Answers to 2nd Review (Nov-19)

Report #1 Submitted on 19 Jun 2019 Anonymous Referee #4

Anonymous during peer-review: Yes
Anonymous in acknowledgements of published article: Yes
For final publication, the manuscript should be: **reconsidered after major revisions**
I am willing to review the revised paper.

This is an interesting case study about soil moisture changes in different depths and daily readings of discharge at five springs over a period of more than 3 years in an ungauged basin in Israel.

  - Thank you for your helpful comments and recommendations!

- Modeling was performed by means of a box model which is not well described in particular with respect to the boundary conditions. Furthermore, a discussion whether the selected points for soil moisture reading are representative for the entire catchment is missing. Surface runoff is not considered at all in the model described. Missing as well is a water balance, any discussion about evaluation and uncertainties of the results.
  - a) "Box model" is added. b) Boundary conditions: It is not clear why this has to appear in the text. The combined reservoir or tank or box is considered 'confined' only vertically (i.e. between soil and bedrock); laterally it is treated as infinite (with lateral expansion >> double the soil thickness). All flows in the soil are considered vertical; therefore, this would be equivalent to a no-flow boundary of the 'stream flow boundary' type. c) It is stressed repeatedly (in sections Area, Discussion and Conclusions) that surface runoff in Wadi Natuf is astonishingly rare and reduced (<1% of P, section 5, Line 549) – therefore, its weight in the water balance is negligible (Line 550). d) Water balance: On the level of the model calculations, the entire tank, box or bucket model is considered by ways of a water balance of calculated in- and outflows. On the regional level, a water balance for Wadi Natuf catchment is performed after regionalisation, which is the main topic of the second part of this study (follow-up article in HESS, as suggested by the HESS editors). e) The evaluation of the results is approached in two ways, as described in Methods and Results. Uncertainties are presented and discussed in both, Results and Discussion.

- It is not clear why this regional case study is divided in two parts. 5 pages introduction were written to express that missing data cannot be circumvented by sophisticated models. Thus the introduction is a kind of review, but not in depths and not complete and thus should be shortened to an introduction for a case study.
  - a) Split into two parts: This was suggested by the editors of HESS after the first review (compare with earlier versions and reviews). b) The first review in addition to the editors' personal recommendations strongly demanded a much more extensive discussion of the state of art. This was followed in the second draft (compare with earlier versions and reviews). The reviewer is correct to comment that one of the main messages of the Introduction is "*to express that missing data cannot be circumvented by sophisticated models*". The Introduction was now condensed to <60% length (2036 words).

- Authors do not define the term “**deeper soil**” and “deep percolation”
    - Deeper soil in this study is a relative term. We changed the text to indicate that it is opposed to surface-near layers (Lines: 314, 399, 411 and 424).
    - Deep percolation is understood as the entry of soil water into the bedrock, unlike infiltration, which is entry from the surface into the soil. Importantly, the paper uses ‘deep percolation” and ‘recharge’ interchangeably. (See Lines 63, 122, 235, 244, 351-352, 365, 420, 464, 495, 517, 522, 552 and 554).
- Table 1: the term “class of recharge potential” is used here, but not addressed before in the entire manuscript
    - Table was 1 was removed, as suggested by the journal. Different classes of recharge potential are described at length in the follow-up paper.
- Fig 6. is not a time series because the sequence of years is random or at least not increasing. Probably better plotting a bar graph. Using abbreviation makes understanding of the figure rather difficult
    - Figure 6 was removed, in order to shorten the article and reduce the number of figures (as suggested by the reviewers and the HESS editors).
- Related to fig 7: What is a “…very good to excellent correlation A correlation test can either accept the null hypothesis or reject it. …”? It looks like that regression coefficient and correlation are mixed up.
    - The first review (reviewer RC#1) had demanded a discussion of the power of prediction in form of statistical checks, such as the Nash-Sutcliffe Efficiency Coefficient (NSE). The terms ‘very good’ and ‘excellent’ are a standard procedure to summarise the results of NSE. However, the reviewer is correct that the combination with the term “correlation” is inappropriate. We therefore replaced it with “match” (“close match”), etc. (Lines 456, 905)
- Fig. 9 and 10: why are these data plotted as "timmatche series" and not as bar graph?
    - a) Figure 9 was removed, in order to shorten the article and reduce the number of figures (as suggested by the reviewers and the HESS editors). b) Figure 10 is now renumbered to Fig. 8 and plotted as columns.
- Table 3: units are missing
    - Ok, corrected (Table 3, now Table 2, Line 481)
- The entire manuscript is cumbersome written and in many parts way too lengthy.
    - We have condensed many parts of the manuscript, although many of the more detailed remarks had been added upon expressed request by the first review (compare with earlier versions and reviews).
- decimetre and metre are used in same places instead of decimeter and meter
    - We use English GB style of language; hence, metres and decimetres…
- page 9: a follow-up-paper is cited: Messerschmid, C., Sauter, M. and Lange, J.: Regionalization of distributed groundwater recharge and leakage calculations in a Mediterranean karst catchment, Wadi Natuf, West Bank, Hydrol. Earth Syst. Sci., - in preparation, 2019b. This is for me a no go.
    - Dear reviewer, the article was originally submitted and first reviewed in a different version. Upon recommendation by the first round of reviews and the editor, it was decided to split that article into a series of two articles, the first of which here under review. The issue was discussed again with the editor and it was decided to proceed – according to the HESS guidelines for manuscripts – as follows: Quote the follow-up article as: *Authors*, *Full Title*, *Journal* & *“in preparation”* (see lines 232, 603, 760 and Appendix H).
    - Thank you very much for your helpful comments and recommendations!

Report #2 Submitted on 02 Jul 2019 Anonymous Referee #5

Anonymous during peer-review: Yes
Anonymous in acknowledgements of published article: Yes
For final publication, the manuscript should be: **reconsidered after major revisions**
I am willing to review the revised paper.

General comments

The authors present a parsimonious approach to estimate recharge in a data-poor karstic region with severe water quantity problems. Idea and approach of that manuscript are highly suited for the journal. However, this manuscript reads like a monograph but not a paper in a scientific journal. I generally appreciate the work that was done over the years under truly harsh conditions. However, this is a paper that needs to keep level of detail reproducible but limited to what is really needed to understand the outcome. In all parts of the manuscript I see a lot of potential condensation. I like the general results and outcomes of this study but this is all hidden in way to much information and words.

- Thank you for the praise, as well as the helpful comments and recommendations.
- We have tried to condense and shorten the manuscript. However, many of the details that seem too long to you (and too cumbersome to the RC#5) had been added upon expressed request by the first three reviewers. We therefore had to strike a compromise between the two conflicting demands…

Moreover, I saw a lot of plots on the spatial variability of recharge but no map resulting from this to put this into a catchment context. Overall, the authors have to decide to either condense everything significantly or to consider another publication format.

- The map with a visualisation of the results on the catchment can only and will be presented after the regionalisation, which is the topic of the follow-up paper of this two-part series of articles.

Specific comments

Abstract: Overall the abstract should put more weight on the results and discussion. At the moment the methodological approach is a bit overemphasized on the cost of quantitative results and their meaning.

- Thank you, we shall oblige (as a compromise between the earlier review and the comments by the HESS editor)…

- L19: I did not know “tank model” but rather “bucket model”. Consider to change that across the manuscript.

  - We shall add the terms bucket model (as requested by you) and box model (see RC#5) upon first mentioning; however, this will be in addition to the term tank model, which was the original term used by Sheffer *et al*. (2010), as quoted in Fig. 5 (was Fig. 6 before).

- L21: Main active hydrological processes may be replaced by “dominant hydrological processes” or “first order controls”.

  - Thank you, we shall comply (Lines 19-20, 67, 527 and 537).

- L24f: Giving some numbers (mm/yr) in addition to the % make sense.

  - Thank you, we have added one such quantification (mm/yr) in the abstract (Line 27), but only as an approximation. Unfortunately, our RC-values (in %)

translate into different annual rates (mm/a), depending on the local precipitation (spatially) and respective year of measurement (temporally): therefore exact quantifications would require too much discussion for an abstract. These details are shown in the now renumbered Table 2 (Line 481).

- The introduction follows an interesting path on how research approaches groundwater recharge. While I found this interesting I would like to see rather a problem-driven not theory-driven approach to groundwater recharge. What is the global problem, what the specific problem, what is already known and where is the gap of knowledge to be filled. I would not omit the structure as it is but suggest to restructure and simplify the introduction. Definitive there is no need for 2 hierarchies of headers in the introduction section. Even one is already too much for me.

  - We have shortened the Introduction to 60%. However, the first reviewers had expressly demanded a description of the 'state of the art', the already published theory on distributed groundwater recharge. So, we are facing conflicting demands on this. The introduction now starts with a general overview over possible research approaches and then narrows down to the problem of spatial variability in ungauged basins in general and in the WAB in particular (with only a brief mention of Wadi Natuf). It then draws conclusions for modelling and presents the aims and motivation.
  - We also reduced the hierarchies of section and sub-section titles.

- Figure 2: Consider to number the different panels. The map seems to be too large when looking at the information content and may be placed side to side with the geological profiles above.

  - Review one had demanded to increase the size of the different parts of Fig. 2. This is why we presented the figure in this form. However, we suggest to keep it up to the final layout of the journal itself, how the Fig. 2 and its different parts shall be arranged.

- Figure 3: This is nice to see but I suggest to move this into the supporting information – this is not needed to understand recharge variability in the catchment.

  - We have done that (Appendix A).

- L303ff: This statement needs referencing.

  - Referencing inserted as Gimbel (2015), see Lines 222, 679 and 874.

- Table 2: You need to include abbreviations into the table caption. Moreover, I don't get the difference between #years measured and years measured.

  - Both were added and adjusted (Table 2 is now Table 1, Line 389).

- Figure 5: I would like to see the ET leaving at the top or do I get something wrong?

  - No, this is not a physical representation of the soil water movement and its directions. In this conceptual graph, ET is not an upward water movement and percolation is not a vertical movement downwards. Rather, the tank 'overflows' in this conceptual representation of the model functioning, and in two different ways (processes), but based on different degrees of soil water saturation. The graph tries not to indicate whether soil moisture moves upward (ET) or downward (DP) with in the tank cylinder. Rather, it indicates that different levels of saturation trigger different processes (to be accounted for by the model) – such as ET during wetting-up and/or DP after saturation excess. See also adjusted captions (Lines 360-361).

- Figure 6: Is the axis really precip divided by recharge?

  - Figure 6 was removed in order to shorten and condensed (as recommended by the reviewers and journal editors)

- L545: Consider “dashed line” not dotted line in the captions.
  - Text and captions were adjusted accordingly (Lines 431 and, 443).

- L591: The part in the bracket does repeat the part of the sentence before that.
  - Ok, this was changed (Line 463).

- Fig. 9: Typo in Y-axis name. Why are the years connected by a line? Wouldn’t it make sense to connect the stations over the year not the other way round?
  - Figure 9 was removed (see answer to RC#4).

- Table 3: Units are missing.
  - Units were added (Table 3, now Table 2 and captions, Lines 481 and 486).

- Fig. 10: Number should separate digits by a point not a comma.
  - Thank you, you are right – this was corrected (now Fig. 8).

- L647f: If this is highly location-specific, what does that mean for your measurement points? Are they representative?
  - Yes they are representative, indeed. In other words, they are “formation-specific” (see Lines 23, 26, 150, 519, 587, 590, 592 and 603) and representative (see Lines 310, 330, 334, 342, 510, 592 and App. D), see also Table 2 and Fig. 8.

- L735ff: The concluding section is too long. Focus on the main objectives and try to restrict it to the main take home messages.
  - The section was shortened considerably, focussing now on the main objectives.
  - Thank you for your helpful comments and recommendations!

Report #3 Submitted on 25 Aug 2019 Anonymous Referee #6

Anonymous during peer-review: Yes

Anonymous in acknowledgements of published article: Yes

For final publication, the manuscript should be: **accepted subject to technical corrections**

see attached referee report - Referee Report: hess-2018-329-referee-report.pdf

- Comments in table below.
  - Thank you for your helpful comments and recommendations! (for the answers and details, see the Table on the next pages)

Referee Report

hess-2018-329
Field-based estimation and modelling of distributed groundwater recharge in a Mediterranean karst catchment, Wadi Natuf, West Bank (Clemens Messerschmid, Jens Lange and Martin Sauter)

Overall assessment:

An important paper that contributes new approaches to the assessment of groundwater recharge in ungauged basins in semi-arid karstified regions. With a few, minor technical corrections the paper can be accepted.

Suggestions for technical corrections:

Line	Original	Recommendations	Remarks	Action
56	When no other option than observations in the unsaturated zone are available, then groundwater recharge has to be equated with deep percolation from the soil cover into the aquiferous bedrock formation.	When no other options are available than observations in the unsaturated zone, groundwater recharge has to be equated with deep percolation from the soil cover into the aquiferous bedrock formation.	x	Ok ✓
62	Hartmann et al., 2013	Hartmann et al., 2012	Check references, lines 892-893	Added
71	(Hrachowitz et al., 2013; Sivakumar et al., 2013.	(Hrachowitz et al., 2013; Sivakumar et al., 2013).	x	Ok ✓
86	(…) accounted for land use, soil and topography (but not geology) but calculated with parameters (…)	(…) accounted for land use, soil and topography (not geology) and calculated with parameters (…)	x	deleted
95	As a challenge however, remains the correct and appropriate linkage and translation from form to function (…).	The correct and appropriate linkage and translation from form to function remains a challenge (…).	x	deleted
96	Messerschmid et al., 2019b	Messerschmid et al., 2019	Check references, lines 946-947: There is only one “Messerschmid et al., 2019”, no a and b	Checked ✓
111	(Seibert and Beven (2009).	(Seibert and Beven, 2009).	x	Ok ✓
117	Hartmann et al., 2012b	Hartmann et al., 2012	Check references, lines 892-893	Ok ✓
118	(Dafny et al., 2009, 2010)	(Dafny, 2009; Dafny et al., 2010)	x	Ok ✓
138-139	Binley and Beven (2003) added that such an intelligent design remains a learning process that may start with insufficient data and adds data as required by the application and (…).	x	Something is missing at the end of the sentence.	deleted
139	Seibert & Beven, 2009)	(Seibert and Beven, 2009)	x	Ok ✓
143	(see Fig. 2a)	(see Fig. 1)	x	Ok ✓
149-150	the basin rapidly became one of the single-largest sources of Israeli water supply	the basin rapidly became one of the single-largest sources for the water supply in Israel	x	No. *‘Israeli’* supply also extends to the WBk
167	Abusaadah (2011)	Abusaada (2011)	Check references, lines 807-808	Ok ✓
199	(of 10 x 18m plot size)	(of 10m x 18m plot size)	x	Ok ✓
203	Hartmann et al. (2012)	x	Check references, lines 892-893	Added

220	However, again, their soil parameters and time series data of soil saturation were (…)	However, their soil parameters and time series data of soil saturation were (…)	x	Changed
242	On the one hand, and at (…)	On the one hand, at (…)	x	Ok ✓
267-268	(…) were complemented by two Automatic weather stations within the catchment by this study.	(…) were complemented during this study by two Automatic Weather Stations within the catchment.	x	Ok ✓
275	(…) of the map (2a) and (…)	(…) of the map (2b) and (…)	x	Ok ✓
281	Wadi Natuf (Fig. 2a, Table 1)	Wadi Natuf (Fig. 2b, Table 1)	x	Ok ✓
285	(Fetter, 1994)	x	Reference missing in references list	Added
312	Messerschmid et al., 2019b	Messerschmid et al., 2019	Check references, lines 946-947: There is only one "Messerschmid et al., 2019", no a and b	Checked ✓
344	(…) (1985) - see section 3.2.2 were collected (…)	(…) (1985) - see section 3.2.2 - were collected (…)	x	Changed
347	(IMS, 2015)	x	Check reference, line 911-912: No year 2015 given.	Changed & added
381	(spring data coverage see, Table C1)	(spring data coverage, s. Appendix C, Table C1)	x	Ok ✓
400	soil thickness matrix (Table D1)	soil thickness matrix (Appendix D, Table D1)	x	Ok ✓
403	Messerschmid et al., 2019b	Messerschmid et al., 2019	Check references, lines 946-947: There is only one "Messerschmid et al., 2019", no a and b	Checked ✓
408	(…) documented in Table E1 and Fig. E1	(…) documented in Appendix E, Table E1 and Fig. E1	x	Ok ✓
427	(…) presented in Table F1	(…) presented in Appendix F, Table F1	x	Changed
474	used the individual annual rainfall coefficients (RC)	used the individual annual recharge coefficients (RC)	Check if "rainfall" or "recharge" coefficient.	Ok, changed ✓
493	(Two exceptions are found here:	Two exceptions are found here:	x	Ok ✓
499	(compare soil depth matrix, Table D1)	(compare soil depth matrix, Appendix D, Table D1)	x	Ok ✓

Line	**Original**	**Recommendations**	**Remarks**	**Action**
534	Fig. 6	x	If it is technically possible, it will be good to distinguish more obviously between P and DP also within the legend. Since the x-axis is not a timeline, it might be better not to draw lines between some of the data, but rather use a different signature or chart type.	deleted
544	Fig. 7	x	If technically possible it would be good to stretch the diagram over the full page width.	Ok ✓, but up to layout of HESS
558	(Table B3)	(Appendix B, Table B3)	x	Ok ✓
595	see Table C1	see Appendix C, Table C1	x	Ok ✓
604	Messerschmid et al., 2019b	Messerschmid et al., 2019	Check references, lines 946-947: There is only one "Messerschmid et al., 2019", no a and b	Checked ✓
616	In sum, for most years, (…)	For most years, (…)	x	Ok ✓

625	Messerschmid et al., 2019b	Messerschmid et al., 2019	Check references, lines 946-947: There is only one “Messerschmid et al., 2019”, no a and b	Checked ✓
630	see Table D1	see Appendix D, Table D1	x	Ok ✓
646	manly	mainly	x	Deleted
691	Messerschmid et al., 2019b	Messerschmid et al., 2019	Check references, lines 946-947: There is only one “Messerschmid et al., 2019”, no a and b	Checked ✓
695	(see Fig. G1)	(see Appendix G, Fig. G1)	x	Ok ✓
707	All in all, (…)	Overall, (…)	x	Ok ✓
707	(Table B1)	(Appendix B, Table B1)	x	Ok ✓
721	shown in Tables B1 and B2	shown in Appendix B, Tables B1 and B2	x	Ok ✓
732	Table H1	Appendix H, Table H1	x	Ok ✓
797	Messerschmid et al., 2019b	Messerschmid et al., 2019	Check references, lines 946-947: There is only one “Messerschmid et al., 2019”, no a and b	Checked ✓

Line	**Original**	**Recommendations**	**Remarks**	**Action**
813-814	Allocca et al. (2014)	x	Not found in the manuscript.	In Table H1
815-816	Allocca et al. (2015) x	Not found in the manuscript.		In Table H1
831-832	Bradford et al. (2002)	x	Not found in the manuscript.	In Table H1
865-866	Freeze (1969)	x	Not found in the manuscript.	In Table H1
869-870	Goldscheider et al. (2007)	x	Not found in the manuscript.	In Table H1
882-883	Gunkel et al. (2015)	x	Not found in the manuscript.	In Table H1
935-937	Messerschmid (2003) Not found in the manuscript.			In Table H1
946-947	Messerschmid et al. (2019b)	Messerschmid et al. (2019)	There is only one “Messerschmid et al., 2019”, no a and b	Checked ✓
950-951	Nativ et al. (1995)	x	Not found in the manuscript.	In Table H1
950-951	Radulovic et al. (2011) Not found in the manuscript.			In Table H1
963-965	Rosenzweig et al. (1972) Not found in the manuscript.			In Table H1
970-971	Sanz et al. (2011) Not found in the manuscript.			In Table H1
981-982	Shachori et al. (1965) Not found in the manuscript.			In Table H1
1013-1014	Weiss et al. (2007)	x	Not found in the manuscript.	In Table H1
1040	technical equipment an interpretation problems	technical equipment and interpretation problems	x	Ok ✓
1116	average of seven years is 101.7%	the average of all 44 years average of seven years is 101.7% of the average of all 44 years	x	changed
1141	Messerschmid et al., 2019b	Messerschmid et al., 2019	Check references, lines 946-947: There is only one “Messerschmid et al., 2019”, no a and b	Checked ✓

Field-based estimation and modelling of distributed groundwater recharge in a Mediterranean karst catchment, Wadi Natuf, West Bank

Clemens Messerschmid[1,2], ~~Jens Lange[1] and~~ Martin Sauter[2] and Jens Lange[1]

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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~~, especially in~~. This is particularly true for hitherto ungauged basins, such as Wadi Natuf, a ~~103km^2~~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 seven years of extensive field observations and measurements and based conceptually on ~~some of the lessons of research on predictions in ungauged basins (PUB research), i.e. by drawing 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~~ and~~. The model was parameterized in a strictly parsimonious manner, as a ~~‘~~one~~ reservoir’~~ dimensional model ~~(~~‘(aka ‘tank’ model~~) of~~, bucket or box model), based on dominant hydrological processes, in particular saturation excess in the soil column~~. Following the recommendations of the PUB community, the model design was developed by determining main active hydrological processes~~, and by 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, 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 ~~conditions. It was found that~~representations. The main result of the model was the determination of formation-specific recharge ~~varies widely at the spatial dimension,~~coefficients, spatially ranging between 0 % and almost 60 % of annual rainfall~~.~~, or up to 300 mm/a 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 (~~a), e.g. observed and physical~~ soil moisture~~ as model parameters~~) and ~~on the level of~~ basin response (~~b), e.g. by comparing~~ signatures of peak ~~deep percolation events (~~recharge~~) with peak~~ and local spring discharge ~~at local springs~~events) under well controlled conditions in isolated sub-catchments. ~~The conceptual~~In

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Formatted: Font: 10 pt, Complex Script Font: Times New Roman, 12 pt, English (United States) principle, our approach ~~investigated basin form and basin response separately. Together with the parsimonious model, it~~ is applicable in many of the scarcely gauged karstic groundwater basins around the world~~, where karstic conditions and~~ with a highly diverse landscape and geology~~ prevail, such as Wadi Natuf in the West Bank~~.

Keywords. Distributed recharge, landscape features, basin signatures, soil moisture, reservoir model, parsimonious approach, PUB, recharge coefficients, saturation excess, deep percolation.

1 Introduction

Knowledge about distributed recharge is important for the exploration, sustainable management, protection and equitable allocation of water resources. ~~This research~~Acquiring recharge information remains complex and challenging for hydrogeological research, especially in ~~karstified aquifers and even more so in~~ the many ungauged basins around the world~~.~~ ~~Karst~~ and particularly in karstified aquifers, which supply about one quarter of world population (Ford and Williams, 2007~~),~~ ~~many of which remain poorly gauged or ungauged.~~). One key issue of water negotiations in ~~contested~~shared groundwater basins is the spatial distribution of water resources in the different zones, such as the recharge ~~zone~~zones of an aquifer.

1.1 ~~Background on~~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 lack of empirical and local knowledge from the field cannot readily be circumvented by ever more 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, 2012b; Dafny, 2009; Dafny *et al.*, 2010).

The study of groundwater recharge and its spatial variability in semi-arid to sub-humid karst regions 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 Josopait (1997) subdivided the field into direct and indirect research approaches or methods~~ of research~~ , (Lerner *et al.*, 1990) ~~or direct and indirect approaches (Dörhöfer and Josopait, 1997)~~ – not to be confused with direct and indirect recharge (see also ~~Scanlon *et al.*, 2002, 2006;~~ Bredenkamp *et al.*, 1995; Simmers *et al.*, 1988; De Vries *et al.*, 2002~~; Lloyd, 1980). Direct~~). While direct approaches determine ~~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 such as surface~~ parameters near the surface by observing runoff, interflow and soil moisture~~ saturation. In contrast~~, indirect approaches ~~usually~~ model ~~integrated~~the basin behaviour ~~based on observations of spring and river discharge and abstractions in the (often confined) productive regions, as well as of storage change, as far as it is measurable through monitoring wells in the deep saturated layers of an aquifer.~~ balancing integral measurements of 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 section 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

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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).

~~Scanlon *et al.* (2002) distinguished three groups of recharge estimation methods, for the unsaturated and the saturated zone as well as for surface water. For the unsaturated zone, Scanlon et al. (2002) listed lysimeter studies, tracer techniques, Darcy's law, numerical modelling and soil moisture balance techniques (e.g. zero flux plane method). When no other option than observations in the unsaturated zone are available, then groundwater recharge has to be equated with deep percolation from the soil cover into the aquiferous bedrock formation.~~

~~Jeannin and Sauter (1998) distinguished between two types of process based karst models, lumped and distributed, for which different types of recharge information are required (also used by Hartmann *et al.*, 2013). 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, 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 problems with spatial differentiation and over parameterization.~~

~~For ungauged basins, some of the lessons of the IAHS-led research decade from 2003 to 2012 on~~ **1.2 Dealing with spatial variability**

Hartmann *et al.* (2013) emphasized the need to focus on process-based approaches; this is especially true for hydrological predictions in ungauged basins (PUB~~) may be useful here. Most PUB studies emphasized the need to use process-oriented models in order to represent complex spatial variability. They observed and advocated a shift from lumped and integrated models to distributed models and from indirect to direct approaches (Hrachowitz *et al.*, 2013; Sivakumar *et al.*, 2013.~~

~~**1.2 Approaches to spatial variability in ungauged basins (results of PUB)**~~

~~To differentiate and quantify the spatially distributed, highly complex and overlapping processes of groundwater recharge, several general lessons can be drawn from~~). In the ~~PUB decade (Hrachowitz *et al.*, 2013), although most studies dealt with runoff rather than recharge. As Hrachowitz, *et al.* (2013) and Sivapalan *et al.* (2003a) reported, most PUB studies, both observed and suggested a shift of the research focus away from data- and calibration-focussed methods and towards the complexities of observable system understanding, which often require direct approaches to describe distributed physical in-situ processes. In order to improve the conceptual realism, Pomeroy (2011) summarized 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.~~

~~**1.2.1 Physical parameters and basins response (signatures)**~~

~~The parameterization of location specific physical landscape characteristics is a starting point for models to ensure a complete and physically realistic representation of~~ absence of field data describing the dominant ~~processes and their respective features (e.g. Franchini and Pacciani, 1991), and they can be loosely divided into three groups including bedrock characteristics, the characteristics of overlying soils and land use and land cover (LU/LC) at the surface: Batelaan and de~~

~~Smedt (2001) accounted for land use, soil and lithology; Batelaan and de Smedt (2007) accounted for land use, soil and topography (but not geology) but calculated with parameters based on literature values, while Aish, Batelaan and de Smedt (2010) used land use and soil type as physical parameters for their spatially distributed model of long term annual average recharge (besides runoff and actual evapotranspiration) in the Gaza Strip. Zomlot *et al.* (2015) emphasised the importance of soil texture and vegetation cover. For an overview, see also Hrachowitz *et al.* (2013) and the discussion in Messerschmid *et al.* (2019b).~~

~~In contrast to the~~hydrological processes and functioning of a basin, it was often recommended to make use of the more readily accessible and measurably physical basin form~~, the hydrological basin function (or impact) already represents the outcome of in-situ processes.~~ (Savenije ~~(~~, 2010) ~~suggested assigning individual hydrological processes and distinct hydrological functions (in his case, runoff) to different~~ and then to differentiate landscape units ~~by dissecting catchments in a semi-distributed way and~~ according to a hydrologically meaningful landscape classification metric~~. As a challenge however, remains the correct and appropriate linkage and translation from~~ to translate form ~~to~~ into function (~~Messerschmid *et al.*, 2019b). Among~~subject to follow-up paper). For the ~~many PUB findings on basin-specific links~~link between physical features and basin response ~~(i.e. between form and function),~~, Eder *et al.* (2003) and Hartmann *et al.* (2013) suggested the use of so-called hydrological system signatures to describe emergent properties of ~~the~~a system – ~~whether~~both, quantitatively or qualitatively – such as flow duration curves or spring hydrographs.

~~1.2.2 The~~

Most of the PUB literature, such as Sivakumar *et al.* (2013) and Hrachowitz *et al.* (2013), stressed the need for ~~**simplification and**~~ parsimony

~~In their quest for a common framework for~~ in hydrological modelling ~~many PUB researchers increasingly realized a need for simplification and parsimony with a focus on dominant local processes, such as simple water balance equation and tank models (Sivakumar *et al.*, 2013),~~, especially under the presence of equifinality in calibrated parameters ~~(Hrachowitz *et al.* (2013)~~ ; see also~~:~~ Grayson and Blöschl (2000); Woods (2002); Sivapalan *et al.* (2003b); McDonnell and Woods (2004); Sivakumar (2004, 2008); Wagener *et al.* (2007); Young and Ratto (2009) and Olden *et al.* (2012). ~~They observed that conventional hydrologic models were often far too complex and require too many parameters and data (Sivakumar *et al.*, 2013). They also place too much emphasis on specific, often preselected independent concepts and mathematical techniques, rather than on the coupling or integration of observations to capture the salient features of hydrologic systems. However,~~ Such parsimonious models stick to the description of simple local processes and the identification of a few but realistic and observable physical parameters and hydrological drivers governing these process (Franchini and Pacciani, 1991; Zomlot *et al.*, 2015). Sivapalan *et al.* (2003a) pointed out that despite the heterogeneity of local parameters and processes~~,~~ the response at the catchment-scale is often characterized by ~~a~~ surprising process simplicity ~~(Sivapalan *et al.*, 2003a). Often, a minimal~~. Hence a small number of ~~the appropriate~~ field observations ~~can~~may describe the main characteristics of a process (Seibert and Beven ~~(~~, 2009~~). Even~~), even in ungauged basins, ~~few measurements~~ and with short time series data ~~may contain most of the information found in long term extensive measurements~~only (Juston *et al.*, 2009; Seibert and Beven, 2009~~), for a detailed understanding of catchment responses at the local scale (~~; Blume *et al.*, 2008~~). A good empirical fit to basin responses could often be achieved with exceedingly simple models (~~; Nash, 1957; Dooge, 1959; Lambert, 1969~~) focussing on processes and using physical parameters directly from the basin (Beven and Kirkby, 1979). And it should be noted that rather than diminishing, this reduction often adds to the reliability and controllability of process outcomes, particularly in karstic environments, which are known for their high spatial variability (Hartmann *et al.*, 2012b), their non-Darcian flow, anisotropic flow fields (Dafny *et al.*, 2009, 2010) and increased problems of equifinality and multicollinearity. Keeping the~~

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~~steps of interpretation, conceptualisation, classification and quantification transparent, was described by Beven & Kirkby (1979) as 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.)~~.

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~~1.2.3 Empirical observations – the PUB paradox~~

~~Most researchers agreed that in order to ensure proper hydrological interpretation, conceptualisation and theorisation in light of complexities of hydrological processes, the research has to be grounded in observation, at least 'some' observations as Sivapalan *et al.* (2003a) pointed out, and it should be designed for specifically targeted measurements (McDonnell *et al.*, 2007). In other words, PUB research repeatedly emphasised the importance of empirical approaches. For example, in South Africa, but also in the Israeli Palestinian Western Aquifer Basin, Kapangaziwiri *et al.* (2012) and Hughes and Kapangaziwiri (2007) were confronted with the problem that, when model parameters were not gauged and measured on site but estimated directly and a priori from physical properties of the catchment, they may show little consistency. Therefore, these methods have to obtain process understanding from empirical experiments and furthermore should be based on fundamental physical laws and theories (Hrachowitz *et al.*, 2013), as well as local knowledge of the observable landscape and climate controls of hydrological processes (Sivapalan, 2003).~~

~~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. They therefore suggested taking a 'hydrologically intelligent choice', i.e. the correct interpretation of the dominant, most relevant features that govern a process while simultaneously keeping observations and measurements simple and at the necessary minimum, for reasons of practicality (e.g. measurement costs and field accessibility). Binley and Beven (2003) added that such an intelligent design remains a learning process that may start with insufficient data and adds data as required by the application and Seibert & Beven, 2009).~~

~~1.3~~

So far, most studies have focused on runoff, rather than on recharge (Sivapalan *et al.*, 2003a; Batelaan and de Smedt, 2001; 2007), but with 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 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 (WAB).

1.3 Existing recharge studies in the Western Aquifer Basin (WAB)

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The Western Aquifer Basin (WAB or Aujah-Tamaseeh in Arabic and Yarkon-Tanninim in Hebrew) is the largest, freshest and most productive groundwater basin in all of Israel and the occupied Palestinian territories (oPt~~ (~~), also known as West Bank and Gaza Strip~~). It spans~~, spanning from the sub-humid Mt. Carmel in the North into the ~~arid~~ Sinai in the South and from the West Bank ~~Mountains~~mountains to the Mediterranean Sea ~~(see Fig. 2a). In the literature, its size ranges between 9,000 and~~with an area of 14,~~167~~148 km^2~~, depending on the boundaries set by different authors (for an overview, see:~~ (SUSMAQ, 2003; ESCWA-BGR, 2013~~). During the pre-utilization period, the WAB drained through two principle karst spring outlets in the Coastal Plain, on which its old Arabic, as well as the more recent Hebrew names are based: Aujah-Tamaseeh or Yarkon-Tanninim, respectively (SUSMAQ, 2002).~~), see Fig. 1. The WAB is a classical 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~~; and the~~. The basin rapidly became one of the single-largest sources of Israeli water supply, ~~potentially~~which also has the

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potential to become one of the largest future sources of Palestinian supply in the West Bank~~ supply~~. 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 ~~almost~~relatively untouched, ungauged and unexplored, ~~not least~~ 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, ~~North~~which is north of Ramallah, down to the Green Line (that separates Israel from the Palestinian West Bank) - see section 2.

~~1.3.1 Existing basin-wide recharge studies in the WAB – approaches and limitations~~

~~Recharge~~Also in the Western ~~aquifer has been the subject~~Aquifer Basin (WAB) the preferred choice 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~~of the existing studies were fully lumped models. This was done primarily to avoid problems with spatial differentiation and over-parameterization (Goldschmidt and Jacobs, 1958~~)~~ ~~or with discharge 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, lumped water budget is permissible, yet contributes little to understand the spatial variability of distributed recharge in the outcrop areas of the West Bank Mountains, particularly on a local scale, where the hydrostratigraphy is more complex (see section 2). Abusaadah (2011) presented a three-dimensional integrated flow model, encompassing plains and slopes as separate recharge and flow zones, however with limited accuracy 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).~~

~~Few authors have attempted to investigate spatial recharge distribution and variability in the WAB. As an exception,~~Some researchers created partially distributed models. Sheffer~~ *et al.* (2010) used a hybrid of lumped basin water budgeting and spatial distribution in the upstream, albeit without independently establishing and testing the sensitive field parameters (physical form) and with little local empirical observation and insights into the complex~~ , 2009 and Sheffer *et al.* (2010) for example applied a distributed ~~recharge processes and their dominant features. Instead, his soil percolation model parameters were taken as estimates from the literature (e.g. Dingman, 1994) and then retrofitted through repeated calibration runs. Sheffer (2009) coupled 3,300 soil moisture “tank” models in the recharge zone with a lumped flow model for basin response. He accounted only for two rock types (permeable~~ basin-wide recharge model to the WAB, which however only distinguished coarsely between two units – permeable carbonatic formations and less permeable~~). Due to his lumped calibration on responses in the remote discharge zone, he had no possibility to check the plausibility of the assumed recharge zone parameters and remained exposed to problems with equifinality and the complex distributed recharge processes.~~

~~Hughes and Mansour (2005) and Hughes *et al.* (2008) published results of a fully distributed so-called “object-oriented” recharge model that separates different inputs and processes, such as runoff, spring flow, soil infiltration and deep percolation (recharge) into individually calculated compartments. However, while their model used a high spatial resolution, it did not distinguish between sub basins but combined all distributed input together into one lumped, integrated basin-wide model~~, chalky or marly rock outcrop. In addition, ~~the parameters themselves were rarely grounded on local field~~

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~~observations. Instead, they employed assumed parameters (e.g. field capacity and wilting point in their soil moisture sub-model), estimated directly and *a priori* from physical properties of the catchment, which led to the aforementioned problems of lacking consistency between physical features and modelled basin response. Their study therefore confirms the~~crucial model parameters, such as soil characteristics were taken from the literature (Dingman, 1994), not gained from in-situ findings ~~from the PUB-decade, e.g. that a thorough understanding of the dominant processes at play must be firmly based on observations and descriptions of physical features, such as land use, soil, geology or structural characteristics (compare~~ in the field (see also: ~~Abusaada, 2011~~Dvory *et al.*, 2016; Weiss and ~~Martínez-Santos~~Gvirtzman, 2007 and ~~Andreu, 2010).~~

~~1.3.2 Local scale recharge studies in the WAB~~

~~Individual empirical~~ Schmidt *et al.*, 2014). Truly spatially distributed and field~~studies~~ -based approaches so far are restricted to studies on ~~winter observations in very localised sub-catchments investigated~~ the local ~~processes of soil saturation, runoff and infiltration on a~~ scale of less than 1 km^2 (Frumkin, 1994; Lange *et al.*, 2003; Arbel *et al.*, 2010; Lange *et al.*, 2010; Steinmann, 2010 and Grodek *et al.*, 2011). However~~, they~~ these studies mainly focussed on runoff rather than ~~on recharge and their analysis was mainly based on differentiating surface characteristics, rather than differentiating between lithostratigraphic units (Steinman, 2010). Lange *et al.* (2003) used tracers in local sprinkler~~recharge. Sprinkler tests ~~(of 10 x 18m~~ on a plot ~~size) near Wadi Natuf to investigate rainfall-runoff relationships and – important for the process understanding – pointed out~~scale (10 m x 18 m) by Lange *et al.* (2003) pointed to the importance of soil saturation excess for surface runoff and recharge ~~(Lange *et al.*, 2003). Otherwise, no regional tracer tests to investigate recharge~~. Similar observations were ~~carried out in the WAB so far, possibly due to the above mentioned lack of intake and observation points (e.g. monitoring wells) in the upstream West Bank recharge zone. 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, 1994; Arbel *et al.*, 2010 and Lange *et al.*, 2010). However, the generalisation of their results is restricted because the contributing areas are unknown and caves may develop their own hydraulic environments (Ford and Williams, 2007); the results may therefore not be representative for larger areas, as pointed out by~~ published by Ries *et al.* (2015~~) – compare also to Sheffer *et al.* (2010), Hartmann *et al.* (2012) and Lange *et al.* (2010).~~

~~**1.3.3 Studies**~~, 2017) in ~~**adjacent catchments**~~

~~Finally, three studies from aquifers adjacent to Wadi Natuf shall be presented. Two empirical field studies in a nearby catchment of~~ the neighbouring Eastern Aquifer Basin (EAB) ~~fitted a soil moisture saturation excess model to soil moisture field measurements (once with three and another time with 4 soil moisture plots) and identified seasonal recharge pulses on an event basis (Ries *et al.*, 2015 and 2017). In line with the aforementioned findings by Lange *et al.* (2003 and 2010), Ries *et al.* (2015 and 2017) showed that soil moisture saturation was the principle process of runoff and recharge generation in the specific field conditions of the mountain areas of the EAB adjacent to Wadi Natuf 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 to~~ that drains towards the Jordan Rift Valley~~, successfully employed a parsimonious recharge and groundwater flow model with two components: they coupled a soil moisture saturation model, similar to that of Sheffer *et al.* (2010) for deep percolation (input) with a karstic double porosity aquifer component for groundwater flow towards a field-monitored spring outlet. However, again, their soil parameters and time series data of soil saturation were not based on empirical field 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).~~ and the Dead Sea.

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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 section 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: Martinez-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). ~~**1.4 Research gaps**~~

~~Two~~ 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) summarized 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 summarize, firstly, only one of the three general venues to estimate recharge~~, cited by~~ (Scanlon *et al*~~. (~~., 2002) are ~~not~~ applicable to Wadi Natuf~~: As discussed in section 1.3 and 2, observations of~~ – the saturated zone ~~are severely limited. Equally, no~~is inaccessible for field measurements and observations and surface water ~~based approaches~~ bodies are ~~a possible venue for recharge studies in Wadi Natuf. Only the unsaturated zone is accessible for field measurements and observations – see also Sheffer *et al*. (2010). As in most, if not all ungauged basins worldwide, also in the WAB, the general problem of a~~absent (see section 2). Secondly, the severe lack of primary empirical field data~~ from observation and measurements has to be addressed and~~ cannot be circumvented by ever more sophisticated advances in modelling. ~~This remains a challenge, as the IAHS-led decade on PUB concluded. Instead~~Therefore, thirdly, new ~~methods are needed that focus on the understanding of~~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 conceptualize, describe, classify and measure 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 on 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~~, while simultaneously adhering to the goal of parsimony and ~~avoid over-~~avoiding exhaustive calibration ~~as well as~~ associated with the problems of equifinality.

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1.5 Aims, motivation and approach

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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~~. A simplified~~ for the first time. The process understanding 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/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~~ (basin from)~~ 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 ~~two different ways~~a novel combination of both, quantitative and semi-qualitative basin observations: On the one hand, ~~and ~~at the level of basin form (physical soil parameters~~ governing recharge (basin form),~~) the modelled soil moisture content was compared to the field~~ measured readings.~~ measurements. On the other hand, on the ~~signature~~level of basin response, the signatures of measured spring flow events ~~with their periods of ~~(peak discharge ~~(basin response) was~~periods) were compared to the modelled periods of deep percolation (DP).~~ In other words, this study used empirical (inductive) approaches to determine spatial variations in groundwater recharge and then tested the model by both, semi-qualitative and quantitative, measured basin observations alike.~~ Finally, the model results of spatially distributed annual recharge coefficients were compared to literature results from former recharge studies in the WAB.

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2 Study area

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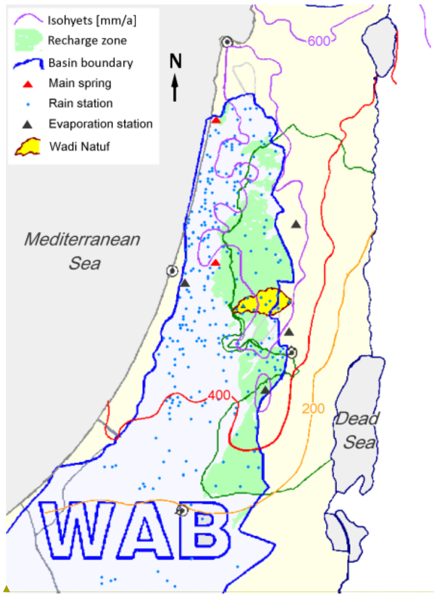
Wadi Natuf is a 103 km^2 catchment stretching from the mountain plateau at the crest of the West Bank at 816 m above sea level (asl) down to its foothills at 138 m asl (Fig. 1). In the Eastern mountain region, the topography is characterized by the rocky mountain crests and high plains with steep terraced slopes towards the Central Wadi Natuf further west. Here, in the midstream catchment, undulating hills with deeply incised ephemeral rivers (~~Wadis~~wadis) dominate, descending further down to the gentle slopes and plains in the lower Natuf region near the outlet of the main ~~Wadi~~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. ~~2~~2a, b) and are therefore exposed to direct infiltration. The climate is typically Eastern Mediterranean with ~~rainfall amounts~~precipitation occurring from November to April, monotonously rising from the semi-arid Western foothills (500 - 600 mm/a) to sub-humid conditions in the Eastern Mountains~~.~~ (above 600 mm/a). 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.



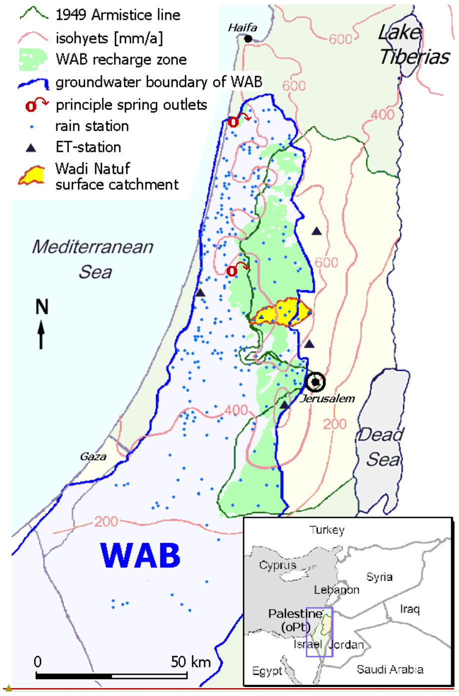


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Figure 1: Western Aquifer Basin (WAB) overview and Natuf location map. Wadi Natuf (in yellow) lies in the uphill recharge zone (shaded green) of the ~~WAB, and~~Western Aquifer groundwater basin, whereas the easternmost part of its surface catchment belongs to the ~~Eastern Aquifer~~ (EAB) Basin. Isohyets ~~(different colours)~~ indicate semi-arid to sub-humid climate in Wadi Natuf. The two former principle spring outlets of the WAB ~~(red triangles)~~ have all but dried up, due to excessive pumpage in Israel. Four ~~evaporation~~evapotranspiration stations (~~black triangles~~ET) around Wadi Natuf were complemented by two ~~Automatic~~automatic weather stations ~~within the catchment by~~(AWS) in this study. ~~Source~~Sources: modified after ~~Ettinger (1996~~Sheffer *et al.* (2010), SUSMAQ (2001), Abusaada (2011) and ESCWA-BGR (2013).

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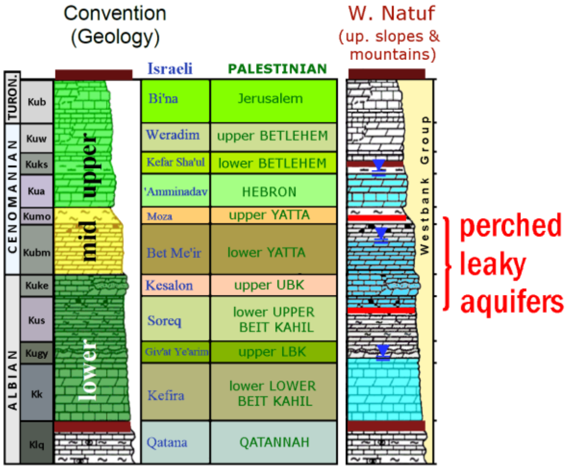

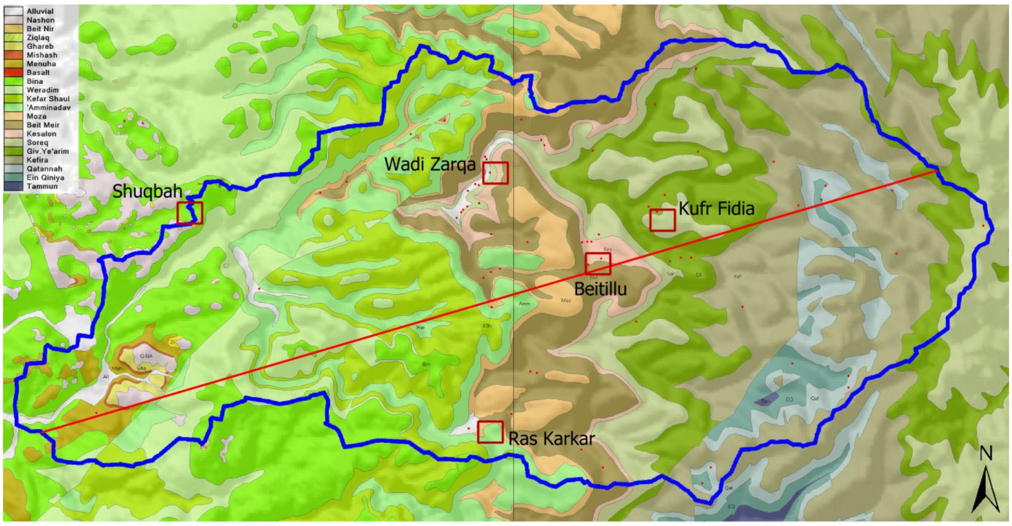

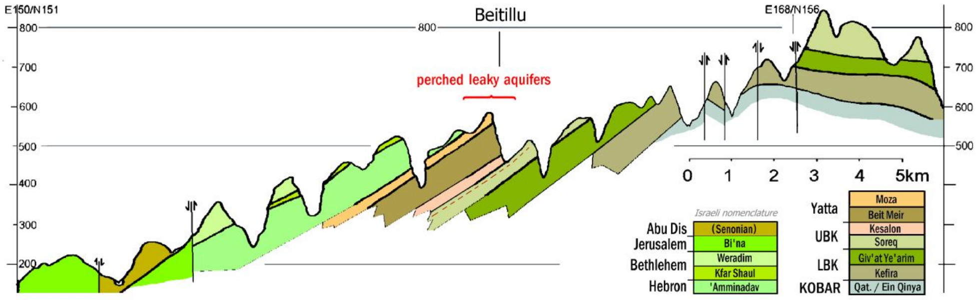

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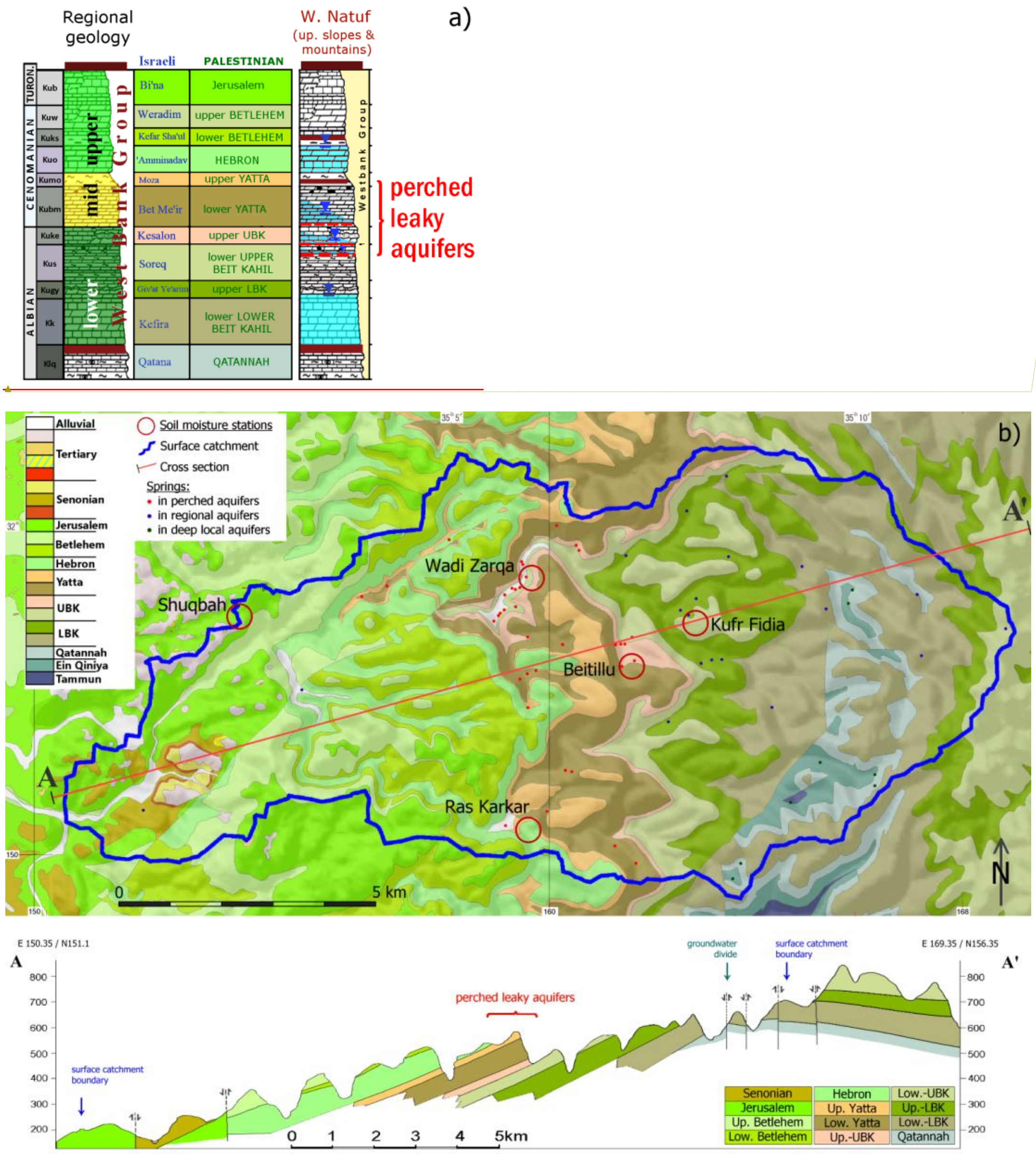

Figure 2: Stratigraphic column (2a) and geological relief map with cross section (2b).
2a: The stratigraphic column shows the regional hydrostratigraphy of the lower, middle and upper West Bank Group (in Israel: *Judea Group*) with only two aquifers (left side), such as the Lower Aquifer (‘lower’ group) and the Upper ~~Aquifers~~Aquifer (‘upper’ group), separated by the yellow ‘mid’ group (left side~~); on~~). 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~~ (l-Yat, u-UBK ~~, e.g. the lower Yatta formation, upper UBK formation and the top of lower UBK formation (abbreviated to l-Yat, u-UBK & top of l-UBK~~ formations~~). The middle columns show the Israeli and Palestinian formation names.
2b: The geological relief map indicates ~~formation names of the Israeli nomenclature in the top left corner of the map (2a) and inside the boxes below the cross section beneath. Palestinian formation names, as used in this study, are on the side~~a selection of the ~~boxes.~~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 ~~boxes~~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

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aquifers crop out. Sources~~—~~: stratigraphic column~~:~~, modified after Dafny (2010); geological map~~:~~, modified after GSI (2000 and 2008); cross section: this study.

Conventionally and on a regional scale, the WAB is subdivided into two main regional aquifer units of mostly karstified carbonates~~—the~~. The ‘Lower Aquifer’ is of Lower Albian age (ca. 113-106 million years) and the ‘Upper Aquifer’ of Upper Cenomanian to Turonian age (ca. 95-89 million years~~) and cover~~). Together they make up around two thirds (64.4 %) of the outcrops in Wadi Natuf (Fig. ~~2a, Table 1). In between, the regional~~ 2b). The remaining third of the catchment consists of aquitards from marl and chalk. According to this conventional view, the regional aquifers 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; 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 ~~impermeable~~ aquiclude section of yellow soft marl (upper Yatta formation or u~~–~~-Yat) and a more carbonatic, ~~and in parts~~ partly karstified intermediate perched aquifer ~~horizons (~~horizon (lower Yatta formation or l–Yat~~) of local distribution that give rise to over 100 small local springs~~), see Fig. 2a (Messerschmid *et al.*, 2003a, 2003b). ~~As shown in Fig. 2a, stratigraphically they stretch between mixed series of carbonates, intercalated with chalk and marl and some chert (l-Yat) and rhythmic alterations of dm-thick dolomites interbedded with cm-thick marl layers (l-UBK formation), ending at its bottom with a conspicuous twin marl layer (see Fig. 3a). L-UBK is overlain by~~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 ~~formation (u-UBK, see Fig. 3b). While small~~ series (Fig. A3b). The third perched aquifer on a local scale is formed by the top of lower 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~~) emerge in large numbers from the isolated perched local aquifers, the recharge areas of the regional Upper and Lower Aquifers on the western flanks of the West Bank are almost entirely~~), 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.

~~**Figure 3. Lithostratigraphic formations.** Twin marl band, located 2.5 km SE of Beitillu (a). It acts as confining layer beneath the top of lower UBK formation (top l-UBK). Cliff-forming coral reef limestone of upper UBK formation (u-UBK) at Wadi Zarqa with high primary porosity but also signs of karstification; the inlet photo shows a 1.5 cm thick remnant of coral branches (b). Colourful, thinly plated limestone of lower Betlehem formation (l-Bet) with fine marl intercalations (c).~~

~~**Table 1: Outcrop (recharge) area, rainfall and classes of recharge potential of the perched aquifers and the main regional aquifers.**~~

~~**formation**~~	~~u–Yat~~	~~**l–Yat**~~	~~**u–UBK**~~	~~**l–UBK**~~	~~“Upper Aquifer”*~~	~~“Lower Aquifer”*~~

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~~area (km^2)~~	~~4.931~~	~~10.182~~	~~2.442~~	~~8.441~~	~~36.732~~	~~29.556~~
~~avg. rain 2003–10^1 (mcm/a)~~	~~2.917~~	~~6.145~~	~~1.502~~	~~5.262~~	~~20.696~~	~~18.452~~
~~class of recharge potential~~	~~V~~	~~IV~~	~~I, II~~	~~III~~	~~(I-III)~~	~~(I-III)~~

~~[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.~~

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 ~~during the dry season disintegrating the soil into fist size crumbs. During the early half of the winter season, these~~. These cracks can act as preferential pathways for infiltration~~, until the soils swell and cracks close during winter and early spring. Except for~~ during the early half of the winter season (as also found by Gimbel, 2015). Soil thickness > 1m was only found at small agricultural plains ~~over~~overlying the aquitard series ~~(like~~such as upper Yatta formation (u-Yat, see Fig. A1~~), no soils with thicknesses larger than one metre were found.~~, Table ~~2 show the typical soil thickness for different formations in Wadi Natuf (see also Appendix F).~~ 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~~), where~~); carbonates show thin soils, while over argillaceous rock, thicker soil covers develop. Equally, soil cover over grassland and terraces were found thin~~ (see Table 2),~~, 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 ('Upper Aquifer'), see also Appendix D. This association of soil depths with other land features will be ~~further discussed in the~~ subject to a follow-up paper on regionalisation~~,~~: Messerschmid *et al.*, ~~2019b).~~ (in preparation).

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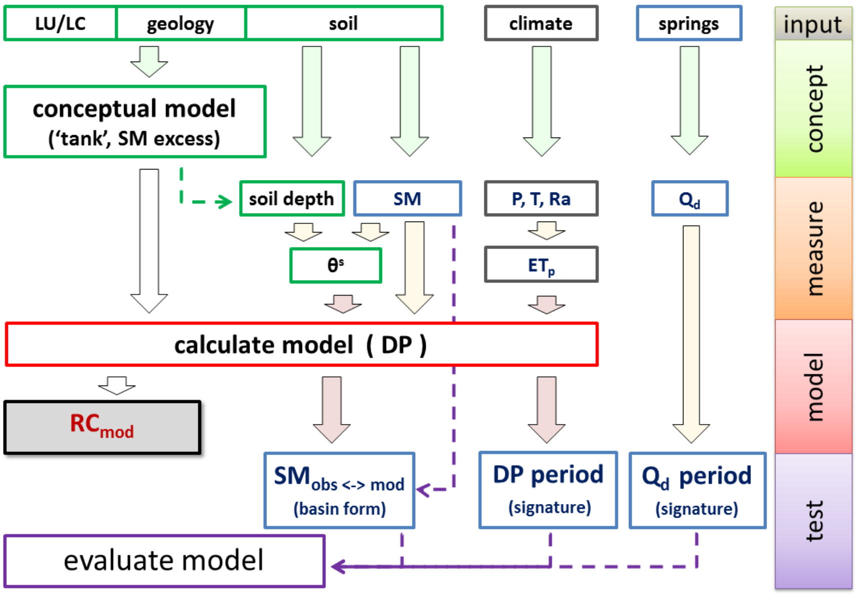
~~**Table 2: Soil moisture measurement data by location (in mm and %).**~~

	~~**Beitillu, gardens**~~	~~**Shuqbah, grassland**~~	~~**Wadi Zarqa, fields**~~		~~**Kufr Fidiah, field**~~		~~**Ras Karkar, terraces**~~	
			~~**upper terrace**~~	~~**hothouse**~~	~~**KF-W**~~	~~**KF-E**~~	~~**RK-W**~~	~~**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~~	~~u–UBK (top l–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$_{max}$ (mm)~~	~~179~~	~~60~~	~~172~~	~~132~~	~~253~~	~~237~~	~~129~~	~~129~~
~~SM$_{min}$ (%)~~	~~8 %~~	~~10 %~~	~~6.5 %~~	~~16.1 %~~	~~10.5 %~~	~~0.5 %~~	~~4.2 %~~	~~4.2 %~~
~~SMm$_{in}$ (mm)~~	~~40~~	~~20~~	~~50.05~~	~~64.4~~	~~68.25~~	~~4.7~~	~~16.8~~	~~16.8~~
~~**θ^s (mm)**~~	~~**139**~~	~~**40**~~	~~**121.5**~~	~~**67.5**~~	~~**185**~~	~~**232.5**~~	~~**112.5**~~	~~**112.5**~~
~~θ_{peak} (mm)~~	~~149~~	~~44~~	~~175~~	~~93~~	~~232~~	~~234~~	~~119~~	~~127~~

~~Note: θ_{peak} is a brief, episodically occurring available water storage above saturation storage capacity (θ^s); SM$_{max}$ and SM$_{max}$ are highest and lowest recurring soil water contents measured in the field (see also section 3.2.4).~~

~~3 Material and Methodology~~

~~As already mentioned in the introduction, this study presents a distributed recharge assessment method for a karst catchment based on hydrological field measurements (soils and springs) and parsimonious modelling (Fig. 4). In the following, the materials used and developed will be presented and the methodology described in more detail.~~



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A prevailing feature in Wadi Natuf, as in most of the Mountain Aquifer (Schmidt *et al.*, 2013), was the finding of a thick unsaturated zone in the up to hundreds of metres thick karstified aquifers 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 or LU/LC), as shown in Fig. 3. The forward-calculating model is parsimonious, i.e. based only on daily precipitation and evapotranspiration (as well as temporally stable location-specific soil parameters) in order to translate soil moisture saturation into deep percolation (DP), 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.

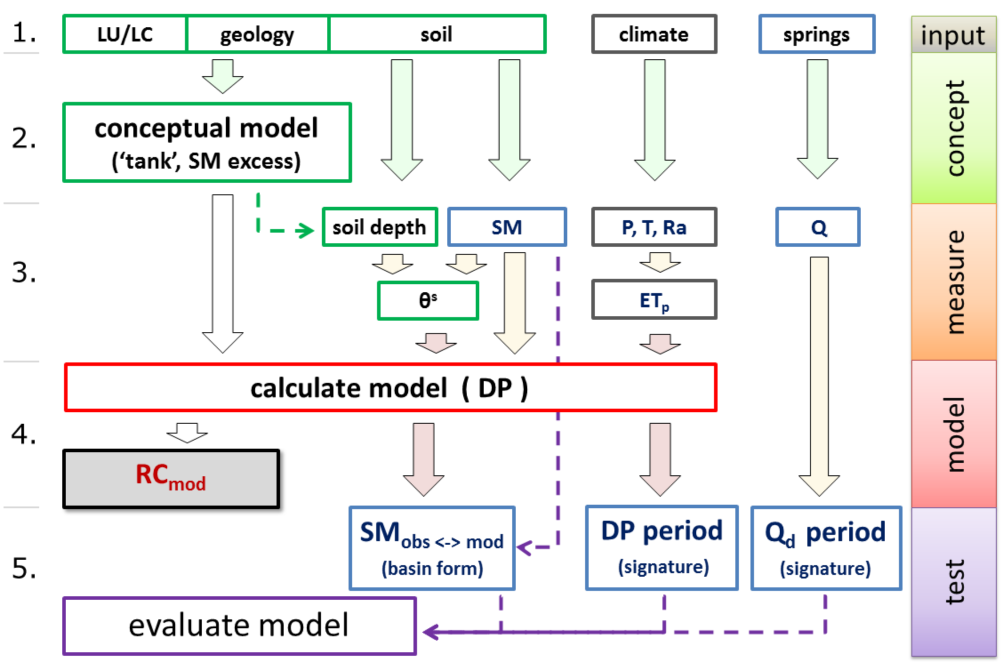

Figure ~~4~~3: Conceptual flow chart of the work steps for the model. First row: measured and observed input such as climate, spring flow, land use and land cover (LU/LC), etc.; second row: conceptualisation of the one-reservoir 'tank' model; third ~~part~~row: actual measurements ~~such as~~of daily values for soil moisture (SM), precipitation (P), temperature (T), solar radiation (Ra), ~~daily~~ spring flow (~~Q_d~~Q), etc.; fourth ~~step~~row: modelling deep percolation (DP) and ~~calculating~~transformation into annual recharge coefficients for each of the modelled formations (RC_{mod}); last ~~part~~row: model evaluation by different tests such as~~, quantitatively, comparing~~ quantitative comparison between observed and modelled soil moisture ~~levels~~contents (*SM_{obs}* and *SM_{mod}*), ~~as well as~~ and semi-~~qualitatively by comparing signatures (~~qualitative comparison between periods~~)~~ of percolation events (DP) and peak discharge at the daily ~~read~~measured springs (~~Q_d~~Q).

3.1 ~~Material~~

~~The material used and developed under this study belongs to three types – climatic drivers, like precipitation and evaporation, hydrological measurements such as soil moisture (SM) and five daily read springs, and finally physical features (soil depth, geology and LU/LC) to set up the recharge or deep percolation model (DP model).~~

~~3.1.1~~ Climatic drivers – rainfall and evapotranspiration

The measurement period for precipitation and evaporation ~~spans~~spanned over nine seasons, from 2003/04 until 2011/12. A complete set of weighted area rainfall data for the five sub-catchments (Fig. 4) was obtained from ~~a previous study,~~Messerschmid *et al.* (2018), originally measured in five minute steps at ten stations ~~and equipped with~~distributed evenly in upper, central and lower Wadi Natuf. The automated rain gauges (tipping buckets) with Eijkelkamp loggers~~,~~ were run in event mode~~; the runoff analysis~~. The model in this ~~previous~~ study ~~(Messerschmid *et al.*, 2018) was based on five-minute steps. Here,~~used the weighted area rainfall precipitation at the ~~data were used~~ five sub-catchments in daily steps~~. The set of~~ (see Table 2 and Fig. 4).

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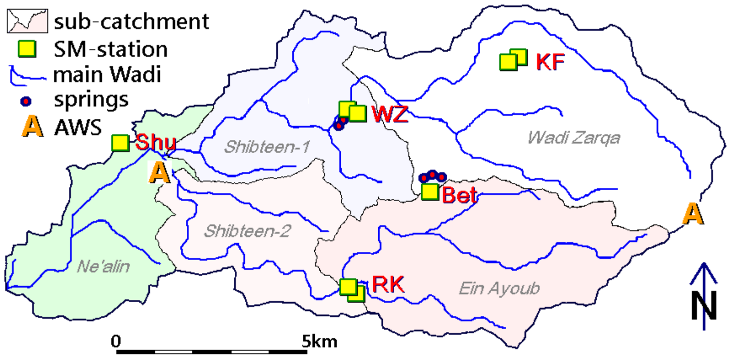

Figure 4: Drainage and measurement stations~~ consists~~**.** Main branches of the northern and southern branches of ~~three~~Wadi Natuf: Soil moisture stations ~~upstream~~(SM) at Shuqbah (Shu), Wadi Zarqa (WZ), Beitillu (Bet), Kufr Fidiah (KF) and Ras Karkar (RK); Daily measured springs at Beitillu and ~~downstream, respectively and of four~~Wadi Zarqa; Automatic weather stations (AWS) in Shibteen (West) and Bir Zeit (East): Sub-catchments (in grey): Ne'alin (West), Shibteen-1 (midstream~~ (in central Wadi Natuf) with weighted area rainfall for the respective sub-catchments (Table 3). ~~, North), Shibteen-2 (midstream, South), Ein Ayoub (South-East) and Wadi Zarqa (North-East).

Daily minimum and maximum temperature and solar radiation data were collected at two Automatic Weather Stations (AWS) for the calculation of potential evaporation ~~with the formula of Hargreaves *et al.* (1985) – see section 3.2.2 were collected at two stations in Wadi Natuf; one~~(Fig. 4). The readings were taken with two Automatic Weather Stations (AWS) of the Type Campbell Scientific with a CR10X data logger and a HMP45D (Y3520067) Sensor. One station was installed upstream at Bir Zeit University at the mountain crest~~. Another~~; 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, ~~2015~~2017), which represented intermediate values between the relatively cool conditions in Bir Zeit and the relatively warm conditions downstream in Shibteen.~~ The readings were taken with an Automatic Weather Station (AWS) of the Type Campbell Scientific with a CR10X data logger and a HMP45D (Y3520067) Sensor.~~

~~3.1.2 Hydrological measurements~~

~~Soil moisture was monitored at eight different stations over a period of seven years. However, due to limitations in budget and field access (particularly severe during the height of the 2. Intifada), the measurements were kept at a minimum (in line with the recommendations by Beven, 2002 and by Seibert and Beven, 2009 – see section 1). Therefore, under a lack of sufficient measurement instruments and manpower to maintain and read the SM stations, it was decided to increase the number of different SM stations and to decrease the period of years each station was run. Of the eight stations, none was read throughout the entire period; instead, the number of measured years at a given station was in a range between one and four years. Table 2 documents the measurement period for each station. Only a maximum of three sets of equipment was available in parallel during any given moment. All in all, 13 years of soil moisture measurements were carried out at the eight locations. Some stations were only measured during one season, others during up to four seasons. The period of measurements at each respective station is documented in Table 2 (section 2).~~

~~Initially two sets of ML2 Theta probes (Delta-T Devices Ltd., Cambridge, GB) were used. Due to malfunction and vandalism they were replaced consecutively by two ECH2O loggers with five sensors (Decagon Devices, Inc., Pullman, USA). Each station was equipped with 2-3 sensors installed at different depths from 5 cm below surface down to 75 cm at~~

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~~the thickest soils (Table 2). Target of the soil moisture (SM) measurements were daily time series data of overall available water content (θ), measured originally in 30-minute steps, then averaged to daily values.~~

Potential evapotranspiration (ET_p) was calculated by the formula of Hargreaves *et al.* (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 Equation (1):

~~SM was measured at different depths by each sensor and then normalised to total water content of the respective soil column.~~

~~In addition to the logging, hundreds of soil samples (150-550 g) were collected throughout the rainy seasons (with an emphasis during the first two seasons) and particularly after rainy events, both, in the surroundings of the SM-stations, as well as at unmonitored sites of different formations and mostly from surface near, but also some from deep soil layers. Their water content was oven-weighed at Bir Zeit laboratory. The target here was to obtain control values to approve the reliability and representativeness of the selected soil stations. Technical problems with the equipment or interpretation of the data (e.g. exaggerated moisture readings) occurred during 8.09% of measured days, mostly during autumn, when the dried up soils were picking up moisture (and once in spring, after the recharge period). The statistics and possible reasons of these misreadings are discussed in Appendix B (Tables B1-B3). No equipment problems occurred during the periods of intensive precipitation and recharge.~~

~~The second set of hydrological field work was the daily spring flow measurement. Taking into account practical considerations such as field accessibility and minimisation of costs and efforts, five springs were selected, which were then continuously measured throughout almost the entire period and on a daily basis (spring data coverage see, Table C1). All selected springs lie near the SM measurement stations and issue from the perched aquifers recharged at the SM plots with very short travel times (see section 4.1.4). Three of these springs belong to the so-called 'Beitillu spring group'; the two other springs to the 'Wadi Zarqa spring group' (see Fig. 2b). The measurements were carried out by hand with stop watch and bucket (an initial installation of water meters proved unreliable). The target of the spring readings was to establish, for the first time in the WAB Mountains, a complete spring hydrograph of high temporal resolution in order to detect the signatures, i.e. the temporal patterns of low and peak discharge for comparison with model results of recharge. The procedure of these calculations is detailed under section 3.2.~~

~~3.1.3 Physical features~~

~~The mapping, measurement and recording of physical features was field based, as well as based on previous work in the literature. The soil in Wadi Natuf was found to consist only of one prevailing soil type, terra rossa (see section 2); field investigations, sampling and granulometric lab tests showed that most of these soils are silty-clayey, with some samples also showing higher clay contents (Messerschmid *et al.*, 2018). This allowed for an important simplification of the requirements for the DP model, which only accounted for variable soil depth but a uniform soil type throughout the study area. The focus of the field work hence was laid on the spatial distribution of soil thickness (b), by digging up the soil down to the soil-rock interface. In many places, a transition zone between soil and bedrock was encountered, with rock content gradually increasing downward. Here, digging usually stopped when in the transition zone the volumetric portion of rock fragments outweighed the soil content. This depth was then taken as the depth of the soil-rock contact horizon. Since soil thickness (b) is a quantifiable parameter and plays a crucial role in the soil moisture – percolation model, much effort was spent on probing the soil depth at many sites for each outcropping formation and on the establishment of a soil thickness matrix (Table D1), where the distribution of soil depth is documented for different LU/LC types and different lithostratigraphic units (see also~~

~~Table 2). The target was to create a simplified but realistic categorization of different geological formations and LU/LC types representing typical soil thicknesses (compare also Messerschmid, *et al.*, 2019b).~~

~~3.2 Methodology~~

~~3.2.1 Rainfall~~

~~In order to estimate average recharge coefficients, it is necessary to first verify that the observation period represents the normal range of long term annual rainfall variations (≥30 years). Since no 30 year record for Wadi Natuf is available, we based our examination on the documented area rainfall of the WAB. The calculations are documented in Table E1 and Fig. E1. As a result, we can state with confidence that the seven years covered in this study happen to match very closely (102%) with the overall range of long-term annual rain heights in the WAB.~~

~~3.2.2 Evapotranspiration~~

~~As already mentioned, the sensitive parameter of actual evapotranspiration (ET~~$_a$~~) was approached through calculations of potential evapotranspiration (ET~~$_p$~~), based on the Hargreaves formula. This approach had already been applied by Schmidt *et al.* (2014) on the Eastern Mountains and Slopes of the West Bank, near Wadi Natuf. The use of the Hargreaves formula and the equation of actual evapotranspiration with potential evapotranspiration during the winter season is based on the assumption that, as shown by Ryu *et al.* (2008) in a semi-arid grassland and very similar climate in California, for most of the cold and wet winter months, i.e. the '*energy limited period*' and during the initial spring period, ET~~$_a$~~ is nearly equal to potential evapotranspiration (ET~~$_p$~~), especially in fine-grained soils such as the silty terra rossa soils in Wadi Natuf, which retain moisture for longer periods (Rushton *et al.*, 2006). ET~~$_p$~~ is calculated by the equation:~~

$$ET_p = \quad 0.0023 * Ra * (T_{mean} + 17.8) * (T_{max} - T_{min})^{0.5} * \lambda^{-1} \qquad (1)$$

where Ra is the daily sum of extra-terrestrial solar radiation (MJ d^{-1}), T_{mean} is the daily mean air temperature ~~during the respective time interval~~ (calculated as average of daily minimum and maximum temperature, in ^{0}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 units of mm d^{-1}.

3.2.~~3 Springs~~

~~The hydrographs of the daily read~~ **Hydrological measurements – soil moisture and springs** ~~allowed us to identify periods of rise, peak and decline in spring flow for each year and each spring (or spring group) individually and in high temporal resolution (daily steps) for the sake of comparison with model results. The representativeness of the flow pattern of the springs was tested and is presented in Table F1. These periods are also referred to as basin signatures (Eder *et al.*, 2003 and Hrachowitz *et al.*, 2013). Winsemius *et al.* (2009) suggested the use of combinations of quantitative and qualitative information from the local or basin scale. While peak flow and recharge periods can act as semi-qualitative information (signatures), quantitative information on physical parameters such as SM) was available from the SM recordings, as discussed in the next section.~~

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Soil moisture content (*SM*) was monitored at eight different stations over a period of seven years (see Table 1). Due to budget limitations and reduced field accessibility (particularly during the height of the 2. Intifada), the measurements were kept at a minimum (as recommended by Beven, 2002 and by Seibert and Beven, 2009 – see sections 1.2, 1.4). It was therefore decided to increase the number of different SM-locations and to decrease the duration of measurement at each station (ranging between one and four 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.

Target of the soil moisture (*SM*) measurements were daily time series data of 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. ~~**3.2.4 Soil moisture (SM)**~~

~~The sensor readings of available SM contents~~Initially two sets of frequency domain reflectrometry 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 (%) based on the difference of dielectric permittivity between water and soil matrix. The loggers recorded in 30-minute 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 Bir Zeit laboratory. These results also served in reconfirming and calibrating the sensor readings.

Each of the sensor readings of volumetric water content (%) from different soil depths ~~were added up~~was multiplied with the thickness of the individual soil sections (m) and then combined to an overall water content of the soil column (as ~~m^3/m^3, % or area normalised to mm~~mm water column within the soil). The continuous soil ~~hydrograph was further~~ moisture hydrographs were then analysed ~~and~~separately for each location ~~separately,~~, resulting in a typical and annually returning minimum (*SM_{min}*) and maximum water content (*SM_{max}*) ~~was found. These values were~~ as temporally stable ~~parameters~~ but ~~differed~~ spatially distributed parameters. The ~~results were also~~ representativeness of each SM station was further confirmed by the many hand collected SM samples~~, tested for soil moisture~~ 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 the ~~formula:~~Equation (2):

$$\theta^s = \cancel{(}(((SM_{max,\,1} - SM_{min,\,1}) * b_1) + ((SM_{max,\,2} - SM_{min,\,2}) * b_2) + ((SM_{max,\,3} - SM_{min,\,3}) * b_3\cancel{)}))) * b_\Sigma \qquad (2)$$

whereby *SM_{max}* and *SM_{min}* were used as measured water content per soil segment volume (m^3/m^3), *$SM_{max,\,1}$* indicates the maximum water content at the first surface-near soil ~~layer~~section and deeper ~~layers~~sections are indicated by successive numbers (2 and 3), and where *b* indicates the soil thickness (m) of the respective soil ~~layers~~sections (1, 2, 3~~). Over a unit area,~~) or the ~~cumulative~~overall soil thickness (b_Σ). θ^s ~~therefore is~~represents the normalised effective maximum storage content in m (or mm) of the whole soil column (see Sheffer, 2009 and Sheffer *et al.*, 2010). ~~The~~ It should be noted that θ^s was derived directly from the field-~~read moisture contents~~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 sections 3.4 (Fig. 5) and 5.1.

The sensor readings included brief periods of water storage beyond ~~the~~ field capacity, such as water in desiccation cracks (especially in heavy storm events during the late autumn and early winter season); ~~in the hydrograph,~~ these peak levels can be noticed as brief overshots of SM-readings (here indicated as *SM_{peak}*) above the otherwise stable levels of annually recurring *SM_{max}*. It should however be emphasized here that the model in its daily budgets fully accounts for these additional

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water amounts ~~are fully accounted for in the daily budgets of the percolation model~~ (see ~~sections~~section 4.1.~~1~~ and ~~5.3~~Appendix B).

Daily spring flow measurements were used as a model check. This high resolution spring flow record, for the first time in 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 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, s. Appendix C, Table C1). Three of these springs belong to the so-called ‘Beitillu spring group’; the two other springs to the ‘Wadi Zarqa spring group’ (near Wadi Zarqa SM station, see Fig. 2b, 4). Their representativeness is discussed in Appendix F.

3.3 Model parameterization (soil thickness)

The soils in Wadi Natuf were found to consist only of one prevailing soil type, terra rossa (see section 2~~.5~~); 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 (SMSP), 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 (*b*) 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, Table D1 and Table 1).

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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 (~~observed SM_{max} or~~ full effective storage capacity θ^s), deep percolation (*DP*) into the bedrock is triggered, here equated with groundwater recharge (Fig. ~~5). When the shallow soils of Wadi Natuf were sufficiently saturated, the model equated actual evapotranspiration with potential evapotranspiration; but when the available water content (above SM_{min}) fell below daily potential evapotranspiration ET_p (mm), actual evapotranspiration ET_a (mm) was limited by water availability. The model thus follows the function:~~ 5). ET_a is limited downwards by available water content (θ_i) and upwards by ET_p:

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$$ETa_{i+1} = \begin{cases} ETp_{i+1} & \text{if } (\theta_i + P_{i+1}) \geq ETp_{i+1} \\ \theta_i + P_{i+1} & \text{if } (\theta_i + P_{i+1}) < ETp_{i+1} \end{cases} \qquad (3)$$

where ~~θ_i~~ θ_i is available soil moisture (mm), P daily rainfall (mm), ET_a daily actual evapotranspiration (mm) and ET_p daily potential evapotranspiration (mm).

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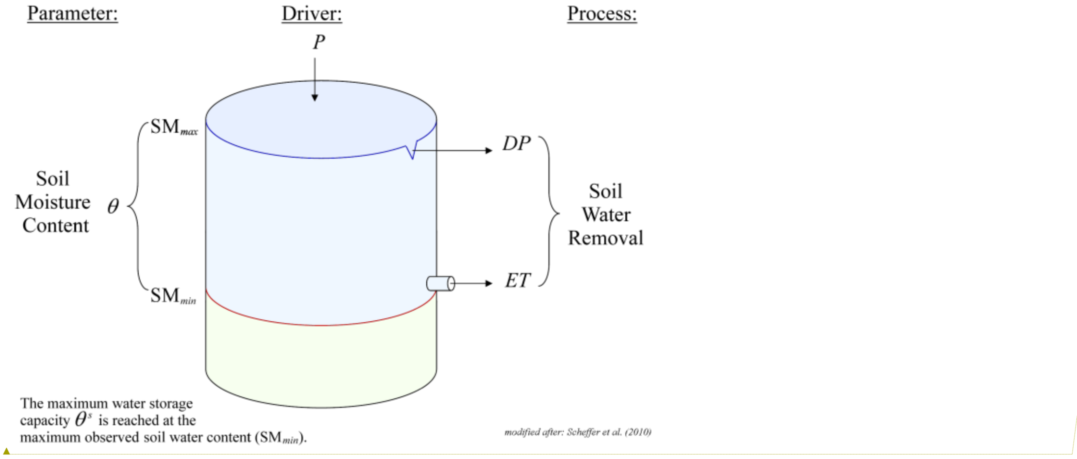

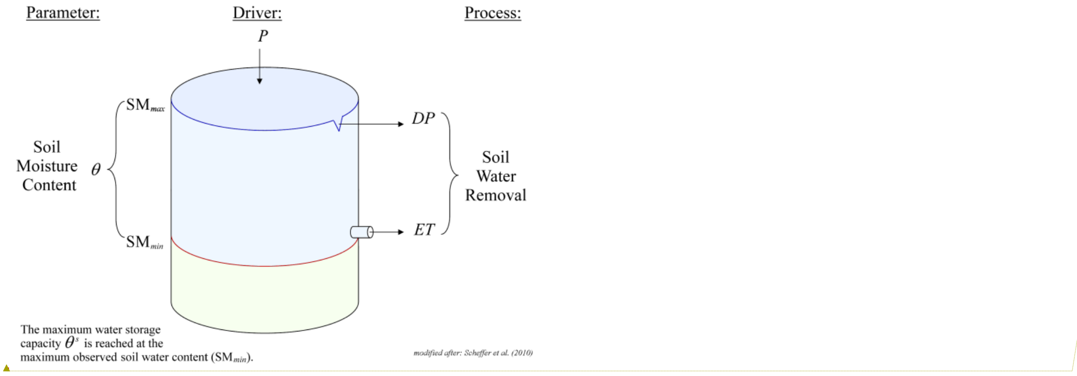

Figure 5: Parsimonious ~~SM-percolation~~ SMSP-model of '*one reservoir saturation excess*' (modified after Sheffer *et al.*, 2010)**.** Parameters and drivers (top) were field-measured for every station and model. The available water content, shown as θ (between SM_{max} and SM_{min}), is seasonally variable but location-specific. ~~Deep~~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*) ~~or recharge is triggered above θ^s.~~is initiated. Precipitation (*P*) was measured~~;~~, potential evapotranspiration ~~was~~ calculated from weather station data and transformed into actual *ET*-values (~~see~~ section 3.~~2~~.2).

~~Secondly, all~~

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, ~~is~~ considered to percolate into the bedrock and represent recharge:

$$DP_{i+1} = \begin{cases} 0 & \text{if } (\theta_i + P_{i+1} - ETa_{i+1}) \leq \theta_{max} \\ \theta_i + P_{i+1} - ETa_{i+1} - \theta_{max} & \text{if } (\theta_i + P_{i+1} - ETa_{i+1}) > \theta_{max} \end{cases} \qquad (4)$$

$$\theta_{i+1} = \theta_i + P_{i+1} - ETa_{i+1} - DP_{i+1} \qquad (5)$$

where θ_{max} is the effective maximum soil water storage and DP is daily deep percolation, i.e. groundwater recharges (mm). 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 made on the reliability of the model to produce the observed physical feature of SM and the other by using the hydrologic response signature of spring flow responding to recharge.

3.~~2.6~~5 Annual and mean recharge coefficients

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~~In line with the PUB recommendations, we again kept it simple and used the individual annual rainfall coefficients (RC) for a direct, somewhat extrapolative calculation of long-term average RCs.~~ First, the annual DP-rates (mm/a) divided by annual station rainfall delivered annual recharge coefficients (RC, in %) for each modelled SM station~~; secondly~~. 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). 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 ~~is based on two assumptions, i.e.~~assumes that our seven~~-~~-year rain observation period ~~is a fair representation of~~fairly represented the long-term averages ~~of both~~ and inter-annual ~~and seasonal~~ distribution patterns of precipitation~~. The~~ (see 3.1 and Appendix E). In order to verify the representativeness of our seven-year observation period for long-term ~~inter-annual rainfall distribution is also discussed in Appendix E. The seasonal distribution however, cannot be sufficiently addressed in this study on spatial recharge distribution. It remains therefore an approximation that remains difficult to be narrowed down and be truly reflective of all scenarios of an event resolution of~~conditions (>30years) and since no long-term precipitation ~~and recharge processes. However, it can already be stated here that it appears not very likely that a true reflection of seasonal distribution would lead to a significant change in overall annual average recharge coefficients.~~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 ~~Soil Moisture modelling~~

~~4.1.1~~ Seasonal soil moisture patterns

Table ~~2~~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.

~~In~~**Table 1: Soil moisture measurement data by location (in mm and %).**

	Shuqbah,	**Beitillu,**	**Wadi Zarqa, fields**		**Kufr Fidiah, field**		**Ras Karkar, terraces**	
land use	**grassland**	**gardens**	**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 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 yrs measured	1	1	1	1	2	1	4	2
hydr. seasons measured	2003/4	2003/4	2005/6	2004/5	2005/6–06/7	2006/7	2005/6–08/9	2007/8–08/9
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 mm over the entire soil column or averaged in % as volumetric share of total soil volume).

The thin soils in Wadi Natuf showed a low water retention capacity (section 4.2, Fig. 6); in summer, soil usually dried up rapidly to ~~a~~an SM~~-~~-content ~~of somewhere~~ between 5 and 10 percent.~~ (Two~~ Table 1 also shows two exceptions ~~are found~~

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~~here~~: In one case, the plot near the ~~hothouses~~greenhouses in Wadi Zarqa (~~Zar-hh~~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 ~~in the bushy landscape near~~(SM_{min} of 0.5%) at Kufr Fidiah (KF-E~~)~~), was a result of vandalism~~.~~ (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 one metre encountered at KF-E, an abandoned agricultural plot, overgrown with ~~almost one metre~~bushes, is a rare exception, and according to our soil depth survey not representative for usual conditions at the top of l-UBK formation (compare soil depth matrix, ~~Table D1). Ultimately, the results of KF-E were excluded from the regionalisation analysis (see sections 4.1.3 and 4.1.4~~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 ~~percolation~~ SMSP-model. In line with our saturation excess model~~,~~ (section 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 ~~2~~1 and ~~in Fig. 6, and as will be~~ discussed below. Another special case however is the occurrence of brief periods with extreme moisture (SM_{peak}) above saturation storage capacity (θ^s). They only occurred during extreme storms or during the early winter months, when desiccation cracks ~~still~~ enabled preferential flow and rapid infiltration into deeper soil layers (see also ~~section 5.3. and discussion of Fig. 7~~Appendix B) and lasted usually less than one day.

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~~Temporal (~~Spatially, the distribution of seasonal~~) variation of recharge did not stand at the focus of this study. However, some brief remarks on the results of the daily percolation model shall~~ soil saturation can be ~~added here.~~differentiated as follows: At locations with thinner soil cover, such Ras Karkar (RK), Wadi Zarqa ~~hothouses~~greenhouses (WZ-~~hh~~gh) and especially in Shuqbah (Shu), full saturation (θ^s) was usually reached by mid or late November. In the ~~deeper~~thicker soils~~ (~~, such as in Kufr Fidiah and Wadi Zarqa~~,~~ upper terrace~~, or~~ (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 2005/06 experienced the most intensive rain event of the entire measurement period and at the same time occurring very late in winter, between 1st and 5th April 2006~~.~~ (Messerschmid *et al.*, 2018). Figure ~~7~~6 gives an example ~~of~~for the ~~hydrographs~~time series of observed and modelled soil moisture (station RK-W). As can be seen, recharge (deep percolation, DP) only ~~occurs~~occurred when full saturation ~~is~~was reached and in form of relatively distinct events of a few days per year, depending on the high-resolution temporal rain distribution of a given season.

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~~**4.1.2 Annual soil moisture and recharge calculations**~~

~~Although in~~

In each year the ~~hydrograph~~level of calculated soil moisture was the result of a unique set of different ~~local~~climatic drivers and of location-specific parameters and ~~different~~ physical features (and thus a result of different overlapping processes~~),~~ ~~certain common patterns~~). Yet, it could be ~~determined: The~~ observed that the levels of available ~~and effective~~ soil moisture~~,~~ (i.e. the water content above ~~the minimum observed soil moisture (~~SM_{min}~~)~~), usually dropped to zero within one or two months after the last major rainfall event~~. The hydrographs of course were location specific, which means, formation-specific. But they were also temporally variable. Instead~~ of a ~~single seasonal rainfall percolation threshold over the years, we rather found accentuated individual patterns of soil moisture accumulation durations for every rainy~~given season~~, depending on the respective temporal distribution of precipitation and evaporation, as shown in~~ (effectively ending evapotranspiration

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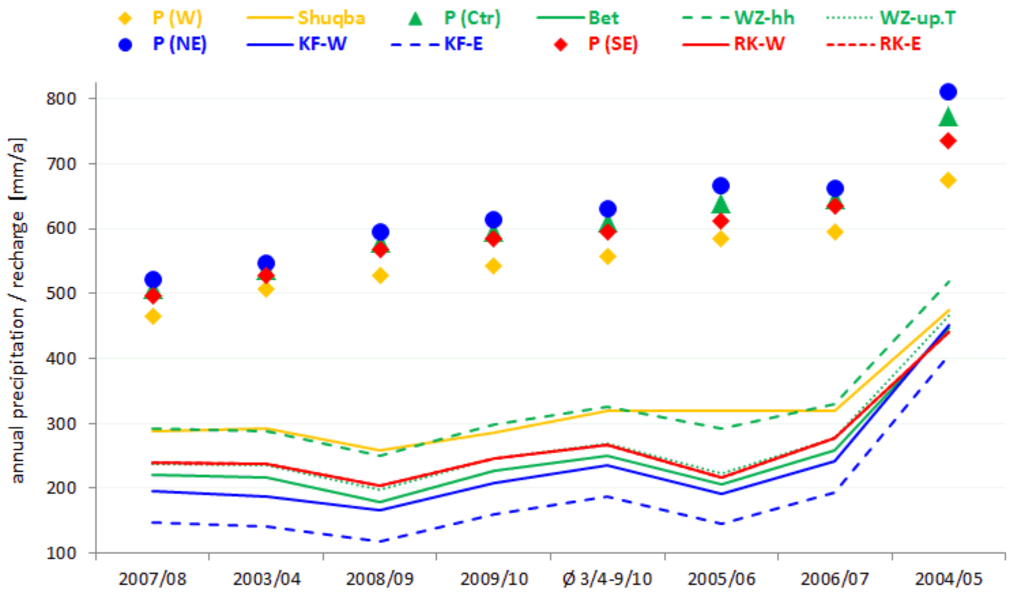
during summer), see Fig. 6.~~ In this diagram, the years on the x axis are sorted by precipitation depth from left to right and from the driest to the wettest seasons. Unlike average areal rainfall, the annual recharge does not rise monotonously from left (dry) to right (wet years). Again, this demonstrates the event character of recharge and the importance of daily time step calculations. Other implications of Fig. 6 are discussed in section 5.2.~~



~~**Figure 6: Annual percolation (DP) and precipitation (P) rates for 8 SM stations and 4 respective precipitation sub-catchments.** The years (x-axis) are ordered by annual rain levels. Towards the right, spatial variability of P increases, but that of DP diminishes (see sections 4 and 5 and in Appendix G).~~

~~4.1.3~~4.2 Quantitative examination of the model (by physical parameters)

Figure ~~7 also allows checking~~6, which presents modelled and observed soil moisture contents, indicates the performance of the soil moisture percolation model. ~~Testing~~ It should be stressed here that no calibration of the model ~~results~~ was performed ~~on two independent levels, first quantitatively on the level of physical features (basin form), e.g. observed versus modelled soil moisture (Fig. 7), and second qualitatively on the level of basin response, e.g. periods of deep percolation or recharge, compared with the periods of peak spring flow (Fig. 8).~~.

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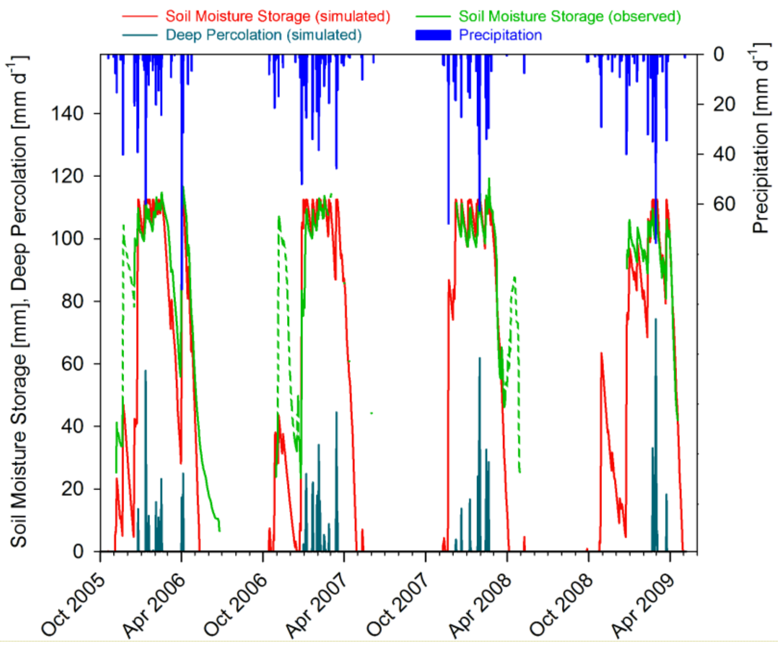

~~**Figure 7: Comparison between observed and modelled available soil moisture at Ras Karkar West (RK-W), 2005/06-2008/09.**~~ ~~Maximum water storage capacity (θ^s, at 112.5 mm) of the modelled moisture level (red) matched well with the observed maximum moisture (green). Brief periods of dotted green lines show questionable and erroneous soil moisture readings (see also section 5 and Appendix B). Deep percolation (DP, triggered above θ^s) is indicated as dark blue column (bottom of the graph), daily rainfall as blue columns (at the top).~~

Some of the readings ~~indicate~~show a mismatch between observed and modelled SM values; these periods are indicated as ~~dotted~~dashed green line, where recorded soil moisture exceeded modelled SM-values~~ by far~~. In some cases, recorded moisture levels even surpassed accumulated seasonal rain (which clearly hinted to equipment failure~~).~~ of the SM-sensors). Both issues ~~shall be~~are further discussed in section 5~~.~~ and Appendix B~~ also presents some statistical analysis on this issue~~. However, ~~this statistical analysis on the~~a comparison between observed and modelled soil moisture (Fig.~~ 7) resulted in a very good to excellent correlation~~ 6) showed a close performance, with an average Nash-Sutcliffe efficiency ~~correlation~~coefficient of 0.73 for all stations, except RK-E (which had a negative ~~correlation~~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 at 0.63, at KF-W and KF-E between 0.79 and 0.96 and at RK-W station at 0.7 (~~Table B3). These results include all periods, dry and wet alike. For winter values alone, where soil moisture lied above the minimum water content (SM$_{min}$), the NSE was found slightly lower at 0.69.~~Appendix B, Table B3).

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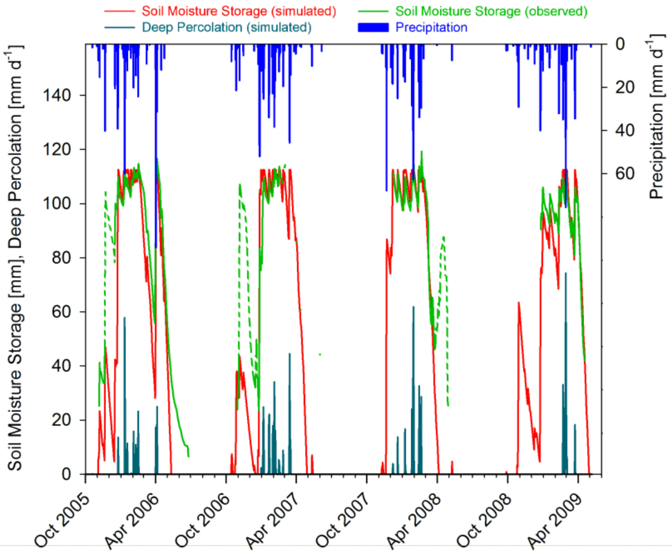

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Figure 6: Comparison between observed and modelled available soil moisture at Ras Karkar West (RK-W), 2005/06-2008/09. Maximum water storage capacity (θ^s, at 112.5 mm) of the modelled moisture level (red) matched well with the observed maximum moisture (green). Brief periods of dashed green lines show questionable and erroneous soil moisture readings (see also section 5 and Appendix B). Deep percolation (DP, triggered above θ^s) is indicated as dark blue column (bottom of the graph), daily rainfall as blue columns (at the top).

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4.~~1.4~~3 Semi-qualitative examination of the model (by ~~peak~~ spring flow signatures)

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~~Since basin form does not necessarily translate linearly into basin function (see section 1.2), the model was additionally examined on the level of basin response: We compared periods of deep percolation (DP) with the signature periods of peak spring discharge, as shown in Fig. 8.~~

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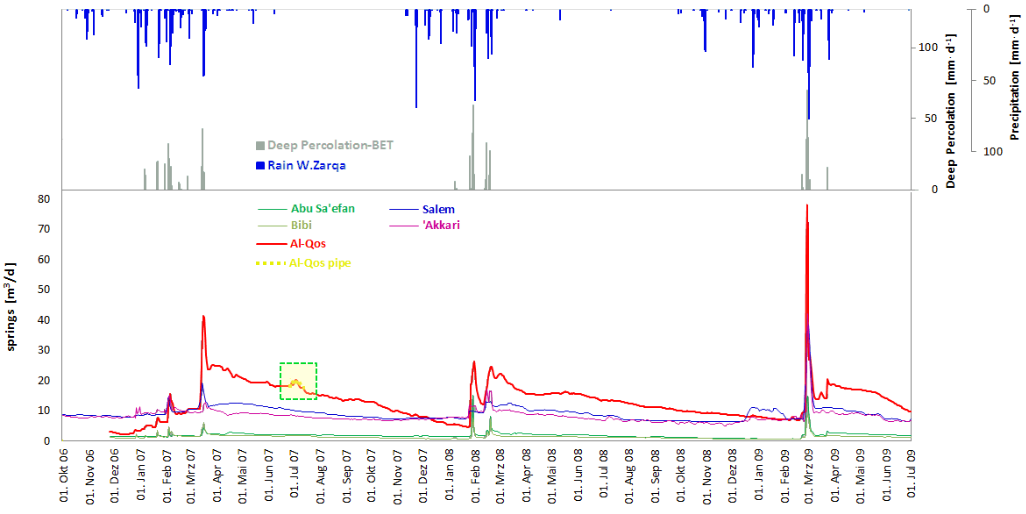
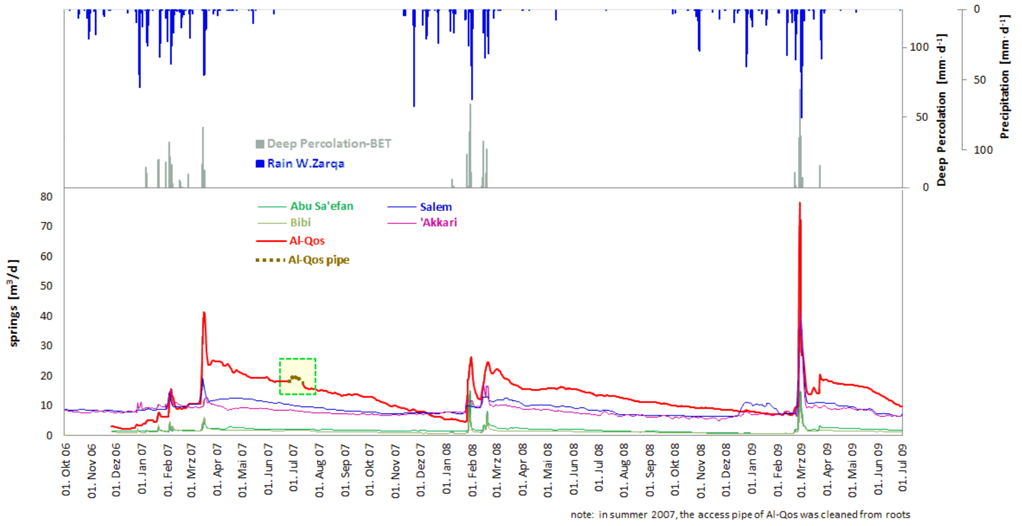


note: in summer 2007, the access pipe of Al-Qos was cleaned from roots

~~Figure 8~~For an additional check, we compared periods of deep percolation (DP) 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 days per year. During very wet winters a maximum of up to 31 days per year (e.g. in WZ-gh); during very dry winters a minimum of only five days 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 2004/05) and 396 mm (in 2008/09), 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 one day 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) and 12.4 (Qos) m^3/d. The smallest spring (Bibi) had a maximum discharge of 9 m^3/d, the largest (Al-Qos) of 78 m^3/d. Both values were approximately six times larger than annual averages. Every slight rise of 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 of increase in discharge at Al-Qos spring were found to show simulated percolation; at Salem spring, the strongest spring in Wadi Zarqa spring group, this was true for all days with more than 0.7 m^3/d rise and at Akkari spring for all days with an increase larger than 0.66 m^3/d.



note: in summer 2007, the access pipe of Al-Qos was cleaned from roots

Figure 7: Signatures of peak spring flow and DP-events. Yellow shaded box: temporary increase in spring discharge, caused by cleaning of the access pipe from plant roots at Al-Qos spring (July 2007). Daily ~~read springs~~measured spring flow at Beitillu spring group is shown in red, olive and green colours (bottom); at Wadi Zarqa group in blue and purple colours~~. Daily~~, daily deep percolation (DP) as grey columns (upper half~~),~~) and precipitation as blue columns (top).

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~~Here, a relatively uniform overall pattern was observable; in most stations, recharge occurred during a period between 11 and 21 days per year, during very wet winters a maximum of up to 31 days per year (e.g. in WZ-hh); during very dry winters a minimum of only five days per year (e.g. KF-E) were recorded. Rainfall thresholds that trigger DP vary strongly between the different years and especially stations, e.g. from 74 mm of accumulated rainfall (Shu) as a minimum to 470 mm (KF-E) as the highest threshold (Fig. 9). For the different years, the gaps between station thresholds ranged between 206 mm (in 2004/05) and 396 mm (in 2008/09), with a multi-~~

Finally, annual ~~average of 290 mm.~~

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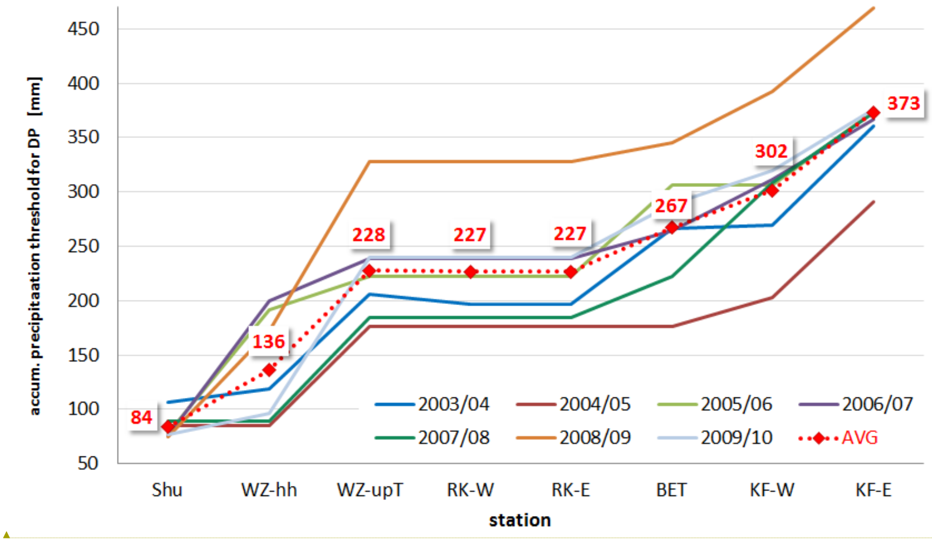

~~**Figure 9: DP thresholds for different years and stations.** Preceding accumulated seasonal precipitation to trigger DP shown in mm.~~

~~Figure 8 also exhibits a very close match between the dates: Observed spring flow in the local perched aquifers picks up with almost no delay, usually within one day after the first modelled recharge event (again, the representativeness of the springs was tested, see Appendix F). This demonstrates both, the karstic nature of the aquifers with rapid flow connections, as well as the very local recharge conditions on the isolated hillsides.~~

~~The most productive springs of the respective groups are Salem (Wadi Zarqa spring group) and Al Qos (Beitillu spring group). As can be seen in Fig. 8, the average of spring flow was lying between 1.3 (Bibi) and 12.4 (Qos) m^3/d. The weakest spring (Bibi) had a maximum discharge of 9 m^3/d, the strongest spring (Al Qos) of 78 m^3/d, i.e. a maximum of ca. six times or 600% of the annual average levels of daily discharges.~~

~~As our semi-qualitative analysis revealed, every slight rise of observed daily spring flow (even very slight increases, by only 8% the amount of the average discharge rates) was connected to our modelled deep percolation or recharge event into the perched aquifers. Comparing the dates of peak spring flow with that of DP events, a complete congruence of the respective dates is apparent. (This analysis was performed for the period until September 2009, during which, all springs had been read reliably, see Table C1). All days with more than 1 m^3/d of increase in discharge at Al-Qos spring (= 8% of average Q) were also found to show percolation in our model. In Salem spring, the strongest spring in Wadi Zarqa spring group, all days with over 0.7 m^3/d rise (= 7.95% of average Q) were recorded during the periods, where the model indicated deep percolation. For~~

~~Akkari spring, all days with an increase larger than 0.66 m^3/d (= 8.3% of average Q) showed modelled recharge at the respective soil moisture model station in Wadi Zarqa.~~

~~Therefore, it can be concluded that the check of the model on two independent levels was very good (see also discussion, section 5); the two methods of examination were a) quantitative on the level of physical basin form (soil moisture levels) and b) semi qualitative on the level of basin signature, i.e. by periods of DP and peak spring flow. In addition, our resulting~~ recharge coefficients were calculated and compared to literature values~~, see Messerschmid *et al.*, 2019b). The results of the model are summarised in~~; see also Appendix H, Table H1. Table ~~3. This table~~2 shows ~~the~~annual DP-rates, annual ~~DP rates, the~~ recharge coefficients (RC) ~~for each year~~ and the average of these annual RC-values (between 30% and 57%) for the entire period, ~~together with~~according to the soil thickness at each station, ranging between 30 cm and 90 cm.

Table ~~3~~2: Annual precipitation and recharge rates (DP), modelled at representative SM locations.

	~~rainfall~~	DP & P in (mm/a)	~~DP~~Deep percolation (DP)						~~DP~~Precipitation (P)	~~DP~~	~~DP~~ ~~DP~~	~~DP~~ ~~DP~~
year	~~area avg.~~Shuqbah	Bet	~~Shuqbah~~ WZ-gh	WZ-~~hh~~upT	~~WZ-upT~~KF-W	KF-~~W~~E	~~KF-E~~RK-W	RK-~~W~~E	~~RK-E~~W	Centre	NE	SE
2003/04	~~529~~291	217	~~291~~289	~~289~~235	~~235~~188	~~188~~140	~~140~~238	238	~~238~~547	532	524	507
2004/05	~~742~~475	448	~~475~~519	~~519~~465	~~465~~452	~~452~~405	~~405~~442	442	~~442~~811	755	724	674
2005/06	~~621~~319	206	~~319~~293	~~293~~223	~~223~~192	~~192~~145	~~145~~218	218	~~218~~666	628	609	585
2006/07	~~632~~319	259	~~319~~331	~~331~~277	~~277~~241	~~241~~194	~~194~~278	278	~~278~~663	636	629	596
2007/08	~~496~~287	221	~~287~~293	~~293~~239	~~239~~196	~~196~~149	~~149~~240	240	~~240~~522	501	493	466
2008/09	~~565~~258	180	~~258~~251	~~251~~197	~~197~~165	~~165~~118	~~118~~204	204	~~204~~594	570	561	528
2009/10	~~582~~286	228	~~286~~299	~~299~~245	~~245~~208	~~208~~160	~~160~~247	247	~~247~~614	586	578	543
average DP	~~–~~319	251	~~319~~325	~~325~~269	~~269~~235	~~235~~187	~~187~~266	266	~~266~~ –	–	–	–
avg. P ('3/4–'9/10)	~~–~~557	601	~~557~~601	601	631	631	588	588	**631**	**601**	**588**	**557**
~~P sub-catchment~~Soil depth (mm)	~~avg. WZ/S1~~320	~~avg. Nea/S1~~500	~~avg. WZ/S1~~400	~~Wadi Zarqa~~770	~~avg. Ayb/S2~~650	940	400	400	–	–	–	–
RC (DP$_{avg}$ / P$_{avg}$)	**~~–~~57 %**	**42 %**	**~~57~~54 %**	**~~54~~45 %**	**~~45~~37 %**	**~~37~~30 %**	**~~30~~45 %**	**45 %**	**~~45 %~~** –	–	–	–

~~Note: For reasons of overview, this~~The table shows ~~only the~~area precipitation of the respective sub-catchments of the SM stations (from Messerschmid *et al.*, 2018) as follows: West (W) uses average ~~area rainfall of entire Wadi Natuf (595 mm/a~~rain of Ne'alin and Shibteen-1 sub-catchments, Centre refers to the average between ~~2003/04 and 2009/10). However, the~~Shibteen-1 and Wadi Zarqa, North-East (NE) is the precipitation in Wadi Zarqa and South-East (SE) represents the average of Shibteen-2 and Ein Ayoub catchments, (Fig. 4). The daily rates of deep percolation (DP) were modelled with ~~the respective sub-catchment precipitation. Area averages for the five sub-catchments of Wadi Natuf (Ne'alin, Shibteen 1, Shibteen 2, Wadi Zarqa and Ain Ayoub) were taken from Messerschmid *et al.* (2018~~these area precipitation values. Minimum and maximum values of DP are underlined (WZ-gh in 2004/05; KF-E in 2008/09). All units are in mm/a, except for the soil depth (mm) and recharge coefficients (expressed as DP$_{avg}$/P$_{avg}$, in %).

4.~~1.5~~4 Summary of model results on annual levels

~~In sum, for~~ The annual percolation rate did not only depend on the annual precipitation, but also on its seasonal distribution. For most years, a rise in annual recharge ~~coincides~~coincided with a rise in total annual rainfall~~.~~, as shown in Fig. 8. The wettest winter (2004/05 with a rainfall of 742 mm/a) showed the highest recharge in each of the stations. However, the driest

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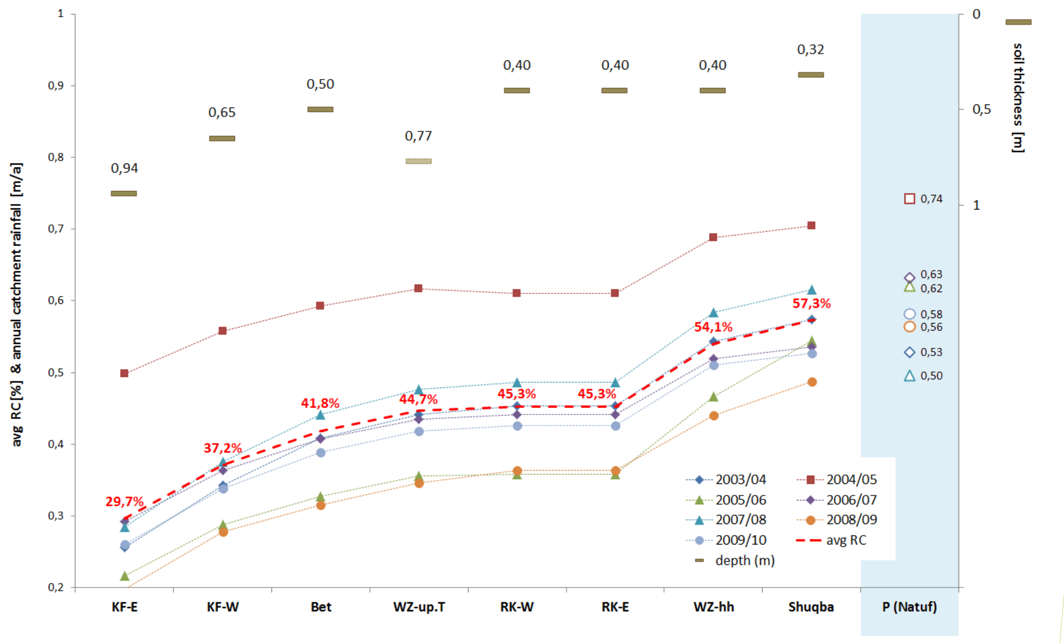
year (2007/08 with 496 mm/a) did not generate the lowest recharge~~.~~, due to the seasonal distribution of very strong precipitation events that triggered high rates of percolation. This ~~demonstrates~~disconnection demonstrated the necessity to first calculate and model recharge in daily time steps in order to ~~reflect~~account for the event character~~, i.e. the~~ of temporal rainfall distribution~~ of the thunderstorm~~ (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 the lowest recharge~~.~~ (see Fig. 8). This general pattern ~~confirms~~confirmed our conceptual approach ~~for a basin classification framework, grounded on a close link between basin form (~~that closely linked soil depth~~) and basin response (~~with recharge~~) – different classes of recharge potential are indicated in Table 1, as will be further discussed in the follow up article by Messerschmid *et al.* (2019b) on recharge regionalisation for the entire Natuf catchment~~.

~~The diagram in Fig. 10 plots different measurement stations on the x axis against the respective soil depths and annual recharge rates on the y axis with a marked and almost consistent linkage between the latter 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 Table D1).~~



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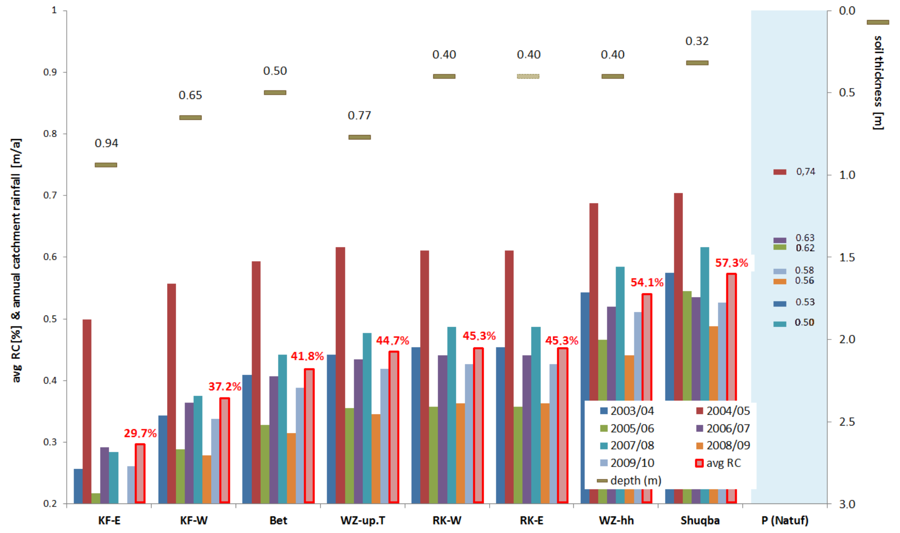

Figure ~~10~~8: Annual recharge coefficients, annual precipitation and soil depth (stations ordered by increasing RC). The coloured lines present annual recharge coefficients by station (x-axis), increasing from left to right (in %). Average annual RC-values (red numbers) are reciprocal to the respective soil depths (as brown bars, with exception of WZ-upT as beige bar). The blue-shaded column at the right indicates annual precipitation - shown as P (Natuf) - as area average (in m/a).

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~~ clearly~~ 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.~~ Hereby, two points can be noted. The~~ Unlike previous studies in the WAB, direct and location-specific assessment of water storage capacity from long-term soil moisture readings ~~is a new approach in the determination of recharge of the WAB. Previous studies only assumed maximum storage capacity by drawing on the general literature but without sufficient~~ was generated as robust and realistic ‘local knowledge’~~, i.e. site-specific field evidence. Instead they manly concentrated on retro-fitting the models through repeated calibration runs. This is particularly important~~ to determine recharge, because the rate of modelled percolation (recharge) ~~is~~was a direct function of SM storage, which ~~is~~was highly location-specific.~~ This highlights the importance of robust and realistic input data. Our~~ 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 ~~simple but field-based and therefore realistic findings. In addition, the~~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 ~~indication~~measure of the mobile, available water inside the soil column, subject to accumulation,

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evapotranspiration, saturation and deep percolation (recharge~~) and without the need for further assumptions. As a second issue, it shall be noted here that in~~). In reality, the processes of soil moisture accumulation, deficit and saturation are complex and depth-dependent. ~~In fact,~~Indeed our sensors installed at different depths indicated slightly different ~~hydrographs of~~ temporal ~~distribution, i.e., the deeper~~SM dynamics. Deeper soil segments ~~picked up moisture content~~reacted later in the season~~, showed the arrival~~ but arrived at a relatively stable maximum plateau value at about the same times as the shallower sensors, but ~~then also~~on the other hand dried up at a slower pace in summer. This ~~is~~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 ~~added~~noted here that most of our soils were only about half a metre thick or less and ~~therefore,~~that even the ~~lower~~lowermost soil segments ~~lie~~were within the reach of ~~many of the typical~~most plants (Mediterranean trees, bushes and shrubs~~).~~), resulting in a low retention capacity. Our calculation method of adding up the measured water contents ~~for each layer separately therefore accounts~~of all sections accounted for the different conditions and processes at varying soil depths and by this ~~provides~~provided a simplified, yet realistic representation of ~~the overlay of all depth dependent~~total soil ~~processes in total~~moisture throughout the soil column.

~~In addition and in line with the findings of~~ Adhering to the PUB ~~decade, the intention of this study was to adhere to the -~~goal of parsimony~~. Our simple~~, our SM saturation and percolation model ~~therefore~~ only accounted for two climatic drivers (P & 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. ~~The applicability of this~~This parsimonious modelling approach is based on ~~three~~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 ~~in formations with more developed epikarst (see Lange *et al.*, 2003). Otherwise~~. Moreover, as discussed in section 2, no signs of indirect recharge processes were observed in the field (with ~~one~~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 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 ~~near rainwater regrouping, mobilisation and accumulation~~runoff-runon processes and found them to occur in a radius of decimetres, at maximum metres (see also Ries *et al.*, 2015). ~~The notable exception where indirect recharge occurs concerns the second process~~This lead to ~~be discussed here – the transmission loss of~~ surface runoff generation on hillslopes, which was largely lost by the aforementioned transmission losses through ~~Wadi~~ the gravel beds~~. Indeed,~~ of the wadis. While this ~~transmission loss~~point and line infiltration along wadi beds could ~~frequently be observed to reach 100% of runoff, with Wadis found dry only a few kilometres downstream of an observed runoff event site in real time. However,~~be considered as ~~shown in~~indirect recharge, previous studies by Messerschmid *et al.* (2018~~),~~) had shown that overall runoff generation in Wadi Natuf was ~~remarkably~~very low ~~at only~~(< 1% of annual area precipitation~~. Secondly, for recharge calculations, runoff can therefore~~). 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 ~~(and under~~, thus also adhering to the PUB goal of simplification and parsimony~~). Thirdly~~. 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

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runoff, must be described as a process of soil moisture saturation excess (see ~~sections~~section 1.3~~.2 and 1.3.3~~). For further discussions on the applicability of soil moisture balance models in the WAB, see Hughes *et al.*, (2005 and 2008).

5.2 Spatial and temporal variability of precipitation and recharge

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The main focus of our approach was ~~clearly~~ the spatial differentiation of recharge, although our model also considered ~~the~~ temporal ~~distribution of recharge~~patterns. Our annual recharge coefficients were based on a model, which was run in daily steps and therefore fully ~~accounts~~accounted for the temporal distribution of ~~a~~rainfall, especially storm ~~event for groundwater recharge calculation. Further analysis of the spatial recharge distribution is provided in Messerschmid *et al.*, (2019b).~~events. The model results of annual recharge coefficients ~~(see Fig. 6) indicate an unobserved~~suggested a relationship between spatial and temporal variability. ~~If~~When the standard deviations for annual recharge and annual precipitation ~~are~~were plotted against each other, we ~~can find a clear relation for each year of modelling (except for the year 2005/06), where in wetter winters with larger~~found that standard deviations for rainfall~~, the~~ increased with annual rainfall (except for the year 2005/06), whereas spatial variability of recharge ~~diminishes~~diminished (see Appendix G, Fig. G1).

Although seven 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 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 (section 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 Some inconsistencies between modelled and observed SM-values~~

~~Another point to discuss is the deviation of observed SM from the modelled SM in several of the stations, particularly during the beginning of the measurement seasons, before the first large rainfall and recharge events. Some of the SM-levels obtained during measurements were unreasonably high and at times reached or even surpassed cumulative rainfall. A deviation of SM$_{obs}$ from SM$_{mod}$ can occur for three reasons: either because the model is inadequate (1) or because the interpretation of recorded field data is complicated by additional factors (2). The third possibility (3) is malfunctioning of the measurement equipment, and it seems clear that at least in the few instances, where alleged levels of SM$_{obs}$ surpassed preceding seasonal precipitation, this latter case was responsible for the deviation from SM$_{mod}$.~~

~~All in all, three of the eight SM stations (RK-W, KF-W and WZ-upT) faced such measurement issues (Table B1). During summer and late autumn and before soil moisture slowly started to accumulate in the soil column, a lumpy to blocky, aggregate structure was encountered in the silty and clayey soils that had dried up and shrunk during summer. The soil formed about fist-size lumps, separated by desiccation cracks. Therefore, preferential flow paths forming along these cracks may lead to increased rates of rapid infiltration and soil moisture accumulation that may cause some of the sensors to read unrealistic moisture levels, if the sensors happen to cross such desiccation crack. It is difficult to assess such a possibility in hindsight since the desiccation cracks are a transient soil pattern and their temporary position remains unknown. However, such unrealistic SM readings did not occur in winter during the recharge events (possible because the temporary desiccation~~

~~cracks had already closed).~~5.3 ~~In addition, hand collected soil samples 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, unrealistic SM readings were also encountered during the end of the rainy season (April 2008) 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; it does not affect the results of the model calculations (Appendix B).~~

~~The overall reliability of SM readings is shown in Tables B1 and B2; all stations except one, RK-E, show an excellent Nash-Sutcliffe efficiency (NSE) coefficient. Therefore modelled SM can be considered a valid representation of actual SM developments over time and for different spatial units.~~

~~5.4~~ Annual recharge coefficients – comparison with other studies

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As observed by Lerner *et al.* (1990), recharge is a temporally highly variable process that is most adequately investigated on the event level (in WAB a time span of half a day to five days). While the model with its daily steps fully reflects the event character during the measurement period, ~~a~~ generalisation of annual recharge coefficients always carries some range of uncertainty~~, since two years with identical annual rainfall can result in very different recharge values, depending on the seasonal distribution of precipitation and hence SM accumulation.~~

. However, as already presented~~ already~~, the individual recharge coefficients calculated for the different formations cropping out in Wadi Natuf ~~range~~ranged between a minimum of 0% (for non-recharging ~~formations~~aquitards like ~~u-Yat~~upper Yatta formation) and a maximum of 57~~%.~~% for highly permeable and intensively karstified limestone aquifers such as 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

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This study ~~contributes to the assessment of~~ provided formation-specific distributed recharge ~~based on soil moisture measurements and other field observations in~~ coefficients in a Mediterranean karst ~~areas~~area with a highly variable lithostratigraphy~~. Its findings extend those of PUB in general – and of Abusaada (2010) for the WAB in particular – that empirical and spatially differentiating field recordings are called for to produce model input parameters that are both, truly spatially distributed and realistic at the same time. Prior work has documented the importance and sensitivity of separate physical features in determining realistic parameters for distributed recharge models (Batelaan and de Smedt, 2001 and 2007, and Savenije, 2010). However, studies on distributed recharge often employed untested, virtual parameters or general data~~ from ~~the literature and performed only semi-distributed models, or models tested only by lumped basin responses, especially in the WAB.~~

~~In this study we based our parameters on long term field measurements and observations and tested soil moisture hydrographs as well as the basin response on small, local, well-controlled sub-catchments of perched hillside aquifers. We found that for virtually all cases, the location specific parameters such as~~a one-dimensional soil water ~~storage capacity were temporally stable, and the main transfer formula, linking the~~balance model, relating percolation ~~process to physical soil properties, remained valid, irrespective of seasonal and inter-annual variations of climatic drivers. Furthermore, we could show that, as suggested by Binley and Beven (2003), an intelligent design and determination of the main processes at hand could enable a strictly~~to SM saturation excess (SMSP-model), applicable in comparable basins all over the world. The parsimonious ~~model to represent the key factors of complex hydrological processes such as recharge and thereby address the needs for distributed recharge models across a wide range of different climates and land forms. Thus, point measurements of soil moisture for various physical patterns of basin form may help to understand dominant mechanisms of deep percolation (recharge) even in hitherto scarcely gauged mountainsheds and deliver the basis for a realistic representation of distributed recharge. This application of parsimonious modelling and empirical field measurements is a novel step in WAB but also for most existing distributed recharge studies in ungauged basins worldwide. Unlike previous SM models in the WAB (Hughes *et al.*, 2008 and Sheffer, 2009), this model was fully distributed, not lumped and based on actual field observations and measurements.~~

~~Since our research was restricted to surface observations of the soil cover, we equated groundwater recharge with deep percolation from the soil into the unsaturated aquifer bedrock. Based on field observations of scarce runoff and lateral overland flow as well as the results by Messerschmid *et al.* (2018), we were able to neglect indirect recharge from runoff (1% in Wadi Natuf) and accounted only for direct recharge (in situ percolation). Lateral water movement on a scale of decimetres and metres however, as from surrounding rock outcrops into soil pockets, was accounted for and included in our percolation model.~~

~~Based on previous PUB recommendations, we kept the actual soil moisture saturation model strictly parsimonious, empirically based and inductive; the employment of such a~~ forward-calculating model ~~is possible even in previously ungauged basins, if the dominant process can be identified and crucial input parameters for the model be gained through direct field observation and multi-annual measurements. Our model was based on the assumption~~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 maximum water storage capacity over each formation and for long-term conditions of wet and dry years.

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The model was based on the observed key process understanding, namely that groundwater recharge can be simplified and described as soil saturation process in a variety of local conditions with a wide range of land features. ~~Another assumption in line with PUB lessons was that specific maximum water storage capacities for the different soil moisture measurement plots can be determined and considered representative for specific aquifer formations. Thirdly, in order to build average coefficients, the measured time series had to be long enough (in our case seven years) to cover the prevailing climatic variations of wet & dry years. Last not least, and as our main assumption in the PUB approach, the recharge potential of the different formations, tested at different SM station, conceptually depends on a few select and interrelated key factors (lithology, land form, soil thickness) that drive and dominate the hydrological process of groundwater recharge.~~

~~As already mentioned, the temporal distribution of rainfall has a strong effect on event and seasonal recharge amounts and a modelling frequency of~~ Hereby, daily modelling steps ~~is~~ were found appropriate ~~under the particular climatic conditions of the WAB recharge areas in the Eastern~~to respond to the typically Mediterranean ~~mountainsides. This climate is characterised by a pronounced two-season annual rainfall pattern and by semi-arid to sub-humid overall annual precipitation depths. More importantly, this study for the first time in the WAB used a truly distributed approach for a great variety of different physical land forms. Instead of introducing untested proxy values as input to the model, and in line with the findings of the PUB decade~~variability of meteorological events (storms) driving recharge. Equally, it was ~~possible to solidly base our basin~~

~~classification for dominant recharge processes on observations of the physical form and based on fundamental laws of physics (and for each of the basin form groups, such as LU/LC, soil depth and lithology, respectively).~~

~~However, some limitations are worth noting. Although our statistical work indicated very good to excellent NSE values, the reasons for some of the discrepancies~~found that our seven 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 ~~observed and~~ modelled ~~SM could not fully be explained. Furthermore, the examination of~~and observed soil moisture and by a temporal overlay of peak spring ~~response signatures, although semi-qualitative, was restricted only to the local hillside aquifers. Yet, it should be emphasized that hardly any study on distributed recharge, and certainly no previous study in the WAB performed such testing on two independent conceptual levels of form and of function~~discharge and deep percolation events.

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~~Further research may take two different directions: on the one hand to focus on the understanding of the effect of temporal differentiation of inter annual recharge variations for each of the formations. On the other hand, this research provides a basis for the regionalisation of the local formation specific recharge values and coefficients in order to estimate total recharge of all litho-stratigraphic in the catchment or on the WAB basin scale. (This regionalisation will be the subject of a follow-up article – see Messerschmid *et al.*, 2019b).~~

A follow-up study will regionalise the here presented formation-specific recharge coefficients to all formations in the entire Natuf catchment (Messerschmid *et al.*, in preparation). 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..

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Appendix A

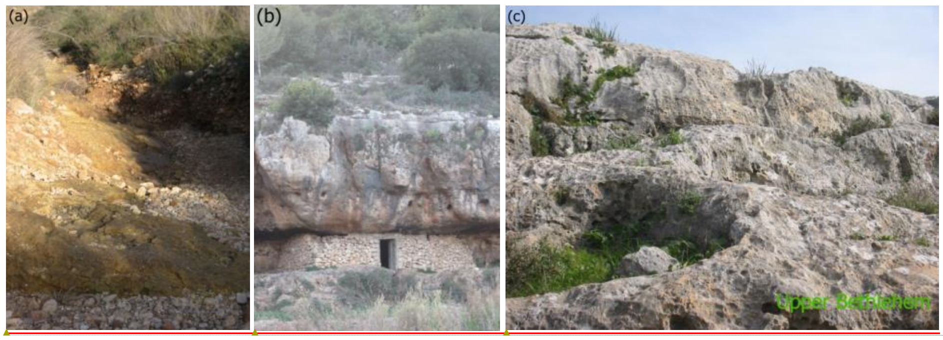

Figure A1: Formation outcrops. Rare outcrops of yellow marls, forming the main regional aquiclude (upper-Yatta ftn.) near Ras Karkar (a), reefal limestone cliff at Wadi Zarqa (upper-UBK ftn.) with high primary porosity, development of karst and ~~epi-karst~~epikarst (b), karstic karren landscape (upper-Betlehem ftn.), a relatively rare example of discontinuous soil cover (soil pockets) in Wadi Natuf (c).

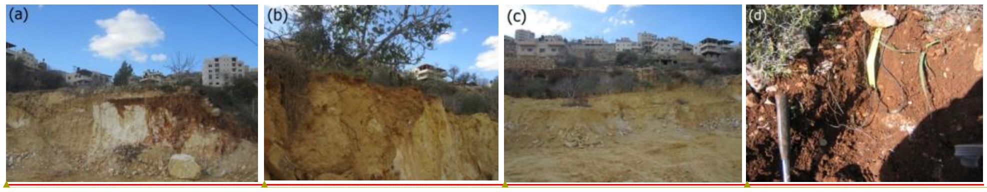

Figure A2: Soil cover. Soil covering marly limestone (bottom Hebron/top Yatta ftn.), with some white caliche-type 'Nari' crust (a, b, c), Ras Karkar soil measurement station (RK-W, lower Hebron ftn.) on natural terraces of thin terra rossa soil (d).

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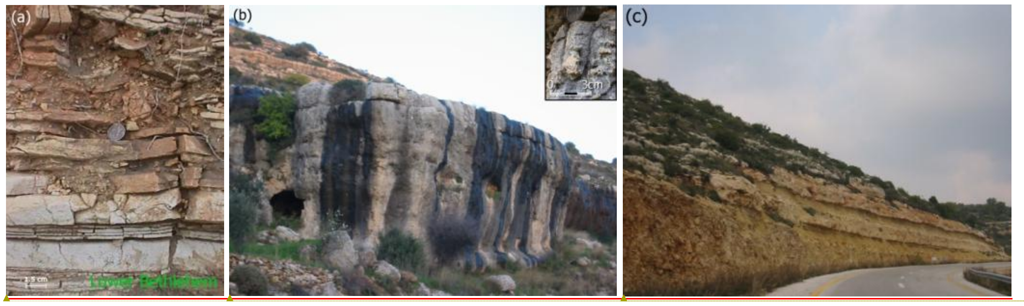

Figure A3. Lithostratigraphic formations: Colourful, thinly plated limestone of lower Betlehem formation (l-Bet) with a more impermeable facies of fine marl intercalations (a) can act as a confining layer beneath upper Betlehem (u-Bet). Cliff-forming coral reef limestone of upper UBK formation (u-UBK) at Wadi Zarqa with high primary porosity but also 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 lower UBK formation (top l-UBK) and the main part of l-UBK beneath.

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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, hand collected soil samples 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, unrealistic SM readings were also encountered during the end of the rainy season (April 2008) at station RK-W. Equipment failure is the most probable explanation here.~~Some technical equipment an interpretation problems were faced at three of the eight SM stations. During brief periods, the devices read out different soil moisture levels than those modelled (and in some cases, SM higher than preceding accumulated rainfall or a rise of SM during a dry period). The following tables show the results of the statistical analysis. Table B1 counts the days with erroneous and questionable readings (together 147 days).~~

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 (Appendix B).

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 days in four stations).

Table B1: Days with misreadings.

soil station	periods	no. of misread days	sum [days]
WZ-~~up.T~~upT	31.10~~–~~. - 5.11.2005	6	6
KF-W	9~~.–~~.11. - 20.11.~~'05~~2005 17~~.–~~.12. - 25.12.~~'05~~2005 29.10~~-~~. - 13.11.~~'06~~2006 18~~.–~~.11. - 22.11.~~'06~~2006	12 +9 +16 +5	42
RK-W	6~~.–~~.11. - 15.11.~~'05~~2005	10 +24	55

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	22.11~~.-~~. - 25.12.~~'05~~ 2005 4~~.-~~.11. - 24.11.~~'06~~2006	+21	
		sub-total	**103**
RK-W (Apr~~-'08)~~- 2008)	17.3~~.-~~. - 29.4.~~'08~~2008	44	44
all stations		**total sum**	**147**

Table B2 compares the days with such "misreadings" to the total number of days measured and modelled, and ~~it~~ indicates their respective shares.~~ Misreadings here are 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 moisture increase during dry spells; the reasons are therefore manifold and misreadings can occur due to desiccation cracks (mostly in autumn) or malfunctioning of the instruments.~~

Together, the 147 ~~day~~ days of questionable ~~data~~measurement records in three stations represent 8.~~1~~09% of all days ~~with SM records (~~recorded (147 days out of 1,818 days of total SM readings), and 0.~~7~~72% of the total model period (20,456 days for the eight stations~~ and,~~, over a seven~~-years), ~~-year period); these results are highlighted in bold font and marked grey ~~in~~within Table B2.

- In WZ-upT, only 6 days of failure occurred (Nov-2005), equivalent to 2.~~9~~90% of recording days.
- In KF-W, 42 days (or 14.~~9~~95%) occurred over the entire read-out period.
- In RK-W, 55 days occurred in early winter 2005 and 2006 (with $SM_{obs} > P_{cumulative}$), equivalent to 8.~~9~~91% of recorded days, in addition to 44 days (7.13%) in April 2008 (together 16.05% failed readings).

Table B2: periods and shares of days with misreadings.

soil station	reference period	no. of days days misread	days misread in 7-year period (2,557 d) – [%]	misread days as share of recorded days – [days, (%)]
WZ-~~up.T~~upT	w/o Apr-'08	6	0.23%	207 (2.90~~%).~~%) .
KF-W	w/o Apr-'08	42	1.64%	281 (14.95%) .
RK-W	w/o Apr-'08	55	2.15%	617 (8.91~~%).~~%) .
RK-W	incl. Apr-'08	99	3.87%	617 ~~-~~(16.05~~%)~~%)*

soil station	reference period	no. of days with SM>P	days misread over total period of 7 years & 8 stations (20,456 d) – [%]	no. of all days read [-] and share of misread days [(%)]
all stations	incl. Apr-'08	147	**0.72%**	1818 ~~-~~(**8.09%**)
all stations	w/o Apr-'08	103	0.50%	1818 ~~-~~(5.67%)
RK-W	only Apr-'08	44	0.22%	617 ~~-~~(7.13%)

* Percentages rounded to the second digit after the comma

Table B3 presents the Nash-Sutcliffe efficiency coefficients for the eight SM stations. All stations (except one, RK-E) show ~~an excellent~~ NSE between 0.40 and 0.96. The one station with a bad ~~correlation~~match, RK-E (with an NSE of -0.35) was excluded from further calculations; its results were not used for the analysis of annual ~~runoff~~recharge coefficients (RC). As a result, we can state that such periods of malfunctioning soil moisture probes are extremely short and rare; ~~thus, they do not put into question the large bulk of soil moisture results, particularly during the important periods of actual deep percolation (recharge) after strong rainfall events and under sufficient preceding pre-wetting of the soils. In addition, these~~therefore, modelled SM can be considered a valid representation of actual SM developments over time and for different spatial units. In

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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 B3: NSE statistics of SM_{obs} versus SM_{mod}

station	NSE
BET	**0.87**
Shu	**0.80**
WZ-upT	**0.63**
WZ-~~hh~~gh	**0.40**
KF-W	**0.79**
KF-E	**0.96**
RK-W	**0.70**
RK-E	-0.35
avg. all (w/o RK-E)	**0.73**
avg. all (incl. RK-E)	**0.60**

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Appendix C

Table C1: Five spring data coverage.

~~Year~~	~~**Abu 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 %~~

Year	**Abu 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 %

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Daily spring readings were carried out by hand (with stop watch and bucket) and by different personnel in the respective spring groups. Beitillu spring group was fully covered for three years. In the first season (2003/04), measurements started late ~~into~~in the season, then were read most of the days in winter and scarcely in summer. In season 2009/10, continuous reading continued until February 2010. The two springs at Wadi Zarqa spring group (Salem & 'Akkari) had the same coverage as Beitillu group in 2003/04 and ~~then~~ were almost uninterruptedly read from December 2005 (season 2005/06) until February 2010. Hence, high coverage was achieved during almost six seasons in Wadi Zarqa and during nearly five seasons in Beitillu.

Appendix D

Table D1: Soil depth matrix.

Hydrostratigraphy	**Upper Aquifer**	**Yatta**	**Lower Aquifer**
Geological formation	Heb., Bet., ~~Jer~~Jerus.	up UBK, Yatta	LBK, ~~low-~~l-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			

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 ~~in red colour~~that were also encountered at the SM stations~~.~~ are shown underlined. Main land form types are ~~shaded grey.~~shown in the dashed boxes. The values for l-UBK formation are representative for the main body of the formation but not for the top of l-UBK (see ~~*). Boxes~~second row, right column). Cells marked NA, represent untypical vegetation and land form types for the respective formations.

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Appendix E

~~The~~If the seven years covered in this study (2003/04-2009/10) are ~~representative~~to be used for calculations of multi-annual averages, they must reflect the range of long~~-~~-term ~~rainfall~~climatic conditions in the basin. Since no long-term climatic records are available for Wadi Natuf, the representativeness of the seven years modelled was compared on the level of the entire WAB area. The Hydrological Service of Israel (HSI, 2016) presents ~~rainfall~~ records of annual area precipitation for six different sub-basins (cell groups) ~~of~~ within the Western Aquifer Basin~~. HSI (2016) divides the WAB into six cells~~ from North to South (Fig. E1). Wadi Natuf lies at the border between the Northern and Central cell group of the WAB and nearby the Jerusalem cell group and was found to be best represented by a mixture of the central, northern and Jerusalem cells of WAB.

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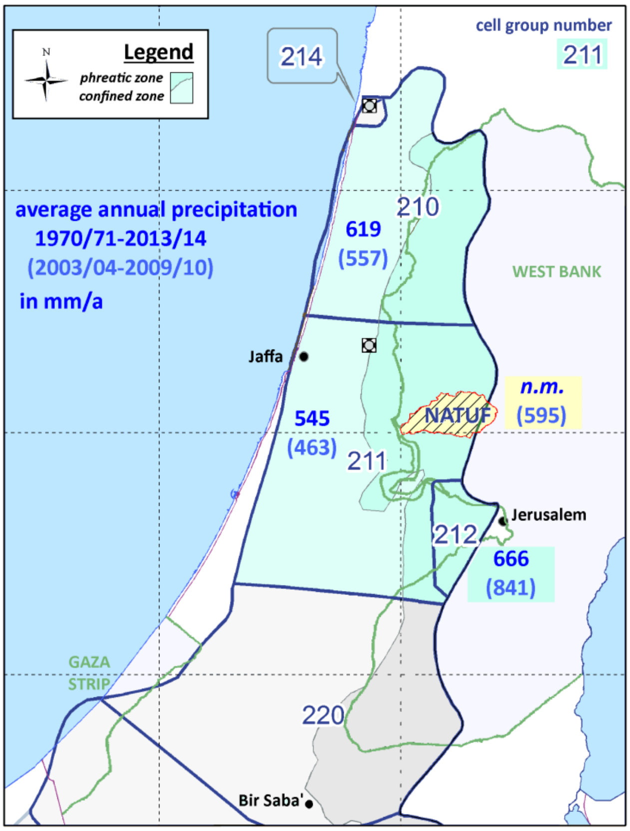

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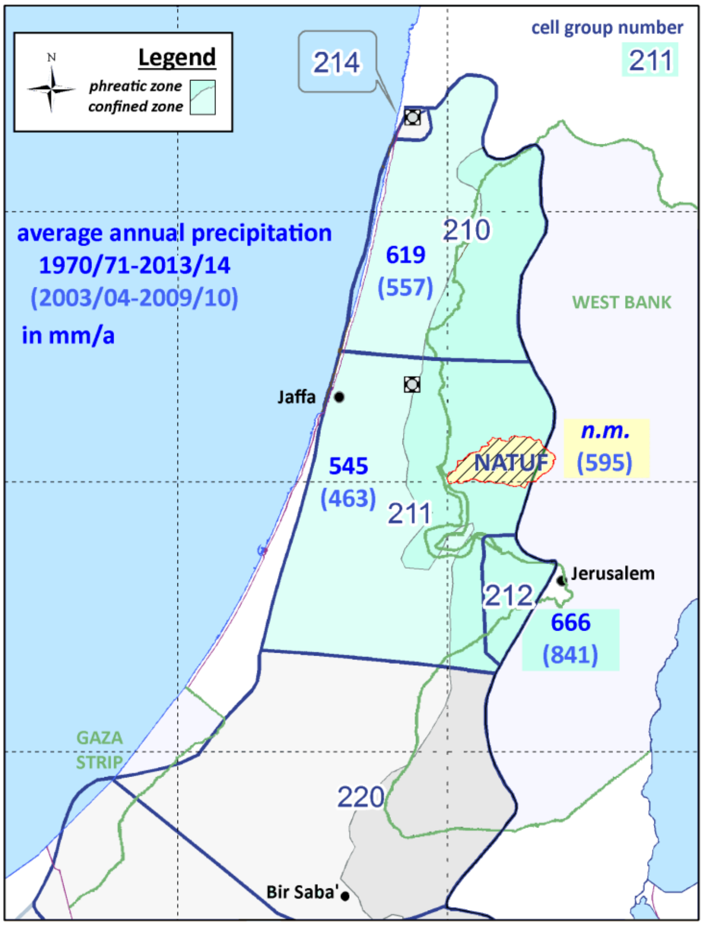

Figure E1: WAB cells of area precipitation (modified after: HSI, 2016). The map indicates area precipitation for two periods, long-term (1970/71-2013/14) and for the seven years of this study. Long-term area rainfall data for Wadi Natuf are not available; the ~~7~~seven-year period was measured by tipping buckets. Precipitation data for the three cells groups, no. 210, 211 and 212 were taken from HSI (2016).

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The period of ~~rainfall~~ documented precipitation records spans 44 years from 1970/71 to ~~1013~~2013/14.~~ Of the 44 years, only~~ Only two of these years were drier and only 12 years were wetter than the seven years studied here. Out of these 12 wet years, only five years (or 11% of the 44 years) were wetter ~~by more than 20%~~ than the maximum in the range of the seven 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.

~~The following analysis was carried out.~~ For each cell group (North~~, centre~~ – 210, Centre – 211 and Jerusalem – 212) the arithmetic mean precipitation was calculated over 44 years and over the seven year period, respectively. Then the average of the three mean values for each cell group was formed, ~~again,~~ for both, the entire and the 7-year period. ~~This average lies at 610mm/yr over~~These value were 610 mm/a for the entire 44 years and ~~at 621mm/yr during~~621 mm/a for the seven years studied here. In other words, the seven years were ~~wetter but only~~ slightly~~; the average of seven years is 101.7%~~ wetter than the average of all 44 years (for the spatial averages of three cell groups), but only by 1.7% (101.7% of 44-year average, marked underlined in Table E1).

~~Especially in highly variant climates, it is recommended, to use~~When the same analysis was done for the median ~~value~~ instead of the arithmetic mean, ~~because it indicates the most probable rainfall. Here, the median was formed for 44 years and seven years, independently and for each cell group, respectively. Again, the average of the three geographic cell groups was formed and~~long-term conditions resulted in ~~slightly different median rain heights, of~~ 600 mm/~~yr long term and of 624 mm/yr for~~a, the ~~7~~seven-year period in 624 mm/a. The ~~short- and~~ long-term and short-term median values were also compared in each cell group independently~~;~~ (their ~~average lies at a ratio of 99.6% between long- and short term rainfall observations. The ratio between the~~ averages ~~(of cell group medians) of seven years and of all 44 years is 99.6%.~~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.

Table E1: Comparison of average rainfall in WAB cell groups, long-term and for the ~~7~~ seven years 2003/04-2009/10.

cell item	type	period	# 210 North	# 211 Centre	# 212 Jerus.	avg. of all three cell groups	item
avg. of all years	long term	1970/71-2013/14	619	545	666	610	avg. of averages (all years)
average 7 years	7-year period	2003/04-2009/10	557	463	841	621	avg. of averages (7years)
ratio			**90~~,~~.0%**	**85~~,~~.0%**	**126~~,~~.3%**	**101~~,~~.7%**	* *ratio between averages*
median of all years	long term	1970/71-2013/14	597	504	698	600	avg. of medians (all years)
median of 7 years	7-year period	2003/04-2009/10	593	460	820	624	~~Avg~~avg. of ~~Medians~~medians (7 years)
~~Ratio~~ratio			**99~~,~~.3%**	**91~~,~~.3%**	**117~~,~~.6%**	**99~~,~~.6%**	* *average of 3 groups*

* The above calculation uses the average between resulting means (610 mm and 621 mm per, respectively). The ~~below~~ calculations below show the average of the ratios, formed in each cell group. WAB annual precipitation was based on data from the Hydrological Service (HSI, 2016). All rain heights are in mm/~~yr~~a, the ratios in percent.

Thus, it can be shown that the seven years of rainfall observation in Wadi Natuf cover almost the entire range of long-term annual rain distribution. Only one single year, the winter of 1991/92 with its century rainfall clearly lies outside the rainfall range covered by our measurement period. ~~As a result, we can state with confidence that the seven years covered in this study happen to match very closely with the overall range of long-term annual rain heights in the WAB.~~

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Appendix F

When signatures of peak spring flow periods were compared with those of recharge (DP), it had to be assured that the ~~hydrographs~~discharge of the selected daily ~~read~~measured springs ~~were~~was representative for the entire spring groups draining the respective aquifers. This could be affirmed by ~~statistical~~ the analysis ~~as~~ shown below. In addition to the five ~~daily read~~ springs that were daily measured, all springs in Wadi Natuf were measured during four key date campaigns ~~(as detailed in Messerschmid *et al.*, 2019b).~~. 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 Table F1 and Table F2.

Table F1: ~~Spring flow comparison~~ Comparison of spring discharge (and standard deviation) between daily ~~read~~measured springs and entire Beitillu (Harat al-Wad) spring group ~~flow~~ during key date campaigns ~~– spring group Beitillu (Harat al-Wad).~~.

Spring flow (m³/d)	03 summer	03/04 winter	04 summer	07 summer	**St. Dev.**
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 Beitillu spring group	**98**	**110**	**61**	**73**	
Relative share of 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 3 springs)	**19.9%**	**20.2%**	**21.4%**	**22.4%**	**1.15%**

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At the four key date campaigns, total spring outflow at Beitillu spring group (Table F1) was lying between 61 and 110 m³/d. 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, total spring outflow at Wadi Zarqa spring group (Table F2) was lying between 165 and 493 m³/d. The two daily monitored springs combined made up 6.8-8.5% of total spring group flow with a standard deviation of 0.72~~%.~~% (bottom right cell).

Table F2: ~~Spring flow comparison~~ Comparison of spring discharge (and standard deviation) between daily ~~read~~measured springs and entire Wadi Zarqa spring group ~~flow~~ during key date campaigns ~~– spring group Wadi Zarqa~~.

Spring flow (m³/d)	03 summer	03/04 winter	04 summer	07 summer	**St. Dev.**
Ein Al-'Akkari 1	13	17	14	7	
Ein Salem 1 (upper)	20	25	10	4	
sum Wadi Zarqa spring group	**414**	**493**	**303**	**165**	
Relative share of 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 2 springs)	**7.8%**	**8.5%**	**7.7%**	**6.8%**	**0.72%**

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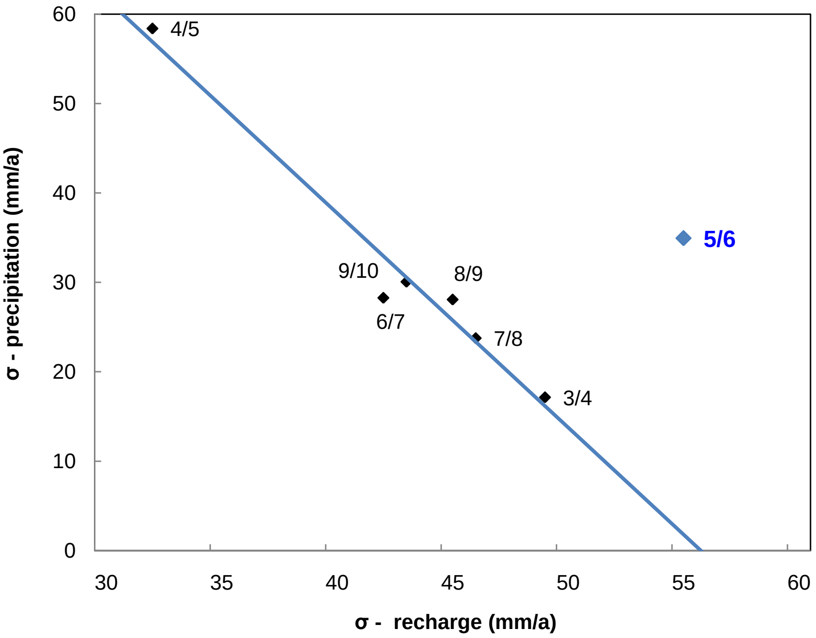
Appendix G

In most years, the variability of precipitation was reciprocal to the variability of recharge – in other words: the wetter the year, the higher the spatial variability of rainfall, but the lower the spatial variability of recharge. Variability here is expressed as the standard deviation (σ) for the values of the different stations. Although one year (2005/06) ~~was excluded~~plotted far from the trend line, the otherwise quite pronounced pattern of the diagram shows that indeed spatial variability of recharge deserves more attention ~~that it was~~than given so far, ~~at least but not only~~since in the WAB, ~~where so far, almost all~~most studies focussed~~ mostly if not solely~~ 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.



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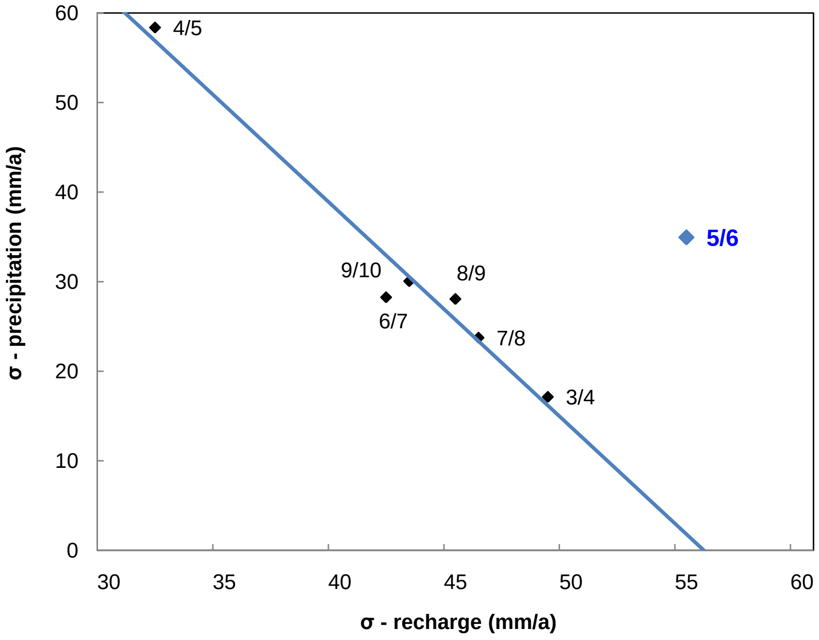

Figure G1: Scaling - standard deviations (σ) of P & DP. Note: the linear trend line excludes the year 2005/06, which deviates from the trend of the other years. In this year, spatial variability of recharge was quite high but nonetheless, spatial variability of recharge was high as well. 2005/06 was 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 drying up of the soils and consequent soil saturation during the event.

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Appendix H

Recharge rates (in mm/a, or calculated as coefficients in %) have been reported in numerous studies within the WAB and adjacent basins~~.~~ of the Mountain Aquifer (such as the Eastern Aquifer Basin, EAB). 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*~~., 2019b~~. (in preparation), 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 Mt. Carmel basin with a very similar geology and climate as in Wadi Natuf). For a small groundwater catchment overlapping with 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 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 for many basins with similar climatic, geological, soil type and landscape conditions.

Table H1: Recharge coefficients in the literature.

author (year)	~~**year**~~	**~~avg~~average**	**max.**	**area**	**time**	**~~based on~~approach**	**how**	**method**	**miscellaneous**
Sheffer *et al.* (2010)	~~2010~~	9-40 %	(52 %)	Mt.~~Aq.~~ Aquifer	annual	SM-model	calibrated numerical water budget model	daily soil saturation	non-~~empirical~~empirically assumed ~~FC~~field capacity (low) and soil thickness (high)
Gunkel *et al.* (2015)	~~2015~~	30 %	-	Mt.~~Aq.~~ Aquifer	annual	model	distributed, field-based, water balance model	TRAIN-ZIN, MOSST	EAB, Wadi Fari'a + Jordan Valley, 6-year measurement period, event-based
Sanz *et al.* (2011)	~~2011~~	34.3 %	34.3 %	Spain	annual	lithology	clay 1.3 %; silt 3.3 %; lst~~+~~ + dol 34.4 %	large areas, ~~SMD + HEP~~soil moisture deficit	as factor of lithology & hydrologically effective precipitation
Cheng *et al.* (2017)	~~2017~~	-	42 %	China	event	~~thick~~ soil	max annual: 32.4 %	>2m thick soils	in one event
Bradford *et al.* (2002)	~~2002~~	39-45 %	45 %	UK Chalk	annual	models	with input data at varying spatial resolutions	~~SMD + HEP methods~~soil moisture & precipitation	UK Chalk, 4 years; SM-deficit & hydrologically effective precipitation
Nativ *et al.* (1995)	~~1995~~	8-55 %	-	N Negev	annual	bromide	in boreholes in fractured chalk	bromide profiles	arid desert climate (P: 200mm/a)
~~Abusaadah~~ Abusaada (2011)	~~2011~~	**36 %**	53.2 %	Mt.~~Aq.~~ Aquifer	annual	flow model	WAB basin-wide water budget	3-dimensional flow model	max. recharge in 2003/04
Dvory *et al.* (2016)	~~2016~~	34 %	54.3 %	Mt.~~Aq.~~ Aquifer	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)	~~2014~~	25-50 %	55 %	Mt.~~Aq.~~ Aquifer	annual	~~spatial~~SM-model	Rain, ~~Etp~~ET_p (spring flow) data	~~SMD+GW~~ model, spring response	EAB at 'Auja spring (spatially distributed): soil moisture deficit & groundwater model
Sheffer *et al.* (2010)	~~2010~~	20-60 %	-	Mt.~~Aq.~~ Aquifer	annual	formula	~~quotes~~ of Guttman & literature quotes on WAB-RC	single-cell flow model	calibrated numerical annual water budget (non-empirical), linear equation
Ries *et al.* (2015)	~~2015~~	33 %	66 %	Mt.~~Aq.~~ Aquifer	annual	model	max. in wet years (avg. in Aujah)	SM model, budget	EAB (mountains and slopes)
Guttman *et al.* (1988)	~~1988~~	**30.6 %**	75.3 %	Mt.~~Aq.~~ Aquifer	annual	model	WAB basin-wide water budget	quasi-3-dimensional flow model	max. recharge in 1991/92 (single-cell water balance model~~)~~ of the Coastal Plain only)
Weiss & Gvirtzman (2007)	~~2007~~	**6-65 %**	-	Mt.~~Aq.~~ Aquifer	annual	formula	of Guttman ('00), G. & Zuckerman ('95)	quasi 3-D flow model	applying Guttman-formula to 4 spring areas, one of which overlaps with Wadi Natuf
Radulovic *et al.* (2011)	~~2011~~	66.3-76.2 %	**76.2 %**	Montenegro	annual	~~spatial~~combination	water budget & other methods (Montenegro)	ranking system and matrix	karst, lithology, structure, landform, runoff, plants, climate, soil, slope (spat. distributed)
Allocca *et al.* (2014	~~2014~~	50-79 %	**79 %**	S-Italy	annual	lithology	precipitation & air temperature	~~empir.~~empirical model, linear regression	correlated with other factors: karst outcrops, morphology, land use, soil type

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Goldscheider & Drew (2007)	~~2007~~	-	**>80 %**	-	event	~~spatial~~literature	bare karstified limestones	-	summary from literature for spatially distributed recharge
Weiss & Gvirtzman* (2007)	~~2007~~	**<10->80 %**	**91 %**	Mt.~~Aq.~~ Aquifer	annual	lithology	max. in 1988 at l-LBK ~~ftn.~~formation.	model, budget, spring response	28-a avg. RC of **47.2 %** at Ein Al-Harrasheh spring groundwater catchment
Allocca (2015)	~~2015~~	35-97 %	**97 %**	Apennine	event	model	storm-by-storm, Apennine	air temp., ET & rain	
Shacori (1965)	~~1965~~	**47 %**	-	Mt.~~Aq.~~ Aquifer	annual	~~spatial~~	Mt Carmel avg. (undifferentiated)	-	
Mero (1958)	~~1958~~	**53 %**	-	Mt.~~Aq.~~ Aquifer	annual	~~spatial~~literature	Na'aman spring	-	~~(quote~~quoted after Lerner *et al.* (1990) for spatially distributed recharge
Rosenzweig (1972)	~~1972~~	**60 %**	-	Mt.~~Aq.~~ Aquifer	annual	landform	Mt Carmel avg. (by landform)	annual on pasture/grassland	while at forest 0 %
~~Messerschmid *et al.*~~**this study**	~~2018~~	**40.8-47.3 %**		Mt.~~Aq.~~ Aquifer	annual	~~3 groups~~SM-model	~~here: alt. 2:~~different formations with typical soil-~~depth group~~depths	~~SM-model, ranking~~saturation-excess percolation	spatially distributed recharge for the WAB in Wadi Natuf (by geology, soil & LU/LC)

* 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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