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Field-based groundwater recharge and leakage estimations in a semi-arid Eastern Mediterranean karst catchment, Wadi Natuf, West Bank

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Abstract

Groundwater recharge processes in semi-arid climates are highly sensitive to spatial and temporal variability (event precipitation). However, in previous research, the spatial distribution of recharge has received relatively little attention. This study differentiates recharge according to the following spatial characteristics: a) soil type and soil condition, b) land forms such as relief, vegetation and land use, and c) lithology and hydrogeological characteristics of the subsurface rock formation. For the first time, this paper analyses and quantifies the specific recharge in the different individual rock formations of the Western Aquifer Basin (WAB). The WAB is a large transboundary karst aquifer that stretches from sub-humid to semi-arid climates from the recharge area in the West Bank Mountains to the Mediterranean Coast. The assessment is based on actual field data, including soil moisture and spring discharge in Wadi Natuf, a 103 km^2 large sub-catchment in the West Bank slopes and mountain region, i.e. the recharge area of the WAB.

A parsimonious soil moisture balance model was set up to calculate daily recharge rates from daily precipitation and evapotranspiration records over an extended period of 7 years (2003/04–2009/10). Unlike in most comparable studies, the simple but solid parsimonious soil moisture and percolation model and the budget calculations were based on actual quantitative field-observations, in contrast to the generally applied model fitting and inverse calibration. The model's daily deep percolation rates were compared with soil moisture field-data and in addition, by comparing major event recharge depths with daily spring discharge response.

This combination of modelling and intensive field measurements, comprising eight different soil moisture measurement stations in six different litho-facies formations allowed identifying and quantifying the recharge characteristics of each formation at high spatial resolution, which is a first in the Western Aquifer.

We found that recharge varies widely at the spatial dimension, ranging between 0 % and almost 60 % of annual rainfall. The spatially variable long-term average recharge coefficients were applied to other outcropping formations by a ranking procedure taking into account each of the three above spatial characteristics (landform, soil and geology).

In addition to the recharge analysis, special emphasis was paid to the examination of the role of perched leaky aquifers positioned between the main regional Upper and Lower Aquifers. The particular geometry of the local aquifers, i.e. hills with well-defined aquifers, leaky aquitard bases and therefore well-defined catchment areas, allowed the quantification of the flow budget. By measuring and budgeting spring group discharge of each leaky sub-aquifer, for the first time also leakage coefficients could be calculated empirically.

The methodology of this study is also applicable to comparable catchments and aquifers outside the region. The resulting mean annual recharge coefficients allow the prediction of the spatial distribution of recharge at any given sub-catchment or management cell size, also beyond Wadi Natuf (in a follow-up paper).

Keywords: perched karst aquifer discharge, parsimonious soil moisture balance model, recharge coefficients, spatial recharge distribution and ranking, aquifer leakage

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1 INTRODUCTION

The Western Aquifer Basin (WAB), also called Aujah-Tamaseeh or Yarkon-Taninim Basin, is a large (9,000-14,000 km^2) carbonate multi-layer aquifer system that is of strategic importance for the water supply of Israelis and Palestinians, providing ca. 20 % of the region's water resources. While the underlying regional aquifers are mainly exploited by Israel, Palestinian villages only have shallow wells in the Upper Aquifer (UA) and otherwise depend on karstic springs fed by intermediate local perched aquifers. Detailed knowledge of the temporal and spatial variability of groundwater recharge and leakage from these perched systems is an essential component for sustainable water resources management (SUSMAQ, 2002). Various methods are available to assess recharge and the optimal technique largely depends on system characteristics and data availability (Simmers et al., 1988; Lerner et al., 1990; De Vries et al., 2002, Scanlon et al., 2002, 2006; Lloyd, 1980). Based on Lerner et al. (1990) and Bredenkamp et al. (1995), Dörhöfer and Josopait (1997) distinguished two principle avenues or procedures for the assessment of groundwater recharge: Firstly, direct procedures to understand, conceptualize, simulate and quantify as closely and differentiated as possible the different components and processes of inflow (infiltration and percolation), taking into account evapotranspiration, surface runoff, interflow, and soil moisture balance. Secondly, indirect, integral procedures based on the assessment of groundwater discharge (such as spring flow, baseflow, and well abstractions) or the assessment of storage changes within the aquifer (Dörhöfer and Josopait, 1997). Especially for karst regions it is important to distinguish between direct (i.e. percolation through the unsaturated zone) and indirect recharge (i.e. localized infiltration after runoff concentration at the surface). For the perched aquifers in the WAB, indirect recharge via transmission loss processes from ephemeral wadis can be neglected. The wadis are deeply incised and all springs emerge above the talgrund of the Wadis. Hence, all spring water in the leaky aquitards is considered to come from the slopes, hilltops and plains above the spring position (Figure 7, Ch. 4). Therefore, concentrated allogenic inputs such as transmission losses cannot contribute to the recharge of the intermediate perched aquifers within the regional aquitard complex. Thus, precipitation can directly be equated with hydrologically effective rainfall (HEP, Bradford et al., 2002).

Moreover, total surface runoff from Wadi Natuf was found to be negligible in an annual balance with overall 0.11 % runoff coefficients (Messerschmid et al. 2018). Direct recharge to the WAB was usually estimated by empirical relationships that relate cumulated annual groundwater discharge at springs and wells to annual rainfall (Goldschmidt and Jacob, 1958; Guttman et al., 1988; Guttman and Zukerman, 1995; Berger 1999). Here, spatially distributed methods that estimate mean annual recharge from surface characteristics (e.g. Andreo et al., 2008) may provide more spatial detail, but have not yet been applied in the WAB. However, spatial characteristics of different lithologies, land forms and soil conditions are of outmost importance to actual recharge (Dvory, et al., 2016, Hartmann et al., 2012 and Allocca et al., 2014). Such spatially differentiated recharge factors were applied by Andreo et al. (2008) and Radulović et al. (2011). Radulović used a matrix of many different factors, meteorological, lithological, landform and structural factors, set up in a matrix of ranked weight. And he called for formation specific data to quantify the main ruling factors for recharge.

In order to understand these processes conceptually, three sets of determining factors can be identified: a) soil moisture storage that largely depends on the soil type and field capacities at different locations, which in turn are strongly correlated to the thickness of the soil in situ; b) Deep percolation / infiltration from the soil via the unsaturated zone also depends on the receptiveness of the underlying bedrock formation that forms the unsaturated zone of the aquifer (Hughes et al., 2005). Recharge infiltration is determined by the lithology and rock type, the degree of karstification and primary porosity as well as by such factors as degree of fracturing and other structural features. Based on a highly simplified approach for large areas in Spain, Sanz et al. (2011) only accounted for three fundamental factors: Precipitation, temperature and in particular, lithology as "the decisive factor, largely responsible for determining recharge rates". They attributed specific RC-values in their ranking of relatively broad groups of lithology, such as alluvial, carbonates, pelites and hard rock; c) Changes in land use and land cover (LU/LC) often outweigh the impact of climatic change on groundwater recharge. This was demonstrated by Scanlon et al. (2006) in their global literature review. Therefore, recharge processes can be generalised and attributed to three different groups, namely geology, soil and landform dominated recharge. Since these three factors strongly depend on the spatial distribution of in-situ conditions such as lithology, soil and landform, the researcher has two options: Either introduce indirect ~~theoretical~~ values from the literature and fit the parameters by ~~repeated~~ calibration, or invest into detailed field work in order to empirically assess and control the spatial variability of the spatial physical factors determining recharge. In contrast to former studies, this analysis will use measured field data and data-based calculations to provide the basis for a spatially distributed recharge assessment.

As for the temporal dimension, and in particular semi-arid climates, annual values for recharge coefficients were found to underestimate recharge. This is why Cheng et al. (2017) postulated to determine recharge on a storm-event basis. This claim was corroborated by a nearby field study that fitted a soil moisture balance model to soil moisture measurements and identified recharge pulses (Ries et al. 2015, 2017). Other field studies quantified event water balances during sprinkling experiments and pointed to the importance of soil saturation for surface runoff and recharge (Lange et al., 2003). Cave drip studies (Frumkin, 1994, Bar-Matthews et al., 1995, Sheffer et al., 2008, 2011) provided point insights into recharge processes, and, combined with hydrological tracers, assessed fractions of old and young recharge waters (Arbel et al., 2010, Lange et al., 2010). However, it is difficult to extrapolate the results from plot scale field experiments or from localised sub-catchments (1km^2, Steinmann, 2010 and Grodek et al., 2011) to larger areas in the WAB, where different geology and surface characteristics prevail (Steinman, 2010). In a humid-temperate environment, Geyer et al. (2008) managed to assess the temporal distribution pulse at the groundwater table of the rapid recharge component by analysing the temporal pattern of the karst spring discharge.

Larger scale recharge studies in the WAB mostly assessed the average actual recharge into the over- and underlying regional aquifers and as such neglected perched upper aquifer layers, simplifying them as regional aquitard (Weinberger et al., 1994). Most studies used numerical models and indirectly assessed average recharge by fitting their Darcian approaches to storage changes in the regional aquifer (e.g. Goldschmidt and Jacob, 1958; Guttman et al., 1988; Guttman and Zukerman, 1995; SUSMAQ, 2005; Dafny et al. 2008, 2010; Hughes et al., 2005, 2008). Sheffer et al. (2010) modelled recharge in the WAB on a daily basis coupling a water balance approach with a groundwater model. Besides pan coefficient and soil thickness, they fitted recharge coefficients for two classes of lithology, namely limestone/dolomite and chalk/marl. Abusaadah (2011) presented a three-dimensional integrated flow model encompassing plains and slopes as separate recharge and flow zones. However, also here, accuracy was limited due to missing data and limited temporal resolution of measurements. He thus called for refined meteorological input, as well as for more details on land use, soil, geology and structural characteristics in the WAB, as many others had done before in other areas (Martínez-Santos and Andreu, 2010).

Groundwater recharge studies, assessing recharge through the spring discharge from well-defined small-scale perched aquifers offer main advantages for the quantification of recharge above other types of techniques: They allow direct measurement of the recharged groundwater, they allow recharge assessment in areas with thick unsaturated zones, such as karst and fractured rock aquifers, they have well defined catchments and account for the spatial variation of the above physical factors, and they allow for the analysis of the temporal variation of the storm-event, important in semi-arid recharge studies. The problem with perched aquifer studies is that leakage through the bottom layer of the aquifer cannot be quantified easily.

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Only very few authors studied perched aquifer systems per se. Peleg & Gvirtzman (2010) and Weiss & Gvirtzman (2007) studied recharge in perched local aquifers and aquitards on small-scale erosionally isolated groundwater catchments simulating spring discharge from these units by numerical models. Their monthly spring flow data did however not reflect the event character of recharge. Weiss and Gvirtzman (2007) treated "the bottom unsaturated layer as if it is saturated". Only Peleg and Gvirtzman (2010) accounted for quantified downward leakage into the deeper layers. They conducted a groundwater flow modelling of multiple-horizon perched karstic aquifers and springs in isolated aquifers, that partly cover strata usually assigned as belonging to the main regional aquitard. However, their model did not include soil moisture balances and was not empirically confirmed by field data. Instead, it was entirely based on the reconstruction of spring outflow and recession curves for the evaluation of hydrological characteristics of the different litho-types and formations. Leakage and transfer rates were found by manual calibration through "trial and error" for each parameter and through numerously repeated model test runs (Peleg and Gvirtzman, 2010: 23).

This study aims at the estimation of lithology-, soil- and landform-specific recharge for the formations in the carbonate aquifers of Wadi Natuf, located in the central WAB and in addition, the assessment of leakage through the perched aquifer bottom. Using high-resolution measurements of precipitation and soil moisture, groundwater recharge is forward calculated as deep percolation (DP) by a parsimonious soil moisture balance model, and compared with spring group discharge measurements to determine downward leakage. We expect that the resulting classification into "recharge units", i.e. units of uniform properties with respect to recharge generation (underlying bedrock lithology, soil type/thickness and landform) will allow the regionalisation to other parts of the WAB, as well as to other leaky carbonate aquifers in comparable settings.

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 asl down to its foothills at 138 m asl (Figure 1). The topography is characterized by undulating hills with deeply incised ephemeral rivers. Within the Natuf catchment, all sub-aquifer formations of the WAB and some of the overlying cover series crop out (Figure 1) and are therefore exposed to direct infiltration. The climate is typically Eastern Mediterranean with rainfall amounts monotonously rising from the semi-arid Western foothills to sub-humid conditions in the Eastern Mountains. Wadi Natuf drains westwards to the Mediterranean Sea and has a low overall runoff coefficient of approximately 0.11 %, mainly due to considerable transmission losses (Messerschmid et al., 2018) into the karstified carbonate materials underlying the wadis. 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) and a Western Aquifer Basin (WAB) on the slopes and foothills of Wadi Natuf. The WAB extends between 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 (Figure 1a).

The general formation dip is 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 (Figure 1). Conventionally, the WAB is subdivided into two main regional aquifer units – the 'Lower Aquifer' of Lower Albian age and the 'Upper Aquifer' of Upper Cenomanian to Turonian age and cover around two thirds (64.4 %) of Wadi Natuf. They are entirely carbonatic and in most parts strongly karstified. According to this conventional view, they are divided by some 100 to 150 m thick marly, chalky and carbonatic series of the so-called 'Middle Aquitard' (Bartov et al., 1981; SUSMAQ, 2002; Messerschmid et al., 2003a, 2003b; ESCWA–BGR, 2013).

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However, closer scrutiny reveals that this regional 'Middle Aquitard' can be further subdivided into an aquitard or even aquiclude section of yellow soft marl (u–Yat) and more carbonatic, and in parts karstified intermediate perched aquifer horizons (l–Yat) that give rise to numerous small local springs (Messerschmid et al., 2003a, 2003b), together covering 13 % of the catchment (Table 1b). They form one focus of the present study. The carbonates – limestones and dolomites – and marls are complemented by smaller portions of chalk, clay and chert in several of the lithostratigraphic units, especially within the Middle Aquitard. Also within the bottom aquitard of Aptian to Lower Albian age, some aquiferous units (Ein Qinya formation) can be found and give rise to local springs along their small outcrop areas near the anticlinal axis (Messerschmid, 2003). 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 and dipping are the principle structural features that dominate and direct groundwater flow. In the intermediate aquifers of the central study area, deeply incised Wadis erode and often completely isolate small local aquifers in individual hills or hill groups. This is in contrast to the thick regional aquifers that form two all-encompassing storage and groundwater flow systems. While small contact springs (Fetter, 1994) emerge in large numbers from the isolated intermediate perched aquifers, the recharge areas of the regional Upper and Lower Aquifers on the western flanks of the West Bank are almost entirely void of springs.

The soil cover in Wadi Natuf consists of terra rossa, mostly with thicknesses in the decimetre range. Although regional maps indicate small portions of rendzina in the central part (near Ras Karkar, Figure 1), no such types of soils were found during intensive field reconnaissance and measurement campaigns. The soils have high clay contents and form desiccation cracks during the dry season. During the early half of the winter season, these cracks can act as preferential pathways for infiltration, until the soils swell and cracks close during winter and early spring. Soil thickness was found to strongly correlate with lithology and landforms. These landforms (Messerschmid et al., 2018) in turn, are attributed to relief, topography, vegetation and land use and strongly correlate with formational geology (Figure 2). Except for small plains over the aquitard series (upper Yatta formation), no soils with thicknesses larger than one metre were found. Tables 7 and A–1 show the typical soil thickness for different formations in Wadi Natuf. Land use and vegetation can also be categorised according to the underlying geology. In the mountains, terraced hills with olive groves dominate, together with grassland and shrubs, beside some barren hills with rock outcrops. The central study area is characterised by formerly used terraces and a relief of stepped hills, a result of both, bedding characteristics and lithology types. This area contains some small plains with agricultural fields (and thick soils) and some areas of exceptional coniferous forest (Messerschmid, 2014). Finally, the foothills in the East exhibit more rock outcrops and grassland with shrubs, together with some olive groves in alluvial plains along the banks of the wadis. This correlation of underlying geology with relief, climate, soil thickness, vegetation and land use is a striking feature of Wadi Natuf. It allows categorizing key elements of recharge with lithological and hydro-stratigraphical characteristics and a ranking of aquifer and recharging potential for different formations.

3 METHODOLOGY

3.1 Regionalization

Available geological maps (GSI, 2000, 2008; Rofe and Raffety, 1963) were updated in the field with special emphasis on refining the hydrostratigraphy. To obtain an overview of soil conditions for different formations, a matrix of typical soil depths for the local formations and landforms was

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established, based on extensive field mapping and sampling (Table 1a, Table A–1). Finally, the outcrop, i.e. recharge areas for the different sub-aquifers and isolated intermediate karstified perched aquifers were delineated by field characterization, mapping, structural and hydrogeological considerations (SUSMAQ, 2001). Thereby it was found that the outcrop areas of most isolated perched aquifers were fully underlain by aquitards (Figures 2a and 3a), as already noticed by Weiss and Gvirtzman (2007) and Peleg and Gvirtzman (2010), e.g. by twin marl bands. This finding allowed for an accurate localization of recharge catchments for each of the isolated perched aquifers and for the calculation of the total annual outflows by the daily measured spring flow data in the respective spring groups. Based on the key date measurements, the total average multi-annual spring outflow per spring group was determined and then the other years calculated according to the specific area rainfall of each year and in each sub-catchment.

3.2 Hydrometric measurements

During a nine year period (2003/04–2011/12) extensive field measurements were conducted, which included records of precipitation (11 tipping buckets and 9 daily rainfall totalizers), weather (2 automatic weather stations; AWS, Type Campbell Scientific with CR10X data logger[1]) in the mountains and foothills, soil moisture (8 soil moisture monitoring plots in half-hour steps), dozens of manual soil moisture sampling sites and daily volumetric spring flow measurements at five individual springs. Field measurement campaigns targeted at the entire number of over 100 springs in Wadi Natuf and were carried out at four reference dates during summer and winter conditions, respectively. These reference date measurements facilitated the regional extrapolation of local daily spring readings to total sums of spring flow for the different aquifer units, either in daily steps or as annual discharge. In order to increase the representativeness of point-scale measurements, parallel soil moisture measurements were carried out at different parallel locations during the field campaign (Table 1a). As a result, SM was measured at eight locations covering six different litho-facies of five formations. All in all, 13 yearly data records of SM-measurements could be obtained, despite data loss, vandalism and damaged field devices. We used ML2-Theta probes (Delta-T Devices Ltd., Cambridge, GB) and ECH2O (Decagon Devices, Inc., Pullman, USA) sensors and loggers, with two to three sensors per plot, installed at depths between 5 and 75cm (Table 1a) and run in half-hour mode. During the period 2003–05, after heavy rain storms, the sensor readings were compared with gravimetric SM lab measurements from hand-collected soil samples at most sites.

3.3 Water balance calculations (SM model)

A parsimonious, soil moisture storage spread-sheet model in daily time steps, which was already successfully applied in the adjacent EAB (Schmidt et al., 2014, Sauter, 1992, Rushton et al., 2006 and Geyer, 2008), was set up with local field capacity and welting point conditions observed in the field. The daily model time step corresponded to daily spring measurements and allowed for the identification of individual recharge events that typically last between one and four consecutive days (Messerschmid et al., 2018). The model input consisted of measured rainfall from the nearest tipping bucket or from the area rainfall in the respective sub-catchment (Messerschmid et al., 2018) and of potential evapotranspiration applying the Hargreaves formula (Hargreaves et al. 1985). For this purpose, mean, maximum and minimum values of maximum air temperature and incoming solar radiation were calculated from the two stations installed in Wadi Natuf[2]. Missing data were filled with Jerusalem station data (IMS, 2015).

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[1] Sensors: Wind – WSS1 (033040), Temp./Rel. humidity – HMP45D (Y3520067), Rain gauge (TB) – ARG100/LX (033505)

[2] For the calculation of potential evapotranspiration ETp, the Hargreaves-equation (Hargreaves and Samani, 1985) was selected. It was developed for semi-arid conditions comparable to the Mediterranean climatic characteristics (i.e. mean temperature, mean annual precipitation depth, precipitation distribution during the course of the year): $ET_p = 0.0023*Ra*(T_{mean}+17.8)*(T_{max}-T_{min})^{0.5}*\lambda^{-1}$

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At each individual site, measured soil moisture values from different depths were averaged and transformed into a daily value of available water AW [mm], according to the field capacity (FC) [%], wilting point (WP) [%] and local soil depth [mm]. As FC the maximum observed SM plateau value was taken. WP was graphically derived from the observed residual minimum SM prior to the first winter precipitation (Table 1a). Effective field capacity (FC_e) [mm] for the model was calculated as the difference between FC and WP and multiplied by soil depth, available water AW (mm) as the difference of measured SM and WP and multiplied by soil depth. It should also be noted that frequently during strong storm events, and particularly in the early half of the season, brief SM peaks (Table 1a) exceeded the plateau values of FC. These overshots can be interpreted as short periods of over-saturation (e.g. Ries et al. 2015) or as bypass flow through preferential pathways (desiccation cracks) in the aggregate soil texture under dry conditions (Ireson and Butler, 2013, Limbrick, 2002). Those SM peaks are fully accounted for by the spread–sheet model for soil moisture budget calculations shown below. The observed values for SM peaks in Table 1a were corrected to available SM, as in the case of effective FC, by deducting WP from measured soil moisture values.

The soil moisture model was tested in the adjacent EAB (Schmidt et al., 2014) and is based on the following two steps: First, when the shallow soils of Wadi Natuf were sufficiently saturated up to field capacity, actual evapotranspiration equalled potential evapotranspiration; when AW fell below daily potential evapotranspiration ETp (mm), actual evapotranspiration Eta (mm) was limited by water availability:

Eq. 1
$$ETa_{i+1} = \begin{cases} ETp_{i+1} & \text{if } (AW_i + P_{i+1}) \geq ETp_{i+1} \\ AW_i + P_{i+1} & \text{if } (AW_i + P_{i+1}) < ETp_{i+1} \end{cases}$$

where AW is available soil moisture (mm), P daily rainfall (mm), ETa daily actual evapotranspiration (mm) and ETp daily potential evapotranspiration (mm).

Second, all additional rainfall infiltrating from the surface and beyond the daily evapotranspiration losses can either be added to the AW storage, or, when FC_e limits are exceeded, is considered to percolate into the bedrock and represent recharge:

Eq. 2
$$DP_{i+1} = \begin{cases} 0 & \text{if } (AW_i + P_{i+1} - ETa_{i+1}) \leq FC_e \\ AW_i + P_{i+1} - ETa_{i+1} - FC_e & \text{if } (AW_i + P_{i+1} - ETa_{i+1}) > FC_e \end{cases}$$

Eq. 3
$$AW_{i+1} = AW_i + P_{i+1} - ETa_{i+1} - DP_{i+1}$$

where DP is daily deep percolation, i.e. groundwater recharge (mm).

3.4 Ranking of annual recharge rates for different formations

Daily DP depths (mm/d) were transformed into yearly recharge rates for each soil moisture measurement station and its respective perched aquifer formation and spring group by multiplying annual DP (mm/d) with the delineated recharge area of the aquifer outcrops:

Eq. 4
$$R = \sum DP_i * AREA * 0.001$$

where R is the annual recharge [m^3/a], AREA [m^2] is the delineated recharge area of the permeable formation and the sum $\sum DP_i$ of daily percolation rates [mm/d] represents the annual accumulated percolation rate in 365 days [mm/a].

As a result, a set of event-based and formation-specific annual recharge values R [m^3/a] was obtained for the five formations monitored by SM measurements, three of which perched intermediate aquifers and another two regional aquifer formations (Table 1a).

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The modelled formations cover the entire range of recharge potential in the aquifers of Wadi Natuf, from the low permeability aquifers with the least recharge potential to the most highly developed, karstified and highly permeable regional aquifers (Jerusalem and Hebron formations, see Table 1a). The pure aquicludes, such as the yellow marls of upper Yatta formation, were considered void of recharge. They are unfractured and with Dvory et al. (2016) can be attributed zero effective matrix porosity.

The remaining five unmonitored formations belong to the Lower Aquifer (l–LBK, u–LBK), the Upper Aquifer (l–Bet, u–Bet) or to a very deep isolated aquifer, separated from the West Bank Group (Ein Qinya). Their recharge potential was grouped according to the three main recharge criteria under three different scenarios[3] – a landform-based scenario as alternative 1 (A.-1), a soil-based (A.-2) and a lithology-based scenario (A.-3) – and ranked accordingly. All three sets of factors are correlated: A.-1 groups the formations according to relief, slope, vegetation and land use, A.-2 according to soil conditions and depth and A.-3 according to litho-facies, karstification, porosity, weathering, joint density and other structural features, mapped in the field (see also Messerschmid et al., 2018). The highest recharge potential in all scenarios was attributed to the uppermost, Turonian (Jer.) and lowermost, Upper Albian (l–LBK) formations (Table 3), as determined in the soil moisture model and budget calculations. The ranking position of the other formations differed between the alternative scenarios. This means that the overall range in annual recharge coefficients (percentage of recharge relative to total precipitation) between the most and least recharging aquifers does not change between the alternatives but is determined by the model and budget calculations. Our ranking distribution only affected the relative position of a formation within the ranked spectrum. The annual recharge coefficients (RC, in % of annual rainfall)) of the soil moisture model and budget calculations were applied to the sub-area rainfall of each formation to obtain annual recharge rates (m^3/a) under each scenario.

3.5 Water balance calculation of spring groups and leakage determination

The water budget for each of the hydrogeologically discrete, isolated spring groups was calculated, based on the measured and calculated spring group outflows and on the inflows, i.e. the modelled formation recharge.

The final step of the analysis was the determination of annual leakage for different perched aquifers by water budget calculations:

Eq. 5 $$L = R - Q$$

where Q is the annual total spring group discharge from the respective isolated aquifer formation [m^3/a] and L is the downward groundwater leakage into underlying strata [m^3/a]. The flow rates were also area normalised to mm/a, as shown in the tables. Q was calculated from single springs to the entire aquifer unit for the year 2003/04 using the reference date measurements of all springs as described above. Then this annual budget was applied to other years according to the area rainfall of the different years in each of the sub-catchments. As already mentioned, this study will not focus on the temporal distribution and inter-annual patterns of recharge, but on its spatial variation. The analysis of long-term records with respect to the temporal variation of recharge and the consequential groundwater flow will be the subject of a follow-up paper. The seven years of rainfall measurements can be considered as representative for the long-term range of climatic conditions and a 7-year average of calculated annual RC is believed to be a valid first approximation because the observed years cover almost the entire range of long-term variation in precipitation in the WAB from very dry to wet years (HSI, 2016).

[3] It should be noted that this step, and this step alone, involved non-empirical estimation and attribution.

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4 RESULT

4.1 Water balance spread-sheet model of soil moisture storage and percolation

As shown in Figure 4, measured and modelled soil moisture matched rather closely, especially during periods of high soil moisture. AW values usually dropped down to zero within one or two months after the last major rainfall event. We did not find a ~~single~~ uniform seasonal rainfall threshold for the initiation of deep percolation but rather an accentuated individual pattern of SM increase according to the temporal rain distribution and prevailing temperature and evaporation in each year. At locations with thinner soils, FC_e was reached by mid-November, in the deeper soils by mid-December. Usually, FC_e conditions prevailed during January and February, on rare occasions until April. The season 2005/06 experienced the most intensive rain event of the entire measurement period occurring between 1st and 5th April 2006. The results of the model – consistently in each year and each location – show distinct and marked daily events of deep percolation (recharge) with usually between 11 and 21 days per year, in very wet winters maxima of up to 31 days per year (WZ-hh) and in very dry winters minima of down to only 3 days per year (KF-E) – see also Figure 5.

Also a close correlation was observed when modelled percolation / recharge were compared with monitored spring discharge from the respective perched aquifers (Figure 5). At the beginning of the season, weak percolation events did not immediately translate into increased spring discharge, while strong events generated pronounced discharge responses. This is in line with a dual porosity aquifer model, where towards the end of the dry summer season matrix reservoirs are depleted and act as a buffer to the very rapidly starting and receding karst and fracture flows. Moreover, the individual character of different perched aquifers becomes evident.

4.2 Annual recharge and leakage

A systematic correlation is observed between maximum annual rainfall and maximum recharge (e.g. 742 mm/a in 2004/05). Minimum annual precipitation depths and minimum annual recharge depths do not necessarily correlate. 2007/08 was the driest year (496 mm rainfall), but not the year with the lowest recharge. This clearly shows the importance of the temporal distribution of the storm events and dry intermediate phases controlling water storage in the soil. This had already been shown for a regional WAB recharge model (Sheffer et al., 2010). Therefore, annual precipitation rates cannot serve as a basis for calculations of recharge. The calculation of recharge by a soil moisture balance approach and daily time steps is a prerequisite to account for the temporal variation of soil moisture and a more realistic estimate of recharge rates as stipulated by Cheng et al. (2017).

Table 2 shows that the study accounts for the variations in soil properties as well as a wide spectrum of climatic conditions i.e. it can be considered as representative. The highest recharge rate relative to rainfall depth was found in a catchment underlain by highly karstified Turonian limestone formations (Jerusalem formation) at the Shuqbah soil moisture measurement site, with over 57 % of recharge.

Note, the typically thin (32 cm) soil cover over Jerusalem formation that allowed for rapid saturation of the SM reservoir (only 40 mm FC_e). By contrast, the lowest recharge was determined for Kufr Fidiah (KF), underlain by Upper Albian soft limestones (lower UBK formation). This formation is slightly marly and chalky at its top and characterized by rhythmic alterations of thin marl beds in the main body of the formation (SUSMAQ, 2002). Because of these characteristics, it can be considered as the top confining layer above the regional Lower Aquifer. Moreover, the highest effective water storage capacities (FC_e of 185 and 23 3mm, respectively) were observed for this formation.

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4.3 Ranking of formation-specific recharge coefficients

The annual recharge coefficients (RC) listed in Table 2 were used for a further analysis of overall recharge in Wadi Natuf. The modelled and qualitatively verified RC-values (Figures 4 and 5) for the eight stations in six different litho-facies of 5 different formations were employed to rank all formations in regional and perched aquifers with respect to their recharge potential.

For the different soil measurement sites eight different recharge rates were derived with high spatial resolution. Annual recharge coefficients ranged between 57 % for highly karstified rocks with very thin soil covers and 30 % in marly limestone formations (Table 3). As already mentioned, the eight soil moisture measurement sites represent a large variety of six different lithofacies of five different formations, covering the entire range of hydraulic properties between karst aquifers and marly aquitards. Based on the annual values of the seven year period of the different stations multiannual RC were determined for every formation type (Table 3). The formation-specific RC-values were applied to the average annual area rainfall rate of the respective formation outcrop, and annual sums of recharge were obtained for the five modelled formation types. Next, the different formations were ranked according to their recharge potential, based on Messerschmid et al. (2018). The three alternative scenarios of such ranking order were run independently according to litho-, soil- and landform-properties. Each formation was attributed a specific RC according to its rank in the respective scenario. This was done in order to minimize bias and reduce the arbitrariness of such qualitative, non-numerical evaluations.

Multiannual overall recharge in Wadi Natuf amounts to ca. 44 % of annual rainfall (Tables 3 and 4). This lies well within the range of RC-values reported in the literature for the Western Aquifer and in other carbonatic Cretaceous aquifers, known as "Mt. Aquifer", i.e. the Eastern Aquifer Basin, Mt. Carmel and the Galilee. A detailed table (Appendix A) lists the regional and other reported recharge coefficients, both, for annual and event-based calculations and together with the methods applied therein (Table A4). Weiss and Gvirtzman (2007) reported maximum rainfall 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 A–4). Allocca (1995) 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, landform-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' & Gvirtzman's average RC of 47.2 % for Harrasheh sub-catchment matches exactly with our maximum area RC of 47.3 %). 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) range at the lower end because of its more arid climatic conditions with less rainfall and higher evaporation rates.

The RC-values for the other scenarios A.–1 and A.–3 are documented in Appendix A (Table A–5). Interestingly, the three ranking scenarios of RC resulted in similar overall sums of annual area recharge (because they differ only in their internal ranking distribution, since we adhered to the empirically tested range of maximum to minimum recharge rates. Overall recharge ranges between 24 and 28 Mm^3/a, basin specific recharge in the WAB from 21-24 Mm^3/a and with the soil-based scenario A.-2 in the middle (Table 4). In the landform-based scenario (A.–1) the highest recharge rate is assigned to the cliff-forming u-UBK formation (Figure 3b), followed by the Turonian and Upper Albian formations that typically are covered by terraces or exhibit barren rock and karren fields. The forests and slopes of lower Betlehem (Figures 2a, b and 3c), Ein Qinya and lower Yatta formations show the lowest recharge rates here. In the second, soil-based scenario (A.–2), recharge coefficients are ranked according to soil thickness (Table 1a), analogously to the SM-DP model. Finally, the third, lithology-based alternative (A.–3) has the highest RC in the maturely karstified massive limestone

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formations (lower LBK and Jerusalem), whereas formations with chalk and marl components are ranked at the lower end of the recharge coefficient spectrum. For further discussion on the relationship between landforms and lithology, see Messerschmid (2014) and Messerschmid et al. (2018).

Wadi Natuf surface catchment covers two groundwater basins, as shown in Table 4. The eastern mountain crest of the surface catchment Natuf forms part of the groundwater catchment of the regional Eastern Aquifer Basin (EAB). In addition, the oldest and lithostratigraphically lowest outcropping formations of the Aptian-Lower Albian *Kobar group* (Tammun, Ein Qinya and Qatannah formations, Figures 1b and 6) are hydraulically separated from the EAB and WAB. Therefore, only the areas west of the Kobar group outcrops form the WAB groundwater catchment (85,5 km^2 or 83 % of Wadi Natuf), as shown in Table 4.

4.4 Spring group budget

The daily records of Qos, Bibi and Abu Sa'efan springs represent Beitillu spring group. The springs Salem and ʻAkkari stand for Wadi Zarqa spring group (Figure 6). Spring discharge of the five springs with daily interval records was combined with the four key date measurement campaigns in three seasons. These campaigns covered all springs of the respective spring groups.

Over the four key date measurement campaigns the outflows at the five daily read springs were found representative for the entire spring group outflow. This allowed us to sum up daily spring flows in the five springs to annual budgets of outflows in the entire spring groups. Thus, the annual discharge of the entire spring group was calculated for a reference year (2003/04).

Finally, discharge was determined for the remaining years according to this pattern of annual distribution of rainfall and of flows, observed in the daily springs.

Table 5 shows the annual spring discharge for each spring group. The discharge variation between dry and wet years was found to be 14 % below average discharge for the driest (2008/09) and 26 % above average for the wettest season (2004/05). The spring group discharge rates obviously directly depend on the recharge area of each group (Table 1b).

The annual spring group discharge was calculated with rainfall data from tipping bucket Wadi Zarqa and with the season 2003/04 as reference season.

4.5 Leakage from the perched aquifers

While the different lithostratigraphic formations of the Upper and Lower Aquifers act as individual large-scale regional aquifers (UA & LA), the intermediate perched aquifers providing discharge to the above springs can be grouped into distinctive spring horizons emerging at the boundary between aquifer horizons and the underlying aquitard (contact springs, Fetter, 1994). Individual well defined catchment areas can be attributed to the spring groups. Therefore, for every one of these spring groups, the individual recharge rates of the aquifer formations can be calculated based on measured spring discharge. Independently, based on soil moisture budget calculations, total recharge can be determined. The difference between total recharge and the fracture of recharge leaving the system at the springs can be regarded as leakage from the perched aquifers into the underlying strata (other intermediate aquifers beneath or the regional Lower Aquifer). Table 6 and Figure 7 show leakage coefficients ranging between 64 % and 89 %.

Peleg and Gvirtzman (2010) reported a 25–year average coefficient of downward leakage of 78.1 %[4] in Batir catchment, SE of Betlehem. Their work was based on numerical modelling "*by assuming a*

[4] calculated after: Peleg and Gvirtzman (2010: 24), Table 2. Mass Balance

constant daily recharge throughout the year, which sums up to the average yearly recharge" in their simulations and was based not on event discharge but on distributed monthly spring readings.
Assuming that only a fraction of total recharge (R) leaves the perched aquifers as spring discharge (Q), leakage (L) and leakage coefficients can be determined for each of the different perched aquifer formations. These rates of R, Q and L can then be regionalised to the total outcrop area of the leaky perched aquifers in Wadi Natuf. Figure 7 presents a conceptual model of the three leaky aquifers in Wadi Natuf.

5 CONCLUSIONS

The study demonstrated that empirical field-measurement based and spatially differentiated approaches to recharge in the Western Aquifer Basin are available. They can be employed to better understand recharge mechanisms with the objective to provide an improved quantitative basis for groundwater resource management. As was already mentioned, the formation-specific recharge rates and the overall results of area recharge in Wadi Natuf match well with the ranges, reported for the Western Aquifer and other carbonatic "Mt. Aquifers". Soil moisture and spring discharge measurements, together with parsimonious soil moisture storage and percolation modelling at high spatial resolution for different lithostratigraphic units, soil conditions and landforms allow for reliable estimates of typical recharge coefficients. In addition, comprehensive water budget information, including leakage between perched aquifer formations was presented for the first time.
Further research will comprise the temporal differentiation of inter-annual recharge variations for each formation and their regionalisation to the entire basin. The replication of this model and measurement campaigns for other soil locations within the wider basin would be a valuable endeavour in the future.
The methodology employed here is believed to be applicable to other types of leaky aquifers in the Mediterranean region, under appropriate climatic and hydrogeological conditions. These conditions form the basic assumptions of our analysis in Wadi Natuf and can be summarised as follows:

(a) daily individual spring discharge variations can be considered representative for the entire respective spring group and can hence be regionalised to entire aquifer formations (if necessary with the help of representative key date measurements),
(b) soil moisture measurement plots can be considered as representative for specific aquifer formations, and representative soil thicknesses as well as effective field capacities can be determined,
(c) the measured time series is long enough (in our case seven years) to cover the prevailing climatic variability (wet & dry years),
(d) the recharge potential of the different formations, conceptually depends on a few select and interrelated key factors (lithology, landform, soil thickness) and can be ranked according to these criteria,
(e) the perched aquifers investigated are isolated, and groundwater catchment areas of the corresponding spring groups can be determined with a high degree of accuracy and reliability; recharge that does not discharge at the springs can be considered and quantified as leakage.

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Table 1.a. Soil moisture measurement data by location (in mm and %)

	Beitillu, garden	Shuqbah, grassland	Wadi Zarqa, fields upper terrace	Wadi Zarqa, fields hothouse	Kufr Fidiah, field KF-W	Kufr Fidiah, field KF-E	Ras Karkar, terraces RK-W	Ras Karkar, terraces RK-E
# years measured	1	1	1	1	2	1	4	2
years measured	3/4	3/4	5/6	4/5	5/6–6/7	6/7	5/6–8/9	7/8–8/9
formation	l–Yat	Jerus	Top l–UBK (u–UBK)		Top l–UBK		Heb	
soil depth (mm)	500	320	770	400	650	940	400	400
sensor depth (mm)	110/110/430	110/190	420/660/750	170/360	130/180/390	50/75/175	50/140/320	100/200
SM peak (mm)	149	44	175	93	232	234	119	127
FC (mm)	179	60	172	132	253	237	129	129
WP (%)	8 %	10 %	6.5 %	16.1 %	10.5 %	0.5 %	4.2 %	4.2 %
WP (mm)	40	20	50.05	64.4	68.25	4.7	16.8	16.8
FC_e (mm)	139	40	121.5	67.5	185	232.5	112.5	112.5

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Table 1.b. Outcrop (recharge) area, rainfall and recharge potential of the leaky perched aquifers and the main regional aquifers

Formation	u–Yat	**l–Yat**	**u–UBK**	**l–UBK**	"Upper Aquifer"*	"Lower Aquifer"*
Area km^2	4.931	10.182	2.442	8.441	36.732	29.556
Ø Rain 2003–10[1] (mcm/a)	2.917	6.145	1.502	5.262	20.696	18.452
Potential	- - -	+	+	+	++	++

[1] average precipitation between 2003/04 and 2009/10
* "Upper Aquifer" stands for Hebron, Betlehem and Jerusalem formations; "Lower Aquifer" for upper and lower UBK formations.

Table 2. Direct percolation/recharge (DP) rates, modelled at representative SM locations & litho-facies

(mm/yr) **SM-Infiltr'n (DP)**	**Rainfall$_{(Natuf)}$** ø area	**DP** **Bet**	**DP** **Shuqbah**	**DP** **WZ-hh**	**DP** **WZ-up.T**	**DP** **KF-W**	**DP** **KF-E**	**DP** **RK-W**	**DP** **RK-E**
2003/04	529	291	289	235	188	140	238	238	217
2004/05	742	475	519	465	452	405	442	442	448
2005/06	621	319	293	223	192	145	218	218	206
2006/07	632	319	331	277	241	194	278	278	259
2007/08	496	287	293	239	196	149	240	240	221
2008/09	565	258	251	197	165	118	204	204	180
2009/10	582	286	299	245	208	160	247	247	228
average DP/~~rech~~	–	251	319	325	269	235	187	266	266
Av. P ('3/4–'9/10)	–	601	557	601		631		588	
P – sub-catchment		ø WZ/S1	ø Nea/S1	ø WZ/S1		Wadi Zarqa		ø Ayb/S2	
[illegible]/ø P	**–**	**42 %**	**57 %**	**54 %**	**45 %**	**37 %**	**30 %**	**45 %**	**45 %**

Note: The deep percolation / recharge rate (DP) was modelled with the respective sub-catchment rainfall on a daily basis. This table shows spatially averaged rainfall (ø 595 mm/yr during 03/04–09/10). Water balance and leakage calculations for the perched aquifers and the ranked formation recharge throughout Wadi Natuf used this area rainfall (Table 6).

Table 3. Formation-specific recharge coefficients (RC) in Wadi Natuf (Alt.–2), all basins

Formation age[1]	Formation name	Potential	Potential Rank	Potential Type	Area km²	Ø Precipitation Mm³/a	Ø Precipitation mm/a	Recharge Alt.–2 RC, %	Recharge Alt.–2 Mm³/a	Recharge Alt.–2 mm/a	Recharge Groups Mm³/a	Recharge Groups mm/a	Recharge Groups fraction %	Group-RC Σ Natuf
1	Alluvial	++	0	Alluv.	1.5	**0.8**	553	57.3 %	**0.5**	317	0.5	317	**2 %**	**57.3 %**
12	l–LBK	+++	1		16.4	**10.2**	624	57.3 %	**5.9**	358	15.8	324	**59 %**	**54.0 %**
3	Jerusalem	+++	2	++	9.3	**5.1**	549	57.3 %	**2.9**	315				
11	u–UBK	++	3	Aquifer	13.2	**8.2**	624	54.1 %	**4.4**	338				
6	Hebron	++	4		10.1	**5.8**	574	45.3 %	**2.6**	260				
9	u–UBK	+	5		2.4	**1.5**	615	54.1 %	**0.8**	333	7.4	262	**28 %**	**44.7 %**
10	l–UBK	±	6	+	8.4	**5.3**	623	44.7 %	**2.4**	279				
4	u–Betl.	±	7	Aquifer	7.7	**4.3**	557	45.3 %	**1.9**	252				
5	l–Betl.	-	8		9.8	**5.6**	571	41.8 %	**2.3**	239				
14	Ein Qinya	±	9	± Aqui-	1.8	**1.1**	613	45.3 %	**0.5**	278	3.1	256	**11 %**	**42.3 %**
8	l–Yatta	- -	10	tard	10.2	**6.1**	603	41.8 %	**2.6**	252				
2	Senon., Apt.	- - -	11	- Aqui-	7.0	**4.1**	595	0 %	**0.0**	0	**0**	0	**0 %**	**0 %**
7	u–Yatta	- - -	12	clude	4.9	**2.9**	592	0 %	**0.0**	0				
Total					**102.6**	**61.1**	**595**		**26.8**	**261**	26.8	261	**100 %**	**(43.9 %)**

[1] the original ranking of age goes from most recent (alluvial = 1) to the oldest (Albian Ein Qinya = 14)

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765 **Table 4.** Alternative scenarios of total recharge in Wadi Natuf – (WAB only)

Scenario	unit	Recharge – all Natuf (WAB)		
		Alt.–2 soil-based	Alt.–1 landform-based	Alt.–3 lithology-based
Recharge	**mcm/yr**	**26.8 (22.6)**	**24.1 (20.6)**	**28.1 (23.9)**
Area	**km^2**		**102.6 (85.5)**	
Recharge	**l/m^2**	**0.26 (0.26)**	0.23 (0.24)	0.27 (0.28)
Recharge	**mm/yr**	**261.4 (264.2)**	234.8 (241.4)	274.1 (279.8)
Avg. Precipitation	**mm/yr**		**595**	
Recharge Coefficient	**%**	**43.8 % (44.6 %)**	39.4 % (40.8 %)	46.1 % (47.3 %)

Table 5. Annual spring groups discharge (and sub-catchment recharge)

Symbol	□	○	○	◇	△		**RAIN**
Spring group (m^3/yr)	**Wadi Zarqa**	**Zarqa Bridge**	**Beitillu,** Harat Al-Wad	**Shakha-reek**	**Nabi Aneer**	**Ain Ayoub**	**Wadi Zarqa**
Formation	UBK[1]	upper UBK		lower Yatta			–
2003/04 (m^3/a)	145.314	7.942	31.102	69.049	5.122	11.372	–
2003/04* (mm/a)	79	74	25	52	26	52	485
2004/05 (max P.)	101	94	32	66	33	66	**617**
2005/06	89	83	28	58	29	58	547
2006/07	87	81	28	57	28	57	533
2007/08	73	68	23	48	24	48	447
2008/09 (min P.)	71	66	23	46	23	46	**435**
2009/10	79	74	25	52	26	52	487
2010/11	71	67	23	47	23	47	447
2011/12 (mm/a)	105	98	33	68	34	69	656
Ø 3/4-9/10 (mm/a)	**83**	**77**	**26**	**54**	**27**	**54**	**507**
Ø 3/4-9/10 (m^3/a)	152.068	8.311	32.547	72.258	5.360	11.901	–
Rech. area (km^2)	1.84	0.108	1.24	1.34	0.20	0.22	–
Rech. 03/04 (m^3/a)	398.704	28.295	324.870	271.467	52.398	44.569	–
Rech. 03/04 (mm/a)	217	262	**262**	203	262	203	485
Q / R 03/4 (%)	**36 %**	**28 %**	**10 %**	**25 %**	**10 %**	**26 %**	–

Reference year 2003/04; reference rainfall station: Tipping bucket at Wadi Zarqa. Within modelling period (2003/04-09/10): maximum flow in 2004/05, minimum flow in 2008/09. [(1)] UBK formation here comprises of two sub-formations and main spring horizons: upper UBK the top of lower UBK (compare with Figures 1b and 7). In blue / grey shaded: area normalised rates in mm/a

Table 6. Water balance of the intermediate 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	km^2	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 intermediate leaky aquifers in Wadi Natuf, not only to the spring group areas. Leakage and spring discharge fractions are related to total recharge from the soil moisture models (as 100 %), while recharge coefficients are related to total rainfall (here average area rainfall of Wadi Natuf).

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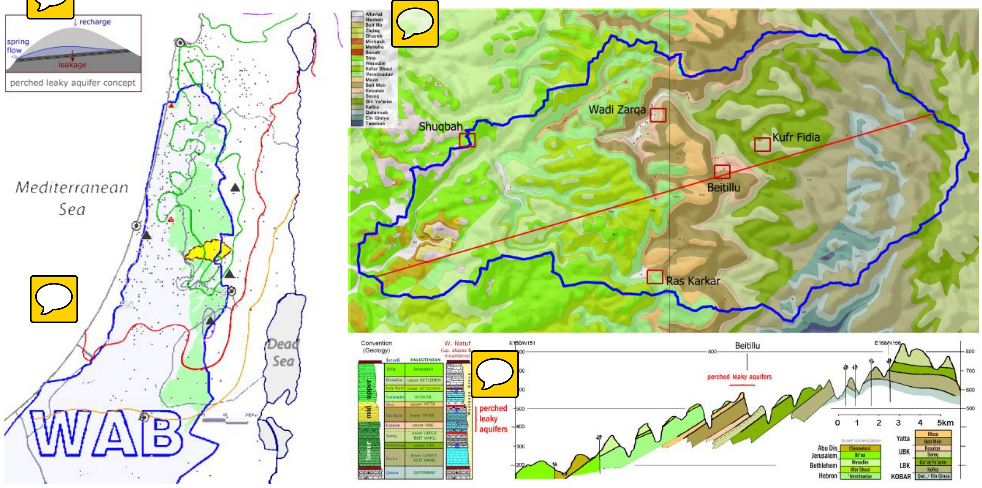

Figure 1.a. Left – Location map and concept inlet; Wadi Natuf (yellow) positioned in the mountains and slopes of the WAB; WAB boundary, aquifer outcrop area (green), isohyets, rainfall stations, main weather stations, main spring outlets (modified after Ettinger, 1996) and schematic concept of perched, leaky aquifers; **Figure 1.b.** Right – Geological relief map, cross-section, main springs and soil moisture locations (red boxes) (Sources: geological map modified after GSI, 2000, 2008; stratigraphic column modified after (Dafny et al. 2010).

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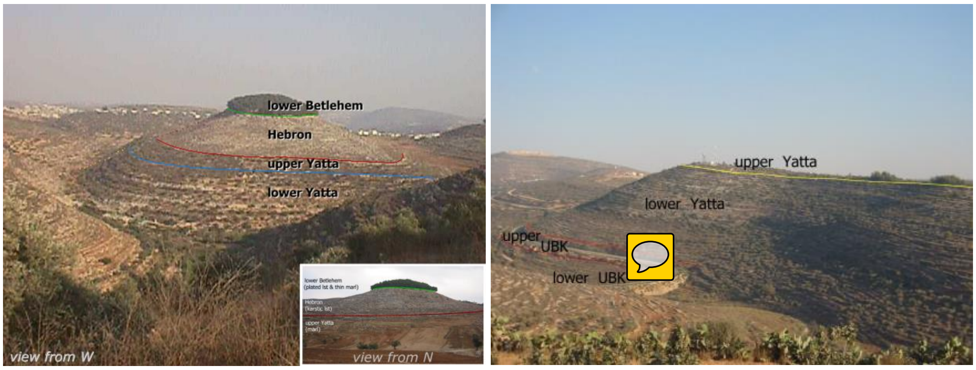
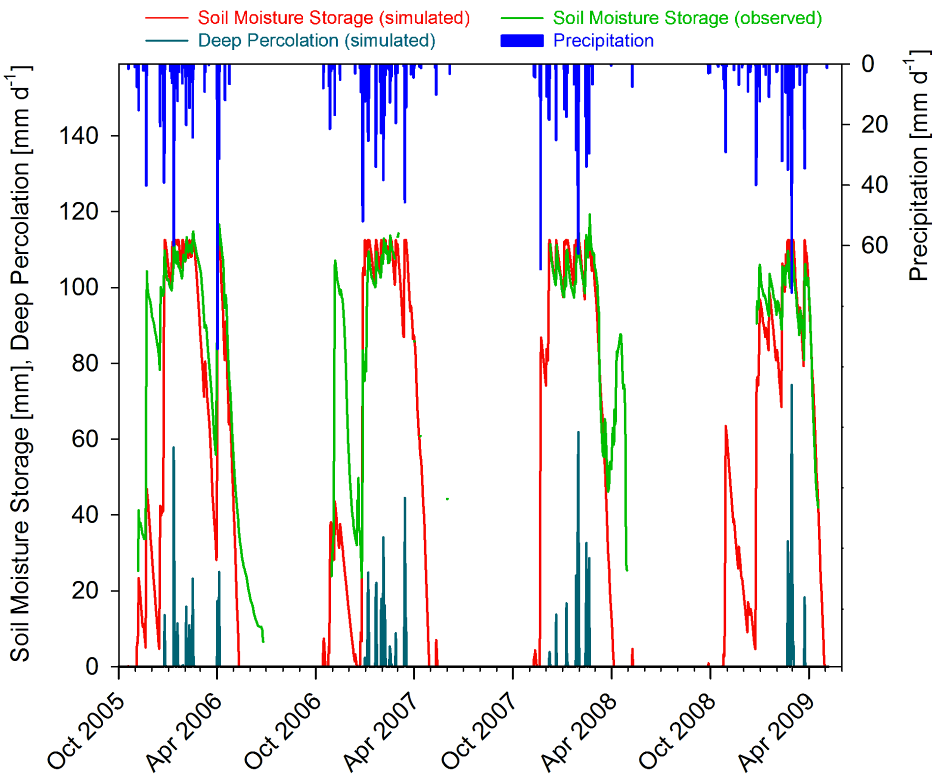


Figure 2.a & 2.b. Correlation of landform and lithology; left: Nabi Ghayth hill, west of Beitillu; right: Nabi Aneer spring group. Note: The karstic limestone of Hebron formation forms outcrops with thin soil cover, bare rock or karren fields and tends to erode into steeper slopes above the soft, mostly eroded upper Yatta formation – the only true aquiclude within the Westbank Group (with levelled agricultural plains in the inlet photo if Fig. 1a. 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 3.a. Twin marl band 2.5km SE of Beitillu (confining layer beneath the top of lower UBK formation); **Figure 3.b.** Cliff-forming coral reef limestone of upper UBK formation at Wadi Zarqa with high primary porosity but also signs of karstification; **Figure 3.c.** Colourful, thinly plated limestone with fine marl intercalations (lower Betlehem formation)



805 **Figure 4.** Comparison between observed and modelled available soil moisture (AW) at Ras Karkar, West (RK-W) during four seasons; in this profile FC_e was set to 112.5 mm. Note: In this station (RK-W), unlike in the other stations, the modelled graph (red) showed a delay in the filling of the soil column at the onset of the rainfall season. (The other stations, like WZ & KF, showed a good match in season onset, or were not fully recorded in early winter, like BET & SHU). A time lag in the measured response at the end of the season was only observed at WZ-hh and KF-W, and for one season also at RK-W, see April 2008, above.

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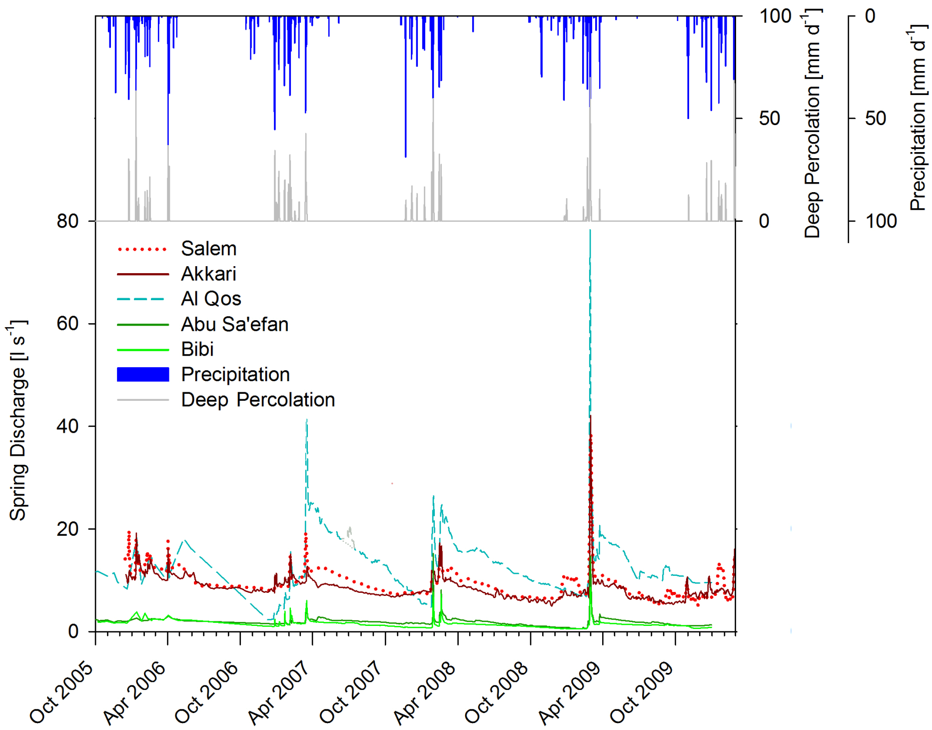

815 **Figure 5.** (DP vs. Q): Beitillu – Rainfall, spring flow and recharge during three seasons. Note: Recharge (DP) values as green bars; daily spring flow as red, blue and yellow lines; daily rainfall as blue bars from top x-axis. The access pipe of Al-Qos spring was cleaned from plant roots in summer 2007, causing a temporary increase in spring discharge.

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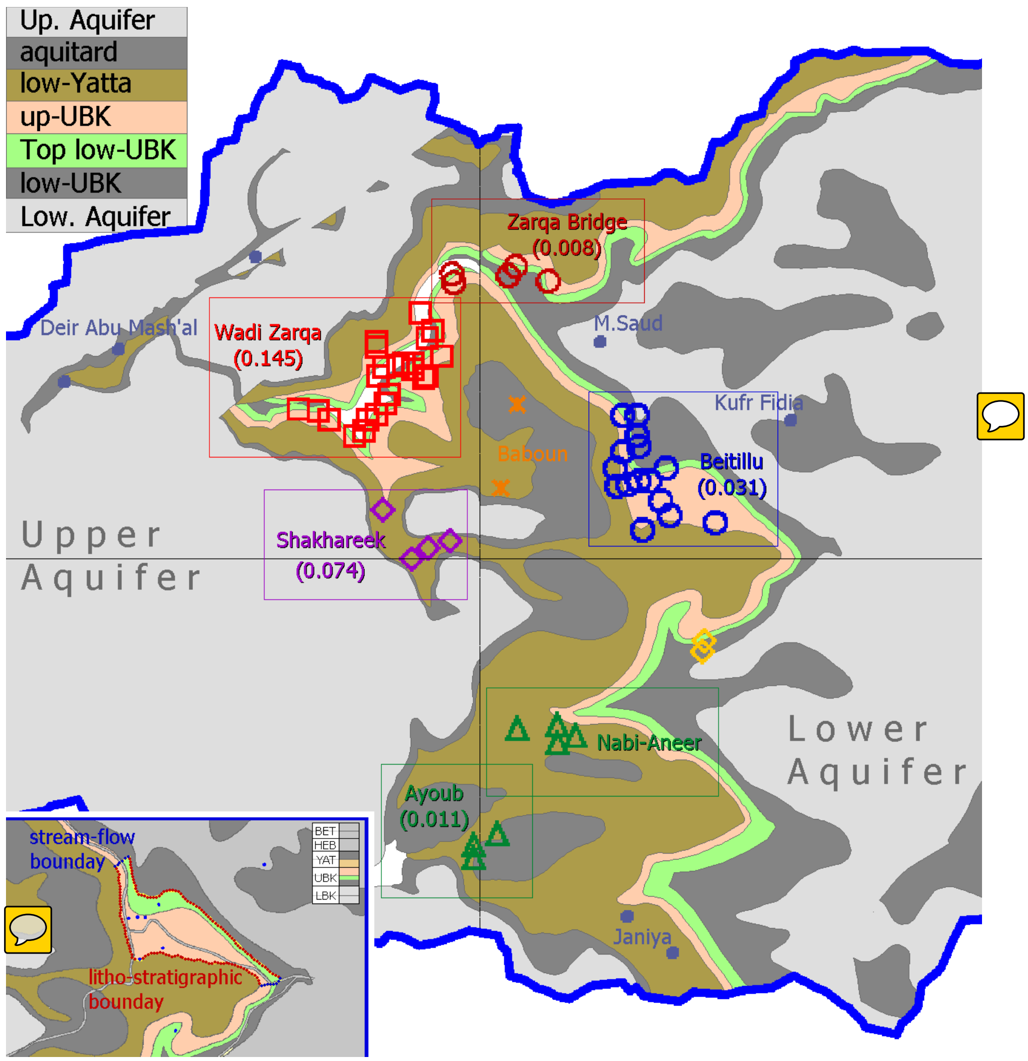

820 **Figure 6: Spring groups in Wadi Natuf** Note: Six spring groups were identified in central Natuf, with two in the North (Zarqa), two in the centre (Beitillu & Shakhareek) and two in the South ('Ayoub & Nabi Aneer). The recharge areas of these perched intermediate aquifers are isolated by outcropping bottom aquicludes (Figures 2a, b and 3a). Source: geological map based on GSI, 2000, 2008

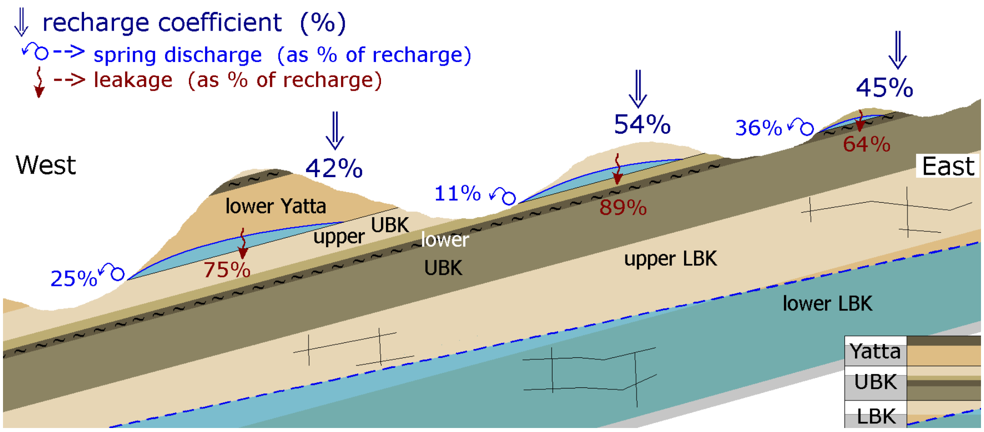

Figure 7: Water budget of the three leaky sub-aquifers in Wadi Natuf (as percentage of rainfall)

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APPENDIX A

Table A1. Soil depth matrix

Hydrostratigraphy Geological formation	**Upper Aquifer** Heb., Bet., Jer.	**Yatta** up UBK, Yatta	**Lower Aquifer** LBK, low UBK*
A) Terraces			
1. terraces with olives	65, 40 cm	**42, 25 cm**	**(49), 26 cm**
2. terraces with other types cultivation	NA	**(25)**	NA
3. formerly used but now uncultivated terraces	NA	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	NA
4. rock plastered plains (karstification)	32	NA	(5), 15
5. dry plains with shrubs and grass cover	**19**	NA	19
C) Slopes			
1. non-terraced slopes with olives	NA	56	49
2. non-terraced slopes with other types of cultivation	**58**	50	NA
3. slopes with shrubs and grass cover	**11, 26, 32**	40	**18**
4. rock plastered slopes	32	NA	**11**
D) Pure rock cover and cliffs			

*Notes: * excl. Top l-UBK, **(grey fill) = main landform types**, red = SM meas. location, NA = untypical landform for lithology,*

Table A2. Data coverage of daily spring flow measurements

Year	**A. Sa'efan**	**Bibi**	**Qos**	**Salem**	**'Akkari**	**∑ Coverage**
2003/04	**57 %**	**35 %**	**54 %**	**58 %**	**58 %**	35–58 %
2004/05	**2 %**	**2 %**	**2 %**	**2 %**	**2 %**	2 %
2005/06	**5 %**	**5 %**	**5 %**	**79 %**	**79 %**	5 % & 79 %
2006/07	100 %	100 %	100 %	100 %	100 %	**full**
2007/08	100 %	100 %	100 %	100 %	100 %	**full**
2008/09	100 %	100 %	100 %	100 %	100 %	**full**
2009/10	**42 %**	**42 %**	**42 %**	**68 %**	**68 %**	42 % + 68 %

Table A3. Outcrop (recharge) area, rainfall and recharge potential of all formations

Age	**1**	**12**	**3**	**11**	**6**	**9**	**10**	**4**	**5**	**14**	**8**	**2**	**7**
Ftn.name	Alluv.	l-LBK	Jerus	u-LBK	Heb	u-UBK	l-UBK	u-Bet	l-Bet	E.Qinya	l-Yat	Senon, Apt	u-Yat
symbol	Al	klk	kub	kugy	kua	kuke	kus	kuw	kuks	kleq	kubm	kuez,klq,klt	kumo
Area km^2	1.535	16.398	9.258	13.158	10.056	2.442	8.441	7.651	9.766	1.820	10.182	7.005	4.931
Ø P. mcm/a	0,848	10,236	5,086	8,215	5,776	1,502	5,262	4,260	5,574	1,115	6,145	4,165	2,917
Potential	++	+++	+++	++	++	+	+	+	-	+	- -	- - -	- - -
Rank	0	1	2	3	4	5	6	7	8	9	10	11	12
Type	Alluv.	++ Aquifer				+ Aquifer			± Aquitard			- Aquiclude	

This table is an expanded version of Table 1b. It lists each formation separately by area, rain and ranking position/recharge potential. *Note: Ein Qinya formation is a local aquifer, which however does not belong to any of the regional aquifer basins. Its recharge potential does not form part of the water balance calculations. Rainfall shows the multiannual average precipitation, calculated with rainfall of the respective sub-catchments.*

Table A4. Recharge coefficients in the literature

author	year	avg	max	area	time	based on	how	method	misc
Sheffer et al.	2010	9-40 %	(52 %)	**Mt.Aq.**	annual	model	calibrated numerical water budget model	daily soil sataruration	non-empirical assumed FC (low) and soil thickness (high)
Gunkel et al.	2015	30 %	-	**Mt.Aq.**	annual	model	distributed, field-based, water balance model	TRAIN-ZIN, MOSST	EAB, Wadi Fari'a + Jordan Valley, 6-yr measurement period, event-based
Sanz et al.	2011	34.3 %	34.3 %	Spain	annual	lithology	clay 1.3 %; silt 3.3 %; lst+dol 34.4 %	large areas, SMD + HEP	as factor of lithology & precipitation
Cheng et al.	2017	-	42 %	China	event	thick soil	max annual: 32.4 %	>2m thick soils	in one event
Bradford et al.	2002	39-45 %	45 %	UK Chalk	annual	models	with input data at varying spatial resolutions	SMD + HEP methods	UK Chalk, 4 yrs
Nativ et al.	1995	8-55 %	-	N Negev	annual	bromide	in boreholes in fractured chalk	bromide profiles	arid desert climate (P: 200mm/a)
Abusaadah	2011	**36 %**	53.2 %	**Mt.Aq.**	annual	flow model	WAB basin-wide water budget	3-dimensional flow model	max. recharge in 2003/04
Dvory et al.	2016	34 %	54.3 %	**Mt.Aq.**	annual	model	1-D dual porosity model (linear)	based on rock properties, karst	local, W of Jerusalem, spatial litho-based differences (abs. maxima: 73.7 %)
Schmidt et al.	2014	25-50 %	55 %	**Mt.Aq.**	annual	spatial	Rain, Etp (spring flow) data	SMD+GW model, spring response	EAB at 'Auja spring
Sheffer et al.	2010	20-60 %	-	**Mt.Aq.**	annual	formula	quotes literature on WAB-RC	single-cell flow model	calibrated numerical annual water budget (non-empirical), linear equation
Ries et al.	2015	33 %	66 %	**Mt.Aq.**	annual	model	max. in wet years (avg. in Aujah)	SM model, budget	EAB (mountains and slopes)
Guttman et al.	1988	**30.6 %**	75.3 %	**Mt.Aq.**	annual	model	WAB basin-wide water budget	quasi-3-dimensional flow model	max. recharge in 1991/92 (*single-cell water balance model*)
Weiss & Gvirtzman	2007	**6-65 %**	-	**Mt.Aq.**	annual	formula	of Guttman ('00), G. & Zuckerman ('95)	quasi 3-D flow model	applying formula to 4 spring areas, one of which overlaps with Wadi Natuf
Radulovic et al.	2011	66.3-76.2 %	**76.2 %**	Montenegro	annual	spatial	water budget & other methods (Montenegro)	ranking system and matrix	karst, lithology, structure, landform, runoff, plants, climate, soil, slope
Allocca et al.	2014	50-79 %	**79 %**	S-Italy	annual	lithology	precipitation & air temperature	empir. model, linear regression	correlated with other factors: karst outcrops, morphology, land use, soil type
Goldscheider & Drew	2012	-	**>80 %**	-	event	spatial	bare karstified limestones	-	summary from literature
Weiss & Gvirtzman*	2007	**<10->80 %**	**91 %**	**Mt.Aq.**	annual	lithology	max. in 1988 at I-LBK ftn.	model, budget, spring response	28-yr ø RC of **47.2 %** at Ein Al-Harrasheh spring groundwater catchment
Allocca	2015	35-97 %	**97 %**	Appenin	event	model	storm-by-storm, Apennine	air temp., ET & rain	
Shacori	1965	**47 %**	-	**Mt.Aq.**	annual	spatial	Mt Carmel avg. (undifferentiated)	-	
Mero	1958	**53 %**	-	**Mt.Aq.**	annual	spatial	Na'aman spring	-	(quote after Lerner et al. 1990)
Rosenzweig	1972	**60 %**	-	**Mt.Aq.**	annual	landform	Mt Carmel avg. (by landform)	annual on pasture/grassland	while at forest 0 %
Messerschmid et al.	2018	**40.8-47.3 %**		**Mt.Aq.**	annual	3 scenar.	here: alt.-2: soil-based senario	SM-model, ranking	WAB in Wadi Natuf

Note: * *for the groundwater catchment of Ein Al-Harrasheh spring, which overlaps with Natuf surface catchment, Weiss & Gvirtzman (2007) reported a 28-year average recharge coefficient of* ***47.2 %.***

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Table A5. Recharge coefficients in alternative scenarios A.-1 and A.-3 (landform & lithology based)

Type	Potential	Symbol	RC (%)		Recharge (mcm/a)		Group recharge (mcm/a)		Group fraction (%)		Group RC, Natuf (%)	
			A.-1	A.-3	A.-1	A.-3	A.-1	A.-3	A.-1	A.-3	A.-1	A.-3
+ Alluvial	++	Alluvial	45.3 %	57.3 %	0.4	0.5	0.4	0.5	**1.6 %**	**1.7 %**	**45.3 %**	**57.3 %**
++ Aquifer	+++	low-LBK	45.3 %	57.3 %	4.6	5.9	13.3	16.3	**55.1 %**	**58.1 %**	**45.3 %**	**55.8 %**
		Jerusalem	45.3 %	57.3 %	2.3	2.9						
	++	up-LBK	45.3 %	54.1 %	3.7	4.4						
		Hebron	45.3 %	54.1 %	2.6	3.1						
+ Aquifer	+	up-UBK	54.1 %	54.1 %	0.8	0.8	7.4	8.3	**30.7 %**	**29.4 %**	**44.6 %**	**49.8 %**
	±	low-UBK	44.7 %	49.4 %	2.4	2.6						
	±	up-Betlehem	44.7 %	49.4 %	1.9	2.1						
	–	low-Betlehem	41.8 %	49.4 %	2.3	2.8						
+ Aquitard	±	Ein Qinya	41.8 %	41.8 %	0.5	0.5	3.0	3.0	**12.6 %**	**10.8 %**	**41.8 %**	**41.8 %**
	- -	low-Yatta	41.8 %	41.8 %	2.6	2.6						
- Aquiclude	- - -	Senonian, Aptian	0 %	0 %	0.0	0.0	0	0	**0 %**	**0 %**	**0 %**	**0 %**
		up-Yatta	0 %	0 %	0.0	0.0						
SUM			-	-	**24.1**	**28.1**	**24.1**	**28.1**	**100 %**	**100 %**	**39.4 %**	**46.1 %**

845 **Figure A1.** Outcrops – a) rare outcrops of yellow marls (upper-Yatta), b) reefal limestone cliff at Wadi Zarqa (upper-UBK), c) karstic karren and soil pocket landscape (upper-Betlehem)

Figure A2. Soil cover – a, b & c) soil covering marly limestone with some white Nari crust (bottom Hebron/Top Yatta ftn.); d) Ras Karkar terrace soil measurement site (lower Hebron ftn.)