. However, recent works and flow models (SUSMAQ #33) indicate a higher groundwater recharge rate. Parallel to these models, a special field work based study is under way in Wadi Natuf to approach recharge amounts by direct methods (Lerner et al, 1990). This paper presents the conceptual approach to recharge estimations and calculations in Wadi Natuf, a 100 km^2 large catchment within the Western Mountain Aquifer Basin (WAB). With an area of 13.000 km^2, the WAB is the largest and most productive groundwater basin in Israel and Palestine.

Introduction to the study area

Recharge assessment constitutes a challenge in an environment of two very thick karstified carbonate aquifers, dipping and increasingly buried towards the west. Some of the difficulties stem from the lack of observation wells in and near the recharge areas, others from the large size of the basin and its complex geological and structural setting. Wadi Natuf lies 5 km NW of Ramallah, on the mountains, slopes and foothills of the Western Basin (*WAB*). Only its easternmost part in the central West Bank Mountains belongs to the Eastern Basin (*EAB*). The conceptual model of Wadi Natuf catchment is based on differentiation of geological and hydrostratigraphic units (Figures 1, 2), climatic variations, land use and relief variability that are studied and measured in an intensive field work campaign starting from the rainy season 2003/04 and scheduled to continue until 2005/06.

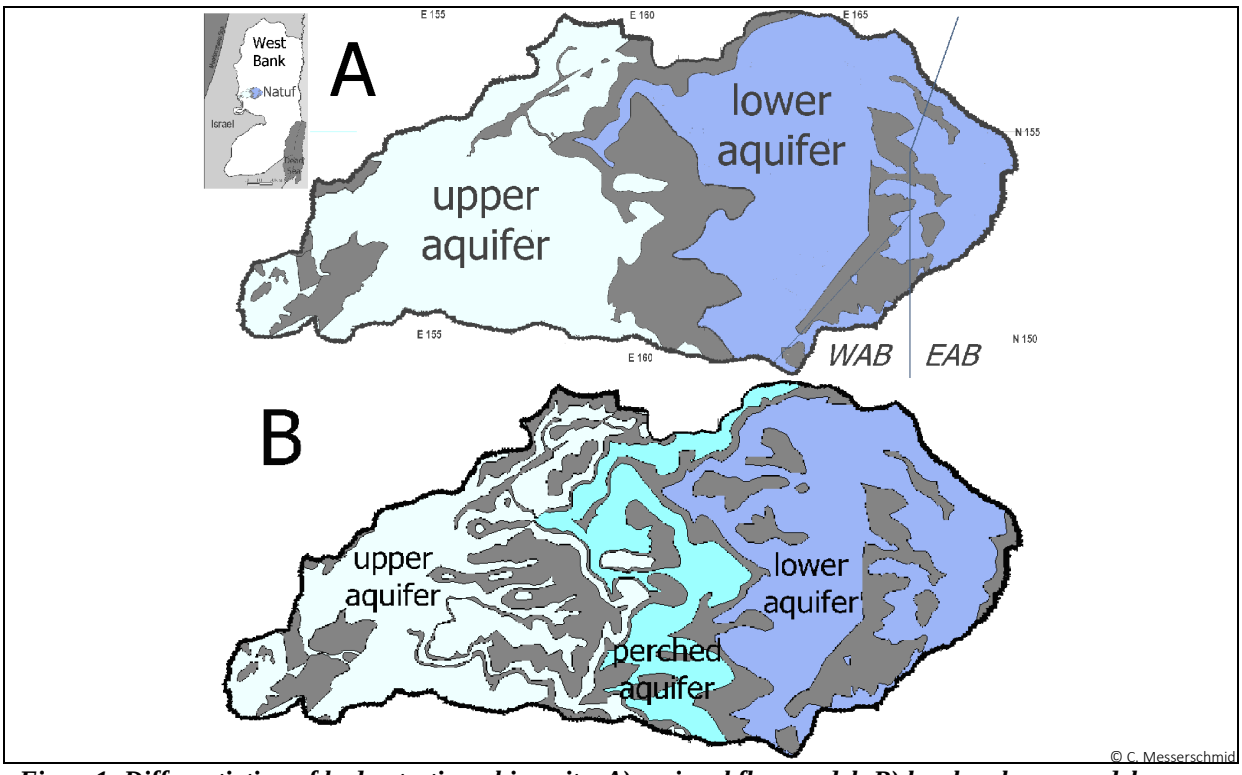

Figure1: Differentiation of hydrostratigraphic units: A) regional flow model; B) local recharge model

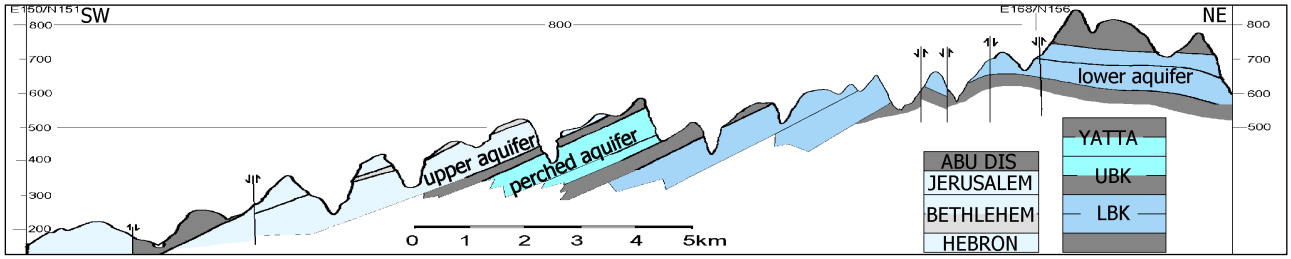

Figure 2: SW-NE Cross section through Wadi Natuf - simplified hydrostratigraphic and lithostratigraphic (box) layers

Two main aquifer units are differentiated (Figure 1a) on a regional scale, such as flow models of the entire Western Basin: The aquifers are of Upper Cenomanian – Turonian and of Upper Albian age, respectively. However, on a catchment scale, a third, middle perched aquifer complex has to be differentiated (Figure 1b). This local aquifer is mainly feeding the small springs in Wadi Natuf.

In most of the area, the formations dip monotonously westwards, with faulting on a local scale (<10 km fault length) in Upper Wadi Natuf and medium scale in the lower basin (>10 km). Groundwater inflow to the well field in the lower Wadi Natuf comes from groundwater catchments that reach beyond the boundaries of the surface catchment of Wadi Natuf. Detailed fracture trace analysis from aerial photographs has previously been executed in the upper half of the catchment.

Recharge mechanisms

Classification of recharge mechanisms (Figure 3) for the various outcropping formations was a central element in setting up the conceptual model.

- Storm runoff and wadi flow is observed on a small sub-catchment scale of around 1 km^2 and up to the scale of the entire Natuf basin.

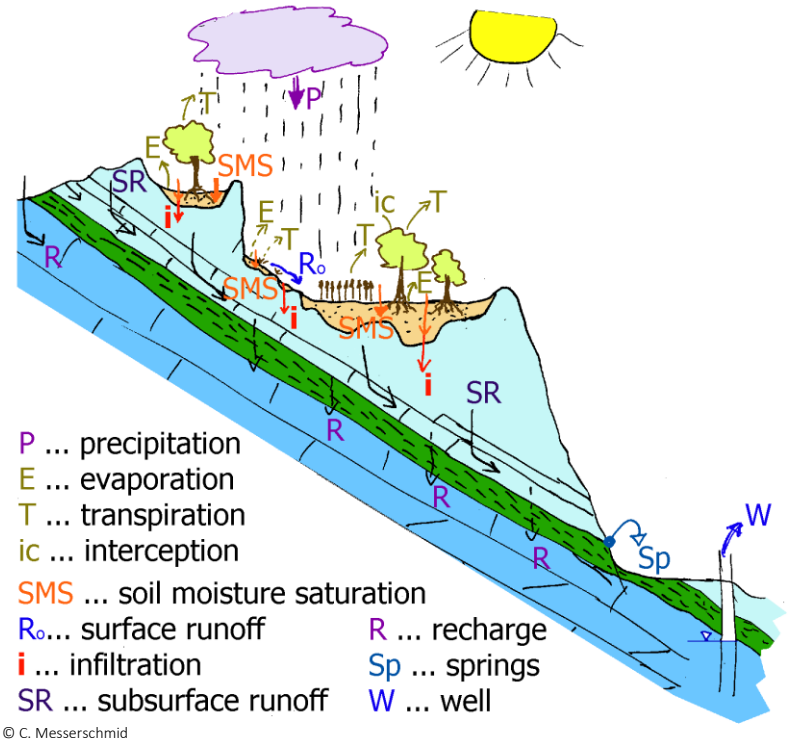

Figure 3: Recharge mechanisms in Wadi Natuf

- More than one hundred small, perched springs emerge from local groundwater bodies, mainly within the separating layer between the two major aquifers. Depending on the recharge–discharge delay time and the groundwater depth, this water can be addressed as subsurface runoff accordingly.
- Soil infiltration tests and soil moisture measurements give point information about the speed of infiltration in the unsaturated zone. Three different groups of soil thickness could be attributed to different formations: The lower aquifer is dominated by cultivated terraces (olives) with medium soil thickness. Conversely, the upper aquifer is characterized by a karstic landscape of predominantly rock outcrops with only minor soil pockets in between. On the outcrops of the middle perched aquifer, a mixture of incomplete terracing, small soil pockets and thick arable soils in the plains mediates between the above two extremes. Factors like evaporation and transpiration not only depend on the climate but also on soil thickness and vegetation cover.

Methods

It is difficult to find a reliable method for this investigation: With only one abstraction well, tapping one of the two aquifers, hydrograph analysis does not promise reliable result in the study area. Spring hydrograph analysis only delivers insights into the small perched middle aquifer from which the bulk of these springs emerge. A chloride balance approach is restricted due to the lack of groundwater sampling points in the area and due to a very wide range of chloride values from the spring sampling points and the one abstraction well. Pure soil moisture balance approaches would be misleading since large areas of the catchment significantly, or even entirely, lack a continuous soil cover. Finally, the similarity of the chemism of the different hydrostratigraphic units makes chemistry based or isotope analysis impossible.

Therefore an overall water balance was chosen for the calculation of the natural replenishment due to rainfall and Wadi bed infiltration. This is based on a “direct methods approach” (Dörhöfer and Josopait, 1997; Lerner et al, 1990) which includes measurements of climatic features such as rainfall, potential and actual evaporation, of hydrological factors as soil saturation and runoff in the form of Hortonian overland flow or wadi flow and of hydrogeological components such as well water levels and spring discharge (Figure 3).

Land forms and ranking of recharge potential

The approach chosen for the catchment was further based on the observation that different geological observations not only occur in specific elevations and climatic conditions but can also be attributed different typical relief, land cover and land use forms. These features together constitute the main factors of recharge. It was therefore possible to introduce a ranking (weighing) of different formations as to their specific recharge potential. As a result of the analysis of measurements and a quantitative estimation of recharge, the ranking of different formations and the attribution of specific recharge values for each formation (Figure 4) will allow for up-scaling the local and point data from the field for larger areas. In a future step, these results then will be applicable to the entire West Bank. The recharge coefficient of each geological formation will be a basis for a large scale numerical West Bank recharge model.

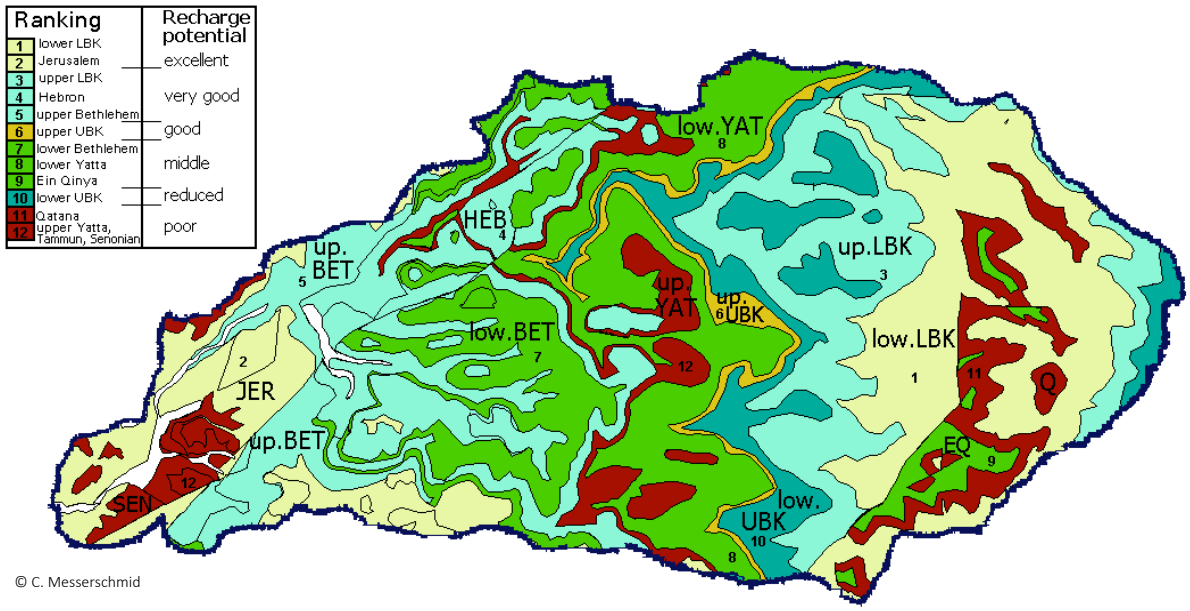

Figure 4: Ranking of recharge potential for different hydrostratigraphic units in Wadi Natuf

Continuation of works

The first measurement period in winter 2003/04 was characterized by steady but gentle rainfall and consequently, an almost complete absence of wadi runoff. Rainfall was measured by nine tipping buckets. Evaporation (Pan and Penman) and soil moisture were recorded at two stations each. The flow of five springs was monitored daily in addition to a continuous water level recording in the observation well. The quantitative analysis of the first season's data is still under way. It will aid in assigning preliminary quantitative weights of recharge to each formation. Two more seasons of measurements are envisaged to generate more reliable results and quantification of recharge figures.

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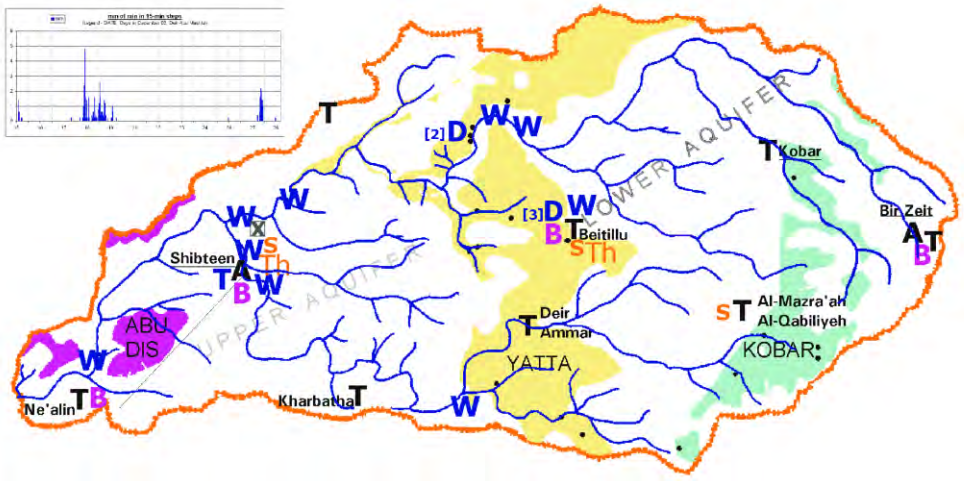
Purchase and installation of field measurement equipment for Wadi Natuf recharge assessment study



Working Report
SUSMAQ-NAT # 68 V 2.0

Prepared by:
SUSMAQ TEAM

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June 2004

Disclaimer

This work report is an output from the Natuf Recharge Estimation Team, part of the SUSMAQ project.

Work reports are designed to present and to communicate the results of work on the SUSMAQ Project without delay. The findings, interpretations and conclusions expressed are those of the authors (the team) and should not be attributed to other collaborators on the SUSMAQ project.

The project does not guarantee the accuracy of the data included in this publication. Information shown in maps, figures, tables and the text does not imply any judgment on legal status of territory or the endorsement of boundaries. The typescript of this paper has not been prepared in accordance with procedures appropriate to formal printed texts, and the partners and funding agency accept no responsibility for errors.

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The SUSMAQ Project

The aim of the project is to increase understanding of the sustainable yield of the West Bank and Gaza aquifers under a range of future economic, demographic and land use scenarios, and evaluate alternative groundwater management options. The project is interdisciplinary, bringing together hydrogeologists and groundwater modellers with economists and policy experts. In this way, hydrogeological understanding can inform, and be informed by, insights from the social sciences. The results of the study will provide support to decision-making at all levels in relation to the sustainable yield of the West Bank and Gaza aquifers.

The project runs from November 1999 to October 2004, and is a partnership between the Palestinian Water Authority, University of Newcastle and British Geological Survey. The project is funded by the United Kingdom's Department for International Development (DFID).

Recharge estimation in Wadi Natuf

The Recharge estimation in Wadi Natuf catchment area is part of the SUSMAQ project.

The recharge assessment focuses on a catchment east of Birzeit down to the Green Line.
It aims to get a better understanding of the mechanisms that control recharge and its quantities.

Primary data have to be produced, covering meteorological data such as rainfall and evaporation, surface water data such as run-off, groundwater data such as spring discharge, water levels and water quality of surface and groundwater and other hydrogeological data such as karst features, aquifer characteristics and vulnerability.

Bibliographical Reference

SUSMAQ-NAT# 68 V0.1 Purchase and installation of field measurement equipment for Wadi Natuf recharge assessment study

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Feedback

This is Version 0.1 of a brief report on the purchase and installation of field measurement equipment for Wadi Natuf recharge assessment study.
The equipment was used in the winter season 2003/04.

The author and the contributors welcome any feedback, both positive and negative! Please, tell us what you think about the ideas and issues raised in this report by contacting the team at one of the addresses above. Your feedback will be appreciated and will help correct possible insufficiencies in planning and setting up the field campaign.

Table of Contents

	Page
Summary outline	**1**
1. Purchase of equipment	**1**
1 a) Equipment and instruments purchased in Newcastle	1
1 b) Equipment produced and purchased in Ramallah	2
2. Field installation	**3**
2 a) Tipping Buckets (TB)	3
2 b) Automatic Weather Station	4
2 c) Wadi, Well and Barometer Divers	4
2 d) Theta Probes	8
2 e) Spring water meters	8
2 f) General conclusions regarding safety of instruments in the field	8
3. Evaluation of main results, achievements and need for follow-up	**10**
4. Photos of instruments in the field	**13**

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– EXCERPTS –

Purchase and installation of field measurement equipment for Wadi Natuf recharge assessment study

SUMMARY OUTLINE

This report gives a short overview of the field equipment used for the Wadi Natuf recharge measurement campaign in the winter season 2003/2004. It provides summary data on the prices of the items and equipment used and an overview over the status of equipment. It then proceeds to give a short overview over the main activities in the campaign and its results from a performance point of view. It will not tackle the technical results of the campaign as they are under process of being generated and will be addressed in detail in the reports to follow. Finally this paper will present the main lessons learnt (again on the performance side) and the most important conclusions and recommendations for the future.

1. PURCHASE OF EQUIPMENT

Most of the measurement instruments were purchased in Newcastle, as listed below. Some of the equipment, especially for the installation works in the field were produced and purchased in Ramallah. A few items, like the spring flow measurement water meters, were borrowed from local institutions (JWU).

a) Equipment and instruments purchased in Newcastle

Most of the measurement instruments, such as the Automatic Weather Stations (AWS), the Tipping Buckets (TB), the Pressure Transducers (Divers), the Theta probes and the data loggers and software packs (Table 1) are not available in Palestine; some of them not even in Israel. They were therefore purchased in Newcastle and an expert on the equipment came twice shortly to help and advise in the field installation.

Table 1: Equipment and instruments purchased in Newcastle

No.	Item	Quantity
1	AWS (MWS 015)	2
2	TB for AWS	2
3	TB & data logger (ARG 100)	9
4	Manual rain totalizer	9
5	Well diver (DI 245)	2
6	Wadi diver (DI 240)	11
7	Baro diver (DI 250)	9
8	Optical interface reader	2
9	Manual flow meter	1
10	Theta probe data logger	3
11	Theta probes	5
12	Soil spiral hand drill	1
9	Water quality meter (MY/6P)	2
13	Drilling machine	1
14	Software	x

The total cost of purchase lays above 20,000 US $. Some of the equipment was not newly purchased but brought 2nd hand – with an assumed value of 50% of the unused equipment (Table 2).

Table 2: Cost of equipment purchased in Newcastle - UK

Supplier	Item	Quantity	Unit price ($)	Total price ($)	2nd hand value (50% $)
Martin Geotechnical Services (UK)	Diver well pressure transducers (DI 245)	2	930	1860	930
Martin Geotechnical Services (UK)	Diver pressure transducers (DI 240)	11	930	10230	5115
Martin Geotechnical Services (UK)	Baro pressure transducers (DI 250)	9	290	2610	1305
Martin Geotechnical Services (UK)	Optical interface reader	2	350	700	350
Camlab (UK)	Water quality Ultra-metre (MY/6P)	2	1380	2760	1380
Environmental Measurements (UK)	Tipping bucket & data logger (ARG 100)	9	760	6840	3420
Environmental Measurements (UK)	Automatic weather station (MWS 015)	2	5900	11800	5900
Environmental Measurements (UK)	Tipping bucket for AWS w/o data logger	2	350?	700	350
Environmental Measurements (UK)	Volumetric rain-gauge	9	88	792	396
Delta-T Devices (AT)	ML2x Theta probes	5	-	-	-
Delta-T Devices (AT)	DL2e data loggers	2	-	-	-
(?)	Manual current metre	1	-	-	-
SUM [$ US]			**TOTAL**	**38,292+**	**19,146+**

b) Equipment produced and purchased in Ramallah

As much as possible, equipment was purchased locally and even produced under the directions of SUSMAQ in local metal workshops in Ramallah, such as evaporations pans, a soil infiltrometer, steel boxes to house the divers in Wadis and culverts and minor items such as a ladder, etc. (Table 3).
The local production of the evaporation pans and the diver steel boxes to be installed in the wadis proved to be very handy, although some problems in the data handling occurred later during the calculation of measured values of evaporation.

Table 3: Equipment produced and purchased in Ramallah

No.	Item	Quantity
1	Evaporation pans	2
2	Cable drum	1
3	Diver steel boxes	16
4	Locks	16
5	Soil sampling equipment	3
6	Infiltrometer	1
7	Drilling machines	2
8	Ladder	1
9	Pipes, connections, records	Bulk

c) Equipment borrowed from other institutions

The local water works in Ramallah, Jerusalem Water Undertaking (JWU), lend their water metres to the SUSMAQ project in order to measure daily spring flow (Table 4).

Table 4: Equipment borrowed from JWU

No.	Borrowed from JWU	Quantity
1	Water meters (1 inch)	3
2	Water meters (½ inch)	2

2. FIELD INSTALLATION

A problem occurred during the transport and import of equipment. The customs procedures in Ben Gurion Airport were lengthy due to a strike and to the very bureaucratic procedures of Israel with respect to import of equipment, especially for the Occupied Territories. The time frame for the measurement campaign was already tight before these problems occurred. Therefore, this delay together with delays for many other reasons led to a final field installation, set up and start of measurements, much later than expected, planned and prepared-for.

On the positive side it proved fortunate that the rainy season began relatively late with no heavy rain storms and with no Wadi flow before end of January 2004. During the installation period field access was relatively good which sped up the very intense installation process. Finally, it was also fortunate that it was also possible to bring some of the equipment by hand-luggage in the airplane.

The main field installation phases were in late October and in late December / early January 2004, well into the rainy season.

Here, not every step of field installation shall be listed in detail. Instead, an overview over the main phases and the most important components of measurement instrument installation shall be presented.

2.a) Tipping Buckets (TB)

The tipping buckets (TB) were installed as soon as the equipment (both, the buckets as well as the loggers) was in the country, field transportation was available and the loggers were set up.

Nine tipping buckets (TB) were set up in a so-called event mode, in which each individual bucket tip after an "event" of 0.2mm rainfall. The TB were distributed evenly over the whole study area. Except for Shibteen, Beitillu and Bir Zeit, all Tipping Buckets were installed on roofs of schools, together with manual rain gauges, read out daily by the teachers..

The first TB and logger to be set up was installed in Shibteen in early November 2003. However, due to problems with the software, the first readings that could be retrieved were from 10.Nov.2003.
The last Tipping bucket was set up in mid December, but the latest date for a first reading recorded from the Tipping Buckets was as late as January 10, 2004 in Mazra'a (Al Qabiliyeh), again for software problems. Table 5 specifies the dates of field installation, the beginning of the read-out period and the last read out recorded in the rainy season 2003/2004. It shall be noted, that the table does not include all read out dates, because some TB were read out more than 10 times during the winter.

Almost all Tipping Buckets were problematic to deal with. Problems occurred mainly with the loggers, in power supply or in the software as well as with the connection cables. For these reasons there are considerable gaps in the measurement period covered. All Tipping buckets except two (Beitillu and Ne'alin) have several, up to more than a month of missing data (!). The gaps have to be filled by comparison with Tipping Buckets from other stations, to daily read outs of manual rain gauges (totalizers) and by comparison of the two additional Tipping Buckets, which were connected in a time mode to the Automatic Weather Station and which proved more reliable, both in power supply and software handling. The two Tipping Buckets set up in time mode and connected to the AWS stations stand in Bir Zeit University (BZU) and in Shibteen (SHI), on the roof of the well guard's house at Well Shibteen # 4.

Table 5: Installation and reading periods for Tipping Buckets

	install	start read	1st read out	2nd read out	3rd read out	4th read out	…	end read
BZU	15-Dec-03	18-Dec-03	6-Jan-04	14-Jan-04	17-Jan-04	24-Jan-04		2-Jun-04
KOB	15-Dec-03	18-Dec-03	6-Jan-04	24-Jan-04	6-Feb-04	***25-Feb-04***		7-Jun-04
MAZ	14-Dec-03	10-Jan-04	24-Jan-04	6-Feb-04	15-Mar-04	1-Apr-04		15-Jun-04
BET	14-Dec-03	14-Dec-03	29-Dec-03	15-Jan-04	20-Feb-04	29-Feb-04		6-Jun-04
DAR	14-Dec-03	15-Dec-03	***14-Feb-04***	29-Mar-04	14-Apr-04	12-May-04		6-Jun-04
KHA	14-Dec-03	14-Dec-03	31-Dec-03	21-Feb-04	20-Mar-04	27-Mar-04		9-Jun-04
DAL	12-Dec-03	15-Dec-03	29-Dec-03	4-Jan-04	21-Feb-04	16-Mar-04		10-Jun-04
SHI	**?-Nov-03**	10-Nov-03	***12-Dec-03***	1-Jan-04	10-Jan-04	28-Jan-04		10-Jun-04
NEA	14-Dec-03	15-Dec-03	31-Dec-03	11-Jan-04	26-Jan-04	21-Feb-04		8-Jun-04

Legend:
BZU = Bir Zeit University; KOB = Kobar; MAZ = Al-Mazra'a Al-Qabiliyeh; BET = Beitillu;
DAR = Deir 'Ammar; KHA = Kharbatha; DAL = Deir Abu Mash'al; SHI = Shibteen; NEA = Ne'alin

2.b) Automatic Weather Station

The two Automatic Weather Stations (AWS) were set up in Shibteen well # 4 on the house of the guard and in Bir Zeit University, Science building, respectively. Main criterion for these locations was the safety of the equipment against damage and vandalism.
During the second mission of Bruce Dudgeon from Newcastle, both AWS were installed, set up and started reading on 15. January 2004. The recording of these stations continued uninterrupted until today and will continue throughout the summer and next winter.

2.c) Wadi, Well and Barometer Divers

A lot of effort was spent on installing and setting up divers to record barometric pressure, Wadi flow, water levels in Shibteen well # 2 and water levels in the evaporation pans next to the AWS (SHI and BZU).
Especially the installation of the Wadi divers, both in gravels and in culverts needed much preparatory and field work. Unfortunately, this winter no flow event (Wadi runoff) occurred, except for one case in a Wadi near Ein Ayoub spring in the southern branch of the Natuf Wadis. In addition, the data from this event could not be retrieved due to a mistake in the setup of the diver at this place. Pure Wadi runoff was measured towards the end of the flood event, by manual flow-meter measurements. Near Shibteen, Wadi flow was recorded and measured by hand, which was a composite of largely spring flow into the Wadi and partly rainfall runoff water.
A positive experience was that the divers functioned quite reliably and were relatively safe in the wadis. Only in one case, was diver stolen and damaged by children in the area. In another case a diver was not stolen but damaged, so that the total loss of divers is two. A third diver was stolen but was given back to SUSMAQ in good working order so that no data loss or damage resulted from this act. This has to be seen as a very respectable result, considering the circumstances of measurements and the experiences of similar field campaigns in the West Bank and the passed years. At different times, more than 16 divers (barometers and well divers included) were out in the field and a loss of only two divers means 'only' 12.5% loss in a season. This proves the advantage of the work-intensive but overall quite cheap divers to more sophisticated automatic Wadi flow measurement stations like weirs etc., because damage to one diver does not endanger the entire measurement campaign.

Table 6 lists the use of the different divers, their read-out and logging periods, respectively.

Table 6: Installation, read-out and logging dates from divers

Diver No.	Type & Location	DATES	read 1	read 2	read 3	read 4	read 5	read 6	read 7	read 8	read 9	read 10	read 11
43611	100m unused												
43612	100m	Date of read out	24-Feb-04	28-Mar-04	31-Mar-04	7-Apr-04							
	SHI well#2	Time	12:33:19	11:41:23	12:17:38	11:58:21							
	still in the field	*FIELD DATA: from*	18-Jan-04	18-Jan-04	28-Mar-04	31-Mar-04							
		To	24-Feb-04	28-Mar-04	31-Mar-04	7-Apr-04							
43881	5m	Date of read out	26-Jan-04	10-Feb-04	1-Mar-04	17-Mar-04	17-Apr-04						
	Wadi NE'ALIN	Time	13:59:54	11:01:30	11:52:39	11:30:07	11:44:21						
		FIELD DATA: from	5-Jan-04	26-Jan-04	26-Jan-04	26-Jan-04	17-Mar-04						
		To	26-Jan-04	10-Feb-04	1-Mar-04	17-Mar-04	17-Apr-04						
43892	5m	Date of read out	25-Jan-04	12-Feb-04	11-Mar-04	29-Mar-04	21-Apr-04						
	ZARQA WCA side	Time	12:19:52	14:39:27	11:15:10	14:52:06	10:32:44						
		FIELD DATA: from	18-Dec-03	18-Dec-03	18-Dec-03	11-Mar-04	11-Mar-04						
		To	25-Jan-04	12-Feb-04	10-Mar-04	29-Mar-04	21-Apr-04						
43894	5m	Date of read out	25-Jan-04	11-Mar-04	29-Mar-04	21-Apr-04							
	ZARQA WCB mid	Time	12:33:04	11:02:16	14:58:54	11:40:34							
		FIELD DATA: from	18-Dec-03	18-Dec-03	11-Mar-04	11-Mar-04							
		To	25-Jan-04	10-Mar-04	29-Mar-04	21-Apr-04							
43896	5m	Date of read out	11-Mar-04	14-Mar-04	1-Apr-04								
	replace 43910 SHI W1g	Time	13:48:14	12:57:29	11:41:35								
		FIELD DATA: from	28-Jan-04	28-Jan-04	14-Mar-04								
		To	11-Mar-04	14-Mar-04	1-Apr-04								
43910	5m stolen & damaged	SHI W1 gravel											
44616	5m	Date of read out	22-Jan-04	28-Jan-04	11-Mar-04	14-Mar-04	1-Apr-04						
	SHI W1CB mid	Time	16:42:38	13:24:14	14:14:20	13:33:25	12:10:29						
		FIELD DATA: from	18-Dec-03	23-Jan-04	23-Jan-04	23-Jan-04	14-Mar-04						
		To	22-Jan-04	28-Jan-04	11-Mar-04	14-Mar-04	1-Apr-04						
44617	5m	Date of read out	28-Jan-04	11-Mar-04	14-Mar-04	1-Apr-04							
	SHI W1CA left	Time	13:33:36	14:23:43	13:27:11	12:02:10							
	stolen but returned	*FIELD DATA: from*	18-Dec-03	18-Dec-03	11-Mar-04	14-Mar-04							
	functioning	*To*	28-Jan-04	10-Mar-04	14-Mar-04	1-Apr-04							
43907	5m	Date of read out	11-Jan-04	22-Feb-04	11-Mar-04	25-Mar-04							
	SHI W2 gravel	Time	14:03:25	14:59:50	12:00:45	11:57:32							
		FIELD DATA: from	18-Dec-03	18-Dec-04	18-Dec-03	14-Mar-04							
		To	11-Jan-04	22-Feb-04	11-Mar-04	25-Mar-04							
44271	5m	Date of read out	28-Jan-04	22-Feb-04	14-Mar-04	25-Mar-04							
	SHI W2CA right	Time	14:17:03	14:08:08	12:31:30	12:15:07							
		FIELD DATA: from	18-Dec-03	18-Dec-04	18-Dec-04	14-Mar-04							
		To	28-Jan-04	22-Feb-04	10-Mar-04	25-Mar-04							
44438	5m	Date of read out	28-Jan-04	12-Feb-04	14-Mar-04	25-Mar-04							
	SHI W2CB mid	Time	14:27:52	14:27:58	12:22:32	12:25:14							
		FIELD DATA: from	18-Dec-03	18-Dec-03	22-Feb-04	14-Mar-04							
		To	28-Jan-04	22-Feb-04	14-Mar-04	25-Mar-04							

continued

continued

Diver No.	Type & Location	DATES	read 1	read 2	read 3	read 4	read 5	read 6	read 7	read 8	read 9	read 10	read 11
new 52040	**5m unused**												
44162	**BARO**	**Date of read out**	**26-Jan-04**	**10-Feb-04**	**1-Mar-04**	**17-Mar-04**	**17-Apr-04**						
	Ne'alin	Time	13:13:22	11:30:18	12:17:03	11:55:54	12:02:46						
		FIELD DATA: from	19-Dec-03	26-Jan-04	26-Jan-04	26-Jan-04	17-Mar-04						
		To	26-Jan-04	10-Feb-04	1-Mar-04	17-Mar-04	17-Apr-04						
44163	**BARO**	**Date of read out**	**14-Jan-04**	**28-Jan-04**	**8-Feb-04**	**22-Feb-04**	**14-Mar-04**	**25-Mar-04**	**12-Apr-04**	**4-May-04**			
	Shibteen (well#4)	Time	11:44:19	15:40:14	13:26:53	17:30:16	11:29:39	10:39:09	10:39:23	12:01:04			
		FIELD DATA: from	19-Dec-03	19-Dec-03	19-Dec-03	19-Dec-03	22-Feb-04	14-Mar-04	14-Mar-04	14-Mar-04			
		To	14-Jan-04	28-Jan-04	8-Feb-04	22-Feb-04	14-Mar-04	25-Mar-04	12-Apr-04	4-May-04			
44164	**BARO**	**Date of read out**	**25-Jan-04**	**12-Feb-04**	**29-Feb-04**	**16-Mar-04**	**29-Mar-04**	**21-Apr-04**					
	Beitillu	Time	13:50:57	14:04:36	11:01:42	13:43:41	12:35:49	11:28:14					
		FIELD DATA: from	5-Jan-04	5-Jan-04	12-Feb-04	12-Feb-04	16-Mar-04	14-Apr-04					
		To	25-Jan-04	12-Feb-04	29-Feb-04	16-Mar-04	29-Mar-04	21-Apr-04					
44165	**BARO**	**Date of read out**	**27-Jan-04**	**6-Feb-04**	**17-Feb-04**	**23-Feb-04**	**15-Mar-04**	**27-Mar-04**	**19-Apr-04**	**29-Apr-04**	**8-May-04**		
	BZU	Time	13:02:45	16:04:30	13:43:24	14:34:23	14:12:28	15:00:50	11:49:50	13:56:37	13:04:42		
		FIELD DATA: from	5-Jan-04	5-Jan-04	5-Jan-04	5-Jan-04	5-Jan-04	15-Mar-04	15-Mar-04	19-Apr-04	29-Apr-04		
		To	27-Jan-04	6-Feb-04	17-Feb-04	23-Feb-04	15-Mar-04	27-Mar-04	19-Apr-04	29-Apr-04	8-May-04		
44169	**BARO damaged**	Wadi Ein Ayoub											
44167	**BARO**	**Date of read out**	**27-Jan-04**	**6-Feb-04**	**17-Feb-04**	**23-Feb-04**	**15-Mar-04**	**27-Mar-04**	**30-Mar-04**	**14-Apr-04**	**19-Apr-04**	**29-Apr-04**	**8-May-04**
	BZU evapo	Time	12:42:46	16:14:38	13:48:35	14:39:05	14:24:03	15:09:57	14:29:48	11:44:38	11:53:37	14:07:52	13:00:34
		FIELD DATA: from	22-Jan-04	27-Jan-04	27-Jan-04	27-Jan-04	27-Jan-04	27-Jan-04	27-Jan-04	30-Mar-04	30-Mar-04	14-Apr-04	29-Apr-04
		To	27-Jan-04	6-Feb-04	17-Feb-04	23-Feb-04	15-Mar-04	27-Mar-04	30-Mar-04	14-Apr-04	19-Apr-04	29-Apr-04	8-May-04
44172	**BARO**	**Date of read out**	**23-Jan-04**	**28-Jan-04**	**8-Feb-04**	**22-Feb-04**	**14-Mar-04**	**25-Mar-04**	**12-Apr-04**	**4-May-04**			
	SHI evapo	Time	11:36:23	13:30:41	13:32:48	17:38:47	11:36:33	10:22:34	10:42:57	12:12:44			
		FIELD DATA: from	18-Jan-04	18-Jan-04	28-Jan-04	28-Jan-04	22-Feb-04	14-Mar-04	14-Mar-04	14-Mar-04			
		To	23-Jan-04	28-Jan-04	8-Feb-04	22-Feb-04	14-Mar-04	25-Mar-04	12-Apr-04	4-May-04			
new 48942	**BARO unused**												
new 48944	**BARO unused**												

2.d) Theta Probes

Theta probes to control and register natural soil moisture were installed at two locations in Wadi Natuf in early January 2004. The Theta probes are connected to a logging unit that was dug in several metres away from the Theta probes. One location chosen was a private garden in Beitillu, in which the risk of steeling or vandalism is largely reduced. However, at some point during the campaign the cables were destroyed by careless ploughing in this little field, which resulted in a data loss for a few days, until the repaired cables could be reconnected. In the garden, three Theta probes were dug into the soil, two at shallow (10-15cm) depths and one at the maximum possible depth at that location (40-50cm).
The other location was chosen in Lower Wadi Natuf at the catchments boundary in Shuqba on a naturally stair-stepped slope facing Shibteen. Here soil thickness did not exceed around half a metre. Only two Theta probes were installed here, one at a shallow depth (10-15 cm) and the other at the maximum possible depth of 30-35cm. In addition, because the location was a publicly accessible area, the logger unit was set in a locked steel box that was in turn cemented onto a foundation platform on the rock outcrops. In late March 2004, the Theta probes were stolen from the location and could not be recovered. The last read outs form this location are from March 11, 2004. However, the most valuable part of equipment, the data logger was not harmed and is safe and in working order. This fact points to a general experience, that measurements on natural conditions and in a natural landscape setting always bear the risk of equipment loss. In each case, therefore a compromise has to be found between investing in safety measures and the risk of lost, stolen or damaged instruments.

2.e) Spring Water Meters

Five springs in central Wadi Natuf were equipped with water meters (water clocks) of the house use type. The water meters continuously record natural spring discharge and are read out on a daily basis by inhabitants in the area. Two springs are measured in Wadi Zarqa and 3 springs in Harat Al-Wad, on the Northern outskirts of Beitillu. All off the springs in Wadi Natuf are small local springs and have been recorded on a daily basis before.

The set-up of the springs partly demanded field work on capturing the spring and concentrating the outflow in one pipe. This led to some delays. In addition, during the first months, local inhabitants disconnected the water meters due to lack of knowledge which resulted in several cases in loss of data for a sequence of hours. However, this method was relatively successful, given the low input of funds. Jerusalem Water Undertaking (JWU) the local water works in Ramallah was approached for lending their equipment for the period of the campaign and was friendly to agree. Thus the water meters will be handed over to JWU towards the end of summer, when the measurements have been concluded.

2.f) General conclusions regarding safety of instruments in the field

As discussed above, the risk of loosing equipment and instruments in field measurement campaigns in an open natural environment in the West Bank is very re4al and always present. In several cases it materialized into equipment actually stolen and/or damaged.
However, more specifically, some observations are of interest for future campaigns.

In all cases SUSMAQ and PWA could follow-up, the theft of equipment was done by children of either the Bedouin tribes or from the villages in the area. No adults have stolen or damaged anything in the entire campaign.
This is largely due to the fact that a relatively great effort was undertaken to inform the local population about the aims and measures of the campaign. This – it was evident – is the best "insurance" against theft or vandalism.

Of course, first of all, it has to be pointed out to the residents of the area, that this campaign has nothing to do with settler and army activities, which by the way do exist even in the field of hydrology in the very area of Wadi Natuf. It should be stressed that the people in the villages were extremely helpful and cooperative.

The efforts of informing the population went hand in hand with awareness rising measures to better protect the natural environment, especially with wild solid waste and waste water dumping in wadis etc. At one point that message was also disseminated by mentioning in the Friday prayers in the local mosque, which proved very effective at least on the short term. For long-term impact, more intensive efforts would have to take place, especially through active cooperation with the concerned population in the villages.

Discussions with the children show that also here, lack of awareness is the most important factor and even in cases of theft and destruction, the marks of the events did not hint to bad intentions but rather to boredom or natural interest, giving the same phenomenon just another name. Discussions and explanations proved very helpful. However, it is not possible to reach all kids in the area, unless an organised effort through all schools of the area is made.
The fact that the children gave back the instruments also hints to this direction. It should be pointed out that the divers are a 10cm long and 2.5cm thick shining steel cylinder with one pointed end. This means, they do look very suspicious to anybody in the region, who after more than 3 years of Israeli counter-Intifadha is very familiar with the different kinds and shapes of ammunition. The destruction of the diver stems from the attempt to open the cylinder (which is not possible without special tools).

No settler or army interference harmed the campaign. This was due to the initial choice of locations, which are at maximum possible distance to any settlement or army camp.

The campaign chose a mix of more sophisticated instrumentation (fully automatic AWS) and more work-intensive and simple instruments, manual rain-gauges, soil sampling and spring measurement. This mix proved to be very successful. The many individual problems encountered in the field on an almost daily basis could be compensated by parallel measurements in adjacent areas. However, due to these problems, even the so-called automatic instruments, like the Tipping Buckets made a very intense control and close follow-up necessary in order to minimise the length of data gaps. This is important to point out since there initially was and partly still is a common misunderstanding that the "automatic" measurements would make actual field presence more and more un-necessary.

One problem encountered was the lack of spare parts at the outset of the season. This led to delays and hence longer periods of missed data due to waiting times for spare parts to arrive. This should clearly be addressed in the next season. In the case of the Theta probes that disappeared, after a while it was even decided not to bring and install new ones because the length of time without measurements was already to large to follow up and close the gap. With respect to divers, not enough experience has been gathered so far to give clear conclusions. Since this season, there were almost o floods in the Wadis whatsoever, the experience with the divers is mainly restricted to dealing with the installation of equipment and its maintenance in working order.

Last not least, it should be pointed out, that a successful monitoring mainly depends on the reliability and permanence of skilled field work input during the monitoring period. It is necessary to have field work personnel trained to deal with any problems on the spot, to be prepared for flexible solutions at any time, to be equipped with spare parts, to have access and means for access to the field and to be committed to regular and reliable field visits and data collection follow-up.
In this respect, SUSMAQ has achieved a great deal during this winter season by hand-on on-the-job training for all aspects, routine work as well as unforeseen eventualities with the employees of PWA/SUSMAQ working on this component.

3. EVALUATION OF MAIN RESULTS, ACHIEVEMENTS AND NEED FOR FOLLOW-UP

Wadi Natuf field measurement campaign was very successful although it started with several handicaps:

1. Natural Recharge Estimation of deep-seated aquifers in a karstified fractured limestone environment in a catchment of 100km^2 scale and with a very diverse morphological, geological and land-use pattern would be a great challenge in any area in the world.
2. In Palestine it was the first campaign ever to be undertaken on such an ambitious scale, density and intensity.
3. In addition, the whole preparations for the field work campaign started as the very last component of the entire project, after it had become clear that BGS will not be able to carry out this activity as planned initially. Only towards the end of the year 2002 (in the fourth year since the start of SUSMAQ project) was this component handed over to Ramallah office staff as a new and additional activity.
4. The Intifadha and especially the measures of Israeli military and settlers – to be summarised under the title of Counter-Intifadha[1] - added largely to the difficulties of executing permanent field work. Every filed visit was turned into a gamble in which the outcome was hardly predictable, with roads blocked of, dug-up, diapered, manned with soldiers or re-opened all of a sudden; with settler roads springing-up and disconnecting existing Palestinian connection roads between villages, with army activities in the field and the ever-frightening presence of settlers in the area; finally, last not least with secondary effects like unprecedented wild dumping of waste water and solid waste in Wadis scheduled or already prepared for measurements.
5. It should be pointed out here that the specific kind of measurement campaign – measuring factors of natural aquifer recharge made it imperative to access the field and the respective sites at any given moment and not planned according to the ups- and downs of the daily "security situation" on the ground but rather largely dictated by natural factors that rule the recharge such as storms in the catchment, snow on the mountains, floods in the wadis, run-off on slopes and in Wadis, broken pipes and damaged constructions, farmer activities and the like. A site that cannot be reached at a distinct day of exceptional run off for example is set of data lost, not to be repeated afterwards.
6. The strong delays – mainly in receiving measurement equipment and reliable field transportation all-times at disposition to the project had a negative impact on the performance. There was not enough time to become familiar with not only the standard procedures of the equipment but especially with all the little tricks and problems that eventually occur and site preparation and field installation could not get off the ground as necessary until late into the rainy season (December 14th 2003). This added to the data gaps in field measurements and to periods of equipment out of working order, longer that necessary on a purely technical level.
7. Finally, it should be noted that not only the equipment but also the natural environment and setting provided unforeseen "surprises" that had to be dealt with in a flexible manner and in ways not to be foreseen beforehand. Wadi Natuf measurement campaign is exceptional, if not unique in its kind as a Palestinian experience. Never before has recharge been investigated in the field on even remotely resembling a scale as it was attempted in Wadi Natuf. Never has there been a full-fledged field measurement campaign, tackling such sensitive, complicated and inter-connected issues as rain, run-off, soil moisture, land use, spring flow, Wadi flow and well water levels. And never before were individual measurements of this kind performed at the same time at such a scale and intensity as during this campaign.

[1] which is in fact an entire system of arbitrary controls, destruction, intimidation and punishment, directed against the civil Palestinian population at large, indiscriminate whether school-children or farmers, business-men or ambulances, Bedouin tribes or university teachers are concerned

8. Many critical and self-critical notes have been addressed in this report in the sections above. Therefore it is indicated to state here unambiguously: The fact that the whole campaign came through the season covering and creating a unique set of real time, simultaneous and natural first hand data, fully comparable to each other and applicable to a wide range of calculation methods constitutes a very powerful achievement and a great success. It is a first and indispensable step towards one of the most challenging factors in water balance in general: Estimating and calculating reliably the by nature very evasive factor of natural groundwater recharge. The extremely sensitive matter of aquifer recharge is not only a basic prerequisite for any successful long term sustainable aquifer management in a typical semi-arid and very challenging karstified aquifer environment[2], it is also a key factor in a densely populated and intensively disputed political environment like the Palestinian-Israeli conflict[3].
9. Out of the a.m. assessment follows: SUSMAQ had to aim high and it succeeded in reaching high. However, one thing should by all means not be forgotten or underestimated: Wadi Natuf recharge estimation campaign, being the first of its kind in Palestine, was but only a first step for reaching the overall goal: To obtain reliable long-term recharge estimates based on several consecutive years of observations[4]. Any failure of continuing this campaign throughout the – say – next two seasons (as a minimum) will largely invalidate the achievements of this season's efforts and its results. A situation in which recharge is based on a single term (and even incomplete) single term observation period will lack the necessary solidity and full control of dynamic factor interdependence, crucial for being accepted in the scientific community and for serving as a reliable tool in future water resources planning and short-term as well as long-term management.
10. Wadi Natuf field measurement campaign HAS TO CONTINUE in the next and after next seasons of 2004/05 and 2005/06, starting from Sep/Oct 2004 on the same pace, level and methodology. It would have been highly desirable to cover several rainy seasons within the period of SUSMAQ project. However, the reasons for failing to this were mentioned above and were beyond the control of the project in general and PWA in specific[5].
11. The next season, by all means, is not to be missed for keeping up measuring. Not only interruption of one season, but also change of scale, methods, pace and locations would create a strong limitation in applicability of results.
12. It is therefore in the interest of securing (and collecting the harvest of) the results of SUSMAQ to provide all necessary support for concluding this activity beyond the regular end of the project. The necessary investment is not very large, since the bulk of equipment has already been purchased and trained staff is available now to reliably and successfully continue and terminate this activity. Not all of the staff involved in Natuf is part of PWA staff and especially the field work staff that has already proven to work with a high motivation, increasing professional skill and personal effort

[2] Characterized by high seasonal fluctuations in recharges and discharges, in water demand, actual consumption and supply.

[3] The Oslo-II interim agreement on aquifer had at its core unreliable and unscientific numbers of "estimated aquifer potential", not based on any scientific or other reference or source but at the same time playing the role as the main criterion for future allocation, re-allocation and shares in groundwater abstractions for the duration of the interim period. The clauses under this agreement and especially the figures referring to the "potential" are the largest and single-most impediment to a successful Palestinian water management that meets demands. They are thus one of the greatest obstacles and challenges in negotiating any future water shares to be agreed upon by both parties. In one word: No successful Palestinian negotiations without reliable and realistic recharge figures.

[4] Both words are underlined because it is not only necessary to gather data from different years with different rain and recharge distribution patterns and amounts, but also to measure on consecutive years with full coverage of data. Any gap in this data would invalidate the over-all approach since the starting point for each season is an important factor in itself that cannot be quantified without the previous measurement season in a highly dynamic and unstable environment as a Mediterranean type semi-arid, multi-aquifer, event-controlled setting as the Western aquifer basin.

[5] Among those especially the fact that responsibility for this most demanding project component shifted entirely at a very late stage of the project, due to the Intifadha, the security situation on the ground., as well as specific British regulations how to deal with them.

13. Additional funds should secure employment of this staff, means of uninterrupted field transportation, spare instruments and spare parts of the measurements. Software and means of data evaluation were prepared under SUSMAQ period and are available at PWA.
14. With a very moderate input of 40.000 $ could this component be concluded over the course of the next two years.

Table 7: Expected additional costs

Funds for instruments	
2 optic cables for divers	700 $
2 more divers (5m range)	1860 $
1 manual current metre	?650 $
1 m-scope (manual w.l. indicator)	?500 $
2 spare TB and data-loggers for TB	1520 $
2 spare read out connection cables for TB	?100 $
6 spare and additional Theta probes	?1200 $
1 manual rain gauge	88$
Sum (approximately)	**6000$**
Funds for spare parts and equipment purchased **locally** (including fuel)	**2000$**
Field transportation 1 jeep fully dedicated to Natuf field work (mid Oct. - mid May = 7 months)	**agreement with PWA**
Salaries Three and a half salaries for field staff (local salary for trained and skilled experienced and independently working hydrology field work staff) for seven months each of the two years 650 $ by 14 months by 3.5 salaries = (to be divided and spread among several people)	**31 850$**
OVERALL SUM	**39,850$**

4. PHOTOS OF INSTRUMENTS IN THE FIELD

Installation of diver box in Wadi gravel (SHI2)

Diver box in flooded Wadi (E.AYOUB)

Diver box in gravel (SHI1)

Damaged and functioning Divers

Tipping bucket (SHI)

TB (DAL)

Evapo pan with diver (SHI)

AWS, 2TB, 1 Evapo pan, 1 manual rain gauge (SHI)

Install diver box (NEA bridge)

Manual flow measuring (SHI 2)

Infiltrometer test (BET), © M. Zaydah

Drill hole for Theta probes (SHU)

Install Theta Probes (SHU)

Read Theta Probes (SHU), © N. Khawaldeh

WATER METRE at Ein As-Salem (Wadi Zarqa)

Manual spring flow measurement at Ein Al-'Idd Al-Ashqar (Wadi Zarqa)

Legend:
SHI = Shibteen; SHI 2 = Shibteen Wadi No.2; SHI 1 = Shibteen Wadi No.1; DAL = Deir Abu Mash'al;
NEA bridge = bridge in Ne'alin; E. Ayoub = Spring and area of Ein Ayoub; BET = Beitillu; SHU = Shuqbah

Palestinian National Authority
Palestinian Water Authority

السلطة الوطنية الفلسطينية
سلطة المياه الفلسطينية

Department for International Development
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UNIVERSITY OF NEWCASTLE

The Sustainable Management of the West Bank and Gaza Aquifers

Wadi Natuf Recharge Estimation - Field Measurement Campaign 2003/04

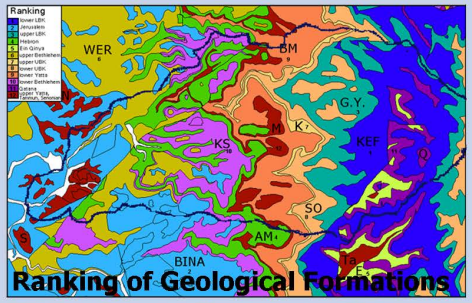
Deir Abu Mash'al

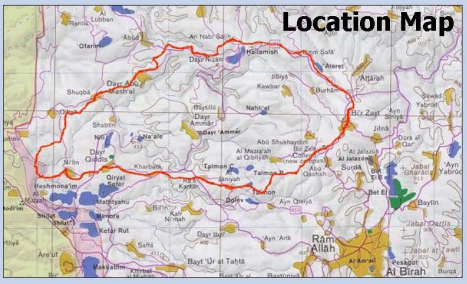
Bir Zeit University

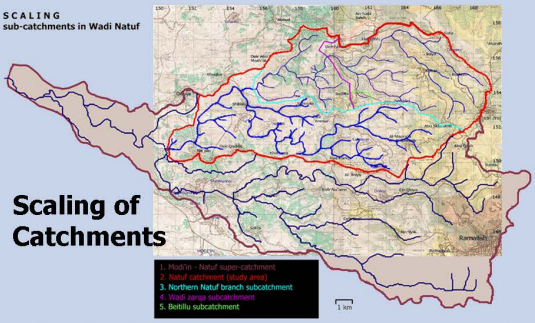
Shibteen Well#4

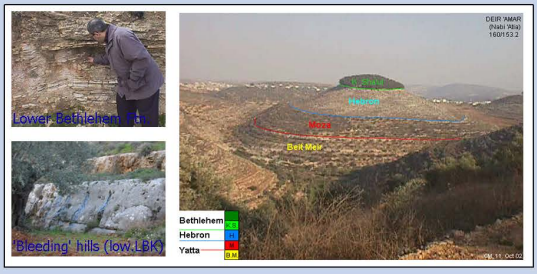
Shibteen Well#4

Tipping Bucket
Automatic Weather Station
Evaporation pan

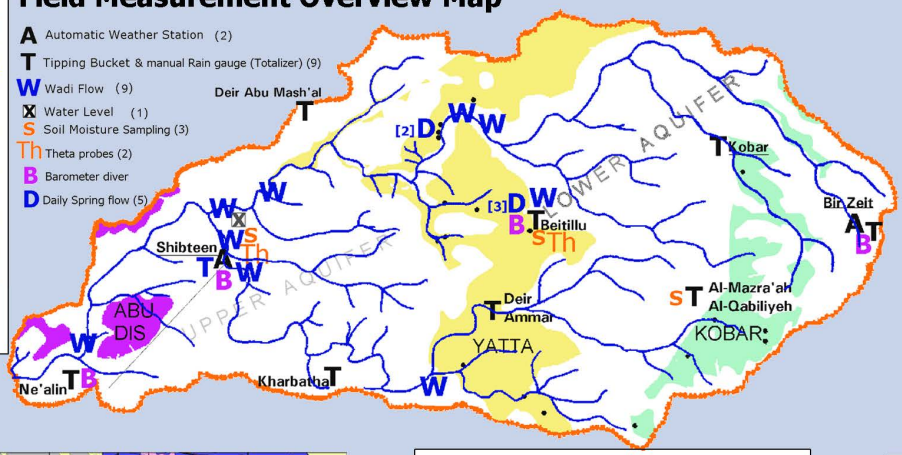








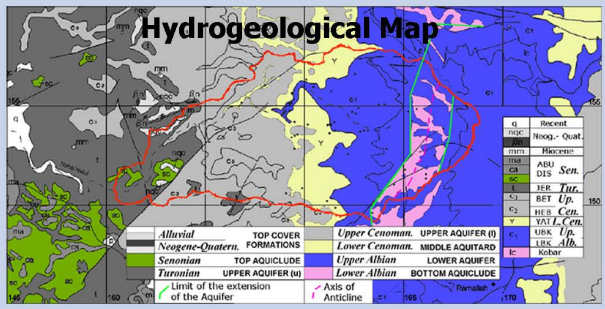
Field Measurement Overview Map



Wadi Flow: Diver & Manual Measurement

Ne'alin Bridge

Ne'alin Bridge



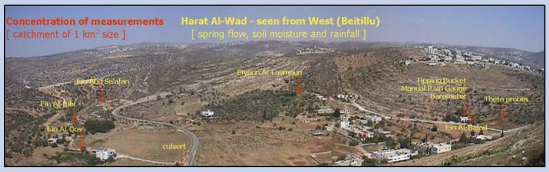
TV-Log and Well diver in Shibteen wells

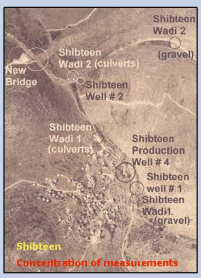
Shibteen Wadi 1 (Hammamah)

Wadi Zarqa

Wadi Ein Ayoub

Shibteen Wadi 2





Soil Test with Infiltrometre (Beitillu)

Soil Moisture Tests - Theta probes in Shuqbah

Appendices of chapter 5

Runoff

5.1 Transmission losses from runoff (Hyd. Proc., 2018) 325

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RESEARCH ARTICLE

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Assessment of transmission loss in a Mediterranean karstic watershed (Wadi Natuf, West Bank)

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Abstract

Run-off transmission loss into karstified consolidated aquifer bedrock below ephemeral streams (wadis) has rarely been described nor quantified. This study presents unique data of long-term high-resolution field measurements and field observations in a semiarid to subhumid Mediterranean carbonatic mountainshed. The catchment with a 103 km^2 surface area is subdivided into 5 subcatchments. Coupled run-off measurements were made in the different stream sections (reaches), and transmission loss calculated from differences in discharge. Rainfall and run-off observations from 9 automated precipitation gauging stations and 5 pressure transducers for automatic water level recording are complemented by manual measurements during 34 run-off events covering a total measurement period of 8 consecutive years. Run-off generation is strongly event based depending on rainfall intensities and depths. Both, run-off generation and transmission losses are related to spatial patterns of bedrock lithologies (and hydrostratigraphy). Transmission losses range between 62% and 80% of generated run-off, with most of the smaller events showing 100% transmission loss. Therefore, although event run-off coefficients in the mountains can reach up to 22%, only 0.11% of total annual precipitation leaves the catchment as run-off. Most run-off infiltrates directly into the regional karst aquifers (Upper Cretaceous carbonate series), with transmission loss intensities of up to 40 mm/h below the stream channels. The factors determining run-off—such as geology, pedology, vegetation cover and land use, relief and morphology, the semiarid to subhumid Mediterranean climate with a strong elevation gradient, and the patchiness of individual storm events distributed over the winter seasons—as well as the lithology and epikarst features of the bedrock are all characteristic for larger areas in the Mediterranean region. Therefore, we expect that our findings can be generalized to a large extent.

KEYWORDS

bedrock lithology, geology, landform, run-off, transmission loss

1 | INTRODUCTION

Groundwater recharge from ephemeral streams (wadis) is an important issue in semiarid climates, where rainfall is either seasonal or flashy, and the occurrence of surface water run-off in fluvial systems is discontinuous. Most of the recharge occurs as direct diffuse infiltration from in situ precipitation on the soils and barren rock outcrops. In some areas concentrated surface run-off in wadis may even be reduced to an insignificant, negligible amount. In karst areas however, wadi discharge as concentrated flow of brief storm run-off events from large catchments may play a rather important role as a mechanism for infiltration of

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groundwater recharge and as a pathway for groundwater contamination.

Most studies in this field so far focussed on unconfined shallow aquifers of alluvial and other unconsolidated rock deposits beneath and next to sections (reaches) of a wadi (Abboushi, 2013; Abdulrazzak, 1995; Bertin & Bourg, 1994; Costa, Bronstert, & Araújo, 2012; Dahan, Shani, Enzel, Yechieli, & Yakirevich, 2007; Harte & Kiah, 2009; Hughes & Sami, 1992; Lange, 1999; Lange, 2005; Morin et al., 2009; Shentsis, Meirovich, Ben-Zvi, & Rosenthal, 2001a, 2001b; Sorman & Abdulrazzak, 1993, Sorman, Abdulrazzak, & Morel-Seytoux, 1997, Schwartz, 2016). In the above studies, rivers and ephemeral streams infiltrate into shallow aquifers; however, they also interact with and receive water from these aquifers, depending on the relative river-stage groundwater level in the respective surface water—groundwater system. Some studies focussed on the surface features of the wadi, such as streambed geometry (Constantz & Thomas, 1997; Costa et al., 2012) or channel width (Walters, 1990). Shentsis, Meirovich, Ben-Zvi, and Rosenthal (1999) studied run-off in arid and hyper-arid catchments of the Negev and developed methods to estimate lateral tributary inflows in desert wadis under transmission loss (TL) that will be adopted in the present study.

Much less attention has been paid to losses from streams into consolidated bedrock, and available data and reports are scarce (Shanafield, Peter, & Cook, 2014). This particularly applies to ephemeral streams and even more so karstic terrains, because here many of the modern approaches to TL are not readily applicable. For example, Walter, Necsoiu, and McGinnis (2012) observed perennial river flows in the Edwards aquifer by remote sensing and measured the length of reaches of run-off before complete loss of flow; yet, such satellite-based remote sensing methods as used by Walter et al. (2012) for perennial streams cannot be employed in many of the episodic or ephemeral streams, because here, surface run-off usually occurs when the wadis are hidden by thick cloud cover of local or regional storms (Lange et al., 2003). The region of this study—the Eastern Mediterranean—is entirely void of studies that quantify TLs into consolidated, karstified bedrock. The absence of such studies in the wider study area is remarkable, because Ford and Williams (2007) emphasize that in the West Bank Mountains most run-off in streams recharges the bedrocks via ponors in the thalwegs. Shanafield et al., 2014 provided an overview of numerous methods for direct field measurements and calculations of TLs. Yet, most of their methods apply to sandy channels, only very few to transmissional losses into consolidated substrata. Those remaining methods can be divided into approaches of (a) groundwater observation and (b) streamflow measurement. The first group is inapplicable for the present study, because no groundwater observation wells exist and the underlying deep aquifer is complex, karstified and overlain by a more than a hundred-metre-thick unsaturated zone. Under these conditions, soil moisture and wadi level data inside the alluvial wadi fill, even if available, would not help to clarify deep percolation processes. From the streamflow measurements approaches, the floodwave front tracking method relates flood arrival times to hydraulic parameters of the underlying strata. This method is highly sensitive to cross-sectional geometry that constantly changes in ephemeral streams. Hence, direct measurement of run-off in combination with water budget calculations along stream reaches is the only practically applicable approach. This approach can constitute a challenge because such investigation methods require extensive fieldwork, especially in areas with only episodic run-off events.

On a more conceptual level, the process of TLs into consolidated bedrock strata concerns the two disciplines of hydrology and hydrogeology, or falls into the gap between them. Hydrogeologists, on the one hand, show keen interest in hard rock aquifer recharge. Studies in this field are abundant but most of them are informed by the understanding that the bulk of groundwater recharge occurs as direct recharge in situ. From a purely quantitative point of view this may well be true (CDM, 1998; De Vries & Simmers, 2002; Goldschmidt & Jacobs, (1958); Guttman & Zukerman, 1995; Rofe and Raffety, 1965; Hughes, Mansour, & Robins, 2008; SUSMAQ, 2001; Simmers, Hendickx, Kruseman, & Rushton, 1997; Zukerman, 1999). In a karst region, most of the indirect recharge through TL occurs along complex epikarst structures. As a result, indirect point recharge such as TLs of surface run-off is nearly always neglected. Hydrogeological studies in the south of France focused on groundwater surface interaction processes in large karst aquifer catchments (Bailly-Comte, Jourde, & Pistre, 2009; Bailly-Comte, Jourde, Roesch, Pistre, & Batiot-Guilhe, 2007) by conceptual lumped parameter models and measurement of karst aquifer recharge from and discharge into surface channels. However, their focus lay on the description of the storage and flow regime in the aquifers and their interaction with the surface water streams, much less on the surface process of actual bedrock infiltration from surface channels.

On the other hand, classical hydrological studies mainly concentrated on surface run-off in streams and quantified TLs into the subsurface. Several authors tried to quantify the effect of landforms and surface features such as relief, vegetation, or land use (Shanafield et al., 2014). However, their focus usually does not cover the complexities of the subsurface geological material, such as the lithostratigraphy and hydrostratigraphy, the aquifer parameters and recharge potential of bedrock, degrees of karstification, and patterns of epikarst (Ries, Schmidt, Sauter, & Lange, 2017). Yet, for the deeper infiltration into consolidated karstic bedrock—unlike sandy channels—such understanding is crucial for the assessment of the recharge potential into underlying aquifers of fractured and karstified rock formations. Therefore, many studies may implicitly incorporate considerations or estimates of TL into the regional water balances (e.g., Gunkel, Shadeed, Hartmann, Wagener, & Lange, 2015), but rarely explicitly and not as a result of direct field observation.

The objective of this study was to assess and quantify TL from run-off in ephemeral streams into the underlying consolidated aquifer bedrock and to differentiate and relate this process to the geology of the receiving formation. Hereby, the level of accuracy and reliability was differentiated for the main channel and lateral inflows from side wadis; minimum rates of TL from the main channel were empirically observed and measured, whereas additional lateral inflows from tributary channels were approximated by estimation.

The investigations presented in this paper reflect both, spatial and temporal variability of infiltration from wadi streams, that is, variations in geology and event rainfall.

2 | STUDY AREA

2.1 | Topography

The study area is a 103 km^2 large mountainous watershed on the western slopes of the Palestinian West Bank (Figure 1). The surface catchment "Wadi Natuf" rises steadily from <200 m a.s.l. at the "Green Line" (the demarcation line between Israel and the West Bank) in the foothills of the Coastal Plain in the west to >800 m a.s.l. at the crest of the West Bank mountain range in the east (near the Palestinian town of Bir Zeit, 10 km north of Ramallah).

Three different groups of land use, vegetation, relief, and correlating geology can be differentiated (Messerschmid, 2014). The upper Wadi Natuf with steep hills is dominated by either grassland with scrubs and barren rock or by terraced hill slopes of tended or abandoned olive cultivation. This area is underlain by the regional lower aquifer, especially in sub-catchment Wadi Zarqa. In contrast, lower Natuf adjacent to the coastal plain (Israel) is characterized by gentle slopes almost exclusively covered with sparse vegetation such as scrubs and sclerophyllous bushes or barren rock. The barren rock locally exhibits expressed epikarst features and mostly belongs to the regional uppermost aquifer, whereas the remaining 44% of the area is covered by more or less confining aquitards (Table 1 and Figure 1). The central area displays a mix of all these relief forms, and stands out with smaller portions of forests and nonirrigated complex cultivation on small plains over the softer marl outcrops. But again, terraces of olive groves and small fields dominate the morphology on the slopes, many of which are now abandoned.

2.2 | Geology

On a regional scale, the hydrostratigraphic division is usually tripartite. The regional lower aquifer of Upper Albian karst lime- and dolostones with 260–375 m thickness (Formations 1, 3, and 6 in Figure 1, SUSMAQ, 2002 and 2003a; Dafny, Burg, & Gvirtzman, 2010) is overlain by a middle aquitard, an 80–160-m-thick series of carbonates with varying degree of marl and chalk content alternating with chalk and marl layers of the lower Cenomanian (Formations 10 and 12, Figure 1, SUSMAQ, 2002 and 2003a; Dafny et al., 2010). The regional upper aquifer again comprises karstified lime- and dolostones of upper Cenomanian–Turonian age with a thickness of 180–300 m (Formations 4, 6, and 2, Figure 1, SUSMAQ, 2002 and 2003a; Dafny et al., 2010). On a local scale, these regional units can be subdivided according into over a dozen lithostratigraphic units and ranked hydrostratigraphically according to their aquifer potential (Figure 1, SUSMAQ, 2003a). Within the "regional aquitard", the carbonatic subseries of lower UBK (*Soreq*) formation (Rank 7, Figure 1) give rise to local perched subaquifers with an abundance of small springs. And both, upper and lower aquifer are also comprised of less permeable, partially tight subseries, interbedded within the main karstified aquifer sections (Formations 7 and 8, Figure 1, SUSMAQ, 2003a). Based on extensive litho- and hydrostratigraphic field work, a ranking order of aquifer potential of the different formations was developed (Figure 1), with the highest potential (ranking Position 1) found in the lower part of the lower aquifer (lower LBK, Figure 1) and the lowest aquifer potential (ranking Position 12) as fully developed aquitards in the yellow marls of upper Yatta formation (Figure 1).

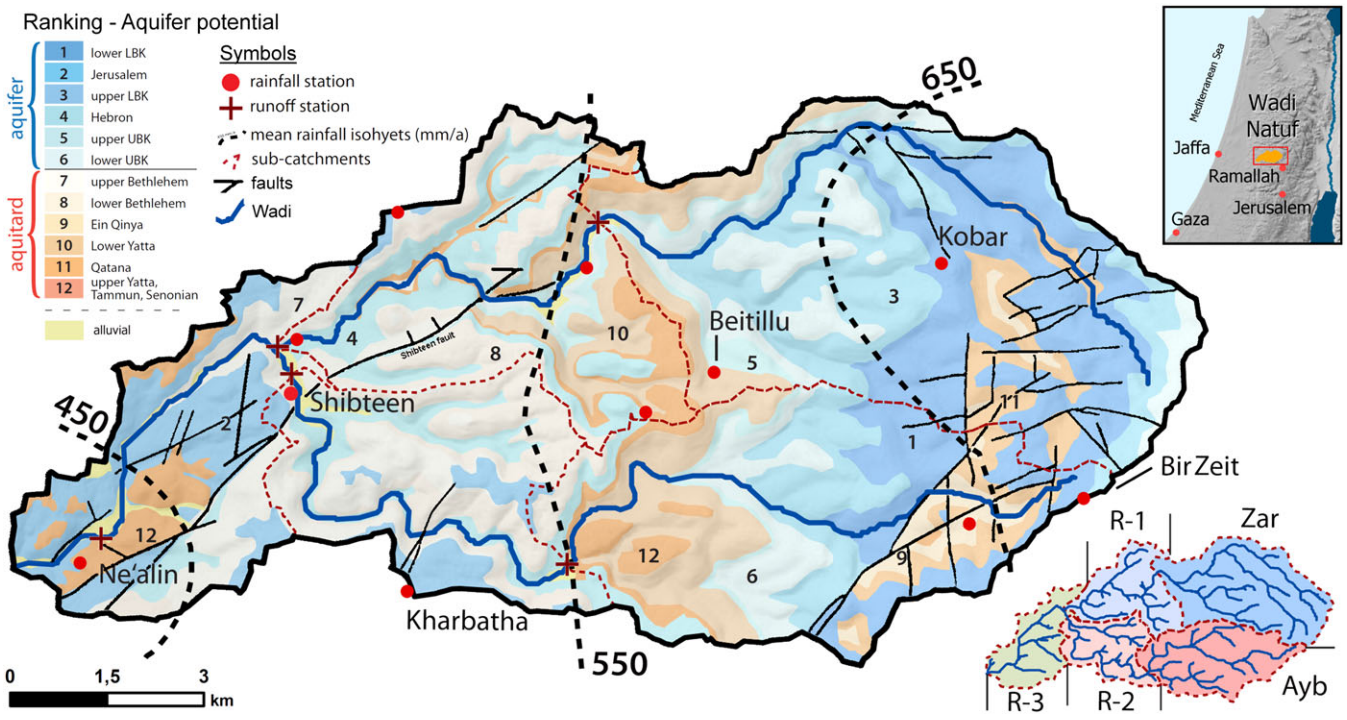

FIGURE 1 Geology, subcatchments, and gauging stations in the Wadi Natuf catchment. Rainfall was recorded in nine tipping buckets during the period of 2003/2004 to 2010/2011 (average isohyets). Run-off was measured at five stations by continuously recording level gauges (pressure transducers) for the following subcatchments: Wadi Zarqa (Zar) and Ein Ayoub (Ayb) in the headwaters; in the central part at the stations Shibteen-1 (Shi-1) and Shibteen-2 (Shi-2)—Also referred to as Reaches 1 (R-1) and 2 (R-2)—And in the downstream outlet of Wadi Natuf at Ne′alin station (R-3). Formations were ranked with respect to their aquifer potential (see Section 2.2)

TABLE 1 Aquifer/aquitard distribution as a proportion of area in the subcatchments (after: SUSMAQ, 2003a)

Geology	Area (km^2)	Natuf (%)	Northern branch		Southern branch		Confluence
			Zarqa (%)	Shi-1 (R-1) (%)	Ayoub (%)	Shi-2 (R-2) (%)	Ne'alin (R-3) (%)
Alluvial	1.5	1.5	0.05	1	-	2	7
Aquifer	59.8	58.2	82	38	56	37	49
Incomplete aquitard	17.4	17.0	0.01	30	2	60	27
Aquitard	23.9	23.3	18	31	42	1	17
Σ All aquifers	61.3	59.7	82	39	56	40	56
Σ All aquitards	41.4	40.3	18	61	44	60	44

Therefore, from the view point of the outcrop surface area, the catchment can be divided into ~60% with fractured, partially karstified lime- and dolostones that form local (perched) and regional (deep) aquifers and another ~40% of more aquitard formation outcrops with a variety of other carbonates, such as chalk with chert and impermeable rocks, that is, mainly marls and clays (Table 1). In the following the term aquifer (aquitard) is understood to include also the unsaturated zone of a formation, as long as the rock content forms an uninterrupted series of equivalent lithologies with comparable aquifer (aquitard) characteristics.

As for young unconsolidated rocks, two types of deposits can be distinguished—alluvial series, mostly flanking the wadis, and gravel fill within the wadis. The alluvial series usually form narrow banks of coarse gravels above the banks of the incised streams. The alluvial outcrops are sparse and make up a mere 1.5% of the catchment area (Figure 1 and Table 1), over two-thirds of which in the downstream subcatchment of Ne′alin (R-3) alone (see Section 4). The gravel fill of the wadis, although very small in area (<0.15 km^2, Table 6), is found in almost all sections of the stream channels; only few sections of the streambed show exposed bedrock and then only for short distances (<20 m length), consisting mostly of smooth limestone banks, unfolded but well jointed, or, in some cases, massive beds of soft marl. The vast majority of wadi floors are filled with fluvial, unconsolidated clastics, washed in from bedrock outcrops on the adjacent slopes, which can be subdivided into three coarsening upwards layers of silt and gravel and minor portions of soil and sand. The gravel fill thus potentially could act as a buffer deposit for prewetting and run-off before true bedrock TL occurs. However, in Wadi Natuf and throughout the measurement period, its buffer storage capacity during run-off event periods was found to be negligible as discussed in Section 3.3.

2.3 | Hydrology

The inlet map in Figure 1 shows the drainage pattern. Most of Wadi Natuf is characterized by a mixture of dendritic and subdendritic flow patterns, and of more structurally controlled subangular stream geometries (Aliewi, Messerschmid, Wishahi, & Nabulsi, 1998). For example in subcatchment Shi-1, the main Wadi follows the locally prominent Shibteen fault (running NE–SW, Figure 1) that forms a tilted elevated block (Shibteen horst). Upstream and midstream Wadi Natuf consists of two main flow branches of similar length (Table 1). Their confluence lies directly downstream of the run-off gauges near the village Shibteen, thus named here Shibteen 1 and Shibteen 2, or briefly Shi-1 and Shi-2. Reach 1 lies in the midstream section of the northern branch, referred to as (R-1). In parallel, Reach 2 (R-2) covers the midstream southern branch and Reach 3 (R-3) starts after the confluence of both branches until it exits Wadi Natuf.

Based on hydrologic and hydrogeological characteristics, that is, drainage network, subcatchment shape and aquifer characteristics, the following spatial distribution of bedrock lithologies was identified (Table 1): a strong contrast between northern and southern subcatchments can be observed in the uphill catchments based on aquifer and aquitard outcrop ratios. More than 82% of the northern area (Zarqa) and only 56% of the southern area (Ayoub) consist of permeable limestone rock. In the midstream areas, the northern and southern subcatchments of R-1 and R-2, only display approximately 40% of aquifer material. The downstream area of R-3 shows approximately 56% of aquifer rocks.

Although run-off is generated on extended areas, TLs are controlled by the conditions along the wadi courses and therefore the proportions of permeable geological material along the length of the wadi course is of interest. Table 2 shows the length of the wadis in the three reaches and the respective proportions of aquifer and aquitard material. Only R-3 shows a higher proportion of confining rock material such as marl and chalk underlying the main Wadi channel (55%), whereas R-1 is slightly dominated by carbonatic rocks underlying the wadis (61%). The channel bedrock in the southern reach R-2 consists almost exclusively (88% of length) of fractured and karstified limestone formations, in a drastic shift from the upstream Ayoub headwaters, which flow over strong aquitards of marl that crop out close to the measurement station Ayb. In contrast, in almost all of upstream Wadi Zarqa, the underlying bedrock under the Wadi course consists of karstified carbonates. Alluvial series flank the wadis in R-2 and R-3, but not in R-1. The deep regional aquifers in the reaches have thick unsaturated zones with water table depths of 100 m and more below ground level, which excludes gaining streams and effluent conditions (Schwartz & Zhang, 2003: 11).

TABLE 2 Aquifer/aquitard distribution as proportion of length under the Wadi courses

	R-1	R-2	R-3
Aquifers	61%	88%	45%
Of which alluvial banks	27%	12%	45%
Aquitards	39%	12%	55%
Of which alluvial banks	—	12%	44%
length (km)	7.3	8.7	6.8

Note. The figures only refer to first order stream channels for which run-off was measured.

3 | METHODOLOGY

One important characteristic pattern of run-off behaviour was observed throughout the measurement period: a consistent appearance of massive, often full TLs occurred in all three reaches, as well as in adjacent surface catchments along the western limb, and slopes of the West Bank anticline (Figure 2, SUSMAQ, (2003b)). Accordingly, the measurement configuration of stations was designed to suit the purpose of determining TLs in the three reaches. The main aim was to measure rainfall and run-off in the subcatchments, to account for storage in the gravel fills of the Wadi channel and to correlate effective TLs with channel bedrock lithologies.

Field measurements started in 2002/2003 to collect first information for setting up the measurement campaign. The fully instrumented measurement period of rainfall and run-off with sufficient measurement coverage included eight rainfall seasons lasting from 2003/2004 until 2010/2011 (Tables 4 and 6).

3.1 | Precipitation

Nine tipping bucket rain gauges were installed in the upper, middle, and lower catchment (Table 3). The automated rain gauges with Eijkelkamp loggers were run in event mode and complemented by rainfall totalizers (funnel cylinders with calibrated cups) that were mostly installed at schools or public buildings and read out daily. Point values for precipitation were interpolated by inverse distance weighting to allocate the representative area of precipitation of the subcatchments.

Annual areal rainfall increases with a monotonous gradient from the western foothills to the eastern mountain crest. The areal average lies at 588 mm/a and ranges between a minimum of 453 mm/a at Ne′alin subcatchment (2007/2008) and a maximum of 812 mm/a at Zarqa subcatchment (2004/2005).

3.2 | Run-off

Stream water levels were measured by Van Essen (Eijkelkamp) pressure transducers (divers) in 5-min time step intervals (Table 3). Most transducers were installed in culverts or controlled, cemented sections underneath a bridge (Nea), except for Wadi Ein 'Ayoub, where the sensor was installed in the open Wadi course (partially in the gravel fill and partially on exposed bedrock) near a road underpass with culverts. To account for changes in bedrock geometry, additional manual measurements were made whenever possible on site during events in the open Wadi as well as at the culverts, measuring water depth and flow velocities by current meters or floaters (for additional information on run-off measurements, see Table A3). Run-off event periods were subdivided to individual storms if no flow occurred in any of the subcatchments for at least 24 hr.

Damage to instrumentation and therefore data loss is unavoidable in this type of run-off environment, particularly during periods of political tension and severed field access such as the second Intifada. Recording equipment was stolen or damaged in the unprotected wadis. Nevertheless, a total of 34 event periods were recorded, during which some or all wadis displayed discharge—on average four event periods per season. Multiplied by the five observed locations, this resulted in a total of 170 potential flow records in the entire set of subcatchments. However, only station Zarqa covered all 34 events. Due to damaged or stolen instruments, only 128 individual flow records were covered by the five stations (coverage of approximately 75%). Out of these 128 recordings, only 72 (56%) exhibited flow, whereas in 56 cases the wadis at the individual stations remained dry. Because the calculation of TLs required simultaneous data coverage upstream and downstream of a channel reach, only 44 events could be evaluated for TLs, of which 14 in R-1, 11 in R-2, and 19 in R-3.

3.3 | Storage of run-off and evaporation from the gravelly wadi fills

Before true losses into bedrock occur, run-off first has to pass the wadi gravel fill. In general, the following relationship between in- and outflows from the gravel was formulated by Shentsis et al. (1999) as

$$TR = E + TL, \tag{1}$$

FIGURE 2 Run-off event at Wadi Shabbabeh, with run-off upstream and dry conditions downstream. Photo taken on the same day. Left: Wadi upstream—Kufr Na′ameh on 4.3.03–2:27 pm. Right: Same Wadi, 6 km downstream—Kharbatha on 4.3.03–2:57 pm

TABLE 3 Rainfall and run-off measurement network

Name	Position	Reach	Branch	Elev. (m a.s.l.)	Area (km^2)	Coverage (number of events)
Rain—Tipping bucket (event mode)						
BZU	Bir Zeit-Univ.	Upper	North	790	6.57	34 (100%)
KOB	Kobar		Mid	649	18.85	34 (100%)
MAZ	Mazra'ah Q.		South	655	10.88	34 (100%)
BET	Beitillu	Middle	Mid	506	13.87	34 (100%)
DAR	Deir 'Ammar		Mid	540	15.49	34 (100%)
KHA	Kharbatha		South	396	7.77	34 (100%)
DAL	Deir Abu M.	Lower	North	471	9.78	34 (100%)
SHI	Shibteen		Mid	229	13.17	34 (100%)
NEA	Ne′alin		Mid	222	7.14	34 (100%)
Run-off—Pressure transducer (5 min)						
Wadi Zarqa	Upstream	Headwater 1	North	332	33.85	34 (100%)
Ein Ayoub	Upstream	Headwater 2	South	358	24.04	18 (53%)
Shi-1	Midstream	Reach 1	North	213	17.30	28 (82%)
Shi-2	Midstream	Reach 2	South	225	13.22	27 (79%)
Ne′alin	Downstream	Reach 3	Both	150	14.24	21 (62%)

with *TR* as transmission run-off after deducting outflows from run-off inflows into the reach; *TL* is the deep percolation into the underlying aquifer bedrock; *E* stands for evaporation from the gravel fill storage after the run-off event. The amount of evaporation from gravel fill was found to be negligible during events as will be shown in Section 4.1. In order to account for the storage capacity during the event, the effective porosity of the gravels had to be determined and the pre-event storage needs to be assessed.

Wadi width was measured in the field by detailed geodetic surveys at the run-off stations and in addition determined from aerial photographs. A generalized average width *W* (Formula 2) of each stream section was found to be 6 m upstream, 9 m midstream, and 8 m downstream (not accounting for the wider alluvial outcrops on the banks of the wadis, see Figure 1) and used for the calculations in Tables 4 and 6.

To assess the alluvial fill of the stream channels, in several sections, trenches were dug by an excavator. Gravel porosities were mapped on site by direct field observation methods (BGR, 2005). The lower sand, silt, and soil layer porosities were determined by standard procedures (water evaporation method, see Fetter, 1980) at the certified labs of Bir Zeit University, Palestine. For this purpose, undisturbed, unconsolidated rock, and soil samples were obtained in the field by soil sample rings (Ø 53 mm, NN) at these trenches. Thus, the profiles of the wadi fill were classified as the following three-part structure (A–C from top to bottom) of rock composition and depth *D* (Formula 1; Figure 3):

- (A) pure, coarse, well rounded gravels on top (*D*: 10, 15, and 20 cm thick from up- to downstream);
- (B) a middle layer of some gravel in a sandy, silty matrix (*D*: 40, 20, and 40 cm thick); and
- (C) a bottom layer void of gravel, with silt and soil and some sand portion (*D*: 10, 35, and 30 cm thick).

Total porosity n_t determined in the laboratory for each layer was found to lie at 21%, 35%, and 35% (from top to bottom, A–C). Effective porosity n_e was estimated at 21% (A), 20% (B), and 27% (C) and lie well in the ranges reported in the literature (BGR, 2005; Freeze & Cherry, 1979; Bear, 1979; Heath, 1983; Morris & Johnson, 1967; Yu, Kamboj, Wang, & Cheng, 2015:23). Total storage capacity or effective gravel porosity (n_0) was then calculated by the following equation:

$$n_0 = L^*W^*D^*n_e \quad (2)$$

with n_0 as the total storage capacity of a reach (in m^3), n_e is the effective unit porosity of the layers A–C (dimensionless, in %), *L* is the length of the Wadi section within the reach (in m), *W* is the average width of the Wadi (in m), and *D* the average thickness of the respective layers (in m). Hence, n_0 or the total storage capacities of the combined three layers of gravel fill at different reaches were found to lie between 4,700 m^3 (Ein Ayoub headwaters) and 10,000 m^3 (R-3, Ne′alin; Table 4). Up to these volumes, water either from rain or from run-off

TABLE 4 Effective gravel porosity (n_0) for different wadi sections (in m^3)

	Symbol	Unit	Zar	Shi-1	Ayb	Shi-2	Nea
Wadi width	*W*	[m]	6	9	6	9	8
Gravel depth (layers A–C)	*D*	[m]	0.6	0.7	0.6	0.7	0.9
Porosity per m Wadi length	$W * D * n_e$	[m^3/m]	0.461	1.046	0.461	1.046	1.462
m Wadi length	*L*	[m]	12,353	7,309	10,282	8,734	6,846
Cumulated gravel storage	n_0	[m^3]	5,692	7,643	4,738	9,134	10,006
Unit area porosity—(A)	$n_{(A)}$	[mm] or [l/m^2]	21	31.5	21	31.5	42
Unit area porosity—(B + C)	$n_{(B+C)}$	[mm] or [l/m^2]	107	134.5	107	134.5	161

Note. The value n_0 here stands for the effective porosity n_e under dry conditions, not accounting for the already wetted portions from preceding events or from the event rainfall depth itself (prior to run-off).

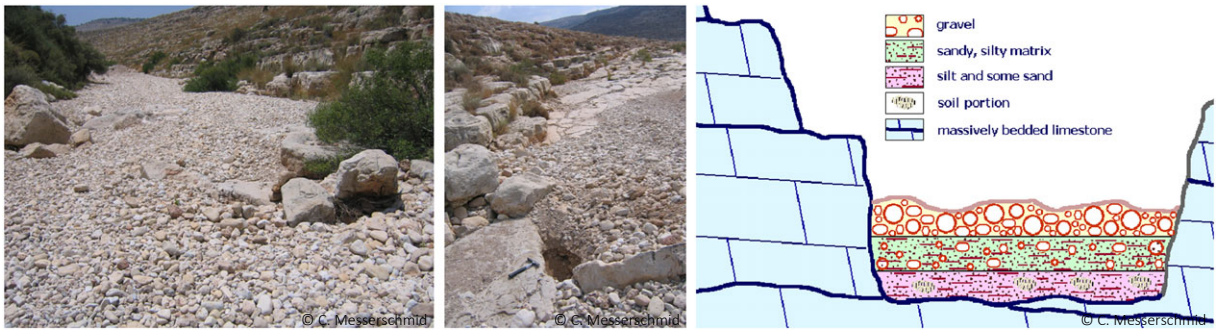

FIGURE 3 Wadi Shi-1: Banked limestone flanking and underlying the wadi gravel fill (left); dug-up gravel diver (middle); schematic sketch of limestone banks and wadi fill with initial infiltration into the gravels and deep bedrock infiltration as real TL (right)

could be stored by Wadi gravels, before deep percolation into the bedrock began.

In order to account for pre-event stored water of the unconsolidated wadi fill, the three layers have to be differentiated. The top layer of pure, coarse gravels (Figure 2, on the right) drained rapidly, whereas the deeper, more pelitic layers possess a water storage retention potential for several weeks, as evidenced in the field and were filled over weeks by seasonal rainfall prior to the start of the first run-off events. The top gravels were only filled by intensive rainfall events, just before the onset of run-off. Table 4 also shows the unit area porosity for the upper layer (A) and the combined lower two layers (B + C) as a product of the respective effective porosities (n_e) and depths (D) in litres per square-metre or mm water column. Section 4.1 will discuss the seasonal rainfall and run-off threshold precipitation for the respective layers.

It was also observed that only rarely, during brief periods of strong run-off events, water levels in the wadi increased sufficiently to flood the wadi course and thus spread water into the elevated alluvial banks adjacent to the wadi. Water loss into the alluvial banks was therefore considered negligible. Finally, another field observation has to be introduced into the conceptual approach, contributing to the understanding of infiltration processes: During many events, field evidence showed that total loss in a reach had occurred long before the end of the reach. This implies that often, not the entire length of the Wadi gravels have to be sufficiently wetted before TLs actually occur.

3.4 | Transmission losses

TLs were calculated on the basis of a channel reach water balance using up- and downstream discharge at control sections and accounting for effective gravel storage. This approach does not account for lateral inflow from less accessible side tributaries. As discussed by Shanafield et al. (2014), this is a common problem in poorly gauged basins such as Wadi Natuf. In fact, the TL rates estimated here represent apparent or minimum TLs of flow originating from the main stream channel. Both, the loss and infiltration rates calculated here, are considered conservative and range at the lower end of possible TLs under diverse conditions encountered during the 8-year measurement period, because they only refer to run-off contributions in the main flow channel, not accounting for possible additional tributary contributions. Such higher TL and infiltration rates could occur during large events, for which higher amounts of lateral inflow have to be accounted for. However, it should be noted that the majority of cases were small to medium events, in which additional losses from lateral inflow are less significant.

The calculation of TL takes into account the length of aquifer bedrock in a reach (Table 2) and the average width of the channel (Section 3.3), as infiltration area on the one hand, and the observed flow rates and TL rates over the entire reach on the other hand. This allows for the differentiation between the reaches and the calculation of individual average infiltration rates for each reach, expressed as rate of infiltration per unit area of Wadi bedrock, that is, m^3/m^2 per hour, or transformed here into mm/h (Table 6).

Lateral inflows could not be calculated on the basis of field observations or measurements. Instead, the possible inflow from tributaries into the main wadi was estimated by an approach following Shentsis et al. (1999) who developed a method, which includes a hydrological-lithostratigraphical analogy (Shentsis et al., 1999) that allows to refine assumed specific run-off coefficients for different lithologies by the use of a loss function:

$$\mathrm{TR} = \mathrm{f}\,(\mathrm{Vu} + \mathrm{Va}) \tag{3}$$

with the net run-off transmission (*TR*) being expressed as an empirical loss function of total combined upstream and lateral inflows (*Vu* + *Va*, see Figure A1). In Wadi Natuf, the shares of aquitards and aquifers in each reach were taken from Table 2, and two independent calculations for maximum and minimum scenarios were run, representing minimum and maximum assumed run-off coefficients from the upstream contributing catchments of Zar and Ayb (Table A1), whereby Ayb stands out with a very high percentage of aquitard outcrops, whereas Zar subcatchment is characterized by larger aquifer shares (Table 1). The arithmetic mean of the two calculations was then used for the preliminary value of *Vu* + *Va*, to be plotted against *TR* (or *TL*) as in Figure A1. In addition, a water budget equation was used according to Shentsis et al. (1999):

$$TR = Vu + Va\text{-}Vd, \tag{4}$$

with *Vu* as the upstream inflow into the reach, *Vd* the downstream remaining outflow after losses, and *Va* the lateral inflows from side wadis. By substituting TR in Equations 3 and 4, the function can be solved to reach a rough estimate for *Va* and a modified TL calculation (Table A4). It should be noted that these estimates contain large uncertainties and should be treated with caution.

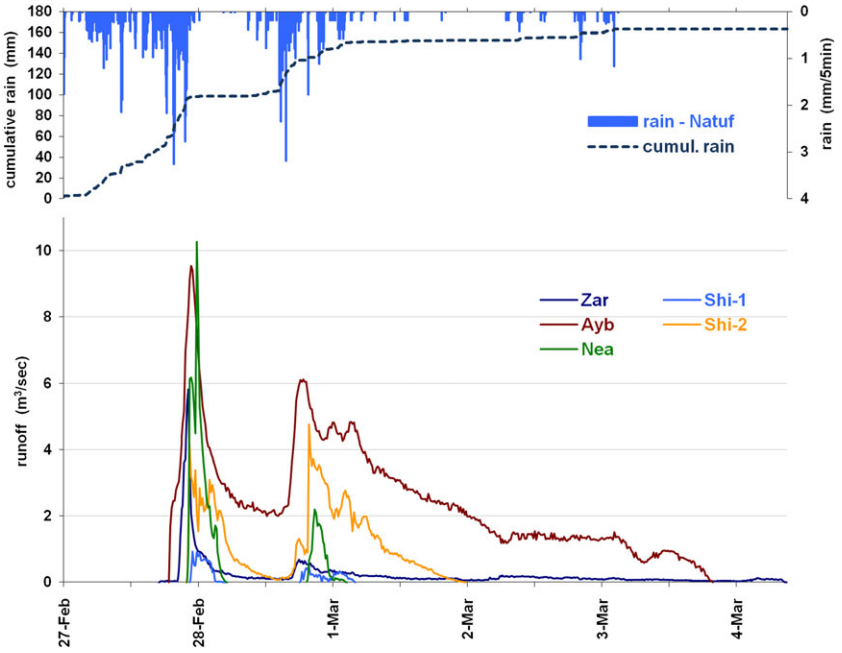

FIGURE 4 Hydrograph of a typical event (February/March 2009); rainfall and run-off recorded in 5-minute intervals. In blue, northern branch with Zarqa (headwaters) and Shi-1 (Reach 1); in red and orange, southern branch with Ayoub and Shi-2 (Reach 2); the downstream Nea (Reach 3), in green, combines flows of reaches Shi-1 and Shi-2

4 | RESULTS

4.1 | Prewetting and wadi fill storage

As shown in Table 4, the total storage capacity of unconsolidated Wadi fill above the bedrock lies between almost 5,000 m^3 in section Ayoub and over 10,000 m^3 in section Ne′alin (Table 4 shows these amounts and rates normalized per wadi length). This storage volume has to be exceeded before TL can occur.

In all wadi sections, pre-event precipitation was sufficient during the entire measurement period to saturate the wadi gravel fill, before run-off started. Prewetting conditions for the alluvial fill were accounted for as follows: no run-off event occurred at the beginning of winter. Typically, for the Mediterranean climate, at the end of the long dry summer period, the gravel fill storage was completely depleted as a result of rapid infiltration (TL) and prolonged evapotranspiration. The depleted gravel storage is being replenished during the first few months of each winter season. During the eight seasons recorded, 95% of all infiltration events and over 99% of the total run-off volume occurred after December. After the first major rainfall events (mostly between January and March[1]), on average 204 mm (between 150 and 290 mm) or 35% of total annual precipitation accumulated already. In the last 2 weeks before the first run-off event at least 82 mm of precipitation occurred. It is assumed that these seasonal rainfalls, prior to run-off, were sufficient to saturate the bottom layers which have a combined storage capacity between 107 mm in the upstream sections and 161 mm in the downstream section (Table 4). Only the top 10–20 cm of rapidly draining clean gravel (layer A) can be considered as effective buffer to run-off losses in the Wadi. This part of the buffer storage thus had to be filled by event rainfall in the hours preceding the onset of run-off. Here, between 21 mm upstream and 42 mm downstream were required for saturation of the gravel buffer (Table 4). In the upstream subcatchments, the run-off threshold was found to lie between 30 and 50 mm for most events and slightly higher in the downstream catchments, where run-off started with several hours delay (see also Section 4.2).

The important implication of this finding for gravel evaporation is that no event water has to account for subsequent evaporation during summer; all water stored in or evaporating from the wadi fill was already accumulated before the onset of the run-off event. Under full saturation the evaporation from wadi gravels as share of the event run-off turns zero. This is why Equation 1 here can be transformed into Equation 5:

$$TR = TL \tag{5}$$

All losses from run-off directly translate into deep infiltration into aquifer bedrock (*TL*), because no water from the run-off accounts for evaporation—*E* turns into zero (percent of run-off water). Therefore, it can be concluded here that intermediate gravel storage plays a very minor if any role in the reduction of flows along the reaches.

4.2 | Event characteristics

Annual rainfall increases with a monotonous gradient from the western foothills to the eastern mountain crest. The 8-year annual depth amounted to 588 mm/a, ranging between 453 mm/a in the Ne′alin subcatchment (season 2007/2008) and 812 mm/a within Zarqa subcatchment (season 2004/2005).

The average run-off event lasted for approximately 34 hr, ranging between 1 and 112 hr. In 90% of all cases, wadi discharge lasted for more than 3 hr. Although run-off at Wadi Ayoub headwater lasted longest (46 hr on average) run-off became flashier downstream, marked by sharp but short peaks. The farthest downstream Ne′alin station recorded only 14 hr of average flow and a very low maximum flow duration of only 28 hr.

The hydrograph in Figure 4 shows a typical flow event during which run-off was recorded for all stations. Total average areal precipitation during this event amounted to 165 mm, with 59% during the first, stronger event period. Note, the relatively constant lag time between run-off

[1]Only in 1 year, 2006, was run-off observed as late as April

onsets at headwater and at midstream stations (along R-1 and R-2) of approximately 1.5–2-hr duration. Discharge sets off at R-3 almost synchronously with that at R-2. The hydrographs show similar shapes at all stations, but with very different flow rates. As a typical pattern, most run-off occurred in the southern headwaters where more marly lithologies crop out (especially near station Ayb, Figure 1), with peaks of 9.55 m^3/s and a cumulative total of 0.862 MCM (36-mm area-specific run-off). The relatively constant flow difference between Shi-2 and Ayb can be explained by TLs in reach R-2 (Figure 4). The graph also shows that at reach R-1 (between Zar and Shi-1) the temporal distribution of peaks and recession has a similar pattern, but consistently with lower amounts of run-off. Total event run-off in R-1 was 91,000 m^3 upstream and 16,300 m^3 downstream. In reach R-2 the total event run-off was much higher with 862,400 m^3 upstream and 220,000 m^3 downstream. Reach R-3, measured at Ne′alin station, combines the flow of both reaches R-1 and R-2 and exhibited a very flashy run-off pattern with brief and high peaks and steep recession curves. Here, total flow added up to 94,400 m^3, compared with a combined headwater flow of Shi-1 and Shi-2 of 236,000 m^3. All observations suggested considerable TLs in all three reaches.

In general, the lag times in reach R-3 are more variable, because this reach receives flow from two independent streams, superimposed in time. Furthermore, reach R-3 shows a more irregular and flashy pattern of flow, and the run-off events here can be grouped into two distinct categories, with either very low (<1,000 m^3) or very high flow quantities (>100,000 m^3). In addition and as already mentioned in Section 3.3, this lack of medium range run-off rates and quantities can be attributed to the presence of alluvials in this reach, which act as a buffer for most of the smaller and medium events.

4.3 | Rainfall–run-off relationships

Run-off coefficients were calculated as overall averages for the entire 8-year observation period. Separate run-off coefficients were calculated for individual events. The run-off coefficients for individual events however accounted only for precipitation generating a flow event and consequently had higher apparent values (Table A1). Consistently and for an extended period, Wadi Natuf shows a remarkably low overall run-off coefficient. Out of a total of 291.8 MCM of rainfall in 5 years, (when Nea station was recording), only 0.328 MCM of run-off left Wadi Natuf (Nea station), resulting in an overall run-off coefficient of 0.11% (Table A1).

Only a weak correlation between total annual rainfall depth and run-off was found (see Table A2), suggesting the individual character of storm events, differing in rain amounts and intensities (Figure 5) and wadi geometric and hydraulic characteristics. Overall, no run-off was triggered for rainfall events of less than 20-mm depth. For rainfall events exceeding 40-mm run-off was observed in every subcatchment. Run-off coefficients in the southern headwaters (Ayb) with the largest areas of marly and other confining rock outcrops (Table 1) amounted to 7.5% of annual rainfall (season 2008/2009) and even 22% of event rainfall during individual events (such as the event of February/March 2009). The northern headwaters (Zar) with larger limestone and dolomite outcrops (Table 1) reached maximum run-off coefficients of only 1.25% of seasonal rainfall (season 2004/2005). Maximum annual area normalized run-off exceeded 50 mm/a in Ayb (season 2004/2005), whereas all other wadis only reached at most or remained below 3 mm/a, even in very rainy winters (Figure 5). An overview on average annual run-off coefficients is given in Table A1. The maximum, again, is found in Ayb (southern headwaters) and the minimum in Shi-1with less than 0.1% of overall annual rain. Due to the consistent TLs, annual run-off coefficients for overall Wadi Natuf (Reach 3, station Nea) were particularly low and only reached 0.11% of annual rainfall.

4.4 | Transmission losses

With only one exception, all 44 recorded events showed a strong correlation between inflow volume and TL (Figure 6). In 48% of the events, losses were complete, and no discharge was recorded at the downstream station, 73% of the events showed losses of more than 70%. Table 5 summarizes discharge and TL statistics for the individual reaches.

In R-2 (red), an overall 80% of headwater discharge is lost into the wadi bedrock (and shallow gravel fills), whereas in R-1, 75% and in R-3 only 62% of TL is recorded. These spatial differences can be linked to the different bedrock lithologies within the wadi courses of each reach. As mentioned above, R-2 is almost exclusively (88% of the length) composed by permeable limestone and dolomite formation

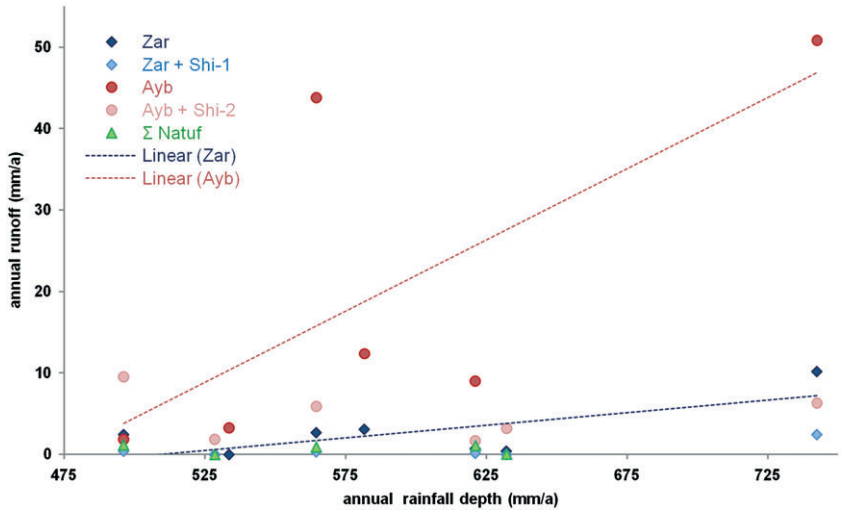

FIGURE 5 Annual rates of run-off (mm/a) at the five stations versus annual rates of rainfall at the cumulative subcatchments (all rain upstream a station is considered here). Due to the transmission losses, observed wadi discharge did not increase gradually but rather decreased with increasing distance in downstream direction. The lowest run-off volumes and area normalized infiltration rates were measured at the outlet of the Natuf catchment at stations Nea (here in green as total catchment precipitation " Natuf")

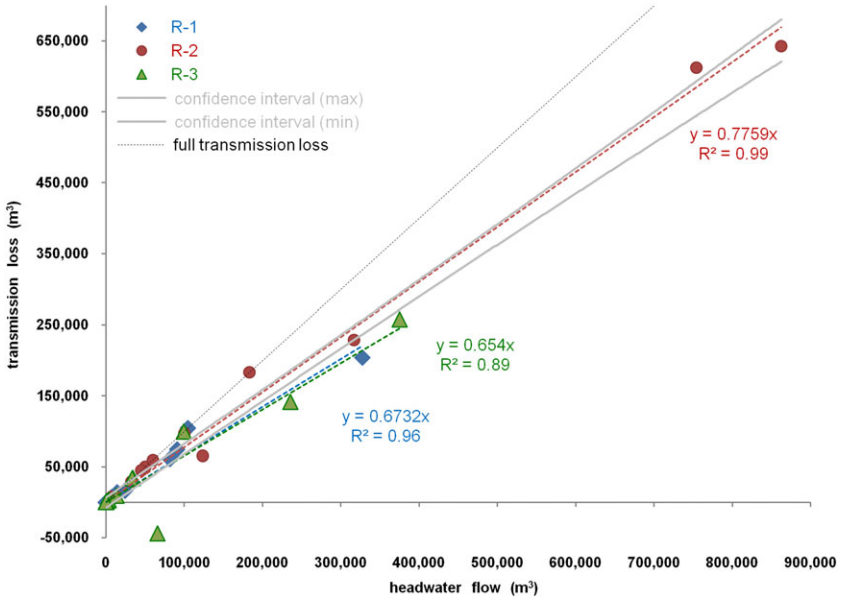

FIGURE 6 Headwater run-off versus transmission loss (m^3/event). The confidence interval is plotted for all reaches together. Note one example of transmission gain in R-3 (Nea) on 2.-4. April 2006, which was the event with the highest rainfall intensities (up to 137 mm/h) of the entire period.

Note: 11.4 mm in 5 min measured on 2.4.2006 at 7:50 am in BZU rainfall gauge; 6.97 mm/5 min in station Nea on 2.4.2006 at 3:00 am

TABLE 5 Transmission losses (TL), overall sums and annual extremes

Item	Unit	R-1	R-2	R-3
Events counted	#	28	11	21
Σ upstream discharge	m^3	660,965	2,535,980	870,460
Minimum annual upstream discharge	m^3/yr	85	44,984	69,448
Maximum annual upstream discharge	m^3/yr	343,725	1,221,204	358,741
Σ downstream flow	m^3	168,501	514,964	328,453
Minimum annual downstream discharge	m^3/yr	0	69,448	483
Maximum annual downstream discharge	m^3/yr	123,603	235,138	117,786
Σ total TL (all years)	m^3	492,464	2,021,015	542,007
TL share of upstream discharge	%	75%	80%	62%
TL—annual average	m^3/yr	70,352	505,254	117,215

Note. Note that in the grey shaded lines, only coupled event periods were considered and counted, whereas absolute maxima and minima (un-shaded lines) also include uncoupled event measurements.

series, whereas R-1 marls and chalks make up 61% of the reach length along the wadi course (Table 2). In downstream R-3, only 45% of the wadi length is underlain by limestone material.

In Table 6 maximum and average TL rates are compared with the lengths of permeable carbonates in the reaches. Infiltration or recharge rates are calculated from direct, real time field observations. The values represent a conservative lower limit of infiltration rates because discharge and therefore TL was frequently found to cease long before the end of the channel reach. However, for very intensive run-off events, the entire length of a reach can be accounted for, because discharge was found to continue until the downstream station. Again, infiltration rates shown here range at the lower end of the spectrum, because they are based on run-off contributions of the main flow channel and do not account for possible additional tributary contributions.

The ranking of aquifer potential (see Section 2.2) refers to the positions shown in Figure 1, where a low number, such as ranking position No. 2 stands for a very well developed karstic aquifer such as Jerusalem formation in Reach 3 and a relatively high number such as ranking position No. 6, stands for a very weak aquifer to aquitard (low permeability limestone with fine marly interbedding), such as the Soreq formation in Reach 1 (compare with Figure 1).

5 | DISCUSSION

5.1 | Effect of landform and geological materials on bedrock infiltration

This study integrates hydrological land surface features, such as morphology, soil, and vegetation to run-off generation, with hydrogeological variables/parameters such as aquifer potential of bedrock underlying the area at large and the stream channels in particular. This relationship was not only observed but also measured and quantified for an extended study period in the field for controlled conditions. This allowed us to gain new insight into the mechanisms of run-off and especially of TL into bedrock for semiarid to subhumid climates.

TABLE 6 Infiltration rates of Wadi bedrock

	Unit	R-1	R-2	R-3
Aquifer length below stream bed	m	4,443	7,664	3,061
Average Wadi bed width	m	9	9	8
Aquifer area under Wadi	m^2	39,986	68,972	24,491
Main aquifer	Name	Soreq (Hebron)	Hebron	Jerusalem (Weradim)
Aquifer potential ranking	#	6 (4)	4	2 (7)
Maximum event TL	m^3	203,981	642,811	257,614
Mean event TL	m^3	35,176	183,729	32,560
Maximum TL intensity	m^3/h	2,197	6,627	4,068
Mean TL intensity	m^3/h	552	2,780	593
Maximum infiltration rate	mm/h	55	96	166
Mean infiltration rate	mm/h	14	40	24

Note. The last lines (infiltration rates) refer to the rates of deep infiltration (or recharge) per unit area of Wadi bedrock, that is, m^3/m^2 per hour, or transformed here into mm/h. Note that for the calculation of the mean TL rate in Reach 3, the event with transmission gain was not considered. As in Table 5, for mean rates, only coupled event periods, for maximum rates also uncoupled events were counted.

By comparing run-off between different subcatchments, the entire set of landforms (topography, vegetation, land use, etc.) is found to strongly impact run-off generation (see run-off coefficients in Table A1) as shown for the correlation of landforms and geology (Section 2). This is why we believe that for Wadi Natuf, the approach for the assessment of run-off and infiltration can be simplified by just considering one factor, that is, the subsurface geology. Therefore, three types of distinct landform correlations have to be distinguished in the three respective reaches.

Furthermore, with respect to TLs into the permeable aquifer bedrock below the wadi gravels (see Table 6), many landform factors such as relief, soil, and vegetation are not applicable to the assessment of infiltration.[2] In sum, the channel bedrock lithology can be grouped as follows: low permeability (aquitards) in marly, chalky, clayey, or otherwise impermeable formations in Ayb headwaters and R-1, permeable limestone, dolomite, and mixed formations (aquifers) in Zar headwaters and R-2, and equal proportions of both types in the R-3 subcatchment. TLs closely respond to and reflect this distribution pattern of geological materials and ensuing aquifer characteristics.

Several circumstances are believed to make the results reliable, such as the long-term observation period of eight seasons in total, the occurrence of wet as well as dry winters, as well as the large number of in total 128 recorded events. The high variability of different geological features with over a dozen different hydrostratigraphic elements ranked according to their aquifer and recharge potential covers a wide range of possible extremes such as minimum and maximum run-off and TL coefficients. The nested configuration of subcatchments, reaches and the overall Natuf catchment adds to the reliability of the findings.

5.2 | Run-off coefficients

As apparent from Figure 5, the run-off coefficients in the different subcatchments are very diverse and strongly linked to the entire set of parameters forming landforms. In Wadi Natuf, there is also a strict correlation between the type of geological material (or lithology) with other factors such as relief, vegetation, soils, and land use—and even climate (Messerschmid, 2014). The headwaters with prevalent lower aquifer outcrops are characterized by terraces, scrublands, and olive groves as well as by rainfall maxima. In contrast, small plains with soils and arable fields are restricted to the soft marly and aquitardal formations of the central area (Figure 1). This allows us to directly correlate the geological material in the subcatchments, that is, the spatial distribution of formation outcrops to the run-off behaviour of the respective areas. This was already found by field investigations and mapping and is being further confirmed by measured data described above. As a consequence, it can be concluded that the larger the proportion of low-permeability material in the subcatchments the higher the run-off coefficients. The Ayb catchment shows a multiannual average of 3.35% (Table A1) with up to 22% for individual events (Ayb, event in February/March 2009, Figure 6). In contrast, the larger the proportion of more permeable limestone and dolomite material in the subcatchments, the lower is their run-off coefficients. This relationship can be observed in particular in the combined subcatchments of Shi-1 + Zar with only 0.08% as well as in the outlet of Wadi Natuf (Nea), that combines northern and southern stream flows in the R-3 subcatchment with a total area run-off coefficient of only slightly above 0.1% (Table A1). This run-off coefficient lies considerably below the usual estimates for the wider area of the Western Aquifer Basin with values of between 3% and 6% (Goldschmidt & Jacobs, (1958); HSI, 2016; Hughes et al., 2008; Rofe & Raffety, 1965; Sheffer et al., 2010; Steinmann, 2010; SUSMAQ, 2002). The average event run-off coefficient of the 128 individual event periods recorded in the five stations (including dry wadis during event periods) was 1.2% of total event rainfall.[3] These run-off coefficients are relatively low compared with those on the western and eastern flanks of the lower Jordan valley. Ries et al. (2017) quote annual run-off

[2]By comparison, the gravel fill and its storage is relatively uniform and thus does not constitute a differentiating factor

[3]The event run-off coefficient does not include precipitation below the run-off threshold value, that is, precipitation depths that fail to trigger run-off in any of the stations.

coefficients between 0.7% and 2.4% on the eastern slopes of the West Bank with similar geology but drier climate and sparser vegetation and soil development. On an event basis, such run-off could rise to 12.6% (Ries et al., 2017: 24). On the Jordanian East Bank of the Jordan Rift Valley with its less carbonatic geology, run-off coefficients between 4% and 11% are reported by Alkhoury (2011) during the same period.

Rainfall recorded during the observation period is in general representative for long-term (multidecade) averages because that period comprises typical average winters as well as extreme (dry or wet) rainfall seasons (Table A1).

5.3 | TLs normalized for Wadi length

TLs can be directly correlated with bedrock lithology. Particularly R-2 with more than 88% permeable limestone and dolomite bedrock below the Wadi gravels (Table 2), shows high TLs, both, in absolute amounts, because the upstream Ayoub subcatchment delivers large flow rates (Table A1), as well as in relative terms, as proportion of upstream flows (80%; see Table 5). The lowest TLs are observed in R-1 (<0.5 MCM in all years, Table 5), where Wadi gravels are underlain by more marly, chalky, or otherwise less permeable series (lower UBK or Soreq formation as the regional aquitard above the lower aquifer and locally the bottom aquitard for numerous perched springs).

TLs observed in Wadi Natuf can be considered as actual bedrock losses into the regional carbonate aquifers (groundwater recharge) and not as losses into the alluvial wadi fill. In Wadi Natuf the ephemeral streams form steep wadis deeply incised into the surrounding carbonate outcrops without expansive alluvial sedimentary deposits (see Figure 3). Moreover, Table 6 shows infiltration rates into the bedrock usually not available from the literature (Costa et al., 2012; Dahan et al., 2007; Schmadel, Neilson, & Stevens, 2010; Sorman & Abdulrazzak, 1993).

Bedrock aquifer infiltration rates were calculated for both, maximum and average TL intensities for all three reaches and again, a clear relationship between lithological composition, aquifer parameters and infiltration rates could be confirmed.

- R-2: The aquifer of Hebron formation (*'Amminadav*, Rank 4) with its massive, strongly karstified Cenomanian limestones and dolostones at the Wadi base in R-2 shows particularly high average infiltration rates of ca. 40 mm/h (Table 6). These strikingly high infiltration rates are related to the karstic nature of the Wadi bedrock and the epikarstic features. In addition, R-2 has only a very short section (5.8% of Wadi length) of low permeability marls (regional aquitard of the Upper Yatta formation, see below).
- R-1: The lowest average infiltration rates of only 14 mm/h were found in R-1 with only short sections of Hebron formation. The bedrock subsurface mainly consists of low permeability interbeddings of marly limestone and dolomitic limestone of the lower UBK (*Soreq*, Rank 6) and Lower Yatta formation (*Moza*, Rank 10) with its strongly confining, soft yellow marls.
- R-3: A low infiltration rate (24 mm/h) was also observed in downstream R-3, where the karstic aquifer of the Jerusalem formation (*Bi'na*, Rank 2) alternates with the slightly aquitardal series of the upper Bethlehem formation (*Weradim*, Rank 7). Upper Bethlehem here is characterized by white, massively bedded but brittle limestone; in the outcrop, this limestone was found very soft and plastic and without any open joints or fractures in the rock fabric that could be considered preferential pathways for water movement.

TLs into underlying aquifer bedrock constituted between 62% and 80% of generated run-off (Table 5), with most of the smaller events showing a 100% TL (almost half of all instances). Maximum infiltration rates reached values of more than 150 mm/h (Table 6), which demonstrate the highly karstic nature of the underlying formations in some of the Wadi reaches. Total losses in all three reaches (excluding the upstream headwater subcatchments) sum up to approximately 0.7 MCM/a on average (Table 5), with a maximum rate of approximately 1.2 MCM/a in winter 2004/2005.[4] These rates are equivalent to average and maximum annual rainfall percentages of 3% and 5%, respectively. TLs could only be measured and calculated for the three reaches, but not for the headwater areas. Therefore, TLs in these upstream subcatchments (Zarqa and Ayoub) can only be estimated to lie in approximately the same range. The southern upstream subcatchment (Ayoub) probably displays lower TL rates, due to the presence of impermeable marls evidenced by clearly increased run-off coefficients. Comparing measured TLs in the three reaches with the areal rainfall in Wadi Natuf, these amounts represent merely up to 0.05% in average and up to 0.08% at maximum of annual rainfall in the entire Wadi Natuf, respectively. In other words, localized groundwater recharge through wadi bed infiltration amounts to a low figure, somewhere in the range between <1% and <3% of total annual area rainfall in average. Although this percentage is relatively low in comparison with total catchment groundwater recharge (well over 35% in Wadi Natuf [SUSMAQ, 2003a]) it is nonetheless a significant amount, particularly with respect to water quality issues. Wadis in the study area are a hot spot of increasing pollution due to the recent spread of unregulated solid waste dump sites and quarries (Messerschmid, 2014), and the TL flux is critical for the transport of contaminants into the karstified groundwater systems.

6 | CONCLUSION

The extraordinarily low overall run-off coefficient of Wadi Natuf (0.11%) ranges far below the published estimates (HSI, 2016; SUSMAQ, 2002). The observed percentages can well be explained and described by TL processes. Despite the low percentage of overall groundwater recharge, TLs account for a major proportion of run-off generated in the catchment, for many events even the entire run-off. They play an important role as point (or line) recharge within the context of contaminant transport along preferential pathways. Such

[4]These figures do not account for the additional unmeasured losses in the headwater sub-catchments

pollution sources were found increasing near the streams, especially from solid waste and quarries in the area (Messerschmid, 2014).

This study combines hydrological with hydrogeological approaches in the assessment of TLs in semiarid to subhumid climates. In particular, the grouping and correlation of infiltration rates with different types of subsurface geological materials provide for the first time field-measured infiltration rates, required by hydrological and groundwater flow modellers that (Shanafield et al., 2014: 528).

Long-term and extensive field work and high resolution measurements provide the basis for a reliable and representative assessment of actual TLs within the main channel, whereas losses in tributary streams could only be estimated. Thereby, deep percolation and groundwater recharge rates in the main wadi could be gained that are applicable for future research and modelling in other, especially in carbonate dominated and karstified study areas.

An opportunity for further research is the investigation of infiltration processes (recharge) of water from the unconsolidated gravel fill into the deep regional karst aquifers.

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APPENDIX A.

TABLE A1 Summary of overall rain and run-off measurements (averages 2003/2004–2010/2011)

Cumulated	Rainfall (all years)				Run-off (not all years)					Run-off coefficient	
	Sum	Avg	Avg	Min-max	Sum	Avg	Avg	Min-max	Yrs	Overall	Event
Subcatchment	MCM	MCM/a	mm/a	mm/a	MCM	MCM/a	mm/a	mm/a	Data	%	%
Zar	169	21.1	622	522–812	0.661	0.08	2.44	0.002–10.2	8	0.39	1.25
Shi-1 + Zar	247	30.8	603	507–773	0.169	0.02	0.47	0–3.0	7	0.08	0.41
Ayb	116	14.5	601	509–764	2.912	0.49	20.19	0.3–58.6	6	3.35	9.12
Shi-2 + Ayb	175	21.9	587	497–735	1.061	0.18	4.75	0.02–9.6	6	0.80	1.69
Nea (all)	482	60.3	588	496–742	0.328	0.07	0.64	0.01–7.2	5	0.11	0.41

Note. This table summarizes only years during which run-off data were available. Grey fields mark stations with incomplete run-off data during several measured seasons, resulting in slightly underestimated overall run-off coefficients. In addition, average event run-off coefficients are added, referring only to measured flow events without precipitation during no-flow periods. Note that the run-off coefficients only account for measured run-off after transmission loss and therefore lie at much lower levels than the run-off coefficients under in situ conditions on the slopes and plains of the study area. Relative contibution values for the individual catchments of the reaches alone could only be based on the estimates for lateral inflow and range widely, depending on the estimation method used.

TABLE A2 Run-off measurements (annual sums)

	Rain	Zar	1c + Zar	Ayb	2c + Ayb	Nea (all)
	MCM/a	m^3/a	m^3/a	m^3/a	m^3/a	m^3/a
2003/2004	54.3	85	–	n.r.	69,448	483
2004/2005	76.2	343,725	123,603	1,221,204	235,138	n.r.
2005/2006	63.8	24,373	7,791	216,655	62,374	110,393
2006/2007	64.9	14,306	28	n.r.	119,310	5,404
2007/2008	50.9	82,825	20,821	44,984	354,862	117,786
2008/2009	58.0	90,995	16,259	1,053,136	219,567	94,388
2009/2010	59.7	104,712	–	297,385	n.r.	n.r.
2010/2011	54.8	66	n.r.	78,935	n.r.	n.r.

Note. Grey fields indicate incomplete data coverage; the symbol "n.r." indicates missing data ("not read").

Runoff measurements

Three of the five gauging sites were located or measured at well controlled road culverts (cemented pipes, see Table A3), in which the problem of in-homogenous flow velocities in the stream is greatly reduced if not negligible. The gauge at station Ne'alin (Nea) was positioned in a rectangular cement channel section under a bridge. Only in one gauging site, the pressure transducers were installed in a natural Wadi (Ayb), however, followed again by well measurable road culverts a few metres downstream. Here, hand measurements encompassed both, the Wadi and the culverts. In all cases, current meter and floater measurements were repeated at different cross-sectional intervals and depths to determine average velocities.

The field measurements were carried out by floaters and current meters. Current meter readings were executed at the entry and exit of the culvert pipes and at different depths. In the floater measurements, average flow velocities were determined by repeatedly measuring the travel time during the pipes of known length with a stop watch. Both procedures were performed in several runs and for different depths inside the water column of the culvert, until a sufficiently reliable range of velocities was reached.

The conversion was calibrated by rating curves for Ayoub wadi gravels. The fit of the rating curve was excellent and therefore the reliability of both, the curve and the calculation fully satisfactory. Due to vandalism, the location of the diver had to be changed prior to the season 2005/2006. Therefore two different rating curves refer to 2003/2004–2005 and to 2005/2006–2011, respectively.

In the controlled culvert and channel section (Zar, Shi, and Nea) hand measurements were used to determine the best fit for the roughness (n), used in the Manning formula (roughness and R-squared values for fitness listed below)

$$Q = 1/n^{*}A^{5/3}{*}1/P^{2/3}{*}S^{1/2}, \quad \text{(A1)}$$

where Q is the flow (m^3/s); n is the roughness coefficient (-), A is the wetted area (m^2), P is the wetted perimeter (m), and S is the slope (m/m).

An approximate range of error in the readings can be stated with Lange et al. (1999: 2163) who documented results from Negev catchments for typical types of gauging sites and as follows: a 15% margin of error for cemented sections as in our culverts and the cemented channel at station Nea, 20% for stable bedrock in wadis as in Ayoub during the first 2 years, and 25% for gravel filled open wadis as in Ayoub after 2004/2005.

TABLE A3 Specifications of run-off gauging sites and field measurements

Station	Type	Diameter (Width)	n-Value (Manning) Rating curve (Ayb)	Estimated uncertainty of flow during assessment (after Lange, Leibundgut, Greenbaum, & Schick, 1999)
Zar	Culvert	Ø 1 m	n = 70,426	15%
Shi-1	Culvert	Ø 1 m	n = 46,743	15%
Shi-2	Culvert	Ø 1 m	n = 77,116	15%
Nea	Cemented channel	b: 11 m	n = 0.017	15%
Ayb	Open Wadi	b: 5 m	y = 0.0157×, R^2 = 0.974 y = 0.0072×, R^2 = 0.997*	20% 25%

Note. All measurements were carried out repeatedly by current metre and floater. The location of Ayoub gauge (Ayb) was changed from bedrock to gravel fill in an open wadi prior to 2005/2006.

Lateral inflow (Va) estimates

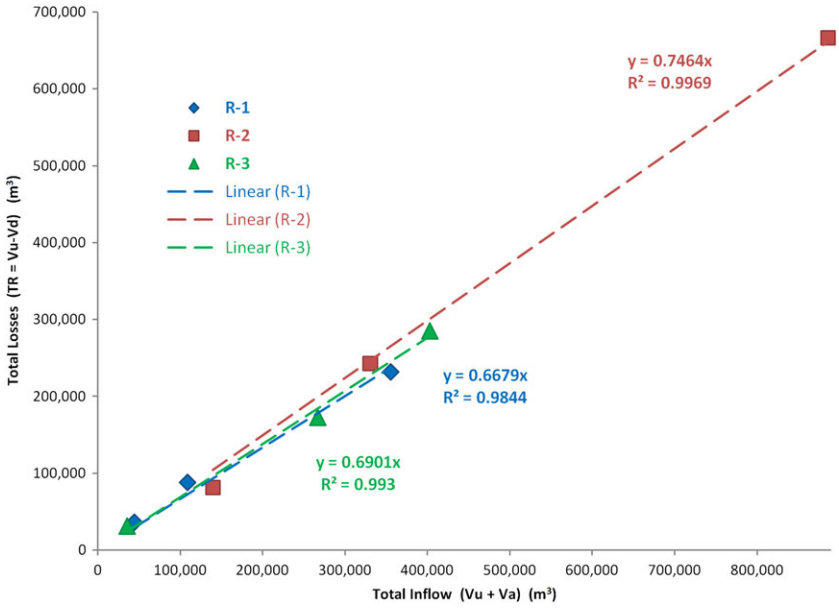

FIGURE A1 Loss function plotting minimum transmission values against minimum Vu + Va. The values for unobserved lateral inflow Va were derived by assuming lithostratigraphically diverse run-off coefficients for each of the three reaches. Transmission values (equal to transmission loss values, Section 3.4.), plotted on the y-axis, still represent the difference between the gauged upstream (Vu) and downstream (Vd) flows

TABLE A4 Lateral inflow estimates and newly estimated total transmission loss (TL; in absolute amounts and as ratio between TL and total estimated inflows)

	No.	Upstream flow	Downstream flow	TL old	TL old	Lateral inflow	inflows	New TL	New TL
Reach	#	Vu	Vd	m^3	%	Va	Vu + Va	m^3	%
R-1	14	660.965	168.501	492.464	74,5%	200.700	861.665	693.164	80,4%
R-2	11	2.535.980	514.964	2.021.015	79,7%	275.997	2.811.976	2.297.012	81,7%
R-3	18	870.282	328.453	541.833	62,3%	311.774	1.182.056	853.603	72,2%

Note. All unshaded values represent m^3. The sums refer to all applicable measured events, not necessarily to total run-off over the measurement period (number of events considered here are shown in the shaded left column).

Appendices of chapter 6

Recharge

6.1 Modelling formation-specific recharge (HESS, 2020) 343

6.2 Recharge regionalisation and leakage estimation (HESS, *draft*) 375

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Field-based estimation and modelling of distributed groundwater recharge in a Mediterranean karst catchment, Wadi Natuf, West Bank

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Abstract. While groundwater recharge is one of the most prominently covered subjects in hydrogeology, the spatial distribution of recharge has been given relatively little attention, especially in semi-arid, karstic aquifers. Under conditions of highly diverse geology, relief, vegetation and land use, the complexity and variability of spatially distributed hydrological processes remains a challenge in many regions around the world. This is particularly true for hitherto ungauged basins, such as Wadi Natuf, a 103 km^2 large karstic Eastern Mediterranean watershed in the Palestinian upstream mountain and recharge area of the Western Aquifer Basin (WAB), which is shared with Israel in the coastal plain. In this first in a series of two papers, distributed recharge is estimated and represented, based on 7 years of extensive field observations and measurements and based conceptually on observable physical landscape features such as geology, land use and land cover (LU/LC) and especially soil conditions. For the first time in the WAB, a forward calculated soil moisture and percolation model (SMSP) was set up with parameters directly gained from field observations. The model was parameterised in a strictly parsimonious manner, as a one-dimensional model (a.k.a. "tank", bucket or box model). This is based on dominant hydrological processes, in particular saturation excess in the soil column, and identifying patterns of linkage between different landscape features. Average soil thickness was encountered at the range of decimetres, rarely above one metre. Both soil thickness and LU/LC features, such as terraced olive groves or forests as well as grassland or barren rock outcrops, were found to be highly formation specific. This linkage allowed us to further simplify the model and its requirements in a realistic manner for eight soil moisture stations, chosen at six different geological formations with typical soil and LU/LC representations. The main result of the model was the determination of formation-specific recharge coefficients, spatially ranging between 0 % and almost 60 % of annual rainfall or up to 300 mm a^{-1} in Wadi Natuf's climate. The karstified main aquifers showed recharge coefficients (RC) above 40 % and even the less prominent slightly aquitardal local aquifers reached RC values above 30 %. The model was separately tested on two conceptual levels: on the level of basin form (soil moisture) and basin response (signatures of peak recharge and local spring discharge events) under well-controlled conditions in isolated sub-catchments. In principle, our approach is applicable in many of the scarcely gauged karstic groundwater basins around the world with a highly diverse landscape and geology.

1 Introduction

Knowledge about distributed recharge is important for the exploration, sustainable management, protection and equitable allocation of water resources. Acquiring recharge information remains complex and challenging for hydrogeological research, especially in the many ungauged basins around the world and particularly in karstified aquifers, which supply about one quarter of the world's population (Ford and Williams, 2007). One key issue of water negotiations in shared groundwater basins is the spatial distribution of water

resources in the different zones, such as the recharge zones of an aquifer.

1.1 Global and specific problems in distributed recharge assessment

A general problem in recharge studies worldwide is that most basins remain poorly gauged or ungauged, particularly with respect to basin function, i.e. the description and drivers of hydrological processes that are usually variable, both spatially and temporally. Such a lack of empirical and local knowledge from the field cannot readily be circumvented by evermore sophisticated modelling approaches and mathematical methods. A second general problem is encountered in karstified aquifer formations with their non-Darcian, anisotropic flow fields, where data from the discharge area cannot be readily used to infer process or parameter information for the upstream recharge areas (Hartmann et al., 2012a, b; Dafny, 2009; Dafny et al., 2010).

The study of groundwater recharge and its spatial variability in karst regions ranging from semi-arid to sub-humid can be approached through three research venues: observations of surface water (where available), of the saturated and of the unsaturated zone (Scanlon et al., 2002, 2006). In addition, Dörhöfer and Jesopait (1997) subdivided the field into direct and indirect research approaches or methods (Lerner et al., 1990) – not to be confused with direct and indirect recharge (see also Bredenkamp et al., 1995; Simmers, 1988; De Vries et al., 2002). While direct approaches determine recharge-governing parameters near the surface by observing runoff, interflow and soil moisture, indirect approaches model the basin behaviour balancing integral measurements of the discharge of springs or rivers at the catchment scale with abstraction rates and aquifer storage based on groundwater level measurements. In specific, for the Western Aquifer Basin (WAB; see Sect. 1.3 below), such indirect approaches cannot be employed in the recharge area, where any groundwater access and thus observations in the saturated zone, like drilling monitoring boreholes, are prevented due to the political circumstances of a long-standing water conflict and occupation. In addition, most WAB catchments carry no surface water, except for occasional storm runoff events, particularly in the recharge zone, such as Wadi Natuf (Messerschmid et al., 2018). The research is left only with direct approaches to determine deep percolation from the soil into the bedrock, which is equated with recharge in this study (see also Schmidt et al., 2014).

1.2 Dealing with spatial variability

Hartmann et al. (2013) emphasised the need to focus on process-based approaches; this is especially true for hydrological predictions in ungauged basins (PUB). In the absence of field data describing the dominant hydrological processes and functioning of a basin, it was often recommended to make use of the more readily accessible and measurably physical basin form (Savenije, 2010) and then to differentiate landscape units according to a hydrologically meaningful landscape classification metric to translate form into function (subject of the follow-up paper by Messerschmid et al., 2020). For the link between physical features and basin response, Eder et al. (2003) and Hartmann et al. (2013) suggested the use of so-called hydrological system signatures to describe emergent properties of a system – both quantitatively or qualitatively – such as flow duration curves or spring hydrographs.

Most of the PUB literature, such as Sivakumar et al. (2013) and Hrachowitz et al. (2013), stressed the need for parsimony in hydrological modelling, especially under the presence of equifinality in calibrated parameters. For more information, see also Grayson and Blöschl (2000); Woods (2002); Sivapalan et al. (2003a); McDonnell and Woods (2004); Sivakumar (2004, 2008); Wagener et al. (2007); Young and Ratto (2009) and Olden et al. (2012). Such parsimonious models stick to the description of simple local processes and the identification of a few realistic and observable physical parameters and hydrological drivers governing these process (Franchini and Pacciani, 1991; Zomlot et al., 2015). Sivapalan et al. (2003b) pointed out that despite the heterogeneity of local parameters and processes, the response at the catchment scale is often characterised by surprising process simplicity. Hence a small number of field observations may describe the main characteristics of a process (Seibert and Beven, 2009), even in ungauged basins and with short time series data only (Juston et al., 2009; Seibert and Beven, 2009; Blume et al., 2008; Nash, 1957; Dooge, 1959; Lambert, 1969).

So far, most studies have focused on runoff rather than on recharge (Sivapalan et al., 2003b; Batelaan and de Smedt, 2001, 2007), but there have been some notable exceptions: for example, Aish et al. (2010) determined recharge distribution in the Gaza Strip; however, here, local data on groundwater depth were available for the recharge zone. The bulk of recharge models worldwide have been using lumped or only partially distributed approaches because they do not require detailed spatial information, but they rather transfer input into output by a set of equations on a basin-wide scale (Jeannin and Sauter, 1998; Hartmann et al., 2013; Abusaada, 2011). This also applies to the Western Aquifer Basin.

1.3 Existing recharge studies in the Western Aquifer Basin (WAB)

The Western Aquifer Basin (Aujah-Tamaseeh in Arabic and Yarkon-Tanninim in Hebrew) is the largest, freshest and most productive groundwater basin in all of Historical Palestine, spanning from the sub-humid Mt Carmel in the north into the Sinai in the south and from the West Bank mountains to the Mediterranean Sea with an area of 14 148 km^2 (SUSMAQ, 2003; ESCWA-BGR, 2013; see Fig. 1). The WAB is a clas-

sical transboundary water basin, subject to negotiations over equitable allocations under international water law (UN-GA, 1997). The intensive use of the basin dates back to the early 1960s starting with deep well drilling in the coastal plain and in the adjacent foothills area. The basin rapidly became one of the single largest sources of Israeli water and also has the potential to become one of the largest future sources of Palestinian water in the West Bank. On the other hand, the WAB's recharge and accumulation areas, which are located in the mountains, slopes and foothills of the West Bank, remain relatively untouched, ungauged and unexplored, due in large part to the continued restrictions imposed on Palestinian water sector and infrastructure development (World Bank, 2009). Within this recharge zone lies Wadi Natuf, a 103 km^2 large surface watershed stretching from the crest of the West Bank mountains, which is north of Ramallah, down to the Green Line (that separates Israel from the Palestinian West Bank under Israeli military occupation; see Sect. 2).

Also in the Western Aquifer Basin, the preferred choice of most of the existing studies were fully lumped models. This was done primarily to avoid problems with spatial differentiation and over-parameterisation (Goldschmidt and Jacobs, 1958; Guttman et al., 1988; Guttman and Zukerman, 1995; Guttman, 2000; Berger, 1999; Abusaada, 2011; and Abusaada and Sauter, 2017). Some researchers created partially distributed models. Sheffer (2009) and Sheffer et al. (2010) for example applied a distributed basin-wide recharge model to the WAB, which however only distinguished coarsely between two units: permeable carbonatic formations and less permeable, chalky or marly rock outcrop. In addition, crucial model parameters, such as soil characteristics, were taken from the literature (Dingman, 1994), not gained from in situ findings in the field (see also Dvory et al., 2016; Weiss and Gvirtzman, 2007; Schmidt et al., 2014). Truly spatially distributed and field-based approaches so far are restricted to studies on the local scale of less than 1 km^2 (Frumkin et al., 1994; Lange et al., 2003, 2010; Arbel et al., 2010; Steinmann, 2010; Grodek et al., 2011). However these studies mainly focussed on runoff rather than recharge. Sprinkler tests on a plot scale (10 m × 18 m) by Lange et al. (2003) pointed to the importance of soil saturation excess for surface runoff and recharge. Similar observations were published by Ries et al. (2015, 2017) in the neighbouring Eastern Aquifer Basin (EAB) that drains towards the Jordan Rift Valley and the Dead Sea.

The so-called "object-oriented" recharge model of the WAB by Hughes and Mansour (2005) and Hughes et al. (2008) separated runoff, spring flow, soil infiltration and deep percolation (recharge) into individually calculated compartments. At first, each compartment had a high spatial resolution but then was lumped into an integrated basin-wide model. Moreover the entire model input was based on a priori estimated parameters, not local field knowledge, which has been found to often result in little consistency (Kapangaziwiri et al., 2012). Such simplified, lumped water budget approaches of course contribute little to the understanding of the spatial variability of distributed recharge, particularly on a local scale, where the hydrostratigraphy is more complex (as explained in Sect. 2). Abusaada (2011) in his three-dimensional integrated flow model of both plains and slopes called for refined data input on land use, soil, geology and structural characteristics in the WAB (see also Martínez-Santos and Andreu, 2010).

1.4 PUB paradox and recommendations

These findings point to the so-called PUB paradox, according to which data-rich catchments are needed to test methods for data-poor environments as Seibert and Beven (2009) noted. Their "hydrologically intelligent choice", focused on the correct interpretation of the dominant process features and on keeping observations at the necessary minimum, for reasons of practicality (e.g. measurement costs and field accessibility). Such an intelligent design remains a learning process starting with insufficient data and adding data as required by the application (Binley and Beven, 2003; Seibert and Beven, 2009). In order to improve the conceptual realism, Pomeroy (2011) summarised three principle aims: to demonstrate the value of observations, to reduce the reliance on calibration and to enhance the capability to predict based on process understanding. In addition, Beven and Kirkby (1979) suggested a three way compromise between (a) the advantages of model simplicity, (b) the complex spatial variability of basin hydrological response and (c) the economic limitations on field parameter measurements.

To summarise, firstly, only one of the three general venues to estimate recharge (Scanlon et al., 2002) are applicable to Wadi Natuf: the saturated zone is inaccessible for field measurements and observations, and surface water bodies are absent (see Sect. 2). Secondly, the severe lack of primary empirical field data cannot be circumvented by evermore sophisticated advances in modelling. Therefore, thirdly, new surface- and process-based direct methods are called for that are firmly based in field observation and measurements of observable features and that find ways to conceptualise, describe, classify and measure the spatially variable and complex recharge processes while simultaneously adhering to the goal of parsimony and avoiding exhaustive calibration associated with the problems of equifinality.

1.5 Aims, motivation and approach

The objective of this study is to investigate spatially distributed recharge in a largely ungauged karst aquifer catchment in order to develop formation-specific recharge coefficients (RC) in the central WAB for the first time. The understanding of the process and physical model parameters were based on specifically targeted measurements (McDonnell et al., 2007) and firmly grounded on fundamental physical laws and theories, as well as local knowledge of the observable

landscape and climate controls of hydrological processes as stressed by Sivapalan (2003) and Hrachowitz et al. (2013). A parsimonious soil and epikarst reservoir or tank model for laterally disconnected one-column elements (Schmidt et al., 2014; Hrachowitz and Clark, 2017) was performed in daily steps and based on observable physical features and empirical field measurements for core parameters of the soil water budget, thus avoiding the need for retrofitting. The model was examined and tested in a novel combination of both quantitative and semi-qualitative basin observations. On the one hand, at the level of basin form (physical soil parameters) the modelled soil moisture content was compared to the field measurements. On the other hand, on the level of basin response, the signatures of measured spring flow events (peak discharge periods) were compared to the modelled periods of deep percolation (DP). Finally, the model results of spatially distributed annual recharge coefficients were compared to literature results from former recharge studies in the WAB.

2 Study area

Wadi Natuf is a 103 km^2 catchment stretching from the mountain plateau at the crest of the West Bank at 816 m above sea level (a.s.l.) down to its foothills at 138 m a.s.l. (Fig. 1). In the eastern mountain region, the topography is characterised by rocky mountain crests and high plains with steep terraced slopes towards the central Wadi Natuf further west. Here, in the midstream catchment, undulating hills with deeply incised ephemeral rivers (wadis) dominate, descending further down to the gentle slopes and plains in the lower Natuf region near the outlet of the main wadi bordering the coastal plain. Within the Natuf catchment, all sub-aquifer formations of the WAB and some of the overlying cover series crop out (Fig. 2a, b) and are therefore exposed to direct infiltration. The climate is typically Eastern Mediterranean with precipitation occurring from November to April, monotonously rising from the semi-arid western foothills (500–600 mm a^{-1}) to sub-humid conditions in the eastern mountains (above 600 mm a^{-1}). Wadi Natuf drains westwards towards the Mediterranean Sea and has a remarkably low overall runoff coefficient of approximately 0.11 %, mainly due to high percolation rates into the bedrock under shallow soils and due to considerable transmission losses (Messerschmid et al., 2018) into the karstified carbonate materials underlying the wadis.

Conventionally and on a regional scale, the WAB is subdivided into two main regional aquifer units of mostly karstified carbonates. The "Lower Aquifer" is of Lower Albian age (ca. 113–106 million years), and the "Upper Aquifer" is of Upper Cenomanian–Turonian age (ca. 95–89 million years). Together they make up around two thirds (64.4 %) of the outcrops in Wadi Natuf (Fig. 2b). The remaining third of the catchment consists of aquitards from marl and chalk. According to this conventional view, the regional aquifers

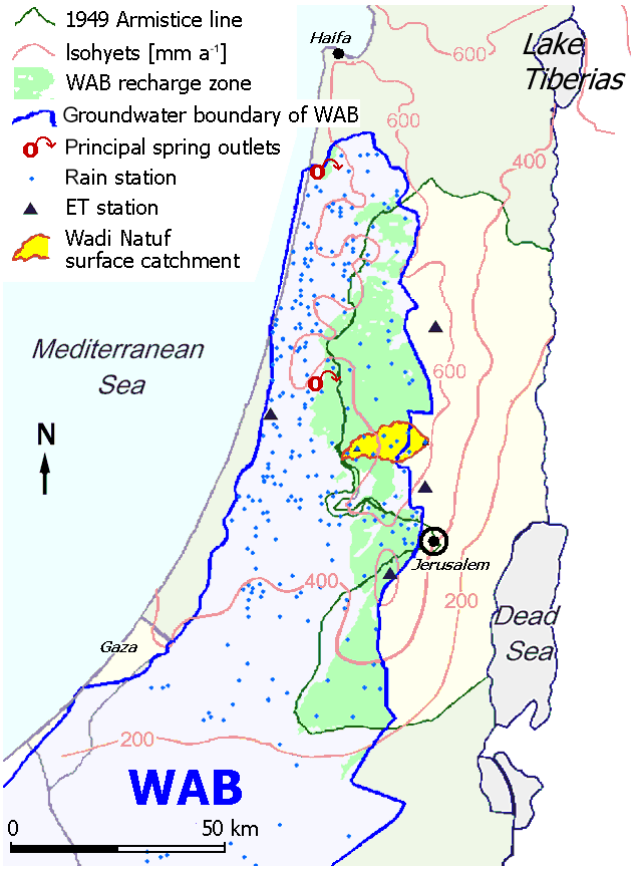

Figure 1. Western Aquifer Basin (WAB) overview and Natuf location map. Wadi Natuf (in yellow) lies in the uphill recharge zone (shaded green) of the groundwater of the Western Aquifer Basin, whereas the easternmost part of its surface catchment belongs to the Western Aquifer Basin. Isohyets indicate a climate in Wadi Natuf ranging from semi-arid to sub-humid. The two former principle spring outlets of the WAB have all but dried up, due to excessive pumpage in Israel. Four evapotranspiration (ET) stations around Wadi Natuf were complemented by two automatic weather stations in this study. Sources: modified after Sheffer et al. (2010), SUSMAQ (2001), Abusaada (2011) and ESCWA-BGR (2013).

are divided by some 100 to 150 m thick marly, chalky and carbonatic series of the so-called "Middle Aquitard" (Bartov, 1981; SUSMAQ, 2002; ESCWA-BGR, 2013). However, closer scrutiny reveals that both the regional aquifers can be further subdivided into more permeable and more impermeable sections (Fig. A3a, A3c). Also the regional Middle Aquitard can be subdivided into an aquitard or even aquiclude section of yellow soft marl (upper Yatta formation or u-Yat) and a more carbonatic, partly karstified intermediate perched aquifer horizon (lower Yatta formation or l-Yat; see Fig. 2a) (Messerschmid et al., 2003a, b). Lower Yatta is underlain by another perched aquifer (upper Upper Beit Kahil formation or u-UBK), which consists of a cliff-forming very permeable reefal limestone series (Fig. A3b). The third perched aquifer on a local scale is formed by the top of lower

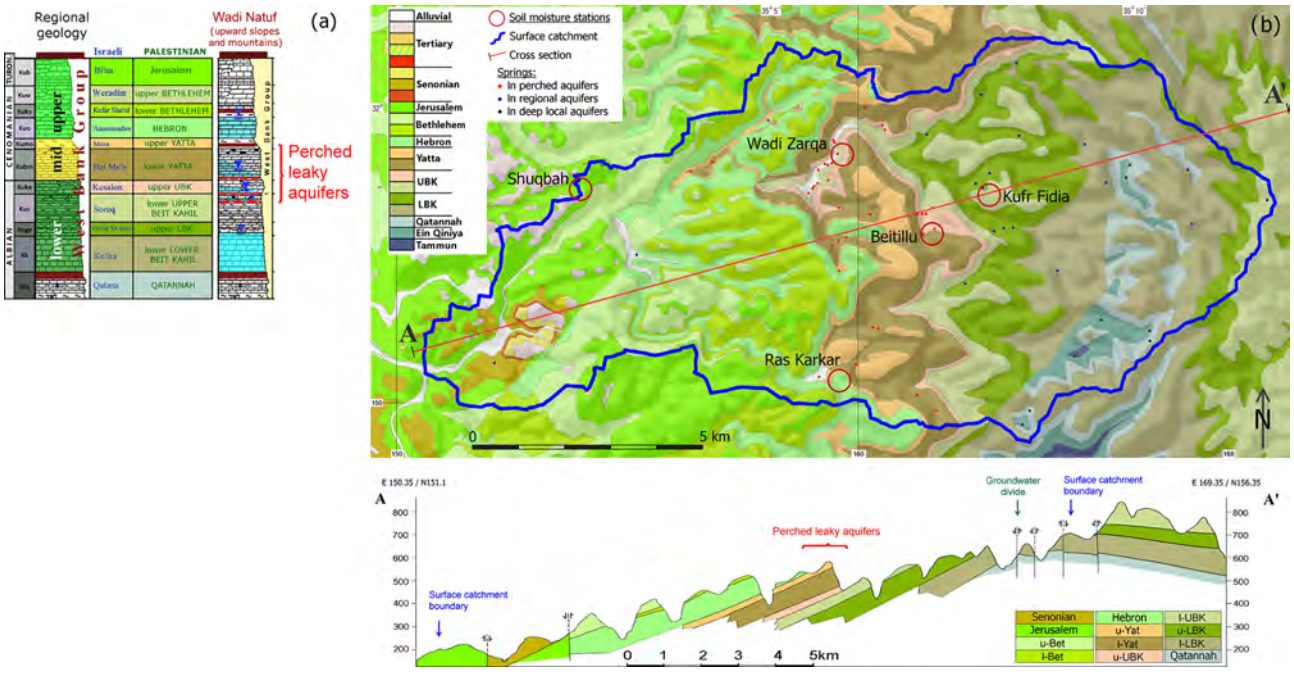

Figure 2. Stratigraphic column **(a)** and geological relief map with cross section **(b)**. **(a)** The stratigraphic column shows the regional hydrostratigraphy of the lower, middle and upper West Bank group (known in Israel as the Judea group) with only two aquifers (left side), such as the Lower Aquifer ("lower" group) and the Upper Aquifer ("upper" group), separated by the yellow "mid" group (left side). On the local scale, they can be differentiated into several sub-units of aquiferal and aquitardal series with three separate perched aquifers in the middle, e.g. the lower Yatta formation, upper UBK formation and the top of lower UBK formation (abbreviated to l-Yat, u-UBK and top of l-UBK). The middle columns show the Israeli and Palestinian formation names. **(b)** The geological relief map indicates a selection of the many small local springs, mostly fed by the perched aquifers in central Wadi Natuf (red dots), partly also locally from within the regional aquifers (blue dots) or from the deep local aquifers (green dots). Red circles inside the map indicate the five areas of the eight soil moisture stations. The cross section indicates the surface catchment of Wadi Natuf and, further to the west, the groundwater divide that separates the Western and Eastern Aquifer Basins at a stratigraphically low position where the Lower Aquifer is fully eroded and the deep aquifers crop out. Sources: stratigraphic column, modified after Dafny (2009); geological map, modified after GSI (2000, 2008); cross section: this study.

Upper Beit Kahil formation (l-UBK), a more chalky and marly limestone series that is underlain by an impermeable twin marl band (Fig. A3c). The three perched local aquifers can be found in central Wadi Natuf where they give rise to over 100 small local contact springs (Fetter, 1994), as shown in Fig. 2b. Together, their outcrops account for about 13 % of the catchment area. On a regional scale, the two perched aquifer series within Upper Beit Kahil formations are considered part of the Lower Aquifer. By contrast to the perched aquifers, most other parts of the regional Lower Aquifer as well as the entire Upper Aquifer within Wadi Natuf are void of springs.

The soil cover in Wadi Natuf consists of terra rossa, mostly with thicknesses in the decimetre range (Fig. A2, Appendix A). Although regional maps (Dan et al., 1975) indicate small portions of rendzina in the central part (near Ras Karkar, Fig. 2b), no such types of soils were found during intensive field reconnaissance and measurement campaigns. The soils were found to have high silt and clay contents. In the dry season, the soils disintegrate into fist-size crumbs and form desiccation cracks. These cracks can act as preferential pathways for infiltration during the early half of the winter season (as also found by Gimbel, 2015). Soil thickness > 1 m was only found at small agricultural plains overlying the aquitard series such as the upper Yatta formation (u-Yat; see Fig. A1, Table 1).

An important and recurring observation during the field work was a pattern where soil thickness is associated to certain types of both underlying bedrock lithology of formations and to the type of land use and land cover (LU/LC); carbonates show thin soils, while over argillaceous rock, thicker soil covers develop. Equally, soil cover over grassland and terraces were found thin, whereas agricultural cultivated fields and garden plots were located over thick soil stratum (see Fig. A2 and Table 1). In other words, typical land forms and soil depths can be identified for the different geological formations in Wadi Natuf, such as the perched aquifers (l-Yat, u-UBK and top l-UBK) and the Hebron (Heb) and Jerusalem formations (Jerus) of the Upper Cenomanian–Turonian main regional aquifer (see also Appendix D). This association of soil depths with other land features will be sub-

ject to a follow-up paper on regionalisation, Messerschmid et al. (2020).

A prevailing feature in Wadi Natuf, as in most of the Mountain Aquifer (Schmidt et al., 2014), was the finding of a thick unsaturated zone in the karstified aquifers up to hundreds of metres thick underlying thin soil cover; hence, all percolation from the soil into the underlying bedrock was considered as deep percolation.

3 Methodology

This study presents a distributed groundwater recharge model for a karst catchment based on extensive hydrological field measurements of three types, namely climatic drivers (like precipitation, radiation and temperature), hydrological processes (such as soil moisture saturation and spring flow) and physical features (soil characteristics, geology and land use/land cover), as shown in Fig. 3. The forward-calculating model is parsimonious, i.e. based only on daily precipitation and evapotranspiration (ET; as well as temporally stable location-specific soil parameters) in order to translate soil moisture saturation into deep percolation, which here is equated with recharge (Schmidt et al., 2014). The one-dimensional soil water balance model was designed as a soil tank with an upper boundary towards the atmosphere and a lower boundary towards the underlying karstified bedrock.

3.1 Climatic drivers: rainfall and evapotranspiration

The measurement period for precipitation and evaporation spanned over nine seasons, from 2003–2004 until 2011–2012. A complete set of weighted area rainfall data for the five sub-catchments (Fig. 4) was obtained from Messerschmid et al. (2018), originally measured in 5 min steps at 10 stations distributed evenly in upper, central and lower Wadi Natuf. The automated rain gauges (tipping buckets) with Eijkelkamp loggers were run in event mode. The model in this study used the weighted area rainfall precipitation at the five sub-catchments in daily steps (see Table 2 and Fig. 4).

Daily minimum and maximum temperature and solar radiation data were collected at two automatic weather stations (AWSs) for the calculation of potential evaporation (Fig. 4). The readings were taken with two automatic weather stations from Campbell Scientific with a CR10X data logger and an HMP45D (Y3520067) sensor. One station was installed upstream at Birzeit University at the mountain crest; the downstream station at Shibteen well no. 4 was located at the transition between the foothills and coastal plain to the west. Missing records were filled up with corrected temperature data from Jerusalem (IMS, 2017), which represented intermediate values between the relatively cool conditions in Birzeit and the relatively warm conditions downstream in Shibteen.

Potential evapotranspiration (ET_p) was calculated by the formula of Hargreaves and Samani (1985). The Hargreaves approach was developed and applied for similar semi-arid conditions (e.g. Ryu et al., 2008) and in comparable areas, such as the adjacent EAB (Schmidt et al., 2014). ET_p is calculated by Eq. (1).

$$ET_p = 0.0023 \cdot Ra \cdot (T_{mean} + 17.8) \cdot (T_{max} - T_{min})^{0.5} \cdot \lambda^{-1}, \quad (1)$$

where Ra is the daily sum of extra-terrestrial solar radiation ($MJ\,d^{-1}$), T_{mean} is the daily mean air temperature (calculated as average of daily minimum and maximum temperature in °C), $T_{max} - T_{min}$ is the daily temperature range, and λ is the latent heat of vaporisation in order to obtain ET_p in $mm\,d^{-1}$.

3.2 Hydrological measurements: soil moisture and springs

Soil moisture (SM) content was monitored at eight different stations over a period of 7 years (see Table 1). Due to budget limitations and reduced field accessibility (particularly during the height of the Second Intifada), the measurements were kept at a minimum (as recommended by Beven, 2002, and by Seibert and Beven, 2009; see Sect. 1.2, 1.4). It was therefore decided to increase the number of different SM locations and to decrease the duration of measurements at each station (ranging between 1 and 4 years, see Table 1). All in all, 13 years of soil moisture measurements were carried out at the eight locations. The locations were chosen at places with minimum slope and without lateral water input from upslope overland runoff.

The target of the soil moisture measurements was daily time series data of the overall available water content (θ). SM was measured at different depths by each sensor and then normalised to total water content of the respective soil column. Initially two sets of frequency domain reflectometry soil moisture sensors (ML2-Theta probes, Delta-T Devices Ltd.) were used. Due to malfunction and vandalism they were replaced by two ECH2O loggers (EM50, Decagon Devices Inc.), each connected to two or three sensors (5TM, Decagon Devices, Inc.) that measured volumetric water content (as a percentage) based on the difference of dielectric permittivity between water and soil matrix. The loggers recorded in 30 min intervals. The readings were averaged into daily values for the purpose of the model. The sensor installation depth varied between a minimum of 5 cm and a maximum of 75 cm at the thickest soils (Table 1). Technical problems with the equipment are discussed in Appendix B (Tables B1–B3).

In order to better relate the spatially discrete SM stations to the overall catchment area, soil samples (150–550 g) were collected randomly at different depths and different times; the absolute water content of the samples was determined by oven weighing at the Birzeit laboratory. These results also served to reconfirm and calibrate the sensor readings.

Each of the sensor readings of volumetric water content (as a percentage) from different soil depths was multiplied with the thickness of the individual soil sections (in metres) and then combined to an overall water content of the soil

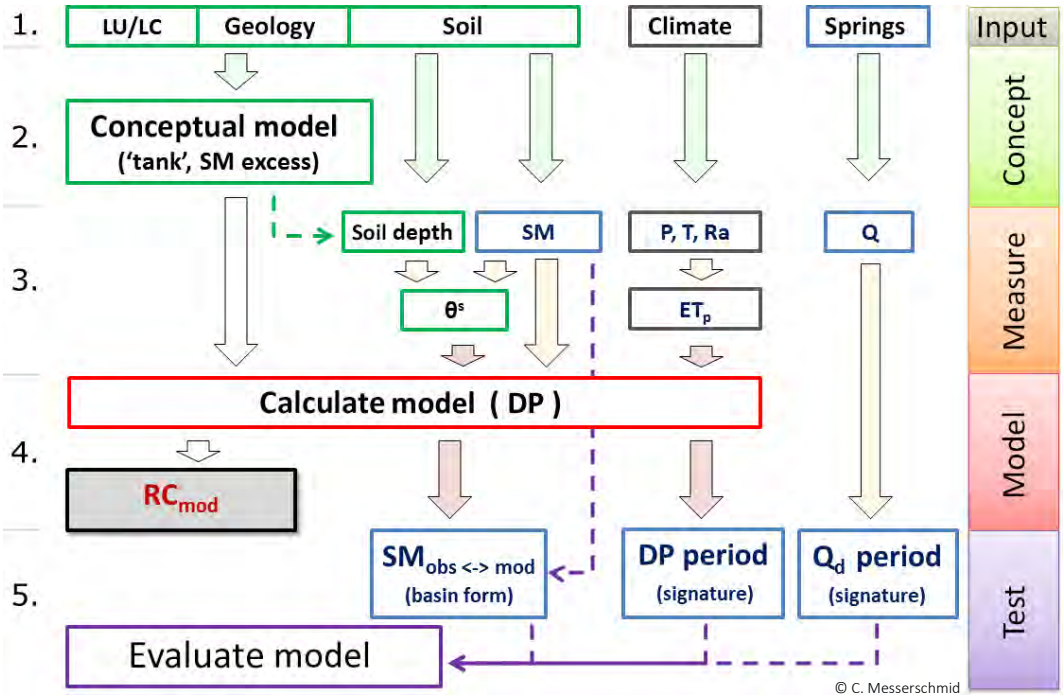

Figure 3. Conceptual flow chart of the work steps for the model. First row: measured and observed input such as climate, spring flow, land use and land cover (LU/LC), etc. Second row: conceptualisation of the one-reservoir tank model. Third row: actual measurements of daily values for soil moisture (SM), precipitation (P), temperature (T), solar radiation (Ra), spring flow (Q), etc.. Fourth row: modelling of deep percolation (DP) and transformation into annual recharge coefficients for each of the modelled formations (RC_{mod}). Last row: model evaluation by different tests such as quantitative comparison between observed and modelled soil moisture contents (SM_{obs} and SM_{mod}) and semi-qualitative comparison between periods of percolation events and peak discharge at the daily measured springs.

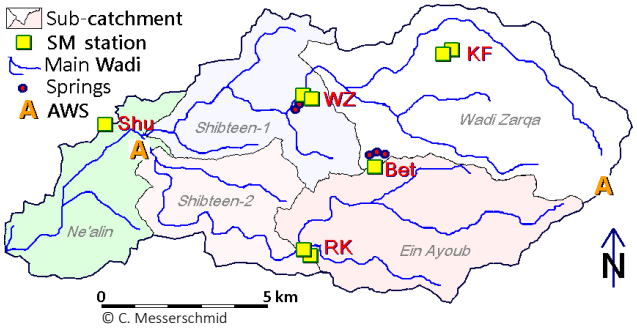

Figure 4. Drainage and measurement stations. Main branches of the northern and southern branches of Wadi Natuf. Soil moisture (SM) stations at Shuqbah (Shu), Wadi Zarqa (WZ), Beitillu (Bet), Kufr Fidiah (KF) and Ras Karkar (RK). Daily measured springs at Beitillu and Wadi Zarqa. Automatic weather stations (AWSs) at Shibteen (west) and Birzeit (east). Sub-catchments (in grey) at Ne'alin (west), Shibteen-1 (midstream; north), Shibteen-2 (midstream; south), Ein Ayoub (southeast) and Wadi Zarqa (northeast).

column (as millimetres of the water column within the soil). The continuous soil moisture hydrographs were then analysed separately for each location, resulting in a typical and annually returning minimum (SM_{min}) and maximum water content (SM_{max}) as temporally stable but spatially distributed parameters. The representativeness of each SM station was further confirmed by the many hand-collected SM samples from the same formations but at other locations. The maximum soil water storage capacity or storage capacity at saturation (θ^s) was then calculated for each SM station and according to Eq. (2).

$$\theta^s = (((SM_{max,1} - SM_{min,1}) \cdot b_1) + ((SM_{max,2} - SM_{min,2}) \cdot b_2) + ((SM_{max,3} - SM_{min,3}) \cdot b_3))) \cdot b_\Sigma, \quad (2)$$

whereby SM_{max} and SM_{min} were used as the measured water content per soil segment volume ($m^3\,m^{-3}$), $SM_{max,1}$ indicates the maximum water content at the first near-surface soil section and deeper sections are indicated by successive numbers (2 and 3), and b indicates the soil thickness (in metres) of the respective soil sections (1, 2 and 3) or the overall soil thickness (b_Σ). θ^s represents the normalised effective maximum storage content in metres (or millimetres) of the whole soil column (see Sheffer, 2009; Sheffer et al., 2010). It should

be noted that θ^s was derived directly from the field-measured values of SM_{max} and SM_{min}, the range of which indicates the maximum amounts of soil water available for evapotranspiration before percolation sets in (see also Sects. 3.4 and 5.1 and Fig. 5).

The sensor readings included brief periods of water storage beyond field capacity, such as water in desiccation cracks (especially in heavy storm events during late autumn and early winter); these peak levels can be noticed as brief spikes of SM readings (here indicated as SM_{peak}) above the otherwise stable levels of annually recurring SM_{max}. It should however be emphasised here that the model in its daily budgets fully accounts for these additional water amounts (see Sect. 4.1 and Appendix B).

Daily spring flow measurements were used as a model check. This high-resolution spring flow record, the first for the WAB mountains, enabled the detection of signatures, i.e. the temporal patterns of low and peak discharge for comparison with simulated recharge by the soil moisture saturation and percolation (SMSP) model. From the large number of over 100 springs discharging from the perched aquifers, five springs from two spring groups (Fig. 4) were selected that can be considered representative for the total spring group discharge, due to their position and proximity to the soil moisture stations. At these springs, daily flow measurements were carried out continuously by metering (by hand) throughout almost the entire period (spring data coverage; see Appendix C, Table C1). Three of these springs belong to the so-called "Beitillu spring group"; the two other springs belong to the "Wadi Zarqa spring group" (near the Wadi Zarqa SM station, see Figs. 2b, 4). Their representativeness is discussed in Appendix F.

3.3 Model parameterisation (soil thickness)

The soils in Wadi Natuf were found to consist only of one prevailing soil type, terra rossa (see Sect. 2); field investigations, sampling and granulometric lab tests showed that the soil was mostly silty clayey, with some samples also showing higher clay contents (Messerschmid et al., 2018). This allowed for an important simplification for the soil moisture saturation and percolation model to only account for one uniform soil type throughout the study area. By contrast, soil thickness (b) plays an important role as a quantifiable parameter in the SMSP model. Therefore it was necessary to determine the typical soil thicknesses at the different geological formations and LU/LC types and to ensure that the selected soil moisture measurement plots were representative for the typical conditions of a given formation. The spatial distribution of soil thickness was established by digging up the soil down to the soil–rock interface. The soil thickness differed between sampling locations, which led to variable sampling depths down to the respective horizon, where in situ lithology prevailed. The results of the soil depth survey are shown in a soil thickness matrix for different LU/LC types and lithostratigraphic units (see also Appendix D and Table D1).

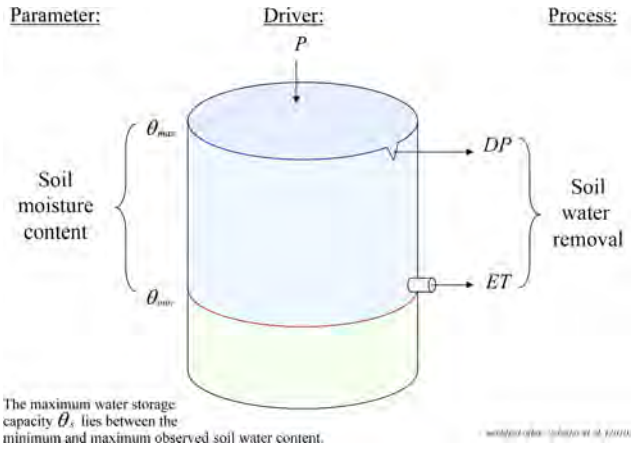

Figure 5. Parsimonious SMSP model of "one-reservoir saturation excess" (modified after Sheffer et al., 2010). Parameters and drivers (top) were field measured for every station and model. The available water content, shown as θ (between SM_{max} and SM_{min}), is seasonally variable but location specific. Discounting runoff, soil water removal is accounted for in two ways: as SM saturation (red line) increases (above SM_{min}), evapotranspiration (ET) is triggered first; when θ^s reaches SM_{max}, deep percolation (DP) is initiated. Precipitation (P) was measured; potential evapotranspiration was calculated from weather station data and transformed into actual ET values (Sect. 3.2).

3.4 Parsimonious soil moisture saturation and percolation modelling: design and processes

The SMSP model implies a classical soil moisture balance approach; soils dry up to minimum water content during summer and then accumulate and store water with successive rainfall during autumn and winter. SM content above SM_{min} is subject to direct evaporation and plant transpiration and has to be deducted in daily steps from the SM content accumulated successively by precipitation. When soil conditions reach saturation (full effective storage capacity; θ^s), deep percolation into the bedrock is triggered, here equated with groundwater recharge (Fig. 5). ET_a is limited downwards by available water content (θ_i) and upwards by ET_p.

$$ET_{a_{i+1}} = \begin{cases} ET_{p_{i+1}} & \text{if} \quad (\theta_i + P_{i+1}) \geq ET_{p_{i+1}} \\ \theta_i + P_{i+1} & \text{if} \quad (\theta_i + P_{i+1}) < ET_{p_{i+1}}, \end{cases} \tag{3}$$

where θ_i is available soil moisture (in millimetres), P is daily rainfall (in millimetres), ET_a is the daily actual evapotranspiration (in millimetres) and ET_p is the daily potential evapotranspiration (in millimetres).

All additional rainfall infiltrating from the surface and beyond the daily evapotranspiration losses can either be added to the available water storage or, when limits of θ^s are exceeded, considered to percolate into the bedrock and repre-

sent recharge.

$$\mathrm{DP}_{i+1} = \begin{cases} 0 \text{ if } (\theta_i + P_{i+1} - \mathrm{ET}_{a_{i+1}}) \leq \theta_{\max} \\ \theta_i + P_{i+1} - \mathrm{ET}_{a_{i+1}} - \theta_{\max} \\ \text{if } (\theta_i + P_{i+1} - \mathrm{ET}_{a_{i+1}}) > \theta_{\max} \end{cases}, \quad (4)$$

$$\theta_{i+1} = \theta_i + P_{i+1} - \mathrm{ET}_{a_{i+1}} - \mathrm{DP}_{i+1}, \quad (5)$$

where $\theta_{\max}$ is the effective maximum soil water storage and DP is daily deep percolation, i.e. groundwater recharges (in millimetres). The testing of the model was reached in two independent ways, by a quantitative comparison of modelled and observed SM values and by a semi-qualitative comparison of recharge periods (DP events) with times of observed spring discharge peaks. In other words, one examination was done on the reliability of the model to produce the observed physical feature of SM, and the other was done by using the hydrologic response signature of spring flow responding to recharge.

3.5 Annual and mean recharge coefficients

First, the annual DP rates (mm a^{-1}) are divided by annual station rainfall delivered annual recharge coefficients (as a percentage) for each modelled SM station. Secondly, DP rates from the model for the different stations representing different formations (Table 1) were referred to the outcrop sizes of the respective formations in Wadi Natuf to obtain annual recharge amounts (R; in $m^3\,a^{-1}$). Then, thirdly, at each station (or for each formation) the seven different annual RC values were transformed into an average recharge coefficient (RC_{avg}). This simplified approach assumes that our 7-year rain observation period fairly represented the long-term averages and inter-annual distribution patterns of precipitation (see Sect. 3.1 and Appendix E). In order to verify the representativeness of our 7-year observation period for long-term conditions (> 30 years) and since no long-term precipitation record for Wadi Natuf was available, the temporal precipitation patterns were compared on the level of the entire WAB and based on long-term records from HSI (2016). The comparison and its results are documented in Appendix E (Table E1 and Fig. E1).

4 Results

4.1 Seasonal soil moisture patterns

Table 1 presents the eight locations of soil measurements, used for the percolation models, with their respective bedrock formations and soil depths as well as the recurring maximum and minimum soil moisture levels, from which the maximum water storage capacity (θ^s) of each location was derived.

The thin soils in Wadi Natuf showed a low water retention capacity (Sect. 4.2, Fig. 6); in summer, soil usually dried up rapidly to an SM content between 5 % and 10 %. Table 1 also

Table 1. Soil moisture measurement data by location (in mm and %).

Land use	Shuqbah, grassland	Beitillu, gardens	Wadi Zarqa, fields		Kufr Fidiah, field		Ras Karkar, terraces	
			Upper terrace	Greenhouse	Cultivated	Abandoned	Rocky	Uncultivated
Symbol	Shu	Bet	WZ-upT	WZ-gh	KF-W	KF-E	RK-W	RK-E
Formation	Jerus	l-Yat	u-UBK		Top of l-UBK			Heb
Soil depth (mm)	320	500	770	400	650	940	400	400
Sensor depth (mm)	110/190	110/110/430	420/660/750	170/360	130/180/390	50/75/175	50/140/320	100/200
No. of years measured	1	1	1	1	2	1	4	2
Hydr. seasons measured	2003–2004	2003–2004	2005–2006	2004–2005	2005–2006 to 2006–2007	2006–2007	2005–2006 to 2008–2009	2007–2008 to 2008–2009
SM_{max} (mm)	60	179	172	132	253	237	129	129
SM_{min} (mm)	20	40	50.05	64.4	68.25	4.7	16.8	16.8
SM_{min} (%)	10 %	8 %	6.5 %	16.1 %	10.5 %	0.5 %	4.2 %	4.2 %
θ^s (mm)	40	139	121.5	67.5	185	232.5	112.5	112.5
θ_{peak} (mm)	44	149	175	93	232	234	119	127

θ_{peak} is a brief, episodically occurring available water storage above saturation storage capacity (θ^s). The soil moisture (SM) values SM_{max} and SM_{max} represent the highest and lowest recurring soil water contents measured in the field at different sensor depths (summed up in millimetres over the entire soil column or averaged as a percentage of the volumetric share of the total soil volume).

shows two exceptions: in one case, the plot near the greenhouses in Wadi Zarqa (WZ-gh), some summer irrigation of crops cannot be excluded. However, it was assured that no irrigation took place during the crucial winter modelling period. In the second case, the extremely low moisture content (SM_{min} of 0.5 %) at Kufr Fidiah (KF-E), was a result of vandalism (a dug-up measurement pit with artificially reduced soil moisture at the then-exposed deeper sections of the soil cover). In any case, such low soil moisture is not representative and the data of this station had to be taken with caution. In addition, the soil depth of almost 1 m encountered at KF-E, an abandoned agricultural plot, overgrown with bushes, is a rare exception, and according to our soil depth survey it is not representative for usual conditions at the top of l-UBK formation (compare soil depth matrix, Appendix D, Table D1).

In contrast to minimum recorded SM values, maximum moisture levels showed a more consistent pattern, which is important because soil saturation is crucial for the SMSP model. In line with our saturation excess model (Sect. 3.4), it should be noted that once this maximum soil moisture level was reached, it remained stable for days and weeks and did not rise any further. Throughout the measured period and at almost all stations, it was found that maximum soil moisture is spatially highly variable and can be associated with the local soil depth, as apparent from Table 1 and discussed below. Another special case however is the occurrence of brief periods with extreme moisture above saturation storage capacity. They only occurred during extreme storms or during the early winter months, when desiccation cracks enabled preferential flow and rapid infiltration into deeper soil layers (see also Appendix B) and lasted usually less than 1 d.

Spatially, the distribution of seasonal soil saturation can be differentiated as follows: at locations with thinner soil cover, such Ras Karkar (RK), Wadi Zarqa greenhouses and especially in Shuqbah (Shu), full saturation (θ^s) was usually reached by mid or late November. In the thicker soils, such as in Kufr Fidiah and the Wadi Zarqa upper terrace (WZ-upT), saturation was usually reached later, by mid-December. In most years, full saturation conditions prevailed during January and February, on rare occasions until April. The season 2005–2006 experienced the most intensive rain event of the entire measurement period, occurring very late in winter, between 1 and 5 April 2006 (Messerschmid et al., 2018). Figure 6 gives an example for the time series of observed and modelled soil moisture (station RK-W). As can be seen, recharge (deep percolation) only occurred when full saturation was reached and in the form of relatively distinct events of a few days per year, depending on the high-resolution temporal rain distribution of a given season.

In each year the level of calculated soil moisture was the result of a unique set of different climatic drivers and of location-specific parameters and physical features (and thus a result of different overlapping processes). Yet, it could be observed that the levels of available soil moisture (i.e. the water content above SM_{min}), usually dropped to zero within 1 or 2 months after the last major rainfall event of a given season (effectively ending evapotranspiration during summer; see Fig. 6).

4.2 Quantitative examination of the model (by physical parameters)

Figure 6, which presents modelled and observed soil moisture contents, indicates the performance of the soil moisture percolation model. It should be stressed here that no calibration of the model was performed.

Some of the readings show a mismatch between observed and modelled SM values; these periods are indicated as a dashed green line, where recorded soil moisture exceeded modelled SM values. In some cases, recorded moisture levels even surpassed accumulated seasonal rain (which clearly hinted to equipment failure of the SM sensors). Both issues are further discussed in Sect. 5 and Appendix B. However, a comparison between observed and modelled soil moisture (Fig. 6) showed similar performance, with an average Nash–Sutcliffe efficiency (NSE) coefficient of 0.73 for all stations, except RK-E (which had a negative coefficient of -0.35 and was excluded from further analysis). In Shuqbah and Beitillu, NSE was found between 0.8 and 0.87; in Wadi Zarqa it was 0.63; at KF-W and KF-E it was between 0.79 and 0.96; and at the RK-W station it was at 0.7 (Appendix B, Table B3; note that the stations names ending with "-W" and "-E" are the western and eastern regions of the area).

4.3 Semi-qualitative examination of the model (by spring flow signatures)

For an additional check, we compared periods of deep percolation with the signature periods of peak spring discharge, as shown in Fig. 7. In most stations, recharge occurred during a period between 11 and 21 d per year. During very wet winters it occurred at a maximum of up to 31 d per year (e.g. in WZ-gh); during very dry winters a minimum of only 5 d per year (e.g. KF-E) were recorded. Precipitation thresholds that triggered DP varied between different years and SM stations, e.g. from 74 mm of accumulated seasonal precipitation as a minimum (in Shu) to 470 mm as the highest threshold (in KF-E). For the different years, the gaps between average station thresholds ranged between 206 mm (in 2004–2005) and 396 mm (in 2008–2009), with a multi-annual mean of 290 mm.

Figure 7 shows a very close match of temporal patterns. Observed spring flow in the local perched aquifers responded with almost no delay, usually within 1 d after the first modelled recharge event. This demonstrates both the karstic nature of the aquifers with rapid flow connections and the very local recharge conditions on the isolated hillsides.

The two most productive springs of the respective groups were Salem (Wadi Zarqa spring group) and Al-Qos (Beitillu spring group). Average spring flow was between 1.3 (Bibi)

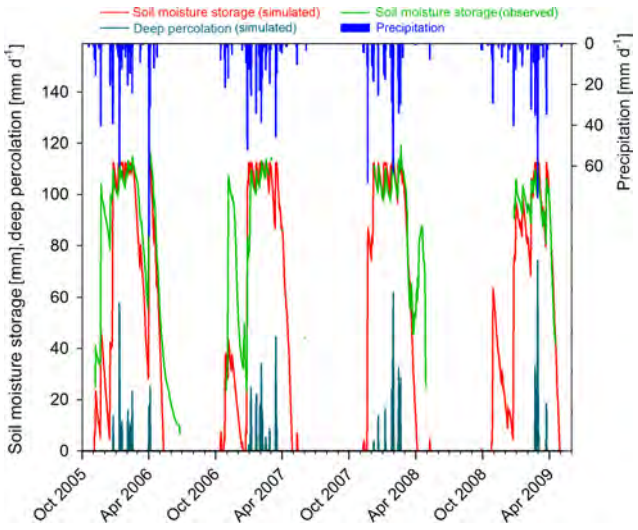

Figure 6. Comparison of observed and modelled available soil moisture at Ras Karkar West (RK-W) from 2005–2006 to 2008–2009. Maximum water storage capacity (θ^s; at 112.5 mm) of the modelled moisture level (red) matched well with the observed maximum moisture (green). Brief periods of dashed green lines show questionable and erroneous soil moisture readings (see also Sect. 5 and Appendix B). Deep percolation (triggered above θ^s) is indicated as a dark-blue column (bottom of the graph); daily rainfall is indicated as blue columns (at the top).

and 12.4 (Qos) $m^3 d^{-1}$. The smallest spring (Bibi) had a maximum discharge of 9 $m^3 d^{-1}$, while the largest (Al-Qos) had one of 78 $m^3 d^{-1}$. Both values were approximately 6 times larger than annual averages. Every slight rise of the observed daily spring flow (by as low as 8 % of the amount of average discharge) was connected to simulated deep percolation or recharge (Fig. 7). Comparing the dates of peak spring flow with that of DP events, a complete congruence of the respective dates was apparent. This analysis was performed for the period until September 2009, during which all springs had been measured reliably (see Appendix C, Table C1). All days with more than 1 $m^3 d^{-1}$ of increase in discharge at the Al-Qos spring were found to show simulated percolation; at Salem spring, the strongest spring in the Wadi Zarqa spring group, this was true for all days with more than a 0.7 $m^3 d^{-1}$ rise and at the 'Akkari spring for all days with an increase larger than 0.66 $m^3 d^{-1}$.

Finally, annual recharge coefficients were calculated and compared to literature values (see also Appendix H, Table H1). Table 2 shows annual DP rates, annual recharge coefficients and the average of these annual RC values (between 30 % and 57 %) for the entire period, according to the soil thickness at each station, ranging between 30 and 90 cm.

4.4 Summary of model results on annual levels

The annual percolation rate did not only depend on the annual precipitation, but it also depended on its seasonal distribution. For most years, a rise in annual recharge coincided with a rise in total annual rainfall, as shown in Fig. 8. The wettest winter (2004–2005 with a rainfall of 742 mm a^{-1}) showed the highest recharge in each of the stations. However, the driest year (2007–2008 with 496 mm a^{-1}) did not generate the lowest recharge, due to the seasonal distribution of very strong precipitation events that triggered high rates of percolation. This disconnection demonstrated the necessity to first calculate and model recharge in daily time steps in order to account for the event character of temporal rainfall distribution (Sheffer et al., 2010; Cheng et al., 2017) before these results can then be used for annual recharge calculations. It is also important to note the strictly reciprocal relationship between soil thicknesses and recharge coefficients. At all stations except for one (WZ-upT), the thinnest soils showed the highest recharge, and the thickest soils showed the lowest recharge (see Fig. 8). This general pattern confirmed our conceptual approach that closely linked soil depth with recharge.

Figure 8 plots different measurement stations with ascending soil depths on the x axis against annual recharge rates on the y axis with a marked and almost consistent linkage between the two (except for WZ-upT). This pattern of association forms the basis of our extrapolation and attribution approach for entire formations and their recharge coefficients (for the representativeness of the soil depths at our SM stations, see Appendix D, Table D1).

5 Discussion

5.1 General approach of process representation

Our results demonstrate that even in ungauged basins a realistic model of distributed groundwater recharge can be obtained through limited field observations of key parameters of the complex percolation process. Unlike previous studies in the WAB, the direct and location-specific assessment of water storage capacity from long-term soil moisture readings was generated as robust and realistic "local knowledge" to determine recharge because the rate of modelled percolation (recharge) was a direct function of SM storage, which was highly location specific. Since distinct land forms of LU/LC and typical soil depths could be related to each geological formation (Table D1), the SM plots and their RC values were formation specific. Existing literature often only provides values for permanent wilting points (pwp) and field capacities (Fc), which are similar but not identical with our measured maximum and minimum SM values. The θ^s value is a direct measure of the mobile, available water inside the soil column, subject to accumulation, evapotranspiration, satura-

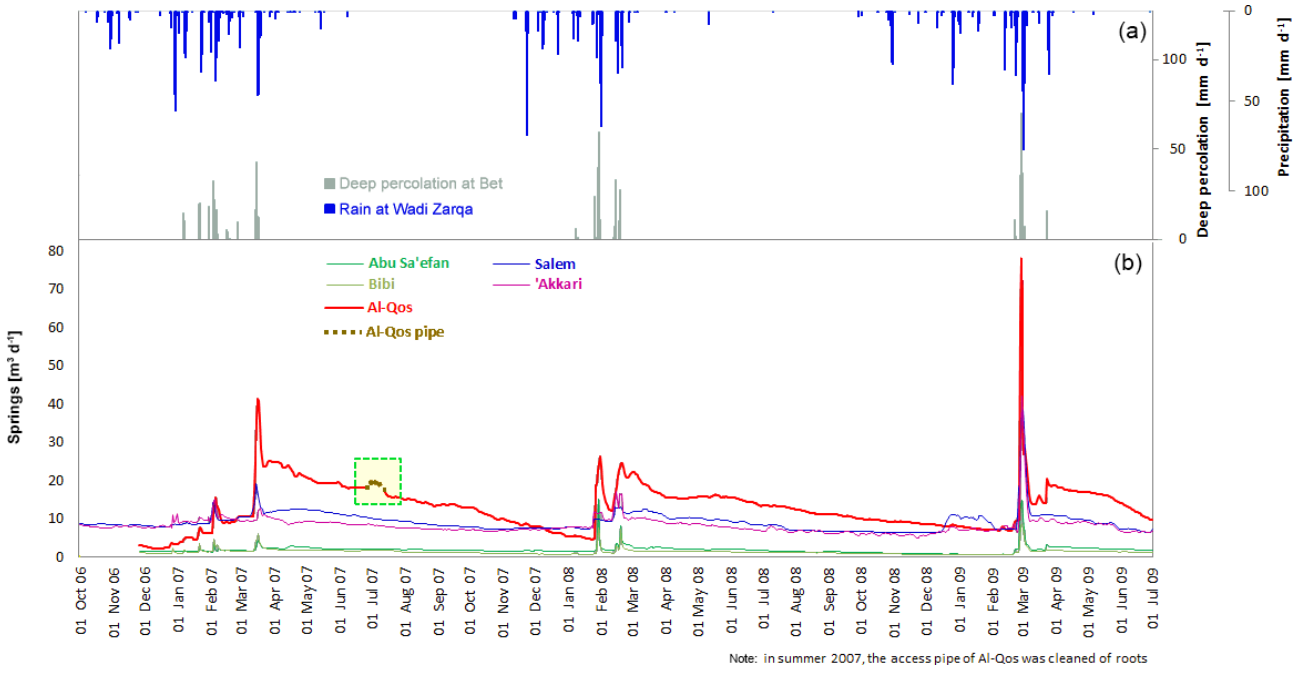

Figure 7. Signatures of peak spring flow and DP events. Yellow-shaded box: temporary increase in spring discharge caused by the cleaning of plant roots from the access pipe at the Al-Qos spring (July 2007). Daily measured spring flow at the Beitillu spring group is shown in red, olive and green **(b)**. At the Wadi Zarqa group in blue and purple, daily deep percolation is shown as grey columns (upper half), and precipitation is shown as blue columns **(a)**.

Table 2. Annual precipitation and recharge rates (DP) modelled at representative SM locations.

	Deep percolation (DP)								Precipitation (P)			
Year	Shuqbah	Bet	WZ-gh	WZ-upT	KF-W	KF-E	RK-W	RK-E	W	Centre	NE	SE
2003–2004	291	217	289	235	188	140	238	238	547	532	524	507
2004–2005	475	448	**519**	465	452	405	442	442	811	755	724	674
2005–2006	319	206	293	223	192	145	218	218	666	628	609	585
2006–2007	319	259	331	277	241	194	278	278	663	636	629	596
2007–2008	287	221	293	239	196	149	240	240	522	501	493	466
2008–2009	258	180	251	197	165	**118**	204	204	594	570	561	528
2009–2010	286	228	299	245	208	160	247	247	614	586	578	543
Average DP	319	251	325	269	235	187	266	266	–	–	–	–
Average P (2003–2004 to 2009–2010)	557	601	601	601	631	631	588	588	631	601	588	557
Soil depth (mm)	320	500	400	770	650	940	400	400	–	–	–	–
RC (DP_{avg}/P_{avg})	57 %	42 %	54 %	45 %	37 %	30 %	45 %	45 %	–	–	–	–

The table shows area precipitation of the respective sub-catchments of the SM stations (from Messerschmid et al., 2018). West (W) uses the average rain of the Ne'alin and Shibteen-1 sub-catchments. Centre refers to the average between Shibteen-1 and Wadi Zarqa. Northeast (NE) is the precipitation in Wadi Zarqa. Southeast (SE) represents the average of the Shibteen-2 and Ein Ayoub catchments (Fig. 4). The daily rates of deep percolation were modelled with these area precipitation values. Minimum and maximum values of DP are bold (WZ-gh in 2004–2005; KF-E in 2008–2009). All units are in mm a^{-1}, except for the soil depth (mm) and recharge coefficients (expressed as DP_{avg}/P_{avg} as a percentage).

tion and deep percolation (recharge). In reality, the processes of soil moisture accumulation, deficit and saturation are complex and depth dependent. Indeed our sensors installed at different depths indicated slightly different temporal SM dynamics. Deeper soil segments reacted later in the season but arrived at a relatively stable maximum plateau value at about the same times as the shallower sensors. On the other hand, they dried up at a slower pace in summer. This was in line with the generally known and expected dominant processes of accumulation, storage, and loss through evaporation and transpiration from roots. It should be noted here that most of our soils were only about half a metre thick or less and that even the lowermost soil segments were within the reach of most plants (Mediterranean trees, bushes and shrubs), resulting in a low retention capacity. Our calculation method of adding up the measured water contents of all sections ac-

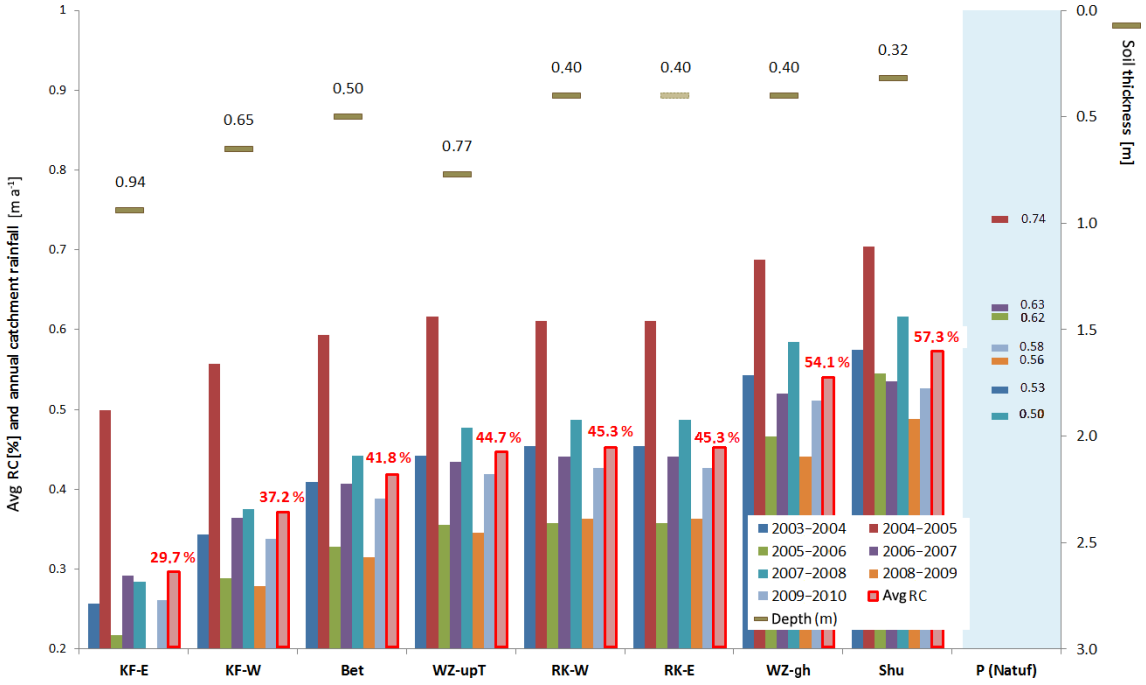

Figure 8. Annual recharge coefficients, annual precipitation and soil depth (stations ordered by increasing RC). The coloured lines present annual recharge coefficients by station (x axis), increasing from left to right (as a percentage). Average annual RC values (red numbers) are reciprocal to the respective soil depths (as brown bars, with the exception of WZ-upT as a beige bar). The blue-shaded column at the right indicates annual precipitation – shown as P (Natuf) – as the area average (in $\mathrm{m\,a^{-1}}$).

counted for the different conditions and processes at varying soil depths, and by this they provided a simplified yet realistic representation of total soil moisture throughout the soil column.

Adhering to the PUB goal of parsimony, our SM saturation and percolation model only accounted for two climatic drivers (P and $\mathrm{ET_p}$) and one spatially distributed physical parameter (θ^s), each set up in daily time steps. The model is a simple one-dimensional tank or combined-reservoir model as already used by Sheffer et al. (2010) and Schmidt et al. (2014) (see Fig. 5). This parsimonious modelling approach is based on two conceptual but field-observed assumptions of dominant processes. Firstly, the model only accounts for direct recharge (as DP) from in situ soil infiltration. Whereas some local lateral water movement on and inside the soils and within the range of a few metres distance has to be expected, this nonetheless is conceptually included here under local processes and therefore quantitatively accounted for as direct recharge. This particularly applies to epikarst outcrops with soil pockets. Moreover, as discussed in Sect. 2, no signs of indirect recharge processes were observed in the field (with the notable exception of transmission losses; discussed below). Ponding as a sign of lateral surface accumulation was restricted to small puddles of a few metres in diameter at their maximum and within clearly discernible, very small topographic depressions. Lange et al. (2003) in their runoff generation sprinkler and tracer tests close to Wadi Natuf also observed such near-surface runoff–runon processes and found them to occur in a radius of decimetres, at maximum metres (see also Ries et al., 2015). This lead to surface runoff generation on hillslopes, which was largely lost by the aforementioned transmission losses through the gravel beds of the wadis. While this point and line infiltration along wadi beds could be considered as indirect recharge, previous studies by Messerschmid et al. (2018) had shown that overall runoff generation in Wadi Natuf was very low ($< 1\,\%$ of annual area precipitation). Hence, runoff, though important during single high intensity events (see also Ettinger, 1996), could be neglected as a significant part of the catchment's overall water budget, thus also adhering to the PUB goal of simplification and parsimony. Secondly, our model accounts for only one dominant recharge generation process: deep percolation from the soil into the bedrock under SM saturation excess. This is in line with the already discussed findings from other studies in the WAB and adjacent basins (Ries et al., 2015, 2017; Sheffer, 2009; Messerschmid et al., 2018; Lange et al., 2003) that agreed that deep percolation or recharge, as much as surface runoff, must be described as a process of soil moisture saturation excess (see Sect. 1.3). For further discussions on the applicability of soil moisture balance models in the WAB, see Hughes and Mansour (2005), Hughes et al. (2008).

5.2 Spatial and temporal variability of precipitation and recharge

The main focus of our approach was the spatial differentiation of recharge, although our model also considered temporal patterns. Our annual recharge coefficients were based on a model which was run in daily steps and therefore fully accounted for the temporal distribution of rainfall, especially storm events. The model results of annual recharge coefficients suggested a relationship between spatial and temporal variability. When the standard deviations for annual recharge and annual precipitation were plotted against each other, we found that standard deviations for rainfall increased with annual rainfall (except for the year 2005–2006), whereas spatial variability of recharge diminished (see Appendix G, Fig. G1).

Although 7 years of modelling may not be enough to draw far-reaching conclusions, we can still conclude that the question of spatial variability of recharge deserves greater attention than that given in most recharge studies, particularly in the Western Aquifer Basin. Within this study, average RC values were calculated from the individually calculated annual values (Sect. 3.5). This somewhat extrapolative approach does not fully reflect the temporal variability and seasonal distribution of rainfall, which may lead to different recharge rates even in years with identical annual rainfall amounts. However, since our study focussed on spatial rather than temporal recharge variability, this inaccuracy seems justified and is in line with the PUB recommendations for simplification (Seibert and Beven, 2009). While our long-term average RC values thus remain somewhat of an approximation, it can already be stated here that it appears likely that a true reflection of seasonal rainfall distribution would lead to a slight but not significant change in the overall average of multi-annual recharge coefficients.

5.3 Annual recharge coefficients: comparison with other studies

As observed by Lerner et al. (1990), recharge is a temporally highly variable process that is most adequately investigated on the event level (in the WAB a time span of 0.5 to 5 d). While the model with its daily steps fully reflects the event character during the measurement period, the generalisation of annual recharge coefficients always carries some range of uncertainty. However, as already presented, the individual recharge coefficients calculated for the different formations cropping out in Wadi Natuf ranged between a minimum of 0 % (for non-recharging aquitards like the upper Yatta formation) and a maximum of 57 % for highly permeable and intensively karstified limestone aquifers such as the Jerusalem formation (see Table 1). These overall recharge values fall well within the range usually quoted for the WAB. Table H1 in Appendix H lists the regional and other reported recharge coefficients both for annual and event-based calculations and together with the methods applied therein.

6 Conclusions

This study provided formation-specific distributed recharge coefficients in a Mediterranean karst area with a highly variable lithostratigraphy from a one-dimensional soil water balance model, relating percolation to SM saturation excess (SMSP model) applicable in comparable basins all over the world. The parsimonious forward-calculating model was restricted to key factors driving recharge with observed spatially distributed formation-specific maximum water storage capacities. The analysis was solidly grounded in intensive field measurements, and no calibration of model parameters was performed. The observed formation-specific correlation with soil depth and land form ensured the representativeness of the maximum water storage capacity over each formation and for long-term conditions of wet and dry years.

The model was based on the observed key process understanding, namely that groundwater recharge can be simplified and described as a soil saturation process in a variety of local conditions with a wide range of land features. Hereby, daily modelling steps were found to be appropriate to respond to the typically Mediterranean variability of meteorological events (storms) driving recharge. Equally, it was found that our 7 years of observation covered the entire range and variability of long-term climatic conditions (30-year maxima and minima). The model was tested by a comparison between modelled and observed soil moisture and by a temporal overlay of peak spring discharge and deep percolation events.

A follow-up study will regionalise the formation-specific recharge coefficients presented here to all formations in the entire Natuf catchment (Messerschmid et al., 2020). The gained recharge coefficients can also be used for a basin-wide distributed recharge model of the entire WAB. The methodology presented here can be applied in many of the still ungauged groundwater basins worldwide.

Appendix A

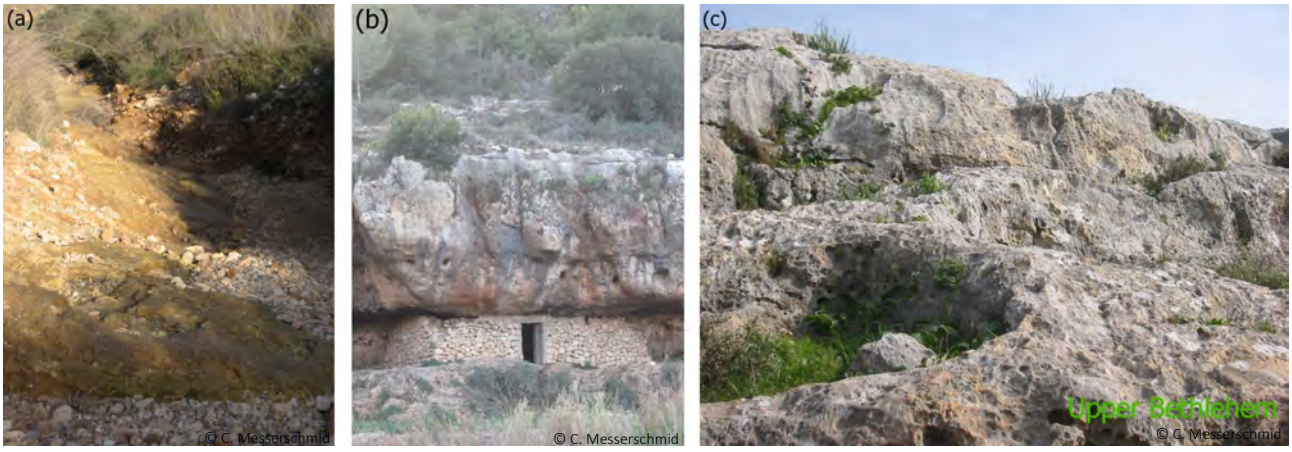

Figure A1. Formation outcrops. Rare outcrops of yellow marls, forming the main regional aquiclude (upper Yatta formation) near Ras Karkar **(a)**; reefal limestone cliff at Wadi Zarqa (u-UBK formation) with high primary porosity and the development of karst and epikarst **(b)**; karstic karren landscape (upper Bethlehem formation) with a relatively rare example of discontinuous soil cover (soil pockets) in Wadi Natuf **(c)**.

Figure A2. Soil cover. Soil covering marly limestone (bottom Hebron/top Yatta formation), with some white caliche-type "Nari" crust **(a, b, c)**; Ras Karkar soil measurement station (RK-W; lower Hebron formation) on natural terraces of thin terra rossa soil **(d)**.

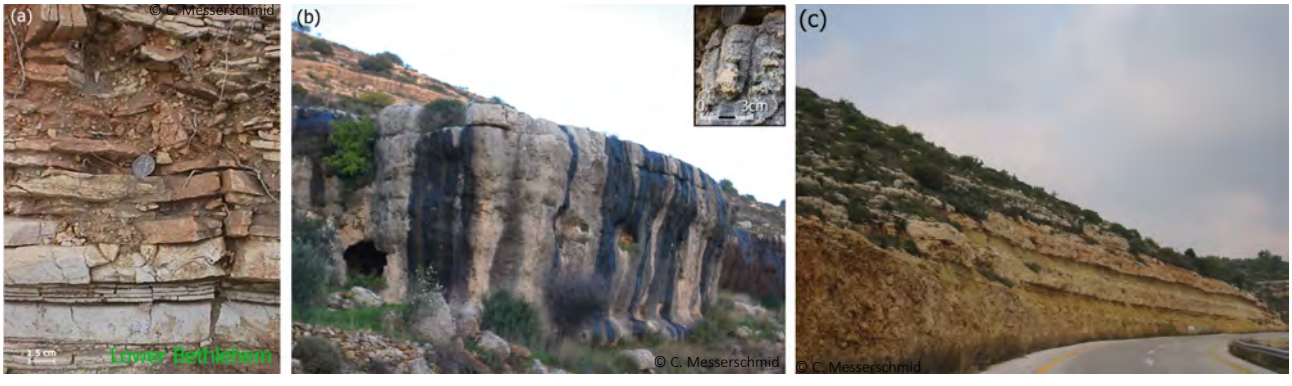

Figure A3. Lithostratigraphic formations. Colourful, thinly plated limestone of the lower Bethlehem formation (l-Bet) with a more impermeable facies of fine marl intercalations **(a)** can act as a confining layer beneath upper Bethlehem (u-Bet). Cliff-forming coral-reef limestone of the upper UBK formation at Wadi Zarqa with high primary porosity but also with signs of karstification; the inlet photo shows a 1.5 cm thick remnant of coral branches **(b)**. Twin band of soft yellow marls, located 2.5 km SE of Beitillu **(c)**; it acts as confining layer beneath the local perched aquifer at the top of the lower UBK formation (top l-UBK) and the main part of l-UBK beneath.

Appendix B

Some technical equipment and interpretation problems were encountered at three of the eight SM stations (RK-W, KF-W and WZ-upT), resulting in unreasonable measurement records or misreadings. "*Misreadings*" here is understood as a general term for strong deviations between SM_{obs} and SM_{mod} or as unreasonable measurement values, either with alleged SM contents above cumulative rain heights or apparent moisture increase during dry spells. The reasons for such deviations of SM_{obs} from SM_{mod} are manifold: first, the model could be inadequate; secondly, the interpretation of recorded field data could have been affected by additional factors; or thirdly, the measurement equipment could have malfunctioned. It seemed clear that at least when levels of SM_{obs} surpassed preceding seasonal precipitation, technical malfunctions occurred. This interpretation was strengthened by the following field observations: during summer and late autumn, before soil moisture slowly started to accumulate in the soil column, a lumpy-to-blocky aggregate structure was encountered in the silty and clayey terra rossa soils, which had dried up and shrunk during summer. These soil aggregates then formed about fist-size lumps, separated by desiccation cracks. By this, preferential flow paths were formed along these cracks, which are known to enable increased rates of rapid infiltration and soil moisture accumulation, as observed by Gimbel (2015) further north in the West Bank. The temporary presence of free water within the desiccation cracks may have caused unrealistic moisture levels if a sensor happened to cross such a crack. However, it is difficult to assess such a possibility in hindsight since the desiccation cracks are a transient soil pattern and their temporary position during measurements remained unknown. It is however important to note that such unreasonable SM readings did not occur in winter during the recharge events when the swelling soil had already closed the temporary desiccation cracks. In addition, soil samples collected by hand during the peak rainy season with independent control readings in the laboratory confirmed the validity of field readings at the automatic SM gauges. In only one instance were unrealistic SM readings also encountered during the end of the rainy season (April 2008); this was at station RK-W. Equipment failure is the most probable explanation here. However, this isolated late event happened long after the period of SM saturation and recharge and did not affect the results of the model calculations.

In addition to these conceptual interpretations, the overall reliability of SM readings was also assessed and analysed statistically. Table B1 lists the days with erroneous and questionable readings (together 147 d in four stations).

Table B2 compares the days with such misreadings to the total number of days measured and modelled, and it indicates their respective shares.

Together, the 147 d of questionable measurement records in three stations represent 8.09 % of all days recorded (147 d out of 1818 d of total SM readings) and 0.72 % of the total model period (20 456 d for the eight stations over a 7-year period).

In WZ-upT, only 6 d of error occurred (November 2005), equivalent to 2.90 % of recording days.

In KF-W, 42 d (or 14.95 %) of error occurred over the entire read-out period.

In RK-W, 55 d of error occurred in early winter 2005 and 2006 (with $SM_{obs} > P_{cumulative}$), equivalent to 8.91 % of recorded days, in addition to 44 d (7.13 %) in April 2008 (totalling 16.05 % of failed readings).

Table B3 presents the Nash–Sutcliffe efficiency coefficients for the eight SM stations. All stations (except one, RK-E) show NSE values between 0.40 and 0.96. The one station with a bad match, RK-E (with an NSE of -0.35) was excluded from further calculations; its results were not used for the analysis of annual recharge coefficients. As a result, we can state that such periods of malfunctioning soil moisture probes are extremely short and rare; therefore, modelled SM can be considered a valid representation of actual SM developments over time and for different spatial units. In addition, the quantities of additional soil water above the maximum storage capacity are fully accounted for by the daily budgets of the percolation model.

Table B1. Days with misreadings.

Soil station	Periods	No. of misread days	Sum (days)
WZ-upT	31 Oct–5 Nov 2005	6	6
KF-W	9–20 Nov 2005	12	42
	17–25 Dec 2005	+9	
	29 Oct–13 Nov 2006	+16	
	18–22 Nov 2006	+5	
RK-W	6–15 Nov 2005	10	55
	22 Nov–25 Dec 2005	+24	
	4–24 Nov 2006	+21	
		Subtotal	103
RK-W (Apr 2008)	17 Mar–29 Apr 2008	44	44
All stations		Total sum	147

Table B2. Periods and shares of days with misreadings.

Soil station	Reference period	No. of days misread	Days misread in the 7-year (2557 d) period (%)	Misread days as a share of recorded days (days (%))
WZ-upT	Without Apr 2008	6	0.23 %	207 (2.90 %)
KF-W	Without Apr 2008	42	1.64 %	281 (14.95 %)
RK-W	Without Apr 2008	55	2.15 %	617 (8.91 %)
RK-W	With Apr 2008	99	3.87 %	617 (16.05 %)*
Soil station	Reference period	No. of days with SM > P	Days misread over a total period of 7 years (20 456 d) and eight stations (%)	No. of all days read (–) and share of misread days (%)
All stations	With Apr 2008	147	0.72 %	1818 (8.09 %)
All stations	Without Apr 2008	103	0.50 %	1818 (5.67 %)
RK-W	Only Apr 2008	44	0.22 %	0617 (7.13 %)

Percentages are rounded to the second digit after the decimal point.

Table B3. NSE statistics of SM_{obs} versus SM_{mod}.

Station	NSE
BET	0.87
Shu	0.80
WZ-upT	0.63
WZ-gh	0.40
KF-W	0.79
KF-E	0.96
RK-W	0.70
RK-E	−0.35
Average of all (without RK-E)	0.73
Average of all (with RK-E)	0.60

Appendix C

Daily spring readings were carried out by hand (with a stopwatch and bucket) and by different personnel in the respective spring groups. The Beitillu spring group was fully covered for 3 years. In the first season (2003–2004), measurements started late in the season and then were read most of the days in winter and scarcely in summer. In the season 2009–2010, continuous readings continued until February 2010. The two springs at the Wadi Zarqa spring group (Salem and 'Akkari) had the same coverage as the Beitillu group in 2003–2004 and were almost uninterruptedly read from December 2005 (season 2005–2006) until February 2010. Hence, high coverage was achieved during almost six seasons in Wadi Zarqa and during nearly five seasons in Beitillu.

Table C1. Five spring data coverage.

Year	Abu Sa'efan	Bibi	Qos	Salem	'Akkari	∑ Coverage
2003–2004	**57 %**	**35 %**	**54 %**	**58 %**	**58 %**	35 %–58 %
2004–2005	**2 %**	**2 %**	**2 %**	**2 %**	**2 %**	2 %
2005–2006	**5 %**	**5 %**	**5 %**	**79 %**	**79 %**	5 % and 79 %
2006–2007	100 %	100 %	100 %	100 %	100 %	**full**
2007–2008	100 %	100 %	100 %	100 %	100 %	**full**
2008–2009	100 %	100 %	100 %	100 %	100 %	**full**
2009–2010	**42 %**	**42 %**	**42 %**	**68 %**	**68 %**	42 % and 68 %

Appendix D

Table D1. Soil depth matrix.

Hydrostratigraphy	Upper Aquifer	Yatta	Lower Aquifer
Geological formation	Heb, Bet, Jerus	u-UBK, Yatta	LBK, l-UBK
(a) Terraces			
1. Terraces with olives	*65, 40 cm*	**42, 25 cm**	**(49), 26 cm**
2. Terraces with other types cultivation	n/a	**(25)**	n/a
3. Formerly used but now uncultivated terraces	n/a	12, 47	46, 51, 22
4. Natural terracing with shrubs and grass cover	(26) *40*	10	**22, 29**
(b) Plains			
1. Arable plains with olive orchards	63, 67	***94***	26
2. Arable plains with other types of cultivation	36	**(56), 50,** ***65, 77***	40
3. Arable plains without cultivation	(58)	56	n/a
4. Rock plastered plains (karstification)	*32*	n/a	(5), 15
5. Dry plains with shrubs and grass cover	***19***	n/a	19
(c) Slopes			
1. Non-terraced slopes with olives	n/a	56	49
2. Non-terraced slopes with other types of cultivation	**58**	*50*	n/a
3. Slopes with shrubs and grass cover	**11, 26,** ***32***	*40*	**18**
4. Rock plastered slopes	*32*	n/a	**11**
(d) Pure rock cover and cliffs			

The soil thickness survey was carried out at representative locations of every outcropping formation, such as different types of vegetation, relief, land use and natural land cover. The table simplifies the results for an overview over different typical soil depths for the regional units of Upper and Lower Aquifers and the regional Middle Aquitard (with the individual formations indicated in line 2). Values that were also encountered at the SM stations are shown in italics. Main land form types are shown in bold. The values for the l-UBK formation are representative of the main body of the formation but not for the top of l-UBK (see second row, right column). Cells marked as n/a represent untypical vegetation and land form types for the respective formations. LBK: Lower Beit Kahil formation.

Appendix E

If the 7 years covered in this study (2003–2004 to 2009–2010) are to be used for calculations of multi-annual averages, they must reflect the range of long-term climatic conditions in the basin. Since no long-term climatic records are available for Wadi Natuf, the representativeness of the 7 years modelled was compared on the level of the entire WAB area. The Hydrological Service of Israel (HSI, 2016) presents records of annual area precipitation for six different sub-basins (cell groups) within the Western Aquifer Basin from north to south (Fig. E1). Wadi Natuf lies at the border between the northern and central cell group of the WAB and near the Jerusalem cell group, and it was found to be best represented by a mixture of the central, northern and Jerusalem cells of the WAB.

The period of documented precipitation records spans 44 years from 1970–1971 to 2013–2014. Only 2 years of these were drier and only 12 years were wetter than the 7 years studied here. Out of these 12 wet years, only 5 years (or 11 % of the 44 years) were wetter than the maximum in the range of the 7 years by more than 20 %. And if we allow for a 10 % margin of rainfall deviation, 82 % of all 44 years (36 of 44 years) lie within the total range.

For each cell group (north – 210, centre – 211 and Jerusalem – 212) the arithmetic mean precipitation was calculated over 44 years and over the 7-year period, respectively. Then the average of the three mean values for each cell group was formed for both the entire and the 7-year period. These values were 610 mm a^{-1} for the entire 44 years and 621 mm a^{-1} for the 7 years studied here. In other words, the 7 years were slightly wetter than the average of all 44 years (for the spatial averages of three cell groups), but this was only by 1.7 % (101.7 % of the 44-year average, marked underlined in Table E1).

When the same analysis was done for the median instead of the arithmetic mean, long-term conditions resulted in 600 mm a^{-1}, and the 7-year period had 624 mm a^{-1}. The long-term and short-term median values were also compared in each cell group independently (their averages are indicated as underlined in Table E1). Table E1 shows the two different calculation methods and the end results of the analysis together with the individual results for each cell group.

Thus, it can be shown that the 7 years of rainfall observation in Wadi Natuf cover almost the entire range of long-term annual rain distribution. Only a single year, the winter of 1991–1992 with its century rainfall, clearly lies outside the rainfall range covered by our measurement period.

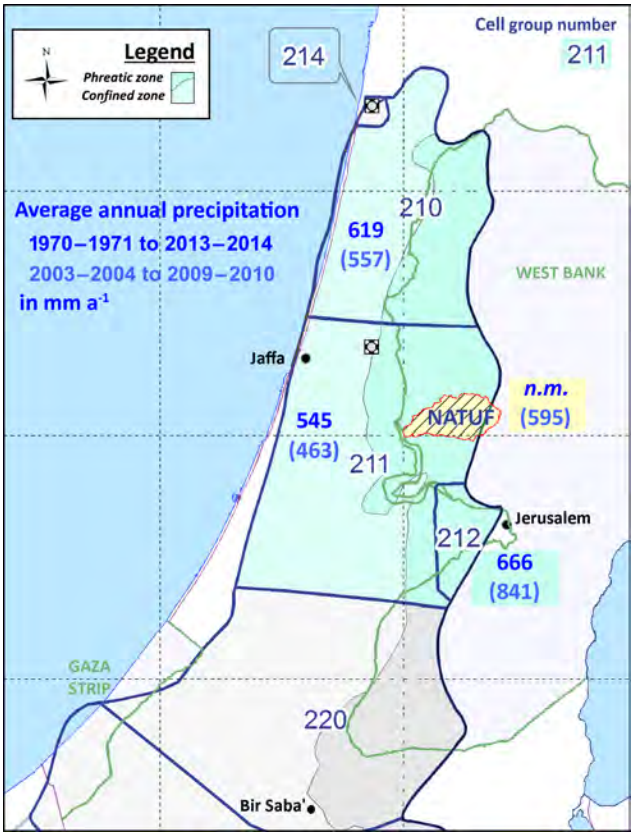

Figure E1. WAB cells of area precipitation (modified after HSI, 2016). The map indicates area precipitation for two periods: long term (1970–1971 to 2013–2014) and the 7 years of this study. Long-term area rainfall data for Wadi Natuf are not available; the 7-year period was measured by tipping buckets. Precipitation data for the three cells groups, nos. 210, 211 and 212, were taken from HSI (2016) (n.m. represents areas which were not measured.)

Table E1. Comparison of average rainfall in WAB cell groups: long term and the seven years from 2003–2004 to 2009–2010.

Cell			No. 210	No. 211	No. 212	Average of all three	
Item	Type	Period	North	Centre	Jerus	Cell groups	Item
Average of all years	Long term	1970–1971 to 2013–2014	619	545	666	610	Average of averages (all years)
Average of 7 years	7-year period	2003–2004 to 2009–2010	557	463	841	621	Average of averages (7 years)
Ratio			90.0 %	85.0 %	126.3 %	101.7 %	Ratio between averages[a]
Median of all years	Long term	1970–1971 to 2013–2014	597	504	698	600	Average of medians (all years)
Median of 7 years	7-year period	2003–2004 to 2009–2010	593	460	820	624	Average of medians (7 years)
Ratio			99.3 %	91.3 %	117.6 %	99.6 %	Average of three groups[a]

[a] The above calculation uses the average between resulting means (610 and 621 mm a^{-1}, respectively). The calculations below show the average of the ratios, formed in each cell group. WAB annual precipitation was based on data from the Hydrological Service of Israel (HSI, 2016). All rain heights are in mm a^{-1}; the ratios are percentages.

Appendix F

When signatures of peak spring flow periods were compared with those of recharge (DP), it had to be assured that the discharge of the selected daily measured springs was representative for the spring groups draining the respective aquifers. This could be affirmed by the analysis shown below. In addition to the five springs that were daily measured, all springs in Wadi Natuf were measured during four key date campaigns. The tables below show that the ratios between the discharge at the combined daily measured springs and the entire spring group discharge were very stable; their relative shares deviated only slightly, as shown by the low standard deviation values in Tables F1 and F2.

At the four key date campaigns, total spring outflow at the Beitillu spring group (Table F1) was between 61 and 110 $m^3 d^{-1}$. The three daily monitored springs combined made up 20 %–22 % of total spring group flow with a standard deviation of 1.15 %. At the four key date campaigns, the total spring outflow at the Wadi Zarqa spring group (Table F2) was between 165 and 493 $m^3 d^{-1}$. The two daily monitored springs combined made up 6.8 %–8.5 % of the total spring group flow with a standard deviation of 0.72 % (bottom right cell).

Table F1. Comparison of spring discharge (and the standard deviation) between daily measured springs and the entire Beitillu (Harat al-Wad) spring group during key date campaigns.

Spring flow ($m^3 d^{-1}$)	2003 summer	2003–2004 winter	2004 summer	2007 summer	SD
Ein Abu Sa'efan	4.1	3.8	2.0	2.0	
Ein Al-Bibi	3.0	1.6	1.4	1.3	
Ein Al-Qos	12.4	16.7	9.6	13.2	
Sum of the Beitillu spring group	98	110	61	73	
Relative share of the group flow (%)					
Ein Abu Sa'efan	4 %	3 %	3 %	3 %	
Ein Al-Bibi	3 %	1 %	2 %	2 %	
Ein Al-Qos	13 %	15 %	16 %	18 %	
Sum of the three springs	19.9 %	20.2 %	21.4 %	22.4 %	1.15 %

Table F2. Comparison of spring discharge (and the standard deviation) between daily measured springs and the entire Wadi Zarqa spring group during key date campaigns.

Spring flow ($m^3 d^{-1}$)	2003 summer	2003–2004 winter	2004 summer	2007 summer	SD
Ein Al-'Akkari 1	13	17	14	7	
Ein Salem 1 (upper)	20	25	10	4	
Sum of the Wadi Zarqa spring group	414	493	303	165	
Relative share of the group flow (%)					
Ein Al-'Akkari 1	3.1 %	3.5 %	4.5 %	4.3 %	
Ein Salem 1 (upper)	4.8 %	5.1 %	3.2 %	2.4 %	
Sum of the two springs	7.8 %	8.5 %	7.7 %	6.8 %	0.72 %

Appendix G

In most years, the variability of precipitation was reciprocal to the variability of recharge. In other words, the wetter the year was, the higher the spatial variability of rainfall was, but the lower the spatial variability of recharge was. Variability here is expressed as the standard deviation (σ) for the values of the different stations. Although a single year (2005–2006) plotted far from the trend line, the otherwise quite pronounced pattern of the diagram shows that indeed spatial variability of recharge deserves more attention than it has given so far since in the WAB, most studies focussed on temporal recharge variability. The trend is in line with general observations worldwide that basin responses in relatively dry climates are more variable than those in wet climates. A similar response pattern was observed for runoff in Messerschmid et al. (2018), where strong precipitation events triggered runoff in all areas alike, whereas weaker rainfall events showed different responses in different areas.

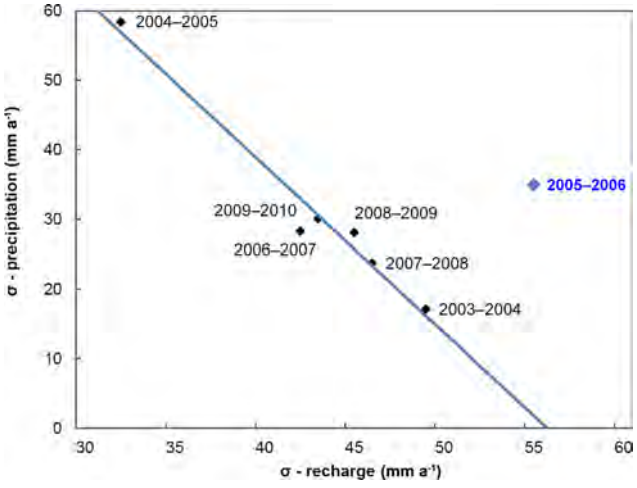

Figure G1. The axes are the scaling of standard deviations (σ) of P and DP. Note that the linear trend line excludes the year 2005–2006, which deviates from the trend of the other years. In this year, spatial variability of recharge was quite high but nonetheless, spatial variability of recharge was high as well. 2005–2006 was a special year because it had an exceptionally intensive storm event (and the strongest during the entire measurement period) very late in the season (early April 2006). The different stations were affected differently by the relatively long dry period before the event and the high precipitation during the event, depending on the soil thickness and therefore on the speed of the drying of the soils and consequent soil saturation during the event.

Appendix H

Recharge rates (in $mm\,a^{-1}$ or calculated as coefficients as a percentage) have been reported in numerous studies within the WAB and adjacent basins of the Mountain Aquifer (such as the Eastern Aquifer Basin). Table H1 presents a collection of findings in the literature from both the WAB as well as other regions of the world and from a large variety of different research methods (highly relevant studies marked in bold). The table shows that with an average area recharge coefficient between 41 % and 47 % (for the WAB portion of Wadi Natuf; see Messerschmid et al., 2020), and with RC values between 30 % and 57 % for the individual aquiferous formations (not the aquitards), the findings of the model match very well with the ranges from the literature. While the lowest figures reported only 9 %–40 % of RC, the highest figures reached over 50 % and up to 60 % of recharge coefficients (in the Mt Carmel basin with a very similar geology and climate as in Wadi Natuf). For a small groundwater catchment overlapping with the Wadi Natuf surface catchment, Weiss and Gvirtzman (2007) found a long-term average of 47 % (see note below Table H1). Both the temporal and spatial variability of reported values are impressive (temporal variability can be detected by comparing the average with maximum RC values; spatial variability emerges from the differences between different basins and sub-basins both within and outside the WAB). In this respect, Wadi Natuf is highly representative of many basins with similar climatic, geological, soil type and landscape conditions.

Table H1. Recharge coefficients in the literature. Models included in the figure are the following. The MOSST model incorporates climate change scenarios and simulates spring outflow of a karstic spring using an ensemble of five lumped hydrological models that consider karst hydrological processes in various ways and complexities (see Hartmann et al., 2012c). "TRAIN-ZIN is a hydrological model that has been developed for simulating hydrological processes and water balances in semi-arid and arid areas and combines conceptual and physically-based approaches." (Gunkel and Lange, 2016) TRAIN (TRAnspiration and INterception) describes the vertical flow, and ZIN describes the horizontal flow (Menzel, 2011).

Author (year)	Average	Maximum	Area	Time	Approach	Manner	Method	Miscellaneous
Sheffer et al. (2010)	9 %–40 %	(52 %)	Mountain aquifer	Annual	SM model	Calibrated numerical water budget model	Daily soil saturation	Non-empirically assumed field capacity (low) and soil thickness (high)
Gunkel et al. (2015)	30 %	–	Mountain aquifer	Annual	Model	Distributed, field-based water balance model	TRAIN-ZIN, MOSST	EAB, Wadi Fari'a and Jordan Valley, 6-year measurement period, event-based
Sanz et al. (2011)	34.3 %	34.3 %	Spain	Annual	Lithology	Clay (1.3 %); silt (3.3 %); limestone and dolomite 34.4 %	Large areas, soil moisture deficit	As a factor of lithology and hydrologically effective precipitation
Cheng et al. (2017)	–	42 %	China	Event	Soil	Maximum annual of 32.4 %	> 2 m thick soils	In one event
Bradford et al. (2002)	39-45 %	45 %	UK chalk	Annual	Models	With input data at varying spatial resolutions	Soil moisture and precipitation	UK chalk, 4 years; SM deficit and hydrologically effective precipitation
Nativ et al. (1995)	8 %–55 %	–	Northern Negev	Annual	Bromide	In boreholes in fractured chalk	Bromide profiles	Arid desert climate (P of 200 mm a^{-1})
Abusaada (2011)	36 %	53.2 %	Mountain aquifer	Annual	Flow model	WAB basin-wide water budget	Three-dimensional flow model	Maximum recharge in 2003/04
Dvory et al. (2016)	34 %	54.3 %	Mountain aquifer	Annual	Model	One-dimensional dual porosity model (linear)	Based on rock properties, karst	Local, west of Jerusalem, spatial litho-based differences (absolute maxima of 73.7 %)
Schmidt et al. (2014)	25 %–50 %	55 %	Mountain aquifer	Annual	SM model	Rain and ET_p (spring flow) data	Model, spring response	EAB at Auja spring (spatially distributed): soil moisture deficit and groundwater model
Sheffer et al. (2010)	20 %–60 %	–	Mountain aquifer	Annual	Formula	Guttman and Zukerman (1995), Guttman et al. (1988), and literature quotes on WAB-RC	Single-cell flow model	Calibrated numerical annual water budget (non-empirical) and linear equation
Ries et al. (2015)	33 %	66 %	Mountain aquifer	Annual	Model	Maximum in wet years (average in Aujah)	SM model, budget	EAB (mountains and slopes)
Guttman et al. (1988)	30.6 %	75.3 %	Mountain aquifer	Annual	Model	WAB basin-wide water budget	Quasi-three-dimensional flow model	Maximum recharge in 1991–1992 (single-cell water balance model of the coastal plain only)

Table H1. Continued.

Author (year)	Average	Maximum	Area	Time	Approach	Manner	Method	Miscellaneous
Weiss and Gvirtzman (2007)	6 %–65 %	–	Mountain aquifer	Annual	Formula	Guttman (2000), Guttman and Zuckerman (1995)	Quasi-three-dimensional flow model	Applying the Guttman formula to four spring areas, one of which overlaps with Wadi Natuf
Radulović et al. (2011)	66.3 %–76.2 %	76.2 %	Montenegro	Annual	Combination	Water budget and other methods (Montenegro)	Ranking system and matrix	Karst, lithology, structure, landform, runoff, plants, climate, soil and slope (spatially distributed)
Allocca et al. (2014)	50 %–79 %	79 %	Southern Italy	Annual	Lithology	Precipitation and air temperature	Empirical model and linear regression	Correlated with other factors: karst outcrops, morphology, land use and soil type
Goldscheider and Drew (2007)	–	> 80 %	–	Event	Literature	Bare karstified limestones	–	Summary from the literature for spatially distributed recharge
Weiss and Gvirtzman (2007)[a]	< 10 %–> 80 %	91 %	Mountain aquifer	Annual	Lithology	Maximum in 1988 at the l-LBK formation	Model, budget and spring response	28-year average RC of 47.2 % at the Ein Al-Harrasheh spring groundwater catchment
Allocca et al. (2015)	35 %–97 %	97 %	Apennines	Event	Model	Storm by storm, Apennines	Air temperature, ET and rain	
Shachori et al. (1965)	47 %	–	Mountain aquifer	Annual	–	Mt Carmel average (undifferentiated)	–	
Mero (1958)	53 %	–	Mountain aquifer	Annual	Literature	Na'aman spring	–	Quoted after Lerner et al. (1990) for spatially distributed recharge
Rosenzweig (1972)	60 %	–	Mountain aquifer	Annual	Landform	Mt Carmel average (by landform)	Annual on pasture and grassland	While at forest 0 %
This study	40.8 %–47.3 %		Mountain aquifer	Annual	SM model	Different formations with typical soil depths	Saturation excess percolation	Spatially distributed recharge for the WAB in Wadi Natuf (by geology, soil and LU/LC)

[a] For the groundwater catchment of the Ein Al-Harrasheh spring, which overlaps with the Natuf surface catchment, Weiss and Gvirtzman (2007) reported a 28-year average recharge coefficient of 47.2 %.

Data availability. The geological map data can be downloaded as image files from https://www.gov.il/he/departments/general/map-1-50000 (last access: 29 January 2020). The GIS vector files for the geological map data were provided by the GSI upon request. Areal rainfall and soil moisture time series data are partly archived at the database of the author and of the SUSMAQ project follow-up organisation HWE (http://hwe.org.ps/, last access: 29 January 2020). It is required to obtain the data from either of these organisations or authors, and it is not possible to make the data publicly available. Field sampling and measurements were undertaken by the SUSMAQ project and the lead author. Selected data can be requested from the author or SUSMAQ follow-up organisation HWE. Selected AWS data inputs and outputs are archived at the lead author; HWE and PWA and can be made available upon request at PWA (http://www.pwa.ps/page.aspx?id=5W6F7La2541180510a5W6F7L, last access: 29 January 2020). ET_p data for the Jerusalem station can be requested from the Israel Meteorological Service (http://www.ims.gov.il/en, last access: 29 January 2020) or downloaded from https://eca.knmi.nl/ (last access: 29 January 2020). A full set of data is available upon request to the lead author (clemensmesserschmid@yahoo.de).

Author contributions. CM undertook all practical elements of this study, including field observation and selection, purchase, instrumentation, and the reading out of measurements. CM also performed the site selection and conceptual approach. CM carried out all calculations, analysis and modelling. CM produced all graphs and figures, maps, tables, and diagrams. CM wrote the original draft. JL and MS reviewed and edited the draft.

Competing interests. The authors declare that they have no conflict of interest.

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Regionalization of distributed groundwater recharge and leakage calculations in a Mediterranean karst catchment, Wadi Natuf, West Bank

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Abstract. Under Spatial distribution of groundwater recharge so far has been paid relatively little attention and rarely been quantified, especially in ungauged basins. This study for the first time details spatially distributed recharge on the catchment scale in a hitherto ungauged basin. It is the second part of a recharge study that presented field-based measurements and parsimonious modelling of deep percolation in the form of soil moisture saturation excess with formation-specific recharge at 8 soil moisture stations and 5 formations in Wadi Natuf, a semi-arid to sub-humid karstic watershed in the Palestinian West Bank (Messerschmid *et al.*, 2019). The regionalisation in this paper was developed through a conceptual basin classification framework that differentiated between three groups of physical basin features (form), e.g. geology, soil and land use/land cover (LU/LC) and whose basin responses (function) were therefore assigned different classes of recharge potential. Our approach combined field-based, empirical (inductive) with extrapolative (deductive) approaches, as recommended by many authors of the research decade on the hydrological Prediction in Ungauged Basins (PUB), led by the International Association of Hydrological Sciences (IAHS). Maximum formation-specific recharge coefficients (RC) were found in strongly karstified formations with 57 % of annual precipitation, minimum values with 42 % in bedded limestones with high contents of marl or chalk. Aquitards of pure clay, marl or chalk showed no recharge. The separate assignment of different recharge classes for each of the three groups of physical features led to slightly divergent recharge results at the overall catchment scale of Wadi Natuf (103 km^2). Average annual recharge was found to reach 24, 27 and 28 mcm/a, or 39, 44 and 46 % of average annual precipitation for the three different groups (geology, soil and LU/LC), respectively.

Due to the particular configuration of isolated hillside aquifers with well controllable boundary conditions of inflows and outflows, it was possible to calculate leakage in three local, perched aquifers. The water budget calculations in these three leaky aquifers drew on the regionalised formation-specific RC-values and on a field survey of total spring group discharge for each of the perched hillside aquifers, resulting in high leakage rates between 65 % and 89 % of annual recharge. The results of formation-specific RC-values are applicable to other catchments in the Western Aquifer Basin; our approach of regionalisation by setting up a schematic conceptual basin classification framework is applicable in many comparable sedimentary basins in the Mediterranean and worldwide.

Keywords. Distributed recharge, classification framework, regionalisation PUB, landscape features, perched aquifers, groundwater leakage

1 Introduction

The assessment and regionalisation of distributed groundwater recharge poses a challenge to hydrologists, particularly in basins with scarce data. Even in well developed and investigated basins, the governing processes of recharge and its spatial distribution often remain poorly understood (Hartmann *et al.*, 2012) or restricted to the local and plot-scale experiments; this is particularly true for karstic aquifers with their diverse and complicated inhomogeneous and anisotropic flow fields (Schmidt *et al.*, 2014 and Geyer *et al.*, 2008). Yet, regionalizing local findings of distributed recharge to wider areas and entire catchments is crucial, not only for developing correct budgeting of inflows on the basin or local scale, but also for sustainable groundwater management, protection and equitable allocation among riparians.

1.1 Background on distributed recharge methods in regional flow systems

Several factors pose a challenge to the estimation of spatially distributed recharge, such as the need for reliable field data or the correct conceptual representation of the aquifer and its flow and recharge processes (Goldscheider & Drew, 2007; Scanlon *et al.*, 2006). Important physical landscape features are often spatially highly variable and localised in nature and therefore difficult to control. Yet, they shape the overlapping processes of groundwater recharge (Batelaan and De Smedt, 2001; Beven and Kirkby, 1979). Most studies of regional recharge therefore resort to lumped aquifer budgeting of observable inflows and outflows (e.g. wells and springs). However, in many of the scarcely gauged basins around the world, such possibilities are missing and are inapplicable for the sub-catchments of large groundwater basins with their lateral groundwater flow connections to neighbouring sub-catchments within the same basin. In addition and as discussed in Messerschmid *et al.*, (2019), where observations of surface water and of the saturated, deeply buried zone of the aquifer are not available, Scanlon *et al.* (2006) recommend a third group of recharge estimation methods which are based on observations within the unsaturated zone (where available within the bedrock or otherwise in the soil cover).

The problems with the regionalisation of distributed recharge are further exacerbated in deeply buried karstic aquifers, known for their non-Darcian flows and anisotropic natural flow fields, which often are further altered and disturbed by human intervention, e.g. well abstractions. In such basins, even a well-controlled basin response based on lumped outflows in the often strongly confined downstream area often does not truly reflect upstream variability in unconfined and outcropping areas, where recharge takes place. This is especially the case in settings where several sub-units are stacked and hydraulically interconnected in one uniformly acting regional aquifer in the downstream abstraction zone, with low gradients and excessive pumping, as Dafny (2009) and Dafny *et al.* (2010) have shown for the Western Aquifer Basin (see also Hartmann *et al.*, 2012; Guttman & Zukerman, 1995 and Abusaada, 2011). Last not least, with respect to spatially distributed recharge from different hydrogeological units, the concept of budgeting in- and outflows only functions correctly when no downward leakage has to be accounted for. This process, however, is often beyond the reach of observations and measurements, particularly in poorly or entirely ungauged basins around the world.

1.2 Approaches to spatial variability in ungauged basins (results of PUB)

The following specifications of approaches to spatial variability will draw on the main lessons and findings of the decade on Predictions in Ungauged Basins (PUB), lead by the International Association of Hydrological Sciences (IAHS). Many authors of the PUB-literature both observed and recommended a shift away from lumped and integrated models and towards distributed models that differentiate hydrological processes, such as soil saturation, runoff or recharge, together with their drivers, e.g. precipitation, evapotranspiration, etc. (Batelaan and de Smedt, 2001, 2007; Hrachowitz *et al.*, 2013 and Sivakumar *et al.*, 2013). This requires a shift from so-called indirect to direct research approaches (Dörhöfer and Jesopait, 1997; Lerner *et al.*, 1990), as discussed in Messerschmid *et al.* (2019).

In order to differentiate and quantify the spatially distributed processes or to identify organizing principles and to formulate a unified theory, research should start with a synthesis of data, process understanding and the link between catchment form and function (Hrachowitz *et al.*, 2013). This can be done by setting up so-called catchment classification and similarity frameworks that relate observable landscape elements to hydrological diversity (Berne *et al.,* 2005) and are based on similarities of hydrological function (McDonnell and Woods, 2004). Sivapalan *et al.* (2003a) summarize that such predictive systems should contain three components – (1) a model that describes key processes, (2) climatic input with the meteorological drivers of basin response and (3) parameters of landscape properties that govern these processes. In other words, basin classification frameworks differentiate, describe and, where possible, quantify the observable physical landscape features, both underground (using geology) and above surface (using soil cover or land use and land cover, LU/LC) and relate them to each other. For their part, Sivakumar *et al.* (2013) offer a three-step procedure for an effective formulation and verification of a catchment classification framework: (1) the detection of possible patterns in hydrologic data and determination of complexity and connectivity levels; (2) the classification into groups and

subgroups based on data patterns, system complexity and connections; and (3) the verification of the classification framework.

1.3 Physical landscape characteristics

According to Franchini and Pacciani (1991), hydrological models should have a complete and physically realistic representation of dominant processes to ensure that parameters are well constrained, thus combining highly location-specific empirical work conceptual efforts, like the correct differentiation of different groups of landscape features that rule the recharge process. Hrachowitz *et al.* (2013) detailed the diverse selections of parameter sets representing catchment characteristics; most studies differentiate between three principal groups of spatial parameters governing recharge (and use one or two of them): Geology and lithology as first group, were used by Sanz *et al*. (2011) in their highly simplified approach over large areas in Spain, accounting (besides meteorological drivers) for ten classes of lithology from clastics and carbonates to pelites and hard rock. The second, most widely used category of soil characteristics is often combined with other parameter groups, such as land use and lithology (Batelaan and de Smedt, 2001). Batelaan and de Smedt (2007) added land use and topography (based on literature values), but not geology. Aish, Batelaan and de Smedt (2010) combined land use and soil-type as physical parameters for their groundwater and recharge model of the Gaza strip, together with meteorological and water level data. By contrast, Zomlot et al. (2015) emphasised the importance of soil texture and vegetation cover. The third group, landscape features, includes topography, vegetation and land use, sometimes combined to so-called land forms or more narrowly restricted to land use and land cover characteristics (LU/LC) (Aish, Batelaan and de Smedt, 2010). Vegetation was used by Sarrazin *et al.* (2018), who tried to avoid data intensive models and developed a large scale parsimonious integrated recharge model for karstic aquifers. By contrast, Radulovič *et al*. (2011) used a great number of distributed physical parameters from all three groups, including geology, karst and structural features but also topography, vegetation and land use. However, their parameters for groundwater recharge in Montenegro were not measured and quantified in the field but conceptually set up and weighted as dimensionless numbers in a matrix of factors, which then were employed as variables in a basin-wide transfer function between spatial characteristics and hydrological response.

In ungauged basins, where information on hydrological basin responses and other functional similarities are missing, physical parameters can be regionalised by using physiographic similarity as a proxy (Arheimer and Brandt 1998, Parajka *et al.* 2005, Dornes *et al.* 2008, Masih *et al.* 2010). However, the correct linkage and translation of point- and plot-scale observations into regionalised findings on the catchment scale often remains a crucial challenge (Hartmann *et al.*, 2013). Seibert (1999) developed relationships between the calibrated model parameters and the physical catchment characteristics of landscape found in the field (like soil, lakes and forest). Seibert and Beven (2009) statistically ranked 10.000 parameter sets according to their performance and selected the best 100 sets for further analysis. Yet, PUB emphasised that regionalisation of observable spatial parameters remains connected to the empirical efforts of field observation and measurements (employing maps, aerial photography, satellite imagery and of course field visits). This article is therefore based on the recharge measurements and modelling in Messerschmid *et al.* (2019).

By contrast to recharge, estimation of groundwater leakage is even further inhibited, as the direct approaches of Dörhöfer and Jesopait (1997) that base on surface observations usually cannot be applied; groundwater leakage in most cases can only be approached through insights into the saturated zone of an aquifer. In the absence of subsurface observation, only water budget approaches of the different hydraulically connected aquifer units apply, and only if in addition, the individual water budgets, the recharge and discharge areas and the boundary conditions of each aquifer unit can be determined with sufficient accuracy.

1.4 Physical basin form and hydrological function (system signatures)

The translation of physical basin form into hydrological function is crucial and challenging, since it involves two discrete conceptual levels and an extraordinary complexity of interactions, which always require an element of deduction, attribution or extrapolation. While physical features (whether metric or unquantifiable) can serve as a physical basis and therefore as indicators of basin impact

(i.e. the function of the basin), they are far from being uniquely correlated to each other (Beven, 2000; Oudin *et al.*, 2010). Importantly, the scale at which the entire complexity of distributed recharge processes and their interactions is fully at play, is the catchment scale (Hrachowitz *et al.*, 2013), and therefore McDonnell *et al.* (2007) emphasise that it is the correct scale for the investigation of hydrological processes in general and of recharge in particular. Many studies suggested the use of physiographic similarity as a proxy for functional similarity (Arheimer and Brandt 1998, Parajka *et al.*, 2005, Dornes *et al.*, 2008, Masih *et al.*, 2010), thus regionalising dynamic catchment response characteristics (such as runoff or recharge) based on physical characteristics (Yadav *et al.*, 2007). This approach can be aided by the use of so-called hydrological system signatures to create a link between physical features and basin response and to describe emergent properties of a system (Eder *et al.*, 2003; Hartmann *et al.*, 2013). Such signatures, e.g. temporal patterns of low and peak discharge, flow duration curves or spring hydrographs, can be employed quantitatively, e.g. for the calibration of models (Hingray *et al.*, 2010), or qualitatively, as indicators of basin response (see Messerschmid *et al.*, 2019; Sivapalan *et al.*, 2003b and Winsemius *et al.*, 2009). In ungauged catchments, signatures can serve for the regionalisation of plot-scale findings into basin-wide overall processes (e.g. Castellarin *et al.*, 2004; Bulygina *et al.*, 2009 and Pallard *et al.*, 2009), or be used to test and investigate modelling results (see Messerschmid *et al.*, 2019). Yadav *et al.* (2007) extrapolated flow metrics to constrain model parameterizations at ungauged sites, thereby avoiding problems of structural and parameter calibration errors in models. In order to determine the limits of validity and acceptability of specific signatures, Winsemius *et al.* (2009) suggested the use of combinations of quantitative and qualitative information from the local or basin scale. And Sawicz *et al.* (2011) used available hydrological information on generally available physical descriptors in 280 catchments in the Eastern USA to create a first order grouping and clustering of catchments, based on their hydrological similarities of observable basin responses such as runoff behaviour. Conceptually, they developed a simple cooking recipe for regionalisation consisting of three steps: (1) classification (to give names), (2) regionalisation (to transfer information), and (3) generalization (to develop new theory), or in brief terms: name it, attribute it, theorize it (Sawicz *et al.*, 2011).

Sivapalan *et al.* (2003a) stated that in ungauged basins predictive systems must be inferred from direct field observation of dominant processes and empirically derived field parameters. They must be firmly based on local knowledge of the observable landscape (and climate) controls of hydrological processes (see also Messerschmid *et al.*, 2019). On the other hand, McDonnell *et al.* (2007) argued that any mapping or characterization of landscape heterogeneity and process complexity must be driven by a desire to generalize and extrapolate observations from one place to another, or across multiple scales. A certain degree of extrapolation is therefore inevitable when attributing physical features and feature ensembles to processes and basin responses (or from the observed to another location). This therefore involves deductive steps. But the need for direct observation remains. PUB theory therefore postulates the imperative of a combination, or better the integration of inductive (experimental and empirical) and deductive approaches in regionalisation (Pomeroy, 2011).

1.5 Western Aquifer Basin – overview and existing recharge studies

Details of the characteristics of the Western Aquifer Basin (WAB) were described in Messerschmid *et al.* (2019). The WAB is an up to 1000 m thick Upper Cretaceous carbonatic karst aquifer (SUSMAQ, 2002) and conventionally divided into two regional aquifer layers (Fig. 1) – an Upper Aquifer (UA) of Turonian to Cenomanian age and a Lower Aquifer (LA) of Upper Albian age, (see Fig. 2a in Messerschmid *et al.*, 2019). However, this simplified regional hydrostratigraphy applies only to the Coastal Plain downstream, with its productive abstraction and discharge zone, where the fully confined aquifer acts uniformly and with a low hydraulic gradient (Dafny *et al.*, 2010); see Table 1, section 2. On a local scale, especially in the phreatic zone upstream, the hydrostratigraphy is far more complex than the above mentioned bipartite division into Upper and Lower Aquifers. In addition, some of these local aquifer units exchange groundwater through downward leakage, as discussed later. Importantly, whereas the productive Coastal Plain is well developed, monitored and gauged through hundreds of Israeli deep wells, the WAB recharge and accumulation zones in the mountains, slopes and foothills of the West Bank, remain almost untouched, ungauged and unexplored. Wadi Natuf, the study area of this

paper, lies almost entirely within the aquifer's recharge zone, with only the most downstream western portion bordering on the productive abstraction zone in the coastal plain (Fig. 1) and with one single abstraction well not far from the western catchment boundary.

So far, only a few authors have attempted the analysis of fully distributed recharge in the WAB (Hughes *et al.*, 2008) and no previous study was based on empirical field evidence, measurements and observations. Sheffer (2009) introduced a semi-distributed, partially lumped recharge model, however with a very coarse lithological differentiation into merely two types of rock, either permeable or less permeable. In addition, Sheffer (2009) took his soil model parameters from the general literature and later adjusted them by calibration. In his own words, he focussed and aimed at '*the understanding of temporal influence on recharge processes'*, rather than on understanding spatial influences (Sheffer *et al.*, 2010; Sheffer, 2009).

During the last two decades, other studies of field-based and empirical investigations on sub-catchment, local and plot-scales were conducted, however mostly without further regionalisation efforts. Chloride mass balance calculations were carried out in the adjacent Eastern Aquifer Basin (EAB) (Marei *et al.*, 2010; Schmidt *et al.*, 2013) and in the central WAB (Jebreen *et al.*, 2018) but contributed little to the spatial differentiation of distributed recharge processes.

1.6 Leakage studies in the WAB

On the slightly smaller scale of individual hillsides (<3 km^2), two studies stand out performing water budget calculations of perched aquifers on isolated hillsides with a well-controlled recharge area and relatively controlled spring outflows (Peleg and Gvirtzman, 2010 and Weiss and Gvirtzman, 2007). These studies also performed calculations on groundwater leakage, which so far in the WAB has been given little attention. These studies followed an indirect approach and calculated deep percolation rates through rainfall-spring discharge relationships as indicator of (strictly localised) groundwater recharge. They reconstructed spring outflow and recession curves and evaluated the hydrological characteristics of the different litho-types and formations mathematically through flow models. Their modelling concept was based on a large number of somewhat problematic assumptions. First, the aquifers that were treated as "perched" in these studies are in fact the main regional and hydraulically well connected aquifers. Secondly, the water movement as downward leakage was not empirically approached and tested through field observation but only assumed as spring leakage coefficient, which was then refitted by repeated calibration. Thirdly, the leakage and transfer rates were not approached through empirical input; rather, the studies simply calibrated each parameter manually through "trial and error" and through numerously repeated model test runs (Peleg and Gvirtzman, 2010). In Weiss and Gvirtzman (2007), the model configuration is set-up without a bottom aquitard beneath the perched groundwater body and instead, the next phreatic aquifer layer below the perched aquifer is "treated as if it is saturated", which clearly does not correspond to the actual field conditions of perched aquifers in the West Bank. In addition, the studies depended on an incomplete historic set of, at best, monthly spring flow measurements and of only a few selected key springs of the hillside catchments. At the level of monthly readings, the event character of recharge, which is controlled by brief, individual storm periods of a few days duration at a time, could not be addressed appropriately. In addition, the sole measured spring, documented in the study, had to be taken as a proper representation of total hillside discharge without further empirical proof. Despite these deficiencies, it is however important to note that these studies stand out as the only ones of their kind in the WAB that at least attempted to quantify leakage, an otherwise particularly elusive factor in most catchments worldwide. Also outside the WAB, leakage remains poorly understood. In the Eastern Aquifer, Ben-Itzhak & Gvirtzman (2005) integrated leakage between Upper and Lower Aquifer into their flow model. And only Frumkin and Gvirtzman (2006) presented empirical and field-work based results on leakage, however for a highly exceptional case of a cross-formational groundwater rise within a geothermal artesian karstic saline anomaly of the WAB.

1.7 Research gaps

Assessment and regionalisation of spatially distributed recharge that is anchored in field observation and measurements, understanding and classification of physical parameters and that is

performed at the catchment scale, remains a gap to be filled. In the WAB, this gap can be summarized as follows. While studies of lumped basin-wide replenishment are widely available, distributed recharge quantification has hardly been attempted and was never based on field-based approaches, observations of physical form and direct measurements of the controlling and spatially variable parameters that rule the recharge process (even less so studies on groundwater leakage). Some empirical point scale studies on recharge have been carried out, albeit without further regionalisation efforts, which is important, as Martínez-Santos and Andreu (2010) pointed out. However, as Sivapalan *et al.* (2003a) emphasise, beyond the empirical requirements of local measurements and recharge modelling, regionalisation approaches should also be grounded in physical observations of basin form, and, if possible, hydrological basin response. On the other hand, Hrachowitz *et al.*, (2013) assert that the regionalisation of the observed and modelled field results will have to include at least some measure of extrapolation and deduction. In order to guide the extrapolation of local recharge into regionalised basin recharge, this procedure should be grounded on and adapted to a basin classification framework. Currently, no such recharge classification framework exists in the WAB.

1.8 Aims and motivation – our study

This recharge assessment in Wadi Natuf presents a novel combination of existing techniques (based on observable processes, parameters and signatures) that adheres to the goal of parsimony and that integrates inductive and deductive steps in order to advance the crucial but challenging task of a realistic representation of distributed recharge. Whereas the previous paper (Messerschmid *et al.*, 2019) was firmly grounded in field observation, measurements and a forward-calculating location-specific model, this current paper extends the findings of the local models in a regionalisation effort to the entire surface catchment area of 103 km^2.

Whereas the objective of Messerschmid *et al.*, 2019 was to investigate spatially distributed recharge in eight specific soil moisture stations and set them up as average annual recharge coefficients, this study undertakes to apply and attribute these findings to the yet unmeasured and un-modelled formations in Wadi Natuf – in other words, to generate formation-specific recharge coefficients for every formation in Wadi Natuf. The procedure consists of two main steps and an additional third step: In a first step, we set up a recharge classification framework for this largely ungauged basin, based on field observations and on basin framework conceptualisation and classification; physical features were divided into groups and recharge classes were attributed in each group. In the second step, we extrapolated the model results, i.e., the location-specific recharge coefficients (RC) of Messerschmid *et al.* (2019) along the previously established grouping and classification scheme. This extrapolation and attribution of the modelled recharge coefficients was based on the understanding of dominant physical parameters and processes. Thirdly and as a by-product, the study also applied the regionalised recharge findings in the local, hydraulically separated perched aquifers on isolated hillsides in central Wadi Natuf. For this, we applied a simple but robust water budget calculation to the local perched aquifers, based on the measured and calculated spring group discharges of each aquifer and resulting in estimates for the annual average groundwater leakage coefficient of the concerned formations.

2 Study area

The 103 km^2 large catchment of Wadi Natuf lies on the western flanks of the West Bank between the Mountain crest in the east and the 1949 Armistice Line ('Green Line') in the west. Much of its topography is characterized by undulating hills with deeply incised ephemeral rivers (Wadis). The catchment is characterised by large spatial variability of climatic drivers (precipitation, evaporation), land use and land cover features (LU/LC), soil thickness and not least, rock lithology of the different geological (litho-stratigraphical) formations (see Fig. 2a in Messerschmid *et al.*, 2019).

2.1 Geology and hydrogeology

One of the reasons for choosing Wadi Natuf as an exemplary sub-catchment on the recharge zone of the Western Aquifer Basin (WAB), besides field accessibility, was the unrivalled litho-stratigraphic diversity, reaching from the deepest outcropping, Aptian formations, all the way up to the top cover series of impermeable chalks from Senonian (and Lower Tertiary) age. All formations of the WAB

are covered in this study (Fig. 2b in Messerschmid *et al.*, 2019). The axis of the West Bank mountain anticlinorium runs approximately 3 km east of the main hydrological divide and structurally divides the thick Cretaceous aquifer complex of the West Bank Group (in Israel: Judea Group) into an Eastern Mountain Aquifer Basin (EAB) portion at the Central Mountain crest (up to 816 m above sea level) and a Western Aquifer Basin (WAB) portion, located mostly on the slopes and foothills of Wadi Natuf (down to 138 m above sea level). The WAB extends from Mount Carmel in the North to the Sinai in the South and from the West Bank Mountains in the East to the Mediterranean Sea in the West (Fig. 1).

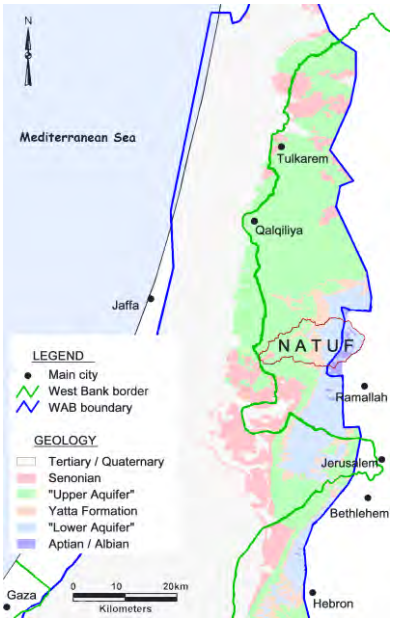

Figure 1. Schematic overview map of the regional Lower and Upper aquifer outcrops in Wadi Natuf and the WAB; modified after Messerschmid *et al.* (2003a).

The formations in the WAB portion generally dip westwards, but since the inclination of strata is steeper than the surface gradient, the series plunge towards the west and are successively overlain by younger series as one follows down the slopes (see also cross section in Fig. 2b in Messerschmid *et al.*, 2019). Conventionally, the WAB is subdivided into two main regional aquifer units – the 'Lower Aquifer' of Lower Albian age with the Lower and Upper Beit Kahil formations (LBK, UBK) and the 'Upper Aquifer' of Upper Cenomanian to Turonian age, with the Hebron, Betlehem and Jerusalem formations (Heb, Bet, Jer). Together, these aquifers cover around two thirds (64.4 %) of the outcrop areas in Wadi Natuf. The aquifers are entirely carbonatic and in most parts strongly karstified.

According to this conventional view – valid on the regional scale – they are divided by some 100 to 150 m thick marly, chalky and carbonatic series of the so-called 'Middle Aquitard' or Yatta formation (Bartov *et al.,* 1981; SUSMAQ, 2002; Messerschmid *et al.,* 2003a, 2003b; ESCWA–BGR, 2013). The regional geology is indicated in the land use and geology map, Fig. 2 (for a detailed geological map, compare with Messerschmid *et al.*, 2019, Fig. 2b). However, closer scrutiny reveals that this regional 'Middle Aquitard' can be further subdivided. The top forms an aquitard or even aquiclude section of impermeable yellow soft marl (upper Yatta, u-Yat). By contrast, the main (lower) part of this 'regional aquitard' is more carbonatic and in parts karstified, however complemented by smaller portions of chalk, marl and chert. These somewhat marly and chalky limestones and dolomites of lower Yatta formation (l-Yat) thus form an intermediate perched aquifer horizon that drains through small local springs.

Also the regional 'Lower Aquifer' (LBK & UBK) must be differentiated on the local scale into more aquiferous and more permeable parts (Table 1). Its top is formed by the conspicuous cliff-forming and very permeable reefal limestone of upper UBK (u-UBK), that also acts as a leaky perched aquifer on the local scale (such as in Wadi Zarqa). By contrast, the lower UBK formation (l-UBK) mostly consists of banked, often chalky dolomites (again with intercalations of marl and chert) with a relatively poor aquifer potential. Its top however was found to be more carbonatic but underlain by a twin marl band (Fig. 3c), which hydraulically separates the top from the main, lower part of l-UBK and above which local contact springs align. This top of l-UBK acts as third local and isolated perched aquifer horizon. It should be noted here that the confining layer underlying the reefal limestone of u-UBK is not a pure marl, but only a somewhat more marly limestone, and therefore the second and third perched aquifers locally my also form a combined perched aquifer (section 5.3). This detailed local situation is usually indicated by the location and alignment of the springs that drain the isolated perched aquifers (further discussion of the spring groups under sections, 4.3, 4.4). The three perched aquifers are all bound to the isolated hilltops of central Wadi Natuf, where they drain through small contact springs (Fetter, 1994).

The regional 'Upper Aquifer' is void of perched aquifers although it too contains formations with thin marl intercalations that reduce their

permeability, such as the colourful plated limestone series of lower Betlehem formation (l-Bet). The outcrops of l-Bet formation are often covered by small forests, because due to the thin marl intercalations, thicker soils develop there (e.g. the forested hilltop in Fig. 3a).

We can thus summarize that almost the entire Upper Aquifer and most of the Lower Aquifer outcrops in the recharge area are void of springs. Only in the intermediate aquifers of the central study area do deeply incised Wadis erode and often completely isolate small local aquifers in individual hills or hill groups, which drain through over 100 hundred small and very small local springs (Messerschmid *et al.,* 2003a, 2003b) with individual spring flow between zero and a maximum of 1.7 l/s. Together, the formations of the three perched aquifer systems cover 13 % of the catchment. These isolated perched hilltop aquifers stand in contrast to the thick regional aquifers that form two all-encompassing storage and groundwater flow systems. The differences between local and regional hydrostratigraphy and the outcrop areas of all formations are documented in Table 1. They form one focus of the present study.

Table 1. Outcrop (recharge) area, average precipitation and formation names in Wadi Natuf – regional and local refined hydrostratigraphies

Age	Formation (symbol)	Area (km^2)	Precipitation (mcm/a)	Local stratigraphy, aquifer potential	Regional Stratigraphy
Recent	Alluvial (All)	1.53	0.85	(minor)	Top Aquiclude
Senonian	Senonian (Sen)	2.38	1.31	–	
Turonian	Jerusalem (Jer)	9.24	5.07	major	**UPPER AQUIFER (UA)**
Upper Cenomanian	u-Betlehem (u-Bet)	7.65	4.26	good	
	l-Betlehem (l-Bet)	9.77	5.58	poor	
	Hebron (Heb)	10.06	5.77	major	
Lower Cenomanian	u-Yatta (u-Yat)	4.93	2.92	–	Middle Aquitard
	l-Yatta (l-Yat)	10.18	6.14	local *	
Upper Albian	u-Upper Beit Kahil (u-UBK)	2.44	1.50	good *	**LOWER AQUIFER (LA)**
	l-Upper Beit Kahil (l-UBK)	8.44	5.26	local (at top) *	
				poor (at bottom)	
	u-Lower Beit Kahil (u-LBK)	13.16	8.21	major	
	l-Lower Beit Kahil (l-LBK)	16.4	10.23	major	
Lower Albian	Qatannah (Qat)	4.56	2.80	–	Bottom Aquiclude
	Ein Qiniya (EQ)	1.82	1.12	good (local)	
Aptian	Tammoun (Tam)	0.06	0.04	–	
SUM		**102.6**	**61.1**		

Note: The area of formation outcrop here is equated with the area for infiltration (recharge). Precipitation here is expressed as average annual amount of area precipitation over the respective formation outcrops and calculated with rainfall of the respective sub-catchments within Wadi Natuf. Ein Qiniya formation is a local aquifer, which however does not belong to any of the regional aquifer units or basins; its recharge potential does not form part of the water balance calculations for the WAB. * perched leaky aquifers with dashed line at bottom; Source: this study.

Also the regional bottom aquitard of Aptian to Lower Albian age contains an aquifer unit, Ein Qiniya formation (EQ), which gives rise to a few local (but un-perched) contact springs along their small outcrop areas near the anticlinal axis (Messerschmid, 2003a). The confining Upper Aquitard is almost entirely made up of impermeable Senonian chalk and therefore void of intermediate aquifers or springs. Unlike in the EAB, most of the faults display limited vertical throws and thus do not act as flow barriers in the WAB (Weinberger *et al.,* 1994). Therefore, folding, dipping and tilting are the principal structural features that dominate and direct the local and regional groundwater flows in the recharge and accumulation areas of the WAB.

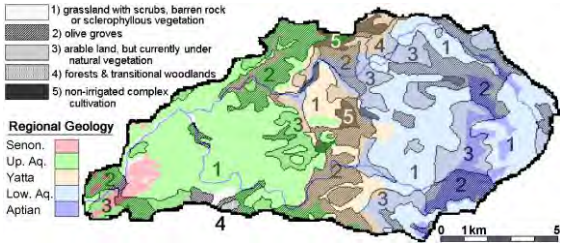

Figure 2. Wadi Natuf Land Use and Land Cover (LU/LC) map and regional hydrostratigraphy in shaded colours (modified after LRC, 2004 and Messerschmid *et al.*, 2003a)**.**

Note: The land cover types 4 and 5 are almost completely restricted to Yatta formation outcrops (and in some places parts of the UBK formations). Type 3 is typically found over outcrops of the regional Lower Aquifer. The Upper Aquifer outcrop area is dominated by type 1 (grassland and barren rock). Olives (type 2) can be found in all areas, but are grown on tended terraces mostly in the steep slopes of the Lower Aquifer outcrops in upper Wadi Natuf.

2.2 Physical landscape features

Wadi Natuf has a rural landscape with less than 5% built-up areas (Messerschmid, 2014). Spatially, the typical land forms vary greatly, ranging from rock outcrops and terraces with olives, over grass- and shrublands, arable but currently uncultivated lands, mixed vegetation and transitional woodlands to agricultural plains and forests (Messerschmid, 2014; LRC, 2004) – see Fig. 2. As Fig. 3 indicates, the land forms in Wadi Natuf are closely related to the underlying geology. The soft marl of u-Yat usually forms an eroded step in the landscape that can develop into small inland plains with cultivated agricultural fields. By contrast, the mixed intercalations of marly, chalky and limey rocks of l-Yat form natural steps and terraces in the landscape, often with a bushy landscape, partly also with trees. The regional aquitard of u-Yat is overlain by the strongly karstified massively bedded limestone of Hebron formation (Heb), which often restricts soil development to small pockets in an otherwise sparsely vegetated karren-field landscape. This karstic formation with an excellent recharge potential (and very low runoff generation, see Messerschmid *et al.*, 2017), in turn is overlain by the already mentioned soft, plated limestone with thin marl intercalations of l-Bet, which not only erodes differently but also allows the formation of thicker soils; Figure 3a shows l-Bet at the top of the hill, conspicuously covered by a little forest and with a sharp boundary to the LU/LC type of the underlying karstic Hebron formation.

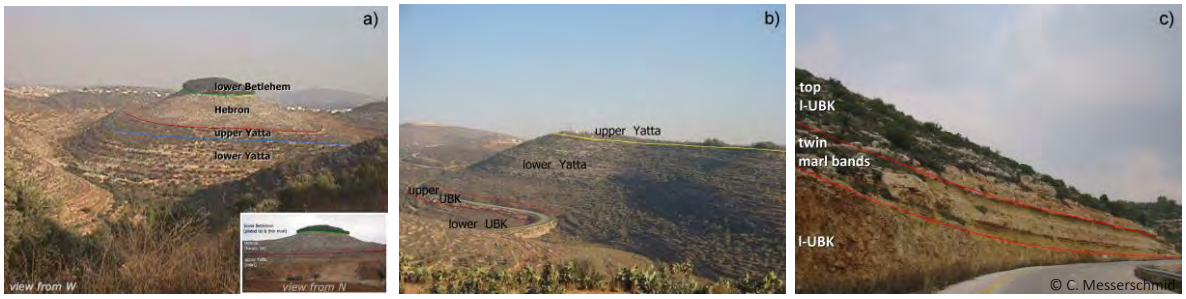

Figure 3. Correlation of landform and lithology. Nabi Ghayth hill, west of Beitillu (a); Nabi Aneer spring group (b). Twin marl band underlying a local perched aquifer (c).

Note: The karstic limestone of Hebron formation forms outcrops with thin soil cover, bare rock or karren fields and tends to erode into steeper slopes above the soft, mostly eroded upper Yatta formation – the only true aquiclude within the Westbank Group (with levelled agricultural plains in the inlet photo in Fig. 3a. By contrast, the top of the hill is formed by lower Betlehem formation; a thinly plated coloured limestone ensemble with fine marl interbedding that lacks karstification and promotes soil development and natural vegetation. Figure 3c shows the twin marl band, underlying and confining Beitillu, Harat Al-Wad spring group (of Top l-UBK formation); potographs by the author.

Typically in Wadi Natuf, this distribution of LU/LC follows the formation outcrops (geology) with great accuracy, discernible even from aerial photographs. Also soil thickness was measured and found to strongly correlate with lithology and land forms (LU/LC) as discussed in the first part of this series (see Table D1 in Messerschmid *et al.*, 2019). For example, in the mountains, where Lower Aquifer formations crop out, terraced hills with olive groves dominate, together with grassland and shrubs, beside some barren hills with rock outcrops. By contrast, the central study area is characterised by a relief of stepped hills with formerly cultivated, but now partly abandoned terraces, caused by both, bedding characteristics and lithology types. This central area also contains some small plains with agricultural fields over thick soils and some areas of exceptional coniferous forest (Messerschmid, 2014), compare Fig. 2. Finally, the foothills in the West exhibit more rock outcrops and grassland with shrubs, together with some olive groves in alluvial plains along the banks of the Wadis.

This recurrent field finding of strict correlation between the three groups of physical features – LU/LC, soil thickness and geology – forms the basis of the classification framework in Wadi Natuf (see sections 3.2, 3.3, 5.1), since it allows categorization of key elements of recharge and the attribution of lithological and hydro-stratigraphical characteristics with the aquifer and recharging potential of the different formations.

3 Methodology

As already described, the regionalisation approach of this study consists of two consecutive procedures, as shown in Fig. 4: a) the identification and parameterization of physical features and their classification in a conceptual response matrix, attributed to classes of hydrological impacts (Fig. 4, rows 1 and 2); and b) the extrapolation and regionalisation of the model results within a classification framework (row 3). In addition to the regionalisation, this research applies the findings regarding formation-specific recharge to the perched local aquifers in order to determine the leakage coefficients of these formations (row 5).

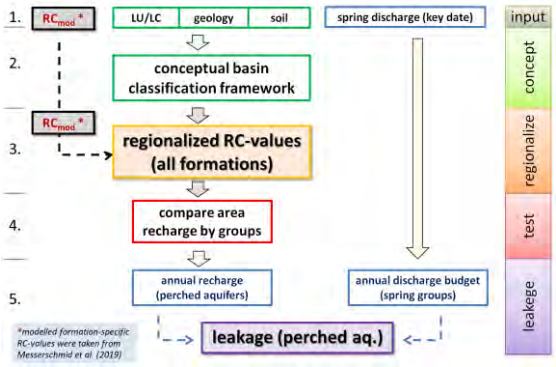

Figure 4. Conceptual flow diagram of work steps
First row: field observations on land forms, geology and soil, together with key date campaign on spring flow measurements; second row: setting up a conceptual classification framework; third row: introducing formation-specific RC-values (from Messerschmid *et al.*, 2019) and regionalisation of RC-values for the entire catchment (all formations and all three groups); fourth row: area recharge calculation and comparison of results for the different groups; fifth row: calculation of downward groundwater leakage in each of the three perched aquifers, using annual recharge of the perched isolated hilltop aquifers and annual discharge budget of respective spring groups.

3.1 Hydrological measurements

In addition to the daily spring flow measurements of five springs, described in Messerschmid *et al.* (2019), four key date campaigns for flow measurements at almost one hundred small and very small springs belonging to different spring groups at each of the perched hilltop aquifers in central Wadi Natuf, were carried out during summer 2003, winter 2003/04, summer 2004 and summer 2007. The metering was done by hand (stop watch and bucket) and concentrated during a period of a few days. The target of the flow measurements at the spring groups was to establish the total discharge of the respective perched aquifers for further budget calculations. More details and the results of these procedures are detailed under section 3.6.

3.2 Physical features

The classification of distributed physical landscape features and their parameters stands at the heart of this study. Mapping, detection, interpretation and where possible, quantification of their parameters was carried out over a period of more than ten years and over 200 field visits to gain local knowledge on specific field conditions. Accordingly, the landscape characteristics in Wadi Natuf could be attributed to three groups: geology, soil conditions and land use/land cover features (LU/LC).

First, existing geological maps in the scale 1:50,000 (GSI, 2001; 2008; Rofe & Raffety, 1963) were corrected, complemented and refined by extensive field mapping and remote sensing (stereoscopic aerial photographs) with the target to detect, describe and interpret the lithological rock content, (chemism, texture, grain distribution), the degree of crystallisation and structural features like folding, faulting, cleavage, jointing, as well as primary porosity and karstic features. Another focus was the refinement of local hydrostratigraphy, in particular with respect to the spring-feeding formations (Messerschmid *et al.*, 2003b; Dafny *et al.*, 2009) and their catchment areas. Of particular interest were not only the spatial pattern and distribution of such features, but especially the comparison of these geological features with the features and distribution of the other groups, i.e. soil and LU/LC. This enabled us to assign particular, spatially distributed geological characteristics to each of the different formations. Besides the field examinations, this work drew on existing literature, such as the first hydrogeological map of the West Bank by SUSMAQ-BGS (2005) and SUSMAQ reports (2002), as well as older geological maps (Rofe & Raffety, 1963; GSI, 2000; 2008) and descriptions of the typical landscape features of the different geological formations in the Ramallah area (Keshet & Mimran, 1993). This re-examination focussed on the distribution of landscape features with respect to their recharge potential and the exact delineation of the outcrop and recharge areas of the different local perched aquifers on erosionally isolated hillsides. This step employed field characterization and mapping as well as structural and hydrogeological considerations (SUSMAQ, 2001).

The second part of field mapping and investigations targeted the soils in Wadi Natuf. Unlike indicated in earlier regional maps (Dan *et al.*, 1975, 1:500,000), no pale rendzinas were found; all soils in Wadi Natuf were of the terra rossa type. Lab tests determined silty to clayey residual soils, which are typical for Mediterranean carbonate environments (see also Messerschmid *et al.*, 2019). The main aim of this sub-study was to investigate soil thickness and its distribution over the area. As already mentioned a conspicuous spatial pattern emerged, namely that typical soil thicknesses formed over different formations (see Fig. 3a, 3b). Appendix D in Messerschmid *et al.* (2019,) presents these results in a soil thickness matrix, where the distribution of soil depth was documented for different LU/LC-types and different lithostratigraphic units.

Thirdly, and similar to geology and soil thickness, land use and land cover characteristics, such as relief, natural vegetation and its alteration by human land use (section 2), can be interpreted as indicators of different hydrological processes that determine recharge. Whereas the differences in landscape units with respect to their runoff potential were discussed in Messerschmid (2014); Messerschmid *et al.* (2018), this study aimed at creating a simplified but realistic categorization of physical, recharge-controlling landscape features and their spatial distribution along the lines of outcropping formations. ARIJ (2012) prepared detailed LU/LC maps for large parts of Wadi Natuf. A simplified earlier version of land cover maps for the entire catchment had been prepared by LRC (2004) and modified by Messerschmid (2014); these maps were refined during the field trips, as documented in Fig. 2.

3.3 Conceptual basin classification framework and regionalisation

Conceptually, as already mentioned, the regionalisation in this study comprises of two main steps (rows 2, 3 in Fig. 4), i.e. the creation of a basin classification framework and the attribution of the model results of Messerschmid *et al.*, (2019) to this framework by extrapolation and regionalisation, which will be further specified in the following. Based on the PUB-understanding that physical characteristics control hydrological processes and thus (hydrological) function follows (physical) form, a conceptual framework was set up, as shown in Table 2. The physical features were divided into three groups, such as LU/LC, soil and geology (columns in Table 2), and within each group separately, the different landscape units were divided into distinct classes of recharge potential (lines in Table 2), based on the available geological literature and our extensive field investigations. Then, each lithostratigraphic formation (numbered a, b, c, etc. in the schematic Table 2) was attributed to a distinct recharge class (from low to high in Table 2; as roman numbers I – V in Table 3). As a result we obtained three independent sets of differently ordered litho-stratigraphic formations, ranked by their recharge potential. This separation allowed us to examine the result of attributed recharge classes separately for each group in order to gain a more realistic picture, to examine the differences in outcomes and to avoid over-simplification in line with PUB-recommendations (section 1.2). Again, this procedure was based on the findings of section 2, namely that such a correlation between the three groups of physical features was clearly discernible in field explorations in Wadi Natuf. It should be noted here that whereas soil thickness was quantifiable in the field, other physical parameters such as LU/LC and geology were not; they were hence differentiated qualitatively and correlated with soil thickness in the aforementioned soil matrix (see Appendix D in Messerschmid *et al.*, 2019).

The general classification framework was then applied to Wadi Natuf and the specific physical features encountered in Wadi Natuf were inserted in Table 2, to obtain a conceptual recharge classification framework, specific for Wadi Natuf (Table 3). Here again, in each of the different groups (columns), the different formations rank differently as to their recharge potential (classes I–V).

The next steps of the recharge distribution analysis were regionalisation and extrapolation by applying the modelled RC-results from the eight SM stations in Messerschmid *et al.* (2019) to the un-modelled formations. These values were inserted into the Wadi Natuf basin classification framework (Table 3), resulting in Table 4. However, the modelled RC-values cover only five of the different litho-stratigraphic formations of Wadi Natuf. Thus, for the remaining un-modelled formations, specific RC-values were assigned by attributing discrete recharge coefficient values to the different classes of recharge potential, again for each group independently (Table 4). After the empirical work of measurement and modelling, this last part includes strong conceptual elements of extrapolation and deduction (section 5).

Table 2. Schematic conceptual basin classification framework

		Groups of physical features					
		LU/LC		Soil thickness		Rock lithology	
		Ftn.	Phys. features	Ftn.	Phys. features	Ftn.	Phys. features
High	Classes of recharge potential	a)	Rock	b)	Thin	c)	Karst
↑		b)	Grassland	a)	Medium	b)	Limestone
		c)	Forest	c)	Thick	a)	Marl
Low		etc.	etc.	etc.	etc.	etc.	etc.

Note that the order of formations (a, b, c, etc.), differs from group to group, thus indicating different ranking orders of formations as to their recharge potential (classes) in each group.

The last step of the recharge analysis (row 4 in Fig. 4) was a comparison of the results of the different groups by summing up total catchment recharge and under consideration of previous findings on lumped area recharge in the WAB.

3.4 Leakage estimation

An additional result and by-product of the recharge modelling and regionalisation was the ability to calculate groundwater leakage in the perched aquifers, based on the formation specific RC-values and the calculation of spring group outflows. Once both these categories of in- and outflows were determined independently, a simple water budget approach could be applied, using the Equation:

$$L = R - Q \quad (1)$$

whereby L represents leakage (in m^3/a), R is the mean recharge amount (m^3/a) and Q stands for the total annual spring group discharge (m^3/a) from each isolated perched aquifer; each of the variables can also be expressed as % of annual rain. This simple procedure was only possible in the perched aquifers with their well controllable catchment areas and outflow conditions. For this purpose, the boundary conditions of these local aquifers had to be determined, based on field mapping and conceptual considerations such as structure and lithostratigraphy (SUSMAQ, 2001) – as discussed in section 2. It should be noted that the leakage calculations are not applicable to the regional aquifers with their complex lateral groundwater flow connections.

In addition to the recharge area, the water budgeting at the perched aquifers also required a determination of the respective spring group discharges (Q in Eq. 1). This last step involved additional field work and analysis. For this purpose, four key date campaigns of comprehensive spring measurements were carried out in summer 2003, winter 2003/04, summer 2004 and summer 2007. The first year of observations (hydrological year 2003/04) was picked as reference year. In two steps, a) total annual spring outflows for the reference year and b) spring flow budgets for other years were calculated.

(a) First, the flows of all measured springs were summed-up for each spring group and each campaign (m^3/d per spring group). Then, the average of the daily spring flows, measured in winter 2003/04 and summer 2004, was used and multiplied by 365 days, which resulted in an annual reference spring flow for the year 2003/04 (Q_{ref} in m^3/a). This approximation of reference annual spring group flow was calculated for each spring group independently (see section 5.3).

(b) In a second step, the average annual area rainfall was calculated for the respective spring group and perched aquifer recharge areas during the period 2003/04 - 2009/10 (for example, Wadi Zarqa spring group area had a seven-year average of 507 mm/a). In addition, the ratio between the seven-year rainfall average and each annual rainfall was determined (for example, in the Beitillu, Harat Al-Wad spring group area, the precipitation in 2003/04 was 96% of average rainfall, whereas in 2004/05, it was 122% of average precipitation, etc.). This spring-group specific annual rainfall ratio was then applied to each spring group and year (see Fig. 6) by using the Equation:

$$Q_i = Q_{ref} * x_i \quad (2)$$

whereby in each spring group, Q_i is annual spring discharge (in m^3/a), Q_{ref} is reference annual spring flow of 2003/04 (in m^3/a) and x_i is the spring group specific ratio for each year (x_i in %).

4 Results

4.1 Basin Classification

Table 3 presents the main result of the conceptual basin classification in Wadi Natuf, whereby for each formation, different categories or "groups" of physical features (columns) are distributed over different classes of recharge potential (lines), based on literature and field observations as well as on conceptual considerations grounded in general physical laws. Figure 2 shows a map of LU/LC types and the simplified hydrostratigraphy of the regional Upper and Lower Aquifers in shaded colours.

Table 3. Conceptual basin classification framework, specific for Wadi Natuf

	group 1 - LU/LC		**group 2 - soil**		**group 3 - geology**		
	formations	features	formations	feat.	formations	features	
I	u-UBK	cliff = rock outcrops	All, l-LBK, **Jer**	--	All, l-LBK, Jer	well dev. karst (& gravel)	Increasing recharge potential →
II	All, l-LBK, Jer, u-LBK, Heb	olive terraces, rock outcrops	**u-UBK**, u-LBK	-	u-UBK, u-LBK, Heb	karstified lst / dol	
III	l-UBK, u-Bet	arable but uncultivated, grass- & shrub-lands	**Heb**, u-Bet, EQ, **l-UBK**	±	u-Bet, l-UBK, l-Bet	lst / dol (some marl/chalk) (*Nari for u-Bet*)	
IV	l-Bet, EQ, l-Yat	mixed, transit. woodlands	l-Bet, **l-Yat**	+	EQ, l-Yat	mixed lst + marl	
V	u-Yat, Sen, Apt	agric. plains, forests	u-Yat, Sen, Apt	++	u-Yat, Sen, Apt	marl (chalk)	

Note: Left column: classes of recharge potential (I – V); middle columns: groups of phys. features (1-3); formation names as in Table 1; soil thickness increases from thin (--) to thick (++). The formations shown in bold type were the ones monitored and modelled. The grouping and class distribution was based on field work and literature, e.g. SUSMAQ (2002), LRC (2004), GSI (2001), Keshet and Mimran (1993), Messerschmid (2014) and Messerschmid *et al.* (2018).

As shown in the table and discussed in sections 2 and 3, the ranking order of some of the formations differs from group to group, based on field observations. For example the upper Yatta formation with its confining marls, always represents the lowest class of recharge potential (Class No. V), and was essentially categorized as an impervious aquitard. By contrast, the upper UBK formation, consisting of reefal limestone, belongs to the most strongly recharging class only under the group of LU/LC features, due to its consistent rocky outcrops in form of cliffs (Class No. I). But under the groups of soil thickness and rock lithology (geology) its recharge potential is surpassed by other formations such as Jerusalem and lower LBK formations (see Table 3).

The second highest recharge class within the LU/LC group is represented by terraced hillsides with tended olive groves (Class No. II). This is due to the thin terrace soils that are kept loose by regular ploughing and the rock walls that further inhibit runoff losses along the slopes (see also discussions of runoff generation in Messerschmid, 2014 and Messerschmid *et al.*, 2018). Large parts of lower UBK (l-UBK) and of upper Betlehem (u-Bet) are dominated by grass- and shrublands, which were categorized by LRC (2004) and ARIJ (2012) as arable but currently not under cultivation (Fig. 2), whereby it should be noted that the areas under cultivation are currently decreasing in Wadi Natuf, especially in areas of settlement expansion (Messerschmid, 2014). To some extent, Table 3 constitutes somewhat of a (necessary) simplification, as in the case of upper Betlehem formation, which contains some areas of slightly karstic karren fields with soil pockets in the Northern part of Lower Wadi Natuf. However, here, the outcropping rock also often develops an erosional caliche-like crust, locally addressed as Nari, which inhibits permeability and percolation.

This analysis ends in a basin classification framework that categorizes different groups of recharge potential and attributes each formation to one of these classes (independently for each group).

4.2 Regionalisation and extrapolation of modelled RC-values

Using the basin classification framework, it was now possible to extrapolate the results of the parsimonious percolation model and attribute the modelled recharge coefficients to other formations (according to the classes of recharge potential in Table 3). As already mentioned this attribution of RC-values was performed for each group of physical features independently, in order to avoid equifinality problems and increase the reliability of the approach. This approach however rests on the assumption that the seven-year period is representative for long-term inter-annual rainfall variability (>30 years). In order to ascertain that the 7-year averages of modelled annual recharge cover the entire range of long-term annual precipitation heights in the WAB, this assumption was tested separately (as detailed in Appendix E in Messerschmid *et al.,* 2019). In brief, we can state here that the seven years from 2003/04 until 2009/10 happened to represent and cover the entire range of long-term basin precipitation (bar one single, exceptional winter in 1991/92). Table 4 shows the modelled and the newly attributed and inserted average annual recharge coefficients for each group. In the table, the RC-values directly taken from the model (Messerschmid *et al.,* 2019) are marked in bold font and red within group 2, which represents soil thickness.

Table 4 lists the 15 different outcropping formations in Wadi Natuf in chronological order from the youngest, alluvial series and impermeable Senonian chalks down to the oldest, also impermeable lower Albian – upper Aptian Tammoun shales formation (Messerschmid, 2003). In between, there are two aquitardal series (Qat, u-Yat) and ten more or less aquiferous formations, almost all of which are partially composed of carbonates (including the unconsolidated carbonate gravels forming the shallow alluvial in the Wadis). However, the recharge coefficients (as fraction of rainfall) of the aquifers deviate by over 15 % between the most susceptible karstic limestones with an RC > 57 % and the more aquitardal series, containing some degree of marl and chalk, be it as discrete thin beds (l-Bet) or as marly and chalky limestones (l-Yat) with an RC of almost 42 %. These high recharge rates are partly due to the much reduced (in fact negligible) rates of runoff generation measured in Wadi Natuf. But more importantly, they are a result of the overall quite modest amounts of actual evapotranspiration, caused by the Mediterranean climate with a rather short but very wet winter season and a prolonged rain-free summer season, in which the dried up soils cannot offer any amounts of water to direct soil evaporation or plant transpiration, undergoing a kind of summer dormancy.

Table 4. Extrapolated recharge coefficients per group

	Wadi Natuf			1. LC/LU		2. Soil		3. Geology	
	Area	Precipitation		Recharge		Recharge		Recharge	
Formation	km²	mcm/a	*mm/a*	RC (%)	*mm/a*	RC (%)	*mm/a*	RC (%)	*mm/a*
Alluvial	1.53	0.85	*553*	45.3%	*250*	57.3%	*317*	57.3%	*317*
Senonian	2.38	1.31	*552*	0.0%	*0*	0.0%	*0*	0.0%	*0*
Jerusalem	9.24	5.07	*549*	45.3%	*249*	**57.3%**	*315*	57.3%	*315*
u-Betlehem	7.65	4.26	*557*	44.7%	*249*	45.3%	*252*	49.4%	*275*
l-Betlehem	9.77	5.58	*571*	41.8%	*239*	41.8%	*239*	49.4%	*282*
Hebron	10.06	5.77	*574*	45.3%	*260*	**45.3%**	*260*	54.1%	*311*
u-Yatta	4.93	2.92	*592*	0.0%	*0*	0.0%	*0*	0.0%	*0*
l-Yatta	10.18	6.14	*603*	41.8%	*252*	**41.8%**	*252*	41.8%	*252*
u-UBK	2.44	1.50	*615*	54.1%	*333*	**54.1%**	*333*	54.1%	*333*
l-UBK	8.44	5.26	*623*	44.7%	*279*	**44.7%**	*279*	49.4%	*308*
u-LBK	13.16	8.21	*624*	45.3%	*283*	54.1%	*338*	54.1%	*338*
l-LBK	16.4	10.23	*624*	45.3%	*283*	57.3%	*358*	57.3%	*358*
Qatannah	4.56	2.80	*613*	0.0%	*0*	0.0%	*0*	0.0%	*0*
Ein Qiniya	1.82	1.12	*613*	41.8%	*256*	45.3%	*278*	41.8%	*256*
Tammoun	0.06	0.04	*614*	0.0%	*0*	0.0%	*0*	0.0%	*0*
SUM / avg.	**102.6**	**61.1**	***595.3***	**39.5%**	***235***	**43.8%**	***261***	**46.0%**	***274***

Note: The modelled RC-values from Messerschmid *et al.* (2019) are indicated in red and bold fonts under the second group (soil conditions). Aquitards void of recharge are shaded grey.

As described before and applied in the modelling code of the SM-saturation excess and percolation model, the rate of groundwater percolation (here equated with recharge) from the soil into the aquifer bedrocks is directly related to the thickness of the soil. In other words, our model and hence also this table is based on the observation and assumption that thicker soils permit less recharge than thin soil covers. Consequently, the highest RC-values are all found in formations with very thin soils and larger portions of rock outcrops (around soil pockets), such as the Turonian limestones of Jerusalem formation at the top of the regional Upper Aquifer and as the bottom of the regional Lower Aquifer, the lower LBK formation (l-LBK), both of which display highly karstified and massively bedded limestone series with strong features of epikarst in the outcrop (SUSMAQ, 2002). These formations also show the highest recharge coefficients in the physical landscape feature group 3 (geology), due to the aforementioned lithological features. However, under the third group (LU/LC), these formations rank lower than the maximum RC-values (instead, the cliff-forming u-UBK formation reaches the maximum here). This is due to the fact that, from a land use and land cover point of view, these two formations had to be grouped into class II of recharge potential (see Table 3), because here, besides the extended grass- and scrub lands, olive groves dominate on the cultivated terraces of l-LBK and on the plains of Jerusalem formation (see LU/LC map, Fig. 2). All the other un-modelled aquiferal formations, such as u-Bet, Hebron, u-LBK and the stratigraphically very low formation of Ein Qiniya, are attributed with intermediate RC-values (between 0% for aquitards and 57 % for the highest potential), according to their class of recharge potential in Table 3.

Note again that Wadi Natuf comprises of a main part belonging to the WAB, a smaller Eastern portion (in the mountains) belonging to the groundwater catchment of the EAB and reduced outcrop areas, older than and stratigraphically below the bottom formations of the regional Lower Aquifer in both, WAB and EAB. Table 5 documents the total recharge in Wadi Natuf (as well as that of the WAB portion only, in brackets and blue colour). The resulting overall area recharge coefficient for the entirety of Wadi Natuf ranges between 39.4 % and 46.1 %, slightly higher for the WAB portion (44.2 % as mean value of the three groups). As can be noted, despite the independent approaches and individual RC-attribution for each group, the final results of average area recharge within the WAB portion match rather closely for each calculation, with 24.1, 26.8 and 28.1 mcm/a, respectively, or in other words, with a deviation of total distributed recharge by less than 10 percent.

Table 5. Annual average recharge in Wadi Natuf for different groups of landscape features – (WAB only)

		Recharge – all Natuf (WAB)		
Scenario	**Unit**	Group 1 landform-based	**Group 2 soil-based**	Group 3 lithology-based
Recharge	(mcm/a)	**24.1 (20.6)**	**26.8 (22.6)**	**28.1 (23.9)**
Catchment area	(km^2)		**102.6 (85.5)**	
Average precipitation	(mm/a)		**595**	
Annual recharge rate	($l/m^2/a$)	0.23 (0.24)	**0.26 (0.26)**	0.27 (0.28)
	(mm/a)	234.8 (241.4)	**261.4 (264.2)**	274.1 (279.8)
Recharge coefficient	(%)	39.4 % (40.8 %)	**43.8 % (44.6 %)**	46.1 % (47.3 %)

Note: mcm/a = million cubic-metres per year, the blue numbers refer only to the WAB-portion with Wadi Natuf.

The values of the soil-based group (middle column, marked bold) take an intermediate position, close to the arithmetic mean of the three groups. Their values were also used for the recharge map in Figure 5. A more detailed translation of the recharge values for different stations into area and aquifer recharge rates is documented in Table A1.

4.3 Leakage estimation

The leakage estimation was based on a simple water budget calculation, accounting for annual recharge and annual spring outflows (Table 6). As already discussed in section 2, the particular geometry of the perched local aquifers and their respective spring groups allowed not only for an exact determination of the catchment or recharge area, but also for a complete budgeting of aquifer outflows. All springs are contact springs and drain the perched aquifers at the contact to the underlying aquitard. Depending on the general formation dip towards west and north-west, the springs are aligned along the outcropping contact line on the northern to north-western faces of the hillsides.

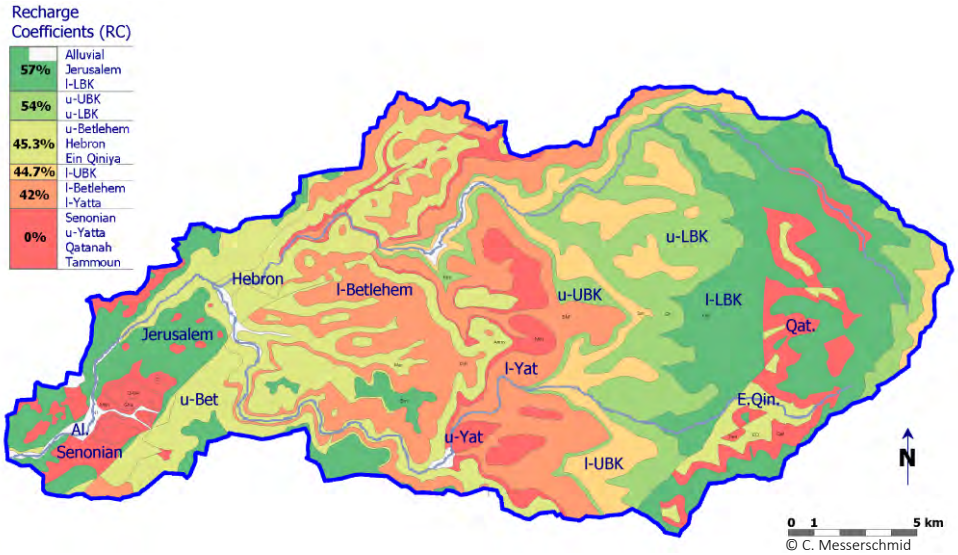

Figure 5. Recharge map of Wadi Natuf – Recharge Coefficients of the soil-based group 2 (RC-values in % of annual precipitation)

Table 6. Average annual spring group discharge (rain and sub-catchment recharge) (2003/04-09/10)

Symbol		□	○	○	△	◇	◇
Spring group	**Unit**	**Wadi Zarqa**	**Zarqa Bridge**	**Beitillu**, (Harat Al-Wad)	**Nabi Aneer**	**Ain 'Ayoub**	**Shakhareek**
Formation		u-UBK	Top l-UBK	Top l-UBK (u-UBK)	Top l-UBK	lower Yatta	
Recharge area	(km^2)	1.84	0.108	1.24	0.20	0.22	1.34
Rain – P	(m^3/a)	932,993	54,763	628,756	101,412	111,553	679,462
RC	**(%)**	**54%**	**45%**	**45%**	**45%**	**42%**	**42%**
Recharge – R	(m^3/a)	504,749	24,479	281,054	45,331	46,629	284,015
Discharge – Q	(m^3/a)	152,068	8,311	32,547	5,360	11,901	72,258

All in all, six different perched aquifer and spring groups could be identified in Wadi Natuf (Fig. 6).

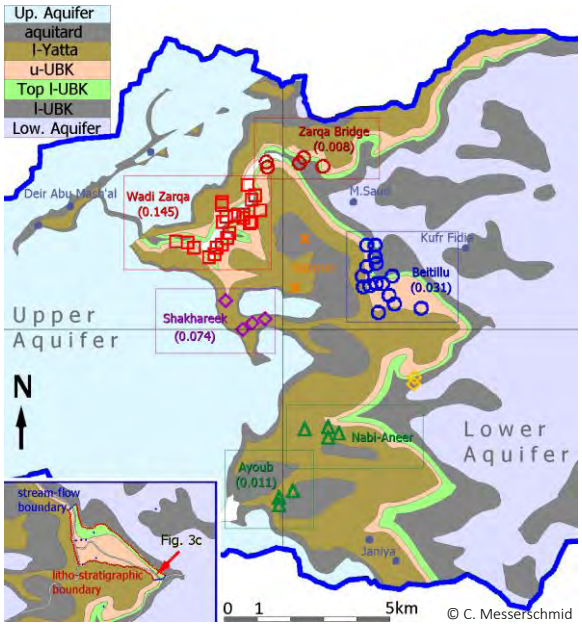

Figure 6. Spring groups in Wadi Natuf.

Note: Six spring groups were identified in central Natuf, with two in the North (Zarqa), two in the centre (Beitillu & Shakhareek) and two in the South ('Ayoub & Nabi Aneer). The recharge areas of these perched intermediate aquifers are isolated by outcropping bottom aquicludes (Fig. 3b, c). Source: this study and geological map based on GSI, 2000, 2008.

The leaky aquitardal layers beneath the perched aquifers were a) the bottom of lower Yatta formation, b) the uppermost part of l-UBK (a somewhat marly limestone beneath u-UBK) and c) a twin marl band in the upper part of l-UBK, right beneath the top of l-UBK, see Fig. 3c (compare also with the stratigraphical column, Fig. 2a in Messerschmid *et al.* (2019). These local hydro-stratigraphical contacts were confirmed by detailed field investigation and mapping (SUSMAQ, 2001 and 2002; Messerschmid *et al.*, 2003a and 2003b).

The budget of the spring groups issuing from the perched aquifers were determined through the four key date campaigns (section 3.4); the hydrographs of the five daily read springs were also found to be representative for the spring groups (see Tables F1, F2 in Messerschmid *et al.*, 2019). The six spring groups are presented in the spring group map (Fig. 6). The diagram in Fig. 7 shows the annual spring group flows together with the precipitation of the respective years at the rain station Wadi Zarqa from 2003/04 until 2011/12.

In Wadi Natuf, annual spring flow was found to reflect annual precipitation quite faithfully. In Fig. 7, the column on the right side indicates the average annual precipitation in Wadi Zarqa during the modelling period 2003/04 – 2009/10.

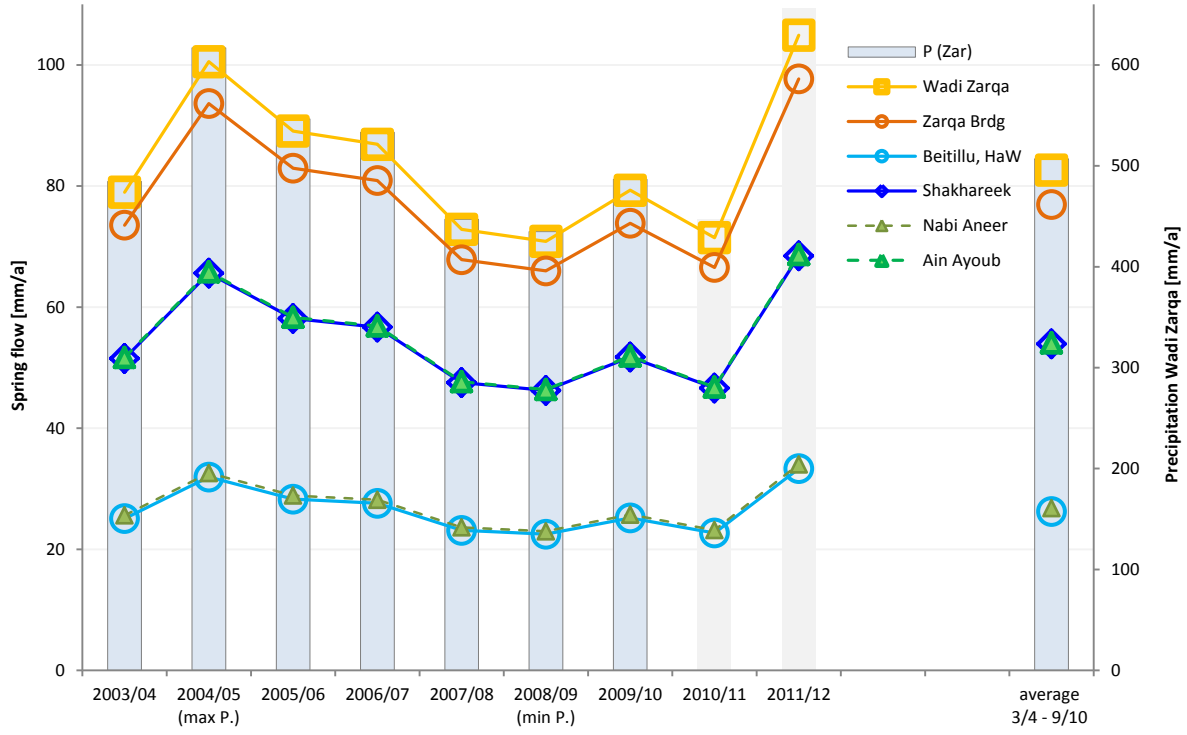

Figure 7. Spring group flow & annual rain. Note: Spring flows were calculated according to the key-date measurement procedure; the years 2010/11 and 2011/12 were covered by precipitation and spring discharge measurements, but not included in the SM-percolation model of Messerschmid *et al.* (2019).

4.4 Spring group recharge

As the spring group map (Fig. 6) indicates, the groups Ash-Shakhareek, and Ain ‘Ayoub belong to lower Yatta formation. Beitillu (Harat Al-Wad), Wadi Zarqa Bridge and An-Nabi Aneer spring groups consist of the top of l-UBK (Beitillu also in combination with u-UBK, see sections 2.1, 5.3). Wadi Zarqa finally is made up of Upper UBK formation. It should be noted again that the well-defined boundary conditions of the perched aquifers, which consist almost entirely of no-flow boundaries (Fig. 6, inlet map), allowed for an exact determination of the respective recharge areas of the perched hilltop aquifers (as fraction of the total respective formation outcrops indicated in Table 1) and the corresponding average annual recharge amounts (see Table 6). The respective recharge of each spring group was calculated by multiplying the area of each perched aquifer catchment with the annual precipitation and RC-values of the respective aquifer formation. Since all spring groups are located along a relatively narrow North-South running strip in Central Wadi Natuf, the

rainfall used for the recharge calculations was based on the precipitation records from the tipping bucket at Wadi Zarqa, located within the largest and most productive of the spring groups, the Wadi Zarqa group.

4.5 Leakage calculations

As indicated in Fig. 6, 8, the amount of lateral groundwater outflows from the hilltop aquifer groups, other than through the measured springs, is negligible (if not nil). We could therefore equate all perched aquifer inflows with calculated recharge and all respective outflows with spring group discharge: this is also because all perched hilltop aquifers lie above the wadis and therefore cannot receive runon form upstream areas. A simple budget calculation, based on Equation (1) represents a mass balance that defines the difference between in- and outflows as downward groundwater leakage from the perched aquifer formation into the next aquifer beneath.

Table 7 summarizes the different perched aquifers by different aquifer formations, as outcropping in Wadi Natuf (compare with outcrop areas in Fig. 7). The table indicates that leakage (L) in the three perched aquifers lies between 64 % and 89 % of average annual recharge. Figure 8 shows a schematic representation of the different flow proportions at each perched formation.

Table 7. Water balance of the intermediate perched leaky aquifers in Wadi Natuf – Recharge, spring discharge and leakage rates

Formation		lower Yatta	upper UBK	Top of lower UBK	**Σ intermediate leaky aquifers**
Area	km²	10.2	2.4	0.8	13.5
Rainfall (**P**)	mcm/a	6.1	1.5	0.5	8.0
	mcm/a	2.5	0.8	0.2	3.5
Recharge (**R**)	mm/a	249	322	266	263
	(R ÷ P)	**42 %**	**54 %**	**45 %**	**44 %**
	mcm/a	1.9	0.7	0.1	2.7
Leakage (**L**)	mm/a	185	287	169	203
	(L ÷ R)	**75 %**	**89 %**	**64 %**	**77 %**
	mcm/a	0.645	0.086	0.082	0.813
Springs (**Q**)	mm/a	63	35	97	60
	(Q ÷ R)	**25 %**	**11 %**	**36 %**	**23 %**

Note: In this calculation, the discharge rates are applied to the total outcrop areas of the different intermediate leaky aquifers in Wadi Natuf, not only to the areas of spring group discharge measurements. Leakage and spring discharge are shown as fractions of the total recharge from the soil moisture models (L ÷ R and Q ÷ R), while recharge coefficients are fractions of total average area rainfall (R ÷ P) in Wadi Natuf.

Figure 8 depicts a cross section, schematically intersecting the spring groups of the three different perched aquifers, together with the coefficients of average annual recharge (R), spring discharge (Q) and downward groundwater leakage (L).

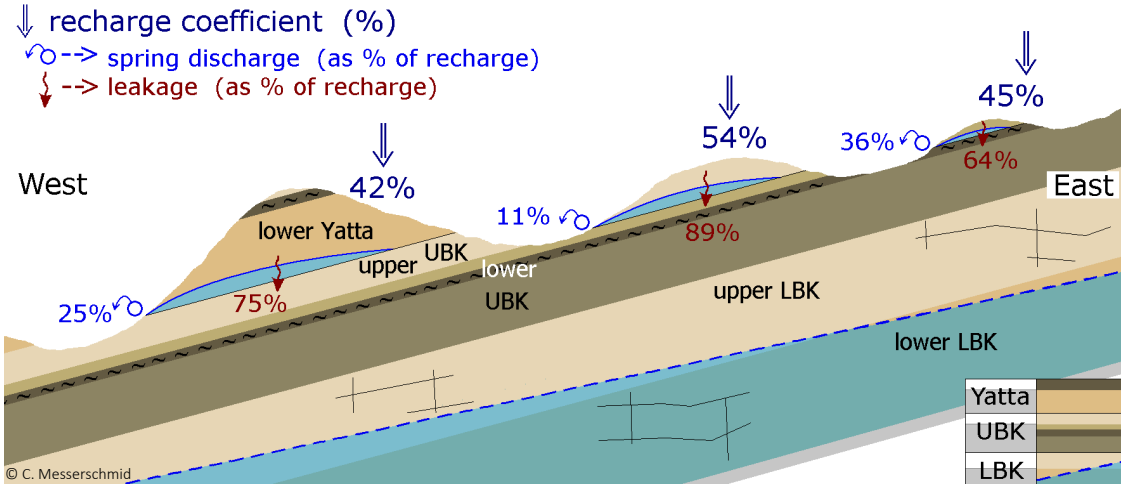

Figure 8. Water budgets of the three leaky sub-aquifers in Wadi Natuf (as percentage of rainfall)

5 Discussion

5.1 General approach of process representation

PUB research had previously suggested new ways and approaches to describe and estimate distributed basin responses, however, so far mostly focussing on runoff. Relatively few PUB studies have focussed on developing insights into the determination of spatially distributed recharge. For example, Savenije (2010) suggested assigning individual hydrological processes and distinct hydrological functions (e.g. runoff) to different landscape units by dissecting catchments in a semi-distributed way and according to a hydrologically meaningful landscape classification metric. Batelaan & de Smedt (2001) accounted for spatial variation of physical features using a water budget of rain, evapotranspiration and runoff. In Batelaan and de Smedt (2007) long-term recharge largely depended on soil and LU/LC differences (with parameters based on literature values). Aish, Batelaan and de Smedt (2010) could not only draw on physical features but also on hydrological basin response knowledge (water levels) in their water balance model of the Gaza Strip. Several authors used dimensionless numbers of 'similarity patterns' to relate physical form to hydrological impact in basin-wide transfer functions (Berne *et al.,* 2005; Woods, 2003 and Radulovič, 2011). Other authors calibrated parameters of the transfer functions such as soil properties (Ali *et al.,* 2012) or LU/LC, soil and geology (Götzinger, 2006). Simple soil water models at the basin scale for daily recharge estimates in moderate climates were used by Dripps *et al.* (2007) and by Finch (2001) as responses to land cover changes.

This study went a step further – combining deductive (conceptual) and inductive (empirical) approaches to determine spatial variations in groundwater recharge, based on qualitative (dimensionless) and on measured quantitative basin observations alike. Our distribution into distinct classes of recharge potential, we would like to stress here again, was an act of attribution and deduction; it was however, firmly grounded in general physical laws, such as permeability of different lithologies or different forms of land use. Only the second group of soil moisture was empirically quantified by repeated field measurements in the form of soil depth probing. The results of this empirical survey of soil depth distribution for different hydrostratigraphical units are documented in the soil depth matrix in Messerschmid *et al.* (2019), Table D1.

Previous authors (Beven, 2000; Hartmann *et al.,* 2013; Seibert, 1999; Hrachowitz *et al.,* 2013) have contended that a given feature of basin form, such as land use and land cover, soil conditions and lithologies does not translate directly into one single possible impact of basin behaviour and instead, the hydrologic response of a basin is the result of an assembly of overlapping processes governed by the interaction of different sets of physical features; as a consequence several possible sets of combinations of parameters can lead to the same results. Zomlot *et al.* (2015) investigated multicollinearity; they assessed the weight and correlation of recharge controlling factors and found – by order of importance – precipitation, soil texture and vegetation cover to be the most meaningful proxies. Therefore, PUB literature concluded that it is necessary to separately control the different main processes at work rather than simply trying to optimise the exact quantification of employed parameters by ever more sophisticated mathematical models. Such multicollinearity of physical expressions was also clearly observed in Wadi Natuf. This is why we tried to avoid problems of multicollinearity and equifinality by testing three conceptual approaches individually and separately in different groups according to physical basin form (grounded in empirical observation). It should be noted here that this approach was based on general knowledge and understanding of processes that can be observed worldwide; for example, high recharge potential can be attributed to areas with barren rock but also to terraces with tended olive groves, where runoff is inhibited by stone walls, where soils are relatively thin and farmers plough and remove weeds twice a year, which in turn reduces plant transpiration and thus slows down the loss of soil moisture. On the other hand, forests and agricultural plains with thick accumulated soils are known to reduce the infiltration, percolation and hence recharge potential. The same is true for different lithologies of receiving bedrock (like carbonatic, argillaceous and arenitic sediments). Although applicable worldwide in principle, our approach of separately accounting for three land feature groups signals a departure from many of the existing studies in other areas, which probably over-simplified matters by combining and subsuming all types of typical landscape features in one group, which then were split into different classes of basin responses.

As already mentioned, and by contrast to most earlier studies in the WAB, the focus of our

approach was clearly the spatial, not temporal distribution and variability of recharge. This work was based on two assumptions: a) that the seven year rain period of the SM-percolation model is a fair representation of long-term averages of both inter-annual and seasonal distribution of precipitation (see Messerschmid *et al.*, 2019) and b) that each of the selected SM stations is representative of the entire formation. Here we draw on the above results for the spatial distribution of physical features (Table 2) and soil depth (Table D1 in Messerschmid *et al.,* 2019) of the respective formations. In addition, our results confirmed that the temporal distribution of precipitation – usually as events of several days duration – strongly affects the percolation rates; a modelling frequency of daily steps was found appropriate under the particular climatic conditions of the WAB recharge areas in the Eastern Mediterranean mountainsides.

As the main aim of our research, we thereby obtained a detailed differentiation of the spatial distribution of recharge with formation-specific recharge coefficients for all formations in Wadi Natuf, which is a representative catchment for the recharge area of the WAB. The results of our three-way conceptual analysis and attribution seemed to suggest that indeed, slightly different results of overall recharge rates follow from the three approaches. However, the relative closeness of the three results, e.g. the total WAB recharge in Wadi Natuf of 24, 26 and 28 mcm/a, respectively, did suggest that each of the three independent transfer procedures between basin form and response was a realistic representation of the processes at hand. In other words, instead of producing an apparently precise figure for groundwater recharge, our analysis resulted in a less "exact" but more robust realistic and nonetheless close range of recharge quantifications.

5.2 Annual RC – overall basin RC – compare with other studies

As presented already, the individual recharge coefficients for the different formations cropping out in Wadi Natuf lie between a minimum of 0% (non-recharging formations) and a maximum of 57%. For the WAB portion of Wadi Natuf, the total average recharge for each group was found at 20.6, 22.6 and 23.9 mcm/a, respectively. (This is equivalent to a WAB recharge coefficient of 40.8%, 44.6 % and 47.3 %, respectively, within Wadi Natuf.) These overall recharge values fall well into the range, usually quoted for the WAB (see Table A1). Also compare with the detailed table in Appendix H of Messerschmid *et al*. (2019) that lists the regional and other reported recharge coefficients, both for annual and event-based calculations and together with the methods applied therein. Weiss and Gvirtzman (2007) reported maximum recharge for one outstanding year (1988) as 91 % of annual rainfall at the small Ein Al-Harrasheh catchment on the SE edge of Wadi Natuf (Table H1). Allocca *et al.* (2014) found in the Apennine that for single events, up to 97 % of event precipitation may percolate and arrive as recharge at the groundwater table. Rosenzweig (1972) reported that for pasture and grassland at Mt. Carmel Basin, land form-specific recharge can amount to 60 % of annual precipitation. Our findings of a range between <40 % and >47 % of overall annual recharge coefficients lie well in the middle of reported literature (incidentally, Weiss and Gvirtzman's average RC of 47.2 % for Harrasheh sub-catchment matches exactly with our maximum area RC of 47.3 %). By contrast, RC-values determined in recent studies in the Eastern Aquifer Basin at 33 % in the upper slopes (Ries *et al.,* 2015) and 25 % in the lower slopes near the Jordan Valley (Schmidt *et al.,* 2014) ranged somewhat lower; this is according to expectations due to the more arid climatic conditions with less precipitation and higher evaporation rates.

5.3 Leakage

The water budget calculations of perched groundwater leakage were only possible due to the well controlled boundary conditions and recharge area of the isolated hillside aquifers: here, all recharge that did not discharge at the springs could be considered leakage. The calculation was simplified by using annual rates of spring group discharge, allowing only for approximations of leakage rates. Yet, this still constitutes a progress since groundwater leakage usually evades observation and had never been documented before in the WAB under such controlled conditions. Previous studies by Peleg and Gvirtzman (2010) and by Weiss and Gvirtzman (2007) did not target truly perched aquifers, but instead assigned quasi-perched conditions for the regional and well-connected un-perched aquifers in the West Bank Mountains. In addition, their approaches were not based on independent measurement-based recharge input but

instead modelled the two unknowns of recharge and leakage simultaneously and by employing indirect methods of lumped modelling and calibration to reach their alleged "leakage" coefficients.

In this study, the annual spring group outflow budgets were was based on the assumption that individual years could be budgeted individually. Here, it should be noted that in the small, local springs of the perched aquifers, multi-annual storage within the matrix porosity of the aquifer formations was extremely low if not negligible. In other words, multi-annual storage and flow of groundwater played a very minor role if any at all. For comparison, see Fig. 8 in Messerschmid *et al.* (2019) that depicts the spring hydrographs of the daily read springs (compare also with the findings by Schmidt *et al.,* 2015 in a larger spring, located in a catchment adjacent to Wadi Natuf but within the EAB). By contrast, the regional springs, such as two enormously strong principal spring outlets of the WAB, which under natural conditions drained the entire basin with annual discharges of up to 220 mcm/a, are well known for their multi-annual storage and delays in discharge.

As already mentioned in section 3.6, the spring group discharge budgets were based on a somewhat simplifying approximation, assuming that annual variations of spring flow reflected precipitation variability. This is not necessarily accurate because for the same annual precipitation rate, the event character of precipitation and recharge processes may lead to different recharge results, depending on the seasonal and event distribution of precipitation and soil moisture storage. However, according to the PUB recommendations, some simplifications are necessary, particularly in otherwise ungauged basins. It should be noted here that this simplifying approach was not used for recharge calculations but only employed in the local spring group budgeting for the sake of estimating annual groundwater leakage rates.

In addition, we were also able to test our approach of averaging the winter and summer flows of the spring groups (during the key date campaigns) as a proxy for average daily spring discharge throughout the year, by using the five closely monitored and daily read springs within these spring groups as comparison. Our statistical analysis showed that the five selected springs were clearly representative for the respective spring groups as a whole: when we compared the shares of these springs with the total group flow during each of the campaigns, we found a low standard deviation of 1.15% for Beitillu and 0.72% for Wadi Zarqa spring groups (for more details, see Messerschmid *et al.*, 2019, App. F).

The final results for the three perched leaky aquifers in central Wadi Natuf indicated high to very high rates of leakage between 65 % and 89 %; this confirmed the tentative qualitative field observations, e.g. that the underlying aquitards were only very partially confining. With a leakage of almost 90 % it may seem justified to combine the lower two perched aquifers (u-UBK and top of l-UBK) and consider them as one local aquifer unit, at least in some places (e.g. Beitillu), see sections 2.1, 4.4. This discrimination between individual and combined aquifers or in other words, their degree of separation or hydraulic connections could be discerned in the field by the geometry of the spring groups, i.e. their alignment along the outcrop lines of contact between the perched aquifers and the aquitards beneath (see section 2.1).

6 Conclusions

This study contributes to the assessment of distributed recharge in a Mediterranean karst area with a pronounced annual rainfall pattern of two seasons (dry and wet) and with a high variability in lithostratigraphy and other related landscape features. In line with the findings of the PUB decade, it was possible to solidly ground our basin classification for dominant recharge processes in observations of the physical form and based on fundamental laws of physics. We found an accentuated spatial variability of percolation fluxes and a strong dependency on three main groups of physical form, namely LU/LC, soil thickness and lithology. For the first time in the WAB, our study used a truly distributed approach for a great variety of different physical land forms by employing extensive direct field observations and intensive multi-seasonal measurements. To extrapolate our findings, we ran three independent sets of basin classification and grouping in classes of recharge potential as observed in our study area.

While our regionalised recharge coefficients originated from plot-scale measurements, the results matched closely with long-term observations reported in the WAB literature. The application, attribution and extrapolation of these coefficients for other, unmonitored formations reflect the ranges

of recharge reported in the same region (WAB and environs) by previous studies that used lumped outflow-based basin-wide modelling (without spatial recharge differentiation). For the leakage estimation, another condition had to be met, namely that the perched aquifers under investigation are erosionally isolated and thus laterally disconnected from other parts of the catchment in order to apply our simple budget calculation.

On the side of spatial differentiation and given the lack of existing hydrological measurements, our approach followed the three way compromise prescribed by PUB (Beven and Kirkby, 1979) between the advantages of model simplicity, the complex representation of spatial variability of hydrological basin response and the economic limitations on field parameter measurement. This was done by applying the simple cooking recipe of Sawicz *et al.* (2011) for regionalisation in ungauged basins, namely classification (to give names), regionalisation (to transfer information) and generalization (to develop new or enhance existing theory).

Our formation-specific RC-values could be further regionalised and applied to other catchments within the WAB and tested in other comparable sedimentary basins with semi-arid to sub-tropical climate, in or outside the Mediterranean. Last not least, we believe that our general methodology, i.e. our schematic basin classification framework (Table 2), which is based on physical sub-basin differentiation and classification (as recommended by PUB), can be applied to any region and basin in the world, where physical features of different kinds can be discerned and attributed to different litho-stratigraphical formations.

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APPENDIX

Table A1 below lists the detailed results of the regionalization of RC-values for individual formations (see also Table 4) and independently for each group of physical features. The table refers to the entire catchment, including WAB, EAB and the erosion zone between the two. The arithmetic mean of the results of all three physical feature groups is indicated in the column to the right. The ranges of recharge coefficient for individual formations lay between 57% and 0% of annual rainfall, each depending on the individual land use, geology and soil type conditions of the formation. The order of formations in this table is listed as groups of differing aquifer potential (second column from the left), from the very permeable and productive regional aquifers reaching, in average of all three physical feature groups to over 50% RC (strong blue) down to in average 42% RC for the weak, somewhat aquitardal local aquifers (brown fonts). The aquitards are assumed as impermeable and contributing no recharge. The relative weight of recharge of each aquifer type group is indicated under "group fraction", indicating the contribution of each group of respective aquifer types between almost 60% (regional aquifers) and only 10% (weak aquifers) of total recharge, summing up to 100%.

The average of total area recharge in Wadi Natuf as arithmetic mean of the three physical landscape feature groups lies at 43.1 %. It should be noted that although the regionalisation was performed for each group of physical features independently, the differences in individual formations equal out to very similar overall recharge rates of approximately 27 ±2 mcm/a (or as percentage, between 39% and 46%), as average over the seven-year measurement and modelling period.

Table A1. Recharge of all formations and aquifer groups in all of Wadi Natuf, detailed by groups of physical features (as coefficients and annual recharge rates)

For-mation	Aquifer Group	Area km²	Ø P mcm/a	RC (%)			Recharge (mcm/a)			Group Rech. (mcm/a)			Group fraction (%)			Group RC, Natuf (%)			Ø RC (%)
				LU/LC	Soil	Geol	LU/LC	Soil	Geol	LU/LC	Soil	Geol	LU/LC	Soil	Geol	LU/LC	Soil	Geol	Σ Natuf
Al	Alluvial	1.5	0.8	45.3%	57.3%	57.3%	0.4	0.5	0.5	0.4	0.5	0.5	1.6%	1.8%	1.7%	45.3%	57.3%	57.3%	53%
l-LBK	Strong Regional Aquifer	16.4	10.2	45.3%	57.3%	57.3%	4.6	5.9	5.9	13.3	15.8	16.3	55.1%	59.1%	58.1%	45.3%	54.0%	55.8%	52%
Jerus		9.3	5.1	45.3%	57.3%	57.3%	2.3	2.9	2.9										
u-LBK		13.2	8.2	45.3%	54.1%	54.1%	3.7	4.4	4.4										
Heb		10.1	5.8	45.3%	45.3%	54.1%	2.6	2.6	3.1										
u-UBK	Inter-mediate Aquifer	2.4	1.5	54.1%	54.1%	54.1%	0.8	0.8	0.8	7.4	7.4	8.3	30.7%	27.7%	29.4%	44.6%	44.7%	49.8%	46%
l-UBK		8.4	5.3	44.7%	44.7%	49.4%	2.4	2.4	2.6										
u-Bet		7.7	4.3	44.7%	45.3%	49.4%	1.9	1.9	2.1										
l-Bet		9.8	5.6	41.8%	41.8%	49.4%	2.3	2.3	2.8										
E.Q.	Weak Aquifer	1.8	1.1	41.8%	45.3%	41.8%	0.5	0.5	0.5	3.0	3.1	3.0	12.6%	11.5%	10.8%	41.8%	42.3%	41.8%	42%
l-Yat		10.2	6.1	41.8%	41.8%	41.8%	2.6	2.6	2.6										
Senon	Aquitard	2.4	1.4	0%	0%	0%	0	0	0	0	0	0	0%	0%	0%	0%	0%	0%	0%
Qat		4.6	2.7																
Tam		0.1	0.03																
u-Yat		4.9	2.9																
Total		**102.6**	**61.1**	**39.4%**	**43.9%**	**46.1%**	**24.1**	**26.8**	**28.1**	24.1	26.8	28.1	**100%**	**100%**	**100%**	**39.4%**	**43.9%**	**46.1%**	**43.1%**

Note that the above values are surface catchment based, including both, WAB and EAB. The table indicates the outcrop area of each formation in Wadi Natuf and the respective area rainfall (here taken as area average and seven-year average for the sake of comparison).