

1. Answer to review of Prof. Goldscheider (2020-04-08)

Dear Prof. Goldscheider,

We would like to thank you for your review and positive feedback. As suggested, we will rephrase some sentences to clarify the text, avoid repetitions, and correct some mistakes. Hereafter we describe the main modifications that will be made to the document based on your comments (major comments addressed are labeled C# and replies are labeled A#). Minor comments are labeled MC# with the reply directly underneath it.

C1: Title: The title is too long (almost three lines). Please shorten to two lines.

A1: We agree that the title needs to be shortened, and we are considering to change it as follows, to also emphasize on the climate change aspect of the work (as mentioned in following comments):

“Calibration of a lumped karst system model and application to the Qachqouch karst spring (Lebanon) under climate change conditions”

C2: Abstract: Something is wrong with the first sentence, which is also too long. Please rephrase.

A2: We agree that this sentence is too long and needs clarification. To reflect more the climate change aspect of the study as well, this first sentence will be rephrased into:

“Flow in complex karst aquifers is challenging to conceptualize and to model, especially in poorly investigated areas, in semi-arid climates, and under changing climatic conditions. It is yet necessary for implementing long term sustainable water management practices.”

C3: 62-65: The research objectives are relevant, but maybe you could add 1-2 additional objectives. Objective no. 2 is very general and could be complemented by a more specific research question, also including the practical relevance of your research, such as the expected climate change impacts and the implications for freshwater availability. Furthermore, objective no. 2 is not completely clear. What do you mean by “its sensitivity” – the sensitivity of the model or of the karst aquifer?

A3: We thank Prof. Goldscheider for this useful comment, and to homogenize with the discussion section, and as suggested, the objectives of the study (lines 62-65) will be rephrased as follows:

“The objectives of this work were 1) to acquire new knowledge of the hydrodynamic functioning of a complex karst aquifer derived from statistical and correlation time series analyses, 2) to illustrate how a semi-distributed lumped model can be calibrated on the basis of this knowledge, and 3) to assess the impact of climate change on the spring hydrodynamic to provide insight on fresh water availability. The approach is demonstrated on the Qachqouch karst spring in the region north of Beirut (Lebanon), a Mediterranean region governed by semi-arid conditions.”

C4: Section 3.3.2 describes the decomposition of spring hydrographs after Jeannin & Sauter in a very general way, but it is not clear if and how this approach was used in the present study. Similar problem in section 3.3.3. In the “material and methods” chapter, please always say clearly what you did in your study, and how you did it, instead of describing general theory.

A4: We agree that information about the use of these methods was missing, and as suggested, a sentence will be added to clarify the use of time series decomposition at the end of the section 3.3.2:

“This time series decomposition was applied to the spring flow rates (box 3, Fig. 2) to verify if spring flows could be relevantly linked to three conceptual reservoirs.”

As well, the use of correlation analysis in the study will be detailed at the end of the section 3.3.3:

“Auto-correlation and cross-correlation analyses were performed on precipitation and on the Qachqouch flow rates time series to estimate the memory effect of the system and the delay between precipitation and the hydrological response of the karst system (box 3, Fig. 2). Auto-correlation and cross-correlation of simulated flow rates were compared to those of the input data, as an additional validation method (box 4, Fig. 2).”

C5: Conclusions: Already in the first sentence of the conclusions, you undersell the importance of your study with respect to climate change impacts on groundwater resources, because you only mention the sensitivity of your MODEL to climatic conditions, which is a rather academic perspective. However, climate change impacts on groundwater resources is a major topic, particularly in the Mediterranean area. I would suggest to emphasize more clearly that your model allows to better predict climate change impacts on groundwater resources, and explain why this is important and how your model could help to make better management decisions. This is a general recommendation, not only concerning the conclusions, but also title, abstract and introduction.

A5: We thank Prof. Goldscheider for this useful comment and to emphasize the climate change aspect of our work, beside the modifications of the title and the clarification of the work objectives (previous comments), the first paragraph of the conclusion (lines 377-381) will be changed to:

“This work aimed at acquiring new knowledge of the hydrodynamic functioning of a complex karst aquifer derived from statistical and correlation time series analyses to optimize the calibration of a semi-distributed lumped model. The model developed for the Qachqouch karst spring in Lebanon (semi-arid climate) was used to assess the impact of climate change on the spring hydrodynamic to provide insight on fresh water availability. Flow rates were analyzed statistically for a better conceptualization of the system, to allow the calibration of a semi-distributed linear reservoir model. The model was used to reproduce current conditions and to analyze the impact of dryer and warmer possible future climate conditions on flow rates.”

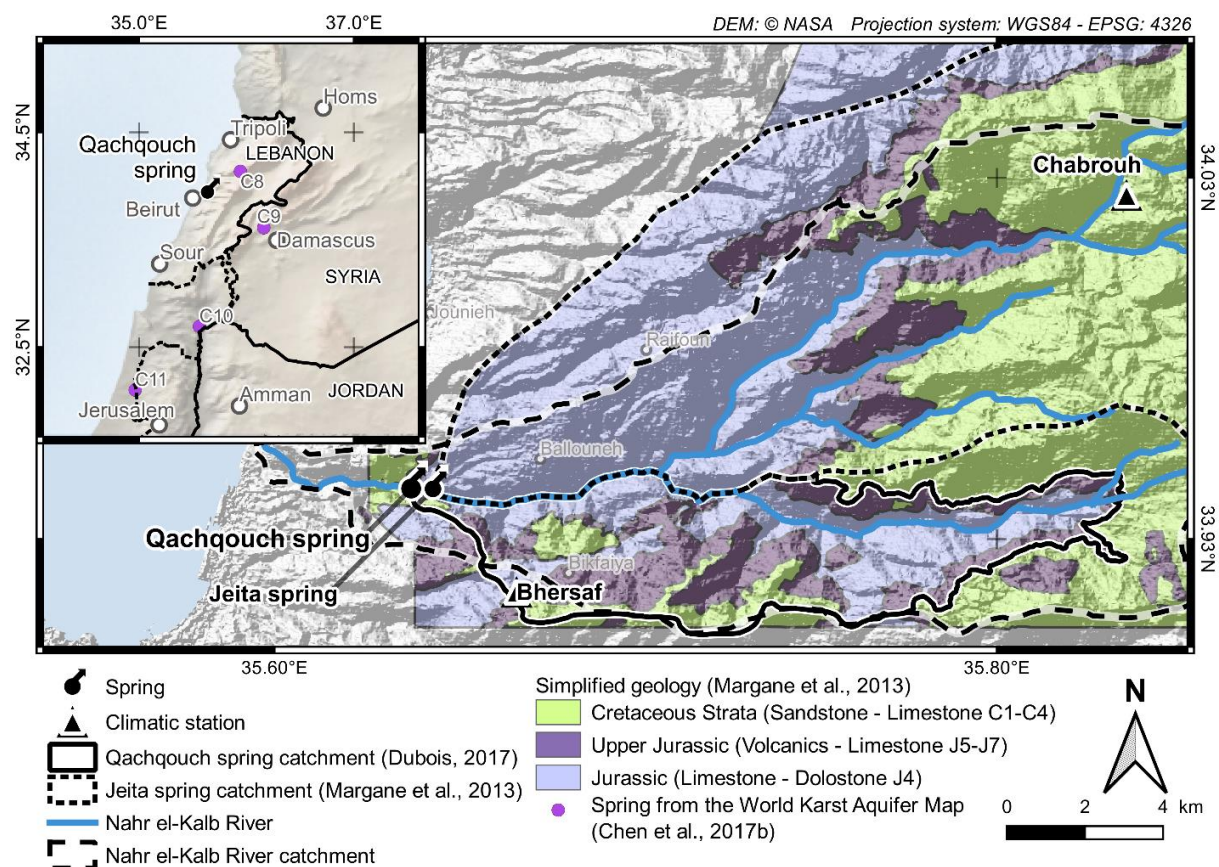
We will also modify the lines 394-396 to underline the use of the main conclusions of the climate change analysis for fresh water management:

“The climate change simulations brought new insights about possible future spring flow conditions, therefore allowing to develop more adapted scenarios for long-term fresh water management. The next steps of management plans should entail coupling of climate change scenarios at the catchment scale with land use change scenarios to improve overall future predictions and investigate solutions to alleviate the expected future depletion of semi-arid karst aquifer systems.”

Answers to the reviewers

C6: Figure 1: The graphical quality of this map should be improved. The hatching for geological units is distracting. I would suggest to use transparent colors instead, on top of some more intense grey shading showing the topography of the area.

A6: We agree that the graphical quality of the figure 1 needs to be improved. As suggested, transparent color for the geological formations will be used in Fig. 1 rather than hatching, making the new version of the figure looking like:



MINOR CORRECTIONS:

MC1: 16, 17 and elsewhere: m3 should be m3

This will be done as suggested.

MC2: 73: km2 should be km2

This will be done as suggested.

MC3: 80: Rearrange sentence to avoid misunderstanding. The spring is located at 64 m asl, not the aquifer.

To avoid confusion about the spring elevation, the misleading sentence L80 will be rearranged into:

“Similar to the nearby Jeita spring (Margane et al., 2013, 2018), the Qachqouch spring is located at 64 m asl and originates from the Jurassic karst aquifer (Fig. 1).”

MC4: 84: quaternary should be Quaternary

This will be done as suggested.

MC5: 84: The expression “high level of karstification” is misleading in this case. In fact, the Messinian salinity crisis created a very low topographic level of karstification. You probably mean high degree of karstification, very intense and very deep karstification.

As suggested, L84 will be corrected to:

“and Quaternary glaciations also contributed to creating a high degree of karstification (very intense and very deep) in the Mediterranean area in several stages”

MC6: 112: Why do you put all measured parameters in brackets? This is the most important information.

As suggested, the list of measured parameters will be taken out of the brackets.

MC7: 124-128: three times “was used” on 5 lines. Avoid repetitions.

To avoid repetitions, L124-128 will be rewritten into:

“Spring flow rates were evaluated by a frequency analysis (Dörfliger et al., 2010; Mangin, 1971; Marsaud, 1997). Flow rates and their frequency of measurements were linked with a log normal distribution, except for outliers arising from variation in flow dynamics.

Following hydrograph decomposition, the method developed by Mangin (1971, 1975) was used to estimate the dynamic volume (V_{dyn}) available in the aquifer during the depletion flow of a karst spring.”

MC8: Heading 4.1 could be shortened.

The heading 4.1 will be shortened to:

“4.1 Qualitative functioning of the system”

MC9: 217: “between 44 and more than 50 Mm³” (call me pedantic, but “between 44 and > 50 Mm³” is an improper use of language and mathematical symbols).

This will be done as suggested.

MC10: 290: “increases the reduction” – slightly confusing. Better say “leads to stronger reduction”.

This will be done as suggested.

MC11: 320-323: Very long and extremely intricate sentence that contains a surprisingly insignificant message. Please split into several sentences, rearrange and rephrase.

The sentence of L320-323 will be re-written into:

“Even though the Qachqouch karst system has been reported to be less complex than that of the neighboring Jeita spring (Doummar, 2012; Margane et al., 2018), it is still comparable to other Middle Eastern karst systems (Fig. 5). Parameters k and i , representing the extent of the phreatic zone, the regulating capacity of the system, and the type of infiltration (Bakalowicz et al., 2008; El-Hakim and Bakalowicz, 2007; Mangin, 1975), classify the Qachqouch spring close to other Lebanese karstic aquifers.”

2. Answer to review of Anonymous reviewer 2 (2020-06-16)

Dear Referee,

We would like to thank you for your comments and positive review aimed at clarifying and improving our paper. As suggested, we will review the text and complete the missing information. Hereafter we describe the main modifications that will be made to the document based on your comments. The interactive comments are addressed first (labeled C#), followed by comments from the annotated manuscript (labeled mC#, comments from the supplementary material).

C1: A lot of important information is provided in the introduction but a clear research gap still needs to be defined, which the authors intent to fill with this particular work.

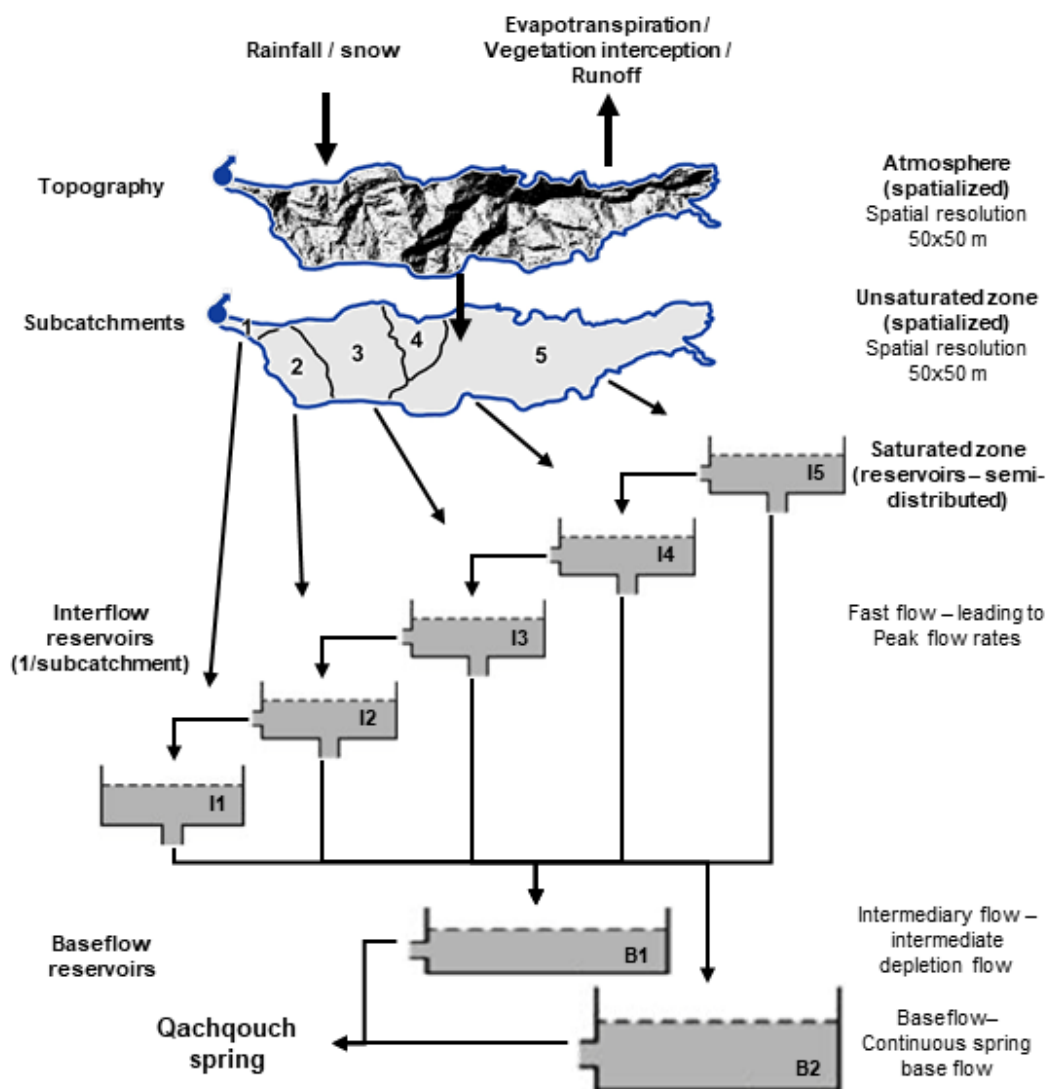
A1: We thank the Referee for this useful comment, and we will provide the missing information by adding L61:

“Nevertheless, little information is found in the literature about the use of time series analysis in groundwater flow modeling for complex karst aquifers to enhance model calibration and estimate the sensitivity of water resources to climate change while lumped models seem to be a good tool to address this question.”

C2: Some clarification of the spatial discretization of the model is necessary. MIKE-SHE is a distributed model, which is here applied fully distributed at the surface but it is operating completely lumped in the subsurface of a set of sub-catchments. Using a sub-catchment approach, this seems to be a semi-distributed application of the MIKESHE model using a fully distributed surface routine, right?

A2: That is exact, and we agree that clarification is needed on the spatial discretization of the model. Indeed, only the surface routine is fully distributed (atmosphere and unsaturated zone). Lumped reservoirs are used for the saturated zone (at the subcatchment scale – for the five interflowing reservoirs I1 to I5 in Fig.3) and for the entire system with two baseflow reservoirs for the entire study area (reservoirs B1 and B2 in Fig. 3). In order to clarify this point, Fig. 3 will be modified to add the spatialization details at each level, as follows.

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Additionally, the L67 (Introduction) will be rephrased as follows:

“A semi-distributed/lumped model, composed of a spatially distributed superficial and unsaturated zone, and a saturated zone composed of interflowing lumped reservoirs, developed using MIKE SHE (DHI, 2016a, b), is calibrated here using observed spring discharge time series.”

C3: Mangin’s method and the decomposition of spring hydrographs are usually applied to hydrograph recessions. Please elaborate how recessions were defined/extracted for the entire time series.

A3: We agree that information on how recessions were estimated from the time series is missing. We will therefore add L142:

“Considering the very similar annual recession for the spring and summer period in 2015, 2016, and 2017, annual recession was considered from the last major flood (occurring in March/April) until the first rainfall event in October (Fig. 2).”

C4: Please explain in more detail the model calibration procedure and how it is linked to the spring flow characterization.

A4: Indeed, the explanation of how the model calibration is linked to the spring flow characterization was missing. In order to rectify this, L195 will be rewritten as follows:

“The model uses 20 parameters defining the atmosphere, the unsaturated zone, the saturated interflow reservoir, and the base flow reservoirs. The time constant of each reservoir from the unsaturated zone is determined from the flow characterization and the recession analysis, therefore reducing the uncertainty in some parameters and the total number of parameters for calibration.”

C5: Some clarification on how and how many scenarios were derived from the IPCC projections for the climate change analysis. Mentioning table 2 already here might be helpful. In many regions, climate change is projected to have strongly different effects on P and T throughout the seasons. Why did this study choose a delta approach for entire years?

A5: We agree that clarification on the climate scenarios are needed, and that a mention of Table 2 in section 3.3.5 would be helpful. For that purpose, we will add after L212:

“A combination of those conditions for ten consecutive years (annual gradient of warming temperature and decreasing precipitation) were applied to the average year (derived from averaging the monitored daily precipitation and temperature) to obtain seven scenarios of changing climatic conditions for the 2030 horizon (Table 2). If annual gradients have been chosen for simplification purposes, the changing conditions in semi-arid conditions actually concern the rainy season (October to April of the following year) when exchanges between the atmosphere and the system are active (runoff, evapotranspiration, infiltration...).”

C6: In the results/discussion, the link between model structure and spring flow characterization is not very clear.

A6: We will include this recommendation and rephrase L270-273 as follows:

“The previous analyses performed on the time series allowed to refine the model geometry by matching the number of reservoirs with the conclusions of the flow characterization. Model parameterization also included setting to fixed values the time constants of the reservoirs, which are usually included in the calibration

process. Model uncertainty has thus been reduced by optimizing the conceptual model on the system hydrodynamic functioning (Enemark et al., 2019).”

C7: Can you provide a sketch of the conceptual model of the system?

A7: We thank the Referee for their suggestion. However, we believe that a conceptual model of the system by itself would be very similar to Fig. 3 and we chose not to add a new figure. However, we will add more details to Fig. 3 to make it clearer and underline in the text that this figure represents a conceptual model of the system. Please refer to A2 for the modified figure and L333-342 will be rephrased:

“Although the model adequately reproduces flow discharge, it underestimates the summer low flows. Measurements recorded during flooding of the spring gauging station might be underestimated due to errors in the discharge water level rating curve for high flow rates. Another explanation could be that the fast flow linked to a highly-developed drainage system is oversimplified in this reservoir model (reservoirs I1 to I5 from Fig. 3). The thickness of the UZ, combined with its lithological heterogeneity, as well simplified in the model (Fig. 3), may contribute to the relatively stable summer low flow by allowing considerable water storage, which is represented by the B2 baseflow reservoir in the model (Fig. 3). In fact, the dolostone could be compared to low-permeability porous media drained by a high-permeability system, thus allowing a large storage capacity in the upper parts of the aquifer. Furthermore, the high degree of karstification of the area, resulting from both the eustatic variations (Messinian) and the quaternary glaciations, leads to a complex drainage system, with three identifiable flow components (fast flow, intermediary flow, and baseflow – Fig. 3) and a probable paleo-network under the current base level. This would enhance the storage capacity of the system, as well as induce rapid flow rate increases (Bakalowicz, 2015; Nehme et al., 2016).”

REVISION FROM THE ADDITIONAL MATERIAL:

mC1: L14 and 62: “a semi-distributed lumped model” – this is contradictory. Pick one: either semi-distributed or lumped.

The text will be changed to “*lumped model*”.

mC2: L21: “Climate change conditions (+1 to +3°C warming, -10 to -30% less precipitation annually, and intensification of rain events)” – in which future? 50 years? 100 years?

The text will be rephrased into:

“Climate change conditions at the 2030 horizon (+1 to +3°C warming, -10 to -30% less precipitation annually, and intensification of rain events)”

mC3: L24: “with flow rates decreasing by 34%” – corresponding to what change of Precip?

The text will be rephrased into:

“with flow rates decreasing by 34 % for scenarios with 30 % loss of yearly precipitation”

mC5: p°2: A lot of important information is provided in the introduction but a clear research gap still needs to be defined, which the authors intent to fill with this particular work.

Please refer to A1 for our answer.

mC6: L67: “A semi-distributed lumped model developed using MIKE SHE” – Isn't MIKE-SHE a distributed model? I think you need to define early in the manuscript what type of model you use.

Please refer to A2 for our answer.

mC7: L127: “Following hydrograph decomposition, the method developed by Mangin (1971, 1975)” – Mangin's method is applied to hydrograph recessions. Please elaborate how recessions were defined for the entire time series.

Please refer to A3 for our answer

mC8: section 3.3.2: Same as above [mC7]: How were recessions extracted?

To define how recessions were extracted, we will add this text after L160:

“To decompose the discharge flow from the spring accordingly to this concept, all decreasing parts of the discharge flow between 2015 and 2018 were used. The peaks higher than 10 m³/s were excluded because of the incertitude on the flow measurement, as well as the portions of sub-vertical and too irregular decreasing slope.”

mC9: L180: “into several sub-catchments” – How many?

The text will be changed for: *“into five sub-catchments”*

mC10: L194: “The complete model is therefore considered a classical lumped model for the saturated zone” – but only within each sub-catchment, right?

Please refer to A2 for our answer

mC11: L195: “physically-based model” – better use the term “fully distributed” here because it's about how the model is discretized for its different domains.

The text will be rephrased for “*fully distributed*”.

mC12: L199-200: “Sensitivity analysis was conducted automatically on single parameters using the Autocal function (DHI, 2016) to identify the parameters to which the model is highly sensitive.” – Please add some more detail on how this sensitivity analysis works?

Following L200, this text will be added:

“The Autocal function performs a local sensitivity analysis by computing the ratio of the perturbation in the simulated discharge flow with the variation of a single parameter, one at a time.”

mC13: section 3.3.5 – Please clarify in a bit more detail on how and how many scenarios were derived from the IPCC projections. A table might be helpful here.

Please refer to A5 for our answer

mC14: section 4.1.1 – Please explain this method a bit better in the methodology [Flow rate frequency].

We will add the following text after L126:

“The evolution of the slope of the curve between the breaking points gives information about the dynamic of the system and the time series. Dörfli et al. (2010) classified the possible configuration and their respective interpretation.”

mC15: L275-281 – Please move interpretations to discussion.

The aforementioned paragraph only presents the comparison of the auto-correlation and cross-correlation of the simulated and observed spring flow, therefore meaning that the model reproduces the spring discharge correctly. We do not think that this paragraph would fit in section 5 since it does not bring a global and interpretative point of view on the functioning of the system. Therefore, we prefer to keep it as it is.

mC16: L283: “from seven potential scenarios for the study area (Table 2)” – these have to be introduced and elaborated in detail in the methods section. In many regions, climate change is

projected to have strongly different effects on P and T throughout the seasons. Why did this study choose a delta approach for entire years?

Please refer to A5 for our answer.

mC17: section 5.2 – Can you provide a sketch of that?

Please refer to A7 for our answer.

3. Corrected manuscript (changes highlighted)

Calibration of a lumped karst system model and application to the Qachqouch karst spring (Lebanon) under climate change conditions ~~Calibration of a semi-distributed lumped karst system model and its sensitivity to climate conditions: the example of the Qachqouch karst spring (Lebanon)~~

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Abstract. Flow in complex karst aquifers is challenging to conceptualize and to model, especially in poorly investigated areas, in semi-arid climates, and under changing climatic conditions. It is yet necessary for implementing long-term sustainable water management practices.
~~Flow in complex karst aquifers is challenging to conceptualize, therefore to model for better management practices, especially in poorly investigated areas, in semi-arid climates, and under changing climatic conditions.~~

The objective of this work were to propose a calibration approach based on time series analyses for a karst aquifer, and to assess the impact of ~~changing climate conditions~~ climate change on the spring discharge. Based on more than three years of high-resolution continuous monitoring, a semi-distributed lumped model was calibrated and validated for the Qachqouch karst spring, north of Beirut (Lebanon). Time series analyses and decomposition of spring hydrographs revealed that the system has a high regulatory function, with considerable storage capacity providing stable flow (minimum flow of 0.2 $\text{m}^3\text{m}^3/\text{s}$) during the dry season, and with flow rates exceeding 10 $\text{m}^3\text{m}^3/\text{s}$ during the wet season, similar to other karst aquifers in the region. Based on this detailed understanding of the hydrodynamics of the system, the model geometry and parameters were validated. Three linear reservoirs were implemented to reproduce the combined contribution of the different flow components of the system. A satisfactory simulation (Nash-Sutcliffe coefficient = 0.72) of measured spring flow rates was obtained after calibration. Climate change conditions (+1 to +3°C warming, -10 to -30% less precipitation annually, and intensification of rain events) were added to a baseline climatic year to produce scenarios of expected spring flow responses. Results show that the Qachqouch karst aquifer is sensitive to decreasing rainfall, which is associated with more pronounced recessions, with flow rates decreasing by 34% and 1-month longer dry periods. Because of the limited influence of snow on the spring flow rate, a warming climate has less impact on spring flow conditions than a reduction in precipitation. Although the model shows that increasing rainfall intensity induces larger floods, recessions and shorter low flow periods, the real impact of high-intensity precipitation events remains uncertain, since the model does not account for complex unsaturated and epikarstic processes. This work shows that

calibrating a semi-distributed lumped model using time series analyses can be an efficient approach to improve simulations of complex karst aquifers, thus providing useful models for long-term sustainable water management.

1 Introduction

35 Around the world, karstic aquifers are strategic water resources that have been used to provide water to populations since early civilizations (Chen et al., 2017a; Ford and Williams, 2007). This is particularly true in Mediterranean areas (Bakalowicz, 2015), where water resources are scarce. The exploitation of karst aquifers remains a challenge because of their highly heterogeneous nature (Bakalowicz, 2005; Ford and Williams, 2007; Stevanović, 2015) and their high vulnerability to contamination from anthropogenic activities, especially under global change conditions (Chen et al., 2018; Doummar and
40 Aoun, 2018a, b; Hartmann et al., 2014; Iván and Mádl-Szőnyi, 2017; Leduc et al., 2017). A decrease in precipitation rates and an increase in temperature have already been experienced in the Mediterranean Basin for the last four decades (Milano et al., 2013), and are expected to worsen according to the climate change scenarios established for the 21st century (Collins et al., 2013; Giorgi and Lionello, 2008; Kirtman et al., 2013).

Hydrogeological modelling of karst systems is a useful approach for sustainable aquifer management, as it allows spring
45 discharge to be simulated (Fleury et al., 2009; Li et al., 2016) and provides a means to account for the impacts of climate change on future flow rates (Chen et al., 2018; Hartmann et al., 2012, 2014). Among the different types of available models, lumped models simplify karst systems (epikarst, conduit network, porous or fissured matrix, superposed karstic series) into a schematic representation of interconnected reservoirs to reproduce spring discharge (Ghasemizadeh et al., 2012; Hartmann et al., 2013; Mazzilli et al., 2017; Sauter et al., 2006). Since these models do not usually require spatial variations in karst
50 hydrodynamic properties and subsurface processes (Chen and Goldscheider, 2014), they are best suited for poorly-characterized karst hydrosystems. These models usually require meteorological data and sometimes river flow data as input (Bailly-Comte et al., 2008, 2010, 2012, Larocque et al., 1998). Usually, their calibration is based on the manual or automatic adjustment of empirical parameters that represent connections between the reservoirs, to reproduce measured spring discharges to the extent possible using rainfall time series as input (Chen and Goldscheider, 2014; Doummar et al., 2012). However, these
55 models are often calibrated to reproduce only the observed outputs of the systems, without accounting for subsurface discretization and distributed physical flow processes (Kong-A-Siou et al., 2013).

In the last 40 years, time series analyses of karst aquifers have been widely used to enhance the understanding of karst aquifer dynamics (Bailly-Comte et al., 2008; Fiorillo, 2014; Jeannin and Sauter, 1998; Larocque et al., 1998; Mangin, 1984), providing information on karst aquifer storage, groundwater travel times, and hydrogeological properties. By including these inferred
60 processes, models of karst aquifers have been successfully calibrated to reproduce karst aquifer groundwater levels, spring flow rates, and chemographs (Adinehvand et al., 2017; Chen and Goldscheider, 2014; Hartmann et al., 2013; Hosseini et al., 2017; Larocque et al., 2000; Schmidt et al., 2014), thereby enhancing their representativeness and usefulness. However, the utility of lumped models calibrated to reproduce only spring flow rates can be limited to estimate water vulnerability to

65 contamination, especially in karstified areas, because input data are not spatially distributed and the flow processes are highly simplified.

~~The objectives of this work were 1) to acquire new knowledge of the hydrodynamic functioning of a complex karst aquifer derived from statistical and correlation time series analyses, 2) to illustrate how a semi-distributed lumped model can be calibrated on the basis of this knowledge, and 3) to assess the impact of climate change on the spring hydrodynamic to provide insight on fresh water availability. The approach is demonstrated on the Qachqouch karst spring in the region north of Beirut (Lebanon), a Mediterranean region governed by semi-arid conditions. The objectives of this work were 1) to illustrate how a semi-distributed lumped model can be calibrated using a robust knowledge of the hydrodynamic functioning of a karst aquifer derived from statistical and correlation time series analyses and 2) to estimate its sensitivity to climate conditions.~~ The approach is demonstrated on the Qachqouch karst spring in the region north of Beirut (Lebanon), which is governed by semi-arid conditions. In 2014, a high-resolution monitoring network was established in the Qachqouch spring catchment area, which 75 previously had only been poorly studied (Doummar and Aoun, 2018a, b; Dubois, 2017). A semi-distributed lumped model developed using MIKE SHE (DHI, 2016a, b) is calibrated here using observed spring discharge time series. Fitting parameters were inferred and refined based on hydrodynamic properties derived from autocorrelation and cross-correlation analyses. The calibrated model was used to assess the sensitivity of flow rates in this karst system to potential variations related to climate change.

80 2 Field Site

The Qachqouch spring, located in the Metn area in Lebanon, 18 km north of Beirut, drains a catchment of approximately 56 ~~km²~~ km², with a northern boundary (shared with the Jeita spring catchment) delineated by the Nahr el-Kalb River (Fig. 1). The topography of the upstream catchment area is relatively mountainous, with elevation ranging between 60 to more than 1,500 meters above sea level (m asl). The catchment of the Nahr el-Kalb River was determined topographically (Margane and 85 Stoeckl, 2013), while the hydrogeology of the Qachqouch spring was further investigated by Dubois (2017). A minor hydrogeological connection was established between the Nahr el-Kalb River and the Qachqouch spring from repeated tracer experiments and micropollutant analyses (Doummar and Aoun, 2018a, b).

Similar to the nearby Jeita spring (Margane et al., 2013, 2018), the Qachqouch spring originates from the Jurassic karst aquifer at about 64 m asl (Fig. 1). The Jurassic formation is mainly comprised of a 1,070 m-thick massive limestone sequence with 90 intertonguing dolostones in the lower parts of the formation resulting from diagenetic dolomitization (Hahne, 2011; Margane et al., 2013; Nader et al., 2007). The catchment area is under the influence of the Yammouneh fault regime (El Hakim, 2005, Hahne, 2011), leading to a high degree of tectonic deformation and fracturing. Sea level variations, especially the Messinian salinity crisis, and ~~quaternary-Quaternary~~ glaciations also contributed to creating a high degree of karstification (very intense and very deep)~~high level of karstification~~ in the Mediterranean area in several stages (Bakalowicz, 2015; Nehme et al., 2016) 95 and the Jurassic limestone (Margane et al., 2013) with karst features, such as lapies, sinkholes, drains, and caves.

The spring is highly polluted due to excessive non-sorted solid waste and untreated wastewater disposal upstream in its urbanized catchment (Doummar and Aoun, 2018a, b). However, during low flow and drought periods, the spring is used to supplement domestic water use in Beirut and its surrounding areas. The spring outlet consists of a 150 m-long concrete tunnel, thereby offering a suitable cross section for flow measurement, except during extensive floods where access to the spring is inundated.

The average yearly precipitation is estimated to be 1,000 mm from one station deployed over the Qachqouch catchment at 950 m asl (local high-resolution monitoring ongoing since 2014), while the average yearly temperature is 16.2°C. Precipitation occurs mostly between November to April, and snow is observed in January and February (above 1,000 m asl), with only limited snow accumulation over long periods in the Qachqouch catchment (Dubois, 2017). Rainfall events are usually intensive, with considerable amounts occurring over relatively short periods (e.g., 461 mm in January, 2019, 97 mm on December 24, 2017, and 43 mm in one hour on October 30, 2017). The average daily air temperature varies between 5°C during winter and 23°C during summer with occasional sub-zero temperatures.

3 Materials and methods

3.1 General approach

The conceptualization of the Qachqouch system (Fig. 2) was developed based on the collection of high-resolution data for over three years, and on the subsurface characterization of the system (box 1, Fig. 2). Flow rate classification was performed to qualitatively characterize the system's functioning (box 2, Fig. 2), and time series decomposition, simple and cross-correlation analyses were performed to estimate the system memory and response time (box 3, Fig. 2). Using this information, a semi-distributed linear reservoir model of the Qachqouch system was conceptualized and parameterized (box 4, Fig. 2). Climate change scenarios were elaborated (box 5, Fig. 2) based on Intergovernmental Panel on Climate Change (IPCC) projections for 2040 to test possible future system responses under different scenarios based on the calibrated and validated model (box 6, Fig. 2). Data and methods theories used for each of these steps are presented in the following sections.

3.2 Meteorological and hydrological data

In the framework of a monitoring project funded by USAID since 2014 (PEER, Cycle 3), two full climatic stations with hourly precipitation, temperature, humidity, wind direction and speed, and solar radiation (one *Campbell-Scientific-Alpine* station with a heated gauge and one *Hobo* station mounted with a data logger) were installed at elevations of 1,700 and 950 m asl respectively (~~hourly precipitation, temperature, humidity, wind direction and speed, and solar radiation~~) in the region of the Qachqouch and Jeita springs. Additionally, a multi-parameter probe (*In situ-Troll 9500*) was installed at the spring discharge to record water level and water temperature every 30 minutes. The discharge flow rates were calculated using a rating curve based on bimonthly measured discharge rates by direct gauging with errors of 8-10% during recession periods. Flow rates exceeding 10 m³/s are considered to be less precise, especially when the section is overflowed. The few gaps in the time series

(less than one month combined) were linearly interpolated and smoothed using a moving average over the entire time series to remove outliers and aberrant values.

130 For the purposes of this study, temperature (-0.45°C/100 m elevation) and precipitation (6%/100 m elevation) gradients were calculated through regression analysis of the incremental and cumulative variations in temperature and precipitation with
140 altitude between the two climatic stations (Doummar et al., 2018).

3.3 Time series analyses

3.3.1 Analyses of the spring flow rate data

135 ~~Spring flow rates were evaluated by a frequency analysis (Dörfliger et al., 2010; Mangin, 1971; Marsaud, 1997). Flow rates and their frequency of measurements were linked with a log normal distribution, except for outliers arising from variation in flow dynamics.~~

~~Following hydrograph decomposition, the method developed by Mangin (1971, 1975) was used to estimate the dynamic volume (V_{dyn}) available in the aquifer during the depletion flow of a karst spring. A frequency analysis was used to characterize spring flow rates (Dörfliger et al., 2010; Mangin, 1971; Marsaud, 1997). A log normal distribution was used to link a given flow rate to its frequency of measurement, except for outliers arising from variation in flow dynamics.~~

140 ~~Following hydrograph decomposition, the method developed by Mangin (1971, 1975) to estimate the dynamic volume (V_{dyn}) available in the aquifer during the depletion flow of a karst spring was used.~~ As shown in Eq. (1) to (3), this method separates the recession of the hydrograph (Ψ) from depletion (φ). It is the equivalent of considering two reservoirs, the first associated with the vadose zone, which drains into the second reservoir, corresponding to the phreatic zone. The total spring flow rate
145 (Q) is divided into:

$$Q(t) = \Psi(t) + \varphi(t) \quad (1)$$

The two parts are detailed in:

$$\Psi(t) = q_0 \cdot \frac{1-\eta \cdot t}{1-\varepsilon \cdot t} \quad (2)$$

$$\varphi(t) = Q_{R0} \cdot e^{-\alpha t} \quad (3) \text{ (known as Maillet equation)}$$

150 Finally, the dynamic volume is obtained by:

$$V_{dyn} = c \cdot \frac{Q_i}{\alpha} \quad (4)$$

with q_0 being the infiltrating flow at the beginning of the flood event [$L^3 \cdot T^{-1}$]; η the infiltration velocity coefficient [T^{-1}]; ε the heterogeneity flow coefficient [T^{-1}]; t the time from the beginning of the flood event [T]; Q_{R0} the fictional flow rate of the depleting curve at the maximum of the flood event [$L^3 \cdot T^{-1}$]; α the depleting coefficient [T^{-1}]; Q_i the flow rate [$L^3 \cdot T^{-1}$] at time t_i
155 when depletion began ($\eta = 1/t_i$); and c the time constant (86,400 s/d for Q_i in m^3/s and α in d^{-1})

The calculation of the parameters listed above allows the two parameters, k and i , used in the karst spring classification proposed by Mangin (1975) to be characterized for comparison with other Middle Eastern and Lebanese springs analysed by El-Hakim and Bakalowicz (2007) and Bakalowicz et al. (2008) (box 2, Fig. 2). The parameter k (Eq. (5)) characterizes the extent of the phreatic zone and its regulating capacity; its processes of storage and discharge of infiltrated rainfall. Karstic springs are supposed to have $k < 0.5$ (Mangin, 1975; Marsaud, 1997), as opposed to $k > 0.5$ characteristic of porous aquifers.

$$k = \frac{V_{dyn}}{V_{trans}} \quad (5)$$

with V_{dyn} being the dynamic volume [$L^3.T^{-1}$] and V_{trans} the average annual transit volume [$L^3.T^{-1}$].

A system with mainly fast infiltration would be characterized by an i close to 0, while a system with mainly slow and delayed infiltration would have an i value of close to 1. The parameter i is estimated using the following ratio at $t = 2$ days (Eq. (6)):

$$i = \frac{1-\eta.(t)}{1+\varepsilon.(t)} \quad (6)$$

3.3.2 Decomposition of the spring hydrograph

Jeannin and Sauter (1998) suggested, based on Forkasiewicz and Paloc (1967), to consider three reservoirs in conceptualizing flow from a fractured rock aquifer: a reservoir with low permeability (reservoir 1), a conduit network (reservoir 2), and an intermediate system (reservoir 3). Each of these can be represented using the exponential drainage of a reservoir based on Darcy's law, with specific recession coefficients (Eq. (7)).

$$Q(t) = Q_1 \cdot e^{-\alpha_1 \cdot t} + Q_2 \cdot e^{-\alpha_2 \cdot t} + Q_3 \cdot e^{-\alpha_3 \cdot t} \quad (7)$$

with Q_1 , Q_2 , and Q_3 being the initial discharge rates of each reservoir [$L^3.T^{-1}$], and α_1 , α_2 , and α_3 the reservoir recession coefficients [T^{-1}], linked to their respective hydraulic conductivities and geometries (Kovács et al., 2005; Fiorillo, 2011).

[This time series decomposition was applied to the spring flow rates \(box 3, Fig. 2\) to verify if spring flows could be relevantly linked to three conceptual reservoirs.](#)

3.3.3 Correlation analyses

The autocorrelation function of a time series $r(p)$ is obtained by measuring the linear dependency of a given signal with itself (Eq. (8)), shifted by the time lag (p), and is deduced from the correlogram $C(p)$ (Eq. (9)).

$$r(p) = \frac{C(p)}{C(0)} \quad (8)$$

$$C(p) = \frac{1}{n} \sum_{t=1}^{n-p} (x_t - \bar{x})(x_{t+p} - \bar{x}) \quad (9)$$

with $C(0)$ the correlogram for $p = 0$, p the time lag ($p = 0$ to m); n the length of the time series; x a single event; \bar{x} the mean of all events; m the cut-off point, which determines the interval over which the analysis is carried out, usually chosen to circumscribe a given hydrograph feature, such as annual or long-term effects.

185 Mangin (1984) suggested that the analysis is only valid until $m = n/3$. Based on the autocorrelation function, the memory effect represents the inertia of the system and the possibility of storage. It is identified as the time when $r(p)$ reaches a small value, and is used to compare karstic hydrosystems relative to one another. Here, this value is set to 0.2, as suggested by Mangin (1984).

The correlation between an input signal, $x(t)$, and an output signal, $y(t)$, is given by a cross-correlation function, $r_{xy}(p)$ (Eq. (10)), obtained from the cross-correlogram $C_{xy}(p)$ (Eq. (11)).

$$190 \quad r_{xy}(p) = \frac{C_{xy}(p)}{\sigma_x \sigma_y} \quad (10)$$

$$C_{xy}(p) = \frac{1}{n} \cdot \sum_{t=1}^{n-p} (x_t - \bar{x})(y_{t+p} - \bar{y}) \quad (11)$$

with σ_x and σ_y being the standard deviations of the time series. The delay of a system is the lag between $p = 0$ and the peak of cross-correlation between input and output.

195 Auto-correlation and cross-correlation analyses were performed on precipitation and on the Qachqouch flow rates time series to estimate the memory effect of the system and the delay between precipitation and the hydrological response of the karst system (box 3, Fig. 2). Auto-correlation and cross-correlation of simulated flow rates were compared to those of the input data, as an additional validation method (box 4, Fig. 2).

3.3.4 Numerical modelling of a semi-distributed linear reservoir

200 The Qachqouch system was modelled using the MIKE SHE software (DHI 2016a; 2016b). The modelled catchment is subdivided spatially into several sub-catchments, in addition to the saturated zone, which is represented as several linked reservoirs (Fig. 3). The model is decomposed into three domains (Doummar et al., 2012). The first domain consists of the atmosphere, composed of rainfall and snow time series spatialized over the spring catchment and its topography (Fig. 3). The second domain entails a spatialized simplified unsaturated zone (UZ), consisting of land use, vegetation, and crop coefficients, such as leaf area index (LAI) and root density (RD) to calculate potential evapotranspiration (PET) based on Penman-Monteith (FAO, 1998), water interception by vegetation (Kristensen and Jensen, 1975), and runoff. The second domain also includes the unsaturated zone, represented using a simple two-layer model to calculate actual evapotranspiration (AET) and subsequent infiltration through the unsaturated zone. The volume of water infiltrating into the third domain, which is the saturated zone (SZ), is then simulated at each time step. The SZ is simulated via linear reservoirs comprised of five interflowing reservoirs, corresponding to the five major sub-catchments of the spring (I1 to I5; Fig. 3), which empty into each other (in topographical order), and includes two base flow reservoirs (B1 and B2; Fig. 3). In this configuration, discharge from the entire system

210

feeding the Qachqouch spring consists of the cumulative discharge of spatially discretized connected reservoirs feeding into a fast flow and a slow flow reservoir with different recession coefficients. The complete model is therefore considered a classical lumped model for the saturated zone, but also a physically based model for the system inputs (atmosphere) and the soil compartment.

The model uses 20 parameters defining the atmosphere, the UZ, and the saturated interflow and base flow reservoirs. The simulated flow rates were compared to measured values using the Nash-Sutcliffe coefficient (NS) and the root mean square error (RMSE) to achieve the best calibration possible with a calibration period (2015/01 – 2018/04) and a validation period (2018/05 – 2019/07). Sensitivity analysis was conducted automatically on single parameters using the Autocal function (DHI, 2016) to identify the parameters to which the model is highly sensitive.

[Calibrating a model of the spring was a necessary step to perform analysis of the impact of changing climate condition on the spring hydrodynamic \(box 4, Fig. 2\)](#)

3.3.5 Sensitivity to future climatic variations

According to the IPCC (IPCC, 2014), at the 2080-2100 horizon, temperature in the eastern Mediterranean Basin will have increased from +2 to +3°C (Representative Concentration Pathway (RCP) 2.6 – optimistic scenario) to +5 to +7 °C (RCP 8.5 – pessimistic scenario) during the December-May rain season relative to the 20th century trend (Collins et al., 2013; Kirtman et al., 2013). Here, the assessment of potential climate change impacts on spring flow rates is undertaken by applying several simple climate change conditions onto climate data from the observation period (average daily temperature and precipitation estimated from the mean observed values) for an average year for the catchment to simulate the expected spring discharge under future conditions (box 5, Fig. 2). According to the global climate model (GCM) IPSL-CM5 and the mid-range RCP 6.0 scenario (Dufresne et al., 2013) adapted for the Lebanese context (Doummar et al., 2018), the expected warming is +0.1 to +0.3°C per year (*i.e.*, a total increase of +1 to +3°C above the current average annual temperature for the 10th year of the 2020-2030 period). A reduction in annual precipitation in the range of -10 to -30 % (Fig. 9) is expected with an increase in evapotranspiration proportional to the rise of temperature.

4 Results

4.1 ~~Classification of spring flows: qualitative~~ Qualitative functioning of the system

4.1.1 Measured flow rates

The interannual (2015 to 2019) average Qachqouch spring flow rate is 2.1 m³/s (1.7 m³/s during calibration period and 3.4 m³/s during validation), and its total annual discharge varies between 44 and >more than 50 Mm³. The average flow rate is 2 m³/s during high flow periods (during a normal year) and recedes to 0.2 m³/s during recession periods, with a maximum recorded >higher than 20 m³/s for a short period of time following a flood event (there is a high degree of uncertainty as to

the exact value of the maximum flow rate since it is higher than $10 \text{ m}^3/\text{s}$). Flow rates for the 2018-2019 hydrological year were particularly high, corresponding an exceptional rainy year (1,800 mm between September 2018 and July 2019 in comparison to the average of 1,000 mm/year). Therefore, this period is only used as a modeling validation period and flow measurement
245 are not included in the time series analysis.

The flow rate frequencies (Fig. 4) can be divided into four different categories based on the slopes of the frequency curve. The interpretation suggested by Dörfliger et al. (2010), based on the shapes of the curves and the positions of the three breaking slope points, can be used to understand the aquifer hydrodynamics. The break in slope between a_3 and a_4 shows that the section at the gauging station is probably overflowed for flow rates above $10 \text{ m}^3/\text{s}$. The flow rates corresponding to slopes a_2 (between
250 0.25 and $3 \text{ m}^3/\text{s}$) and a_3 (between 3 and $10 \text{ m}^3/\text{s}$) are interpreted as the presence of two distinct temporary storages within the aquifer. Flow rates of less than $0.25 \text{ m}^3/\text{s}$ (break in slope between a_1 and a_2) correspond to water that is slowly released from the aquifer. This generally confirms that the flow rates are related to a single aquifer with two interacting base flow reservoirs corresponding to a capacitive and conductive function, or slow and fast flows, with no inter-aquifer exchanges, therefore facilitating further interpretation of the time series analyses.

255 **4.1.2 Recession coefficients**

The coefficients k and i , representing the regulation capacity of the system (storage/discharge of rainfall) and the infiltration conditions (fast versus delayed) respectively, were calculated for the Qachqouch spring based on the 2015, 2016, and 2017 recessions (Fig. 5). Although the Qachqouch system has a high regulation capacity ($k = 4$ years), similar to a porous aquifer, it has an average infiltration delay, i , of 0.5, characterizing a system with significant storage recharged by both fast and slow
260 infiltration, which classifies Qachqouch system among the other Lebanese and Middle Eastern karstic systems (El-Hakim and Bakalowicz, 2007).

4.1.3 Decomposition of the spring discharge time series

Assuming that the spring discharge can be represented using several draining reservoirs (with the drainage function following Darcy's law), 77 depletion coefficients (Mangin, 1975) were calculated over the entire time series (Fig. 6). These coefficients
265 can be classified into three categories. In the first, the summer dry period has low flow rates, around $0.25 \text{ m}^3/\text{s}$, and slow depletion, characterized by α values of 0.004 d^{-1} on average (α_1). In the second category, flow rates are less than $7 \text{ m}^3/\text{s}$, while having faster depletion and α values of 0.050 d^{-1} on average (α_2). The highest flow rates are found in the third category, and occur at the beginning of the depletion, with very fast depletion related to α values of 0.220 d^{-1} on average (α_3).

4.1.4 Correlation analysis

270 The autocorrelation function of rainfall (performed with a maximum lag of 1/3 of the available time series) shows a rapid decrease to zero, while that of the spring flow rates shows a slow decrease, with a memory effect of approximately 50 days (Fig. 7a). This means that the system has a substantial regulation capacity, similar to that reported for other Lebanese springs

(Bakalowicz et al., 2008; El-Hajj, 2008). The peak of the cross-correlation function of rainfall (input) against spring flow rates (output; also performed with a maximum lag of 1/3 of the available time series) is 0.52 (Fig. 7b). It is delayed by approximately one day, characterizing a fast infiltration component with a strong correlation to the rainfall events. The inertia of the rest of the system tends to smoothen the input signal, as portrayed by the slow decrease in the cross-correlation function from $r_{xy}(p) = 0.25$. An annual cycle (not fully displayed here) is visible with an increase in $r_{xy}(p)$ starting again at 270 days.

4.2 Simulated past flow rates

The discharge of the Qachqouch spring for the 2015 to 2019 hydrogeological years was successfully simulated using the integrated semi-distributed linear reservoir model (Fig. 8). The model was simulated since 2012 to allow for a spin up period before the calibration and validation time span (2015-2019). The calibrated model parameters are presented in Table 1. A satisfactory fit is observed between the simulated and the measured flow rates, with an NS of 0.70 (0.60 during calibration; 0.74 during validation) and a RMSE of 1.57 m³/s (1.27 m³/s during calibration; 2.17 m³/s during validation). The average simulated flow rate is 2.0 m³/s (1.7 m³/s during calibration; 3.0 m³/s during validation), very close to the average measured flow rate of 2.1 m³/s (1.7 m³/s during calibration; 3.4 m³/s during validation), although the calibration period did not include the exceptional year. Even though the annual recession periods are well simulated by the model, the simulated summer flow rates reach values of lower than 0.1 m³/s (for approximately 70 days); values that were not reached in the measured flow rates. The exceptional 2018-2019 year with high precipitation rates and an important spring flow response induces a relatively higher mean residual error. The parameters to which the model was found to be most sensitive (Table 1) are the base flow reservoirs specific yields and time constant, the fraction of percolation to the base flow reservoir (reservoir B2 from Fig. 3), and the time constant for percolation between the interflow reservoirs. The previous analyses performed on the time series allowed the model geometry (number of reservoirs and their parameters) and the ranges of these parameters to be refined during calibration, thereby reducing model uncertainty by optimizing the conceptual model on the system hydrodynamic functioning (Enemark et al., 2019).

Larocque et al. (2000) have shown that verifying the consistency of simulated flow rates in a karst aquifer is possible by performing autocorrelation and cross-correlation analyses on the simulated values and comparing the results with the time response functions of the observed data. The autocorrelation function of the measured and simulated flow rates are similar here, with a simulated memory effect that is slightly longer (62 days) than that of the real system (50 days). The cross-correlogram of the simulated spring discharge generally fits those of the measured discharges, with similar delays (approximately one day) between input (rainfall) and output (spring discharge), and a similar shape of the cross-correlation function (Fig. 7b). The model therefore generally reproduces both the fast and slow response of the system to infiltration well.

4.3 Simulated future responses to climate changes

The climate change conditions derived from seven potential scenarios for the study area (Table 2) have been applied over ten consecutive years to compare the system responses in the tenth year to a baseline scenario, obtained by averaging the monitored

305 climatic data (precipitation and temperature) on a daily basis to produce an average year (Fig. 9). The seven climatic scenarios were calculated from the baseline by applying the respective climatic conditions to it.

Scenarios 1 and 2, with less precipitation, lead to notably lower annual discharge flows than the baseline scenario (11 to 34 % lower; Fig. 9 and Table 2). The reductions in spring discharge for the warming scenarios (scenarios 3 and 4) are not pronounced (not represented on Fig. 9). However, combining warmer temperatures with a reduction in precipitation (scenarios 5 and 7)
310 ~~leads to stronger reductions~~~~slightly increases the reduction~~ in spring flow rates (12 to 36 % lower than for the baseline; Fig. 9 and Table 2). The scenario with intensified precipitation events (scenario 7) produces higher peak flows than the baseline scenario.

Although the duration of summer low flows (*i.e.*, the number of days where discharge is ~~lower than~~ 0.2 m³/s) increases accordingly with reductions in precipitation and rising temperatures, only scenarios 2 and 6, corresponding to a 30 % reduction
315 in precipitation, led to a notable increase in summer low flow duration, by more than a week per year (Table 2). Scenario 7, with intensified precipitation events, led to a shorter duration of summer low flows than for the baseline scenario, as well as to a slightly higher mean annual flow rate.

5 Discussion

5.1 Dynamic functioning of the spring: a comparative approach

320 Many authors have linked spring discharge from a karstic aquifer to the functioning and geometry of the system (e.g., Fiorillo, 2014) using various methods of spring recession analysis. In this study, the flow rate return probability provided qualitative information regarding the system functioning. This method shows that this karst system stores large volumes of water during high flow periods and releases water during the low flow period. This has been further investigated and confirmed through the decomposition of the spring hydrograph and the recession analyses that allowed fast and delayed infiltration components to be
325 identified. The latter was also observed in the autocorrelation and cross-correlation functions, with a slow decrease in the correlations over time and a short delay between the input and output signals (*i.e.*, cross-correlation peak).

These results provide a conceptual representation of the transfer function (Bailly-Comte et al., 2008; Marsaud, 1997). The classification of the spring hydrograph recessions into three categories (Fig. 4b) is interpreted as corresponding to three major reservoirs representing different hydraulic conductivity zones (Fiorillo, 2011; Kovács et al., 2005) or two different hydraulic
330 stages of the system (Fiorillo, 2014), including a transient stage as previously modelled by Kovács and Perrochet (2008) for synthetic karst spring hydrographs. It can be interpreted that after a rainfall event, a first reservoir or zone with high hydraulic conductivity evacuates water rapidly and produces high flow rates at the Qachqouch spring via a well-developed karstic drainage network (peak of the cross-correlation rainfall-spring discharge; Fig. 7b). Then, depending on the season, a second reservoir or zone with lower hydraulic conductivity contributes to an intermediate depletion rate. Independently from the flow
335 periods, the slowest transfer function continuously feeds the spring base flow, an influx of water that is associated with a third

reservoir or zone, with the lowest hydraulic conductivity. As a result, these depletion coefficients are useful to describe the spring discharge and can be used as calibration parameters to which the model output is highly sensitive.

~~Even though the Qachqouch karst system has been reported to be less complex than that of the neighboring Jeita spring (Doummar, 2012; Margane et al., 2018), it is still comparable to other Middle Eastern karst systems (Fig. 5). Parameters k and i , representing the extent of the phreatic zone, the regulating capacity of the system, and the type of infiltration (Bakalowicz et al., 2008; El-Hakim and Bakalowicz, 2007; Mangin, 1975), classify the Qachqouch spring close to other Lebanese karstic aquifers. Even though the Qachqouch karst system has been reported to be less complex than that of the neighboring Jeita spring (Doummar, 2012; Margane et al., 2018), based on the karst system classification (parameters k and i , representing the extent of the phreatic zone, its regulating capacity, and the type of infiltration — Bakalowicz et al., 2008; El-Hakim and Bakalowicz, 2007; Mangin, 1975), it is comparable to other Middle Eastern karst systems.~~ In this region, karst aquifers are characterized by their relatively thick unsaturated zone and saturated aquifer (the sum of the respective thicknesses being greater than 1,000 m), leading to a high regulating capacity with a complex drainage structure (El-Hakim, 2005; El-Hakim and Bakalowicz, 2007; El-Hajj, 2008; Hosseini et al., 2017; Petalas et al., 2018; Schmidt et al., 2014). The high regulation of the spring discharge transforms the input (mostly rainfall with occasional snowmelt) into annual to pluri-annual cycles and therefore constrains the cross-correlation function between the input and the output of the system to low values compared to other systems or similar values for systems in similar hydrogeological context (Table 3). This can be explained by the duality of the stable low flow during the dry season (resulting from the redistribution of rainfall events to sustain continuous flow) and the flood flow following precipitation events (high flow rates during the wet season).

5.2 Conceptual model of the Qachqouch system

Although the model adequately reproduces flow discharge, it underestimates the summer low flows. Measurements recorded during flooding of the spring gauging station might be underestimated due to errors in the discharge water level rating curve for high flow rates. Another explanation could be that the fast flow linked to a highly-developed drainage system is oversimplified in this reservoir model. The thickness of the UZ, combined with its lithological heterogeneity, may contribute to the relatively stable summer low flow by allowing considerable water storage. In fact, the dolostone could be compared to low-permeability porous media drained by a high-permeability system, thus allowing a large storage capacity in the upper parts of the aquifer. Furthermore, the high degree of karstification of the area, resulting from both the eustatic variations (Messinien) and the quaternary glaciations, leads to a complex drainage system, with a probable paleo-network under the current base level. This would enhance the storage capacity of the system, as well as induce rapid flow rate increases (Bakalowicz, 2015; Nehme et al., 2016).

Based on water chemistry and stable isotopes, a link between the intermittent Nahr el-Kalb River and the Qachqouch system has been demonstrated (Doummar and Aoun, 2018a, b), but is not taken into account in this study. If the simulated flow rates at the outlet are well represented, the link between the river and the aquifer is indirectly represented in the model, since the

river could be considered to be an indirect source to the karst system, which depends on the same input as the model (precipitation). The river-aquifer link is probably determining for transport through the system.

370 **5.3 Dynamic functioning and spring responses to potential future climatic variations**

According to the simulated climate change scenarios, the climate context (semi-arid) and similarly to previous studies (Chen et al., 2018; Hartman et al., 2012; 2015, 2017), a decrease in annual rainfall (-10% to -30%) could lead to lower discharge at the outlet, especially if combined with an increase in temperature (a 36% reduction in discharged volume), meaning that total precipitation drives spring discharge. The depletion time of the karst aquifer is expected to decrease, leading to summer water
375 shortages (flow rates of less than 0.2 m³/s during the dry season) occurring earlier in the season and lasting for longer periods of time (up to +25 days annually). Given the uncertainty on summer low flows (simulated past flow rates <lower than 0.1 m³/s for the summer period, lower than any observed data at the outlet), the prediction of whether or not the spring would be dry for a period of time could not be ascertained with this model.

Although increasing temperatures leads to higher AET rates (Table 2), variations in temperature do not seem to significantly
380 impact the modelled results, unlike Chen et al. (2018) for some of the studied springs. This can be explained by the fact that AET rates are already close to zero during the dry season (no rain between May to early November). It is also coherent with the fact that spring flow is not substantially affected by snow melt, as catchment delineation and stable isotope data have shown (Doummar and Aoun, 2018b), unlike other major neighboring springs (Doummar et al., 2018).

The delay in the recession period and the fewer water shortage days simulated under the intensified precipitation scenario
385 (scenario 7) are due to the distribution of more intense precipitation events on a daily time step that leaves the simulated soil reservoir frequently dry, even during the wet season, and therefore restricting the soil water consumption for AET. During the wet days, AET meets PET and the rest of the water goes mainly to recharge the system. Overall, as AET slightly decreases, recharge to the system slightly increases. It is important to emphasize that the model response to a high-intensity precipitation event would most likely change if simulations were run on an hourly time step. This is especially important when considering
390 exceptionally intense precipitation events, creating flooding at the spring, such as the recorded 42.5 mm in one hour on October 30, 2017, which was followed by an unusual flood at the spring for this time of the year. More work is required to include climate change scenarios with a focus on changes in rainfall distribution patterns, and especially to include higher rainfall intensities during the flood season and less annual rainfall. However, the potential effect of rainfall intensification could be balanced out or exacerbated by the long-term evolution in catchment land use (e.g., effects of vegetation cover drying earlier
395 in the season, reforestation programs, intensive landscaping, etc.). Climate change scenarios at the catchment scale should be coupled with land use evolution scenarios in the model to better understand the future functioning of the karst system.

6 Conclusion

400 This work aimed at acquiring new knowledge of the hydrodynamic functioning of a complex karst aquifer derived from statistical and time series correlation analyses to optimize the calibration of a semi-distributed lumped model. The model developed for the Qachqouch karst spring in Lebanon (semi-arid climate) was used to assess the impact of climate change on the spring hydrodynamic to provide insight on fresh water availability. Flow rates were analyzed statistically for a better conceptualization of the system, to allow the calibration of a semi-distributed linear reservoir model. The model was used to reproduce current conditions and to analyze the impact of dryer and warmer possible future climate conditions on flow rates.
405 ~~The objectives of this work were to optimize the calibration of a karstic spring model, based on the knowledge of the hydrodynamic functioning of the system, and to understand its sensitivity to climate conditions, with the example of the Qachqouch karst spring in Lebanon. Flow rates were analyzed to better conceptualize the system, and a semi-distributed linear reservoir model, calibrated based on this conceptualization, was used to reproduce current conditions and to analyze possible future climate conditions.~~

The results show that the system has significant storage capacity, enabling water flow to be sustained throughout the year.
410 Although the karst aquifer has this inter-annual regulatory capacity, similarly to that of other Middle Eastern karst systems, it also has a substantial fast flow component due to its favourable geological context for karstification. The combination of these conditions explains the high contrast between high flow rates observed during the wet season (\leftrightarrow higher than $10 \text{ m}^3/\text{s}$) and depletion reaching $0.20 \text{ m}^3/\text{s}$ during the dry months.

Data analyses allowed a conceptual model to be developed through the decomposition of the time series into three reservoirs,
415 which helped to calibrate the model. This comprehensive approach allowed the regular spring recession rates and durations and the input/output correlation to be satisfactorily reproduced, even for a year with exceptional precipitation rates, and even though the model has been calibrated on a short period (3 hydrological years). Based on this model, the simulation of future climate conditions has shown that the spring flow rates are mainly sensitive to rainfall, with a non-linear response, with 36% losses in spring flows after 10 years of a 30% reduction in rainfall and summer low flow periods that could be extended by
420 one month. The low sensitivity to increased temperatures is an indication that the Qachqouch spring may be more resilient to warmer conditions than it is to dryer conditions. The impact of intensified precipitation events remains uncertain. The climate change simulations brought an insight about possible future spring flow conditions, therefore allowing to develop more accurate scenarios for long-term fresh water management. The next steps of management plans should entail local coupling of climate change scenarios (at the catchment scale) with land use evolution scenarios to improve overall future predictions, as
425 ~~the latter were not considered here, or investigate solutions to alleviate the expected future depletion of semi-arid karst aquifer systems. The next step should entail local coupling of climate change scenarios (at the catchment scale) with land use evolution scenarios to improve overall future predictions, as the latter were not considered here.~~

This work shows that calibrating a model based on time series analyses and decomposition of the spring hydrograph is an efficient methodology to enhance the quality of simulations for complex highly-karstified and poorly-investigated systems.

430 This approach could be applied to other karstic systems to simulate current or future flows, and is a compromise between
characterization efforts and simulation results when climate change impacts have not yet been assessed.

7 Author contribution

All authors contributed to developing the approach and writing the paper. Simulations were performed by JD and figure
preparation by ED. Based on JD's funding acquisition, data was collected by JD's team, which included ED at the time. SP
435 [and ML](#) took on the publication fees.

8 Competing interests

No competing interests.

9 Acknowledgements

This work was funded by a USAID PEER Science project (award number 102881; Cycle 3) and the publication fees covered
440 by HydroScience Montpellier [and NSERC-Discovery Grant RGPIN-2015-06744 at UQAM](#). The authors would also like to
thank Fouad Andari and Michel Aoun for their help during fieldwork. Mr. Roland Abourahal is thanked for providing space
for the meteorological station and for facilitating local contacts. The kind support of Engineer George El Kadi, Mr. Antoine
Zoghbi, and the Mount Lebanon Water Establishment is highly appreciated.

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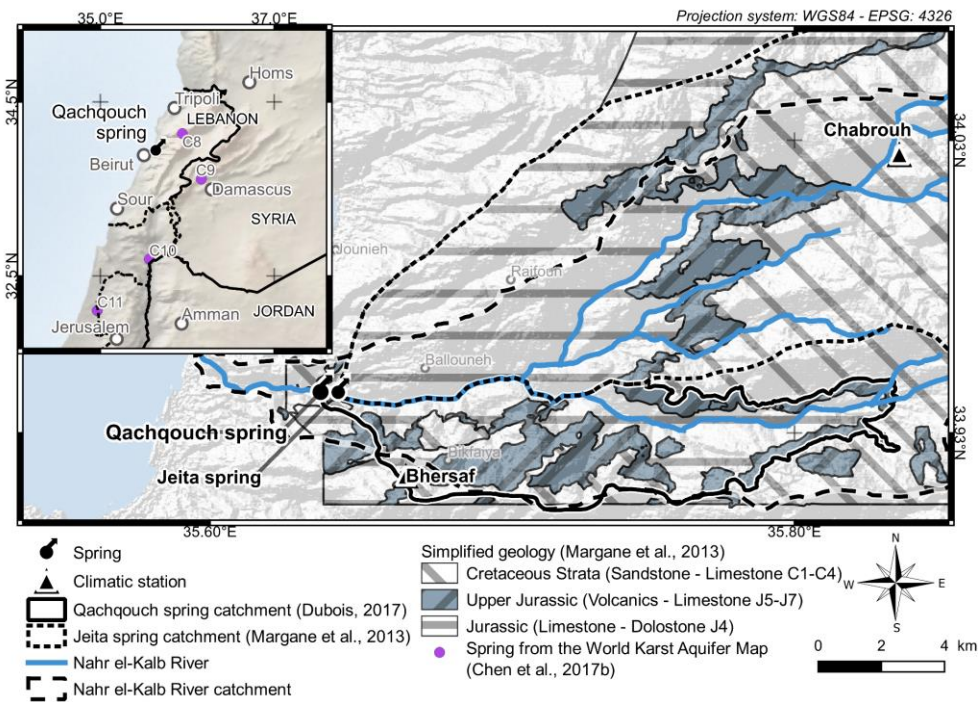
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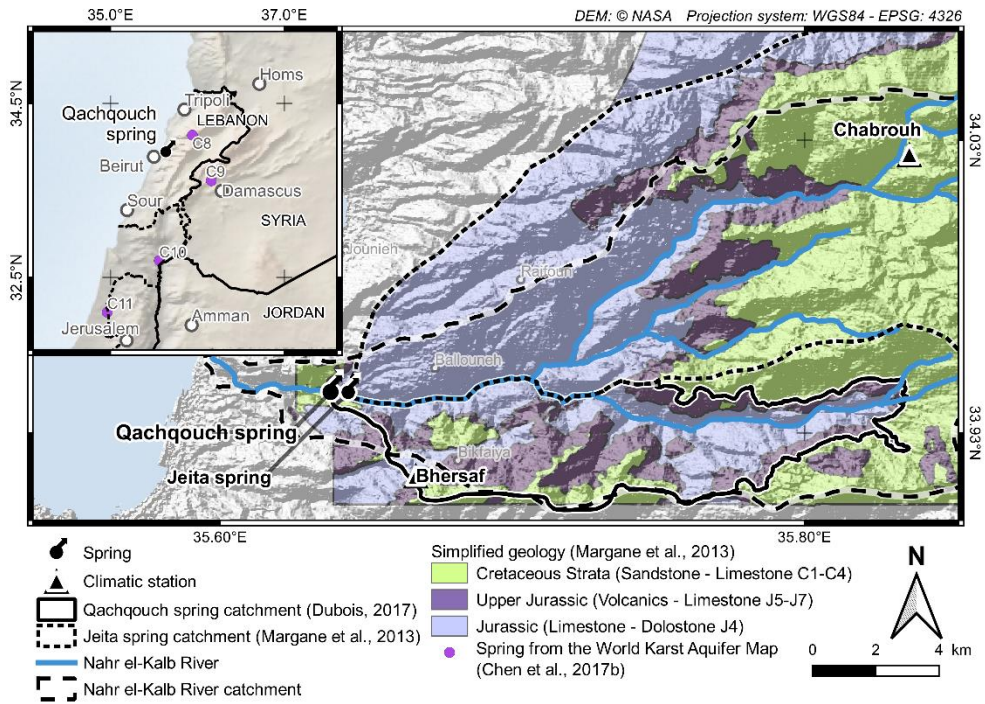


Figure 1: Location of the Qachqouch karst spring near Beirut (Lebanon).

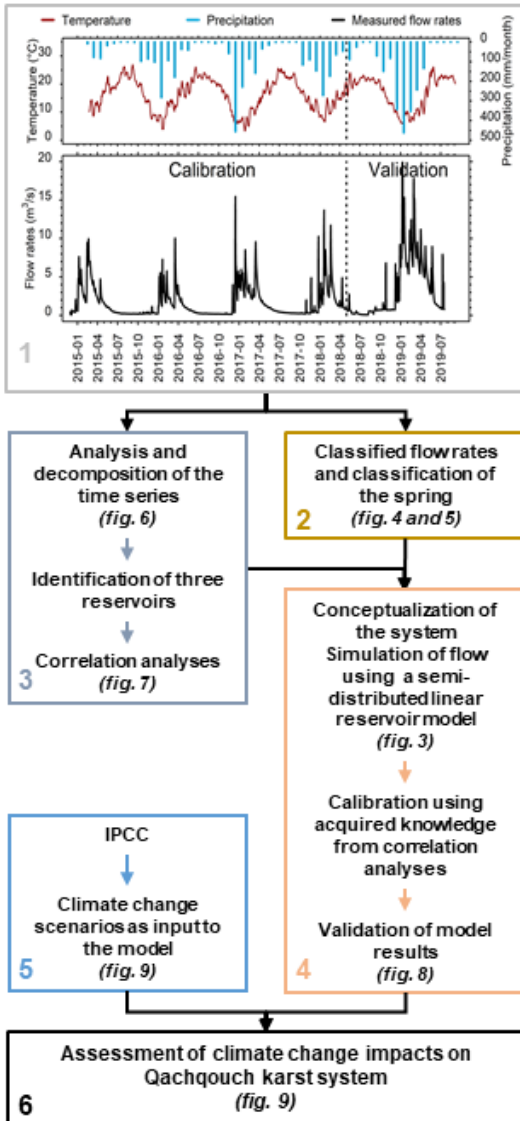
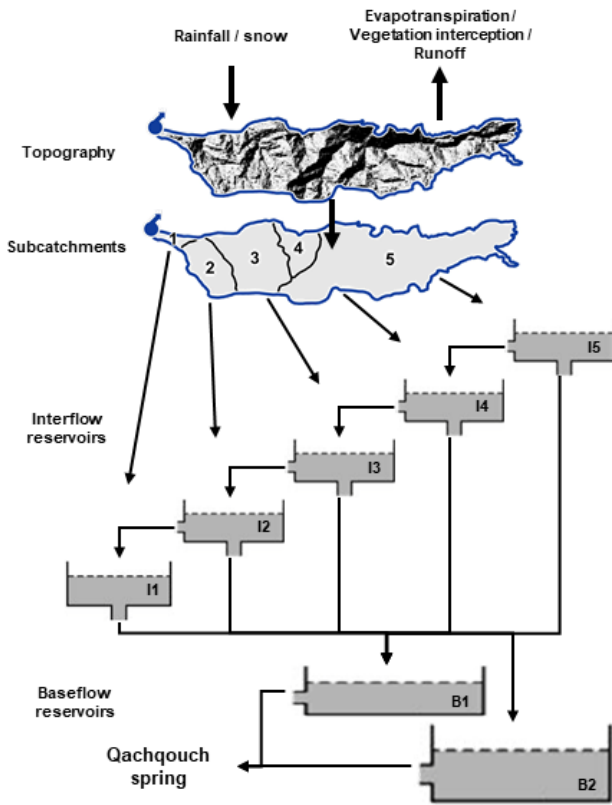


Figure 2: Schematic representation of the six-step methodology adopted for model conceptualization and the calibration.



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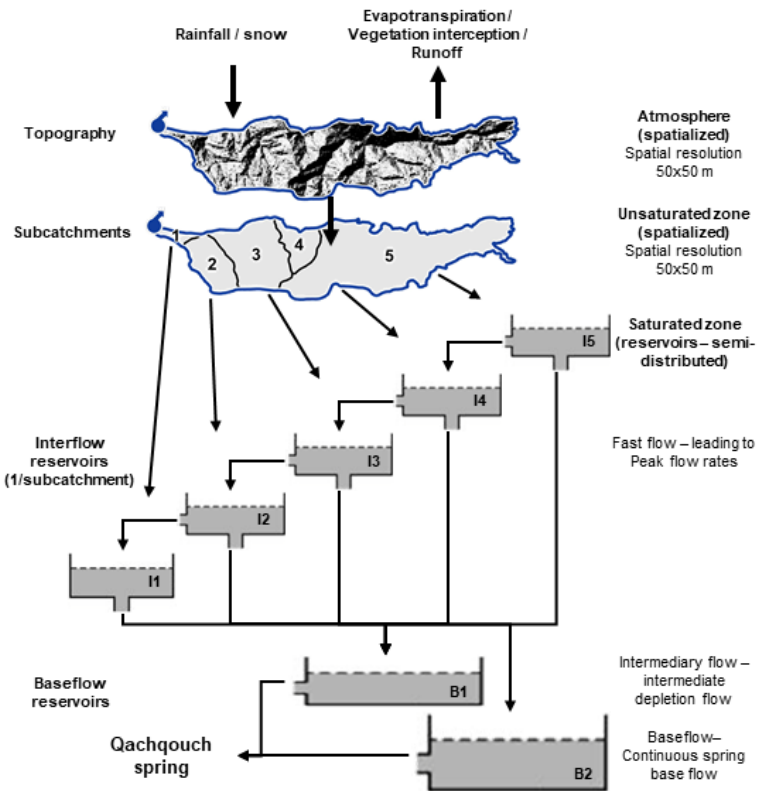


Figure 3: Conceptual map of the model, using the internal structure of MIKE SHE (DHI, 2016a, 2016b).

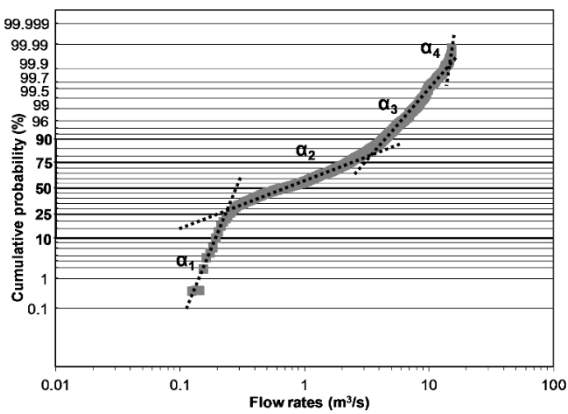


Figure 4: Cumulative probability of flow rates and their classification by slope (α_1 to α_4) for the 2015-2018 period.

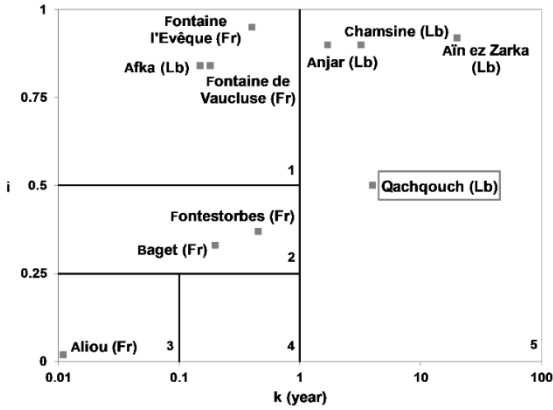


Figure 5: Qachqouch spring within the classification of karstic springs as a function of their k and i parameters (El-Hakim and Bakalowicz, 2007). Fr = France and Lb = Lebanon.

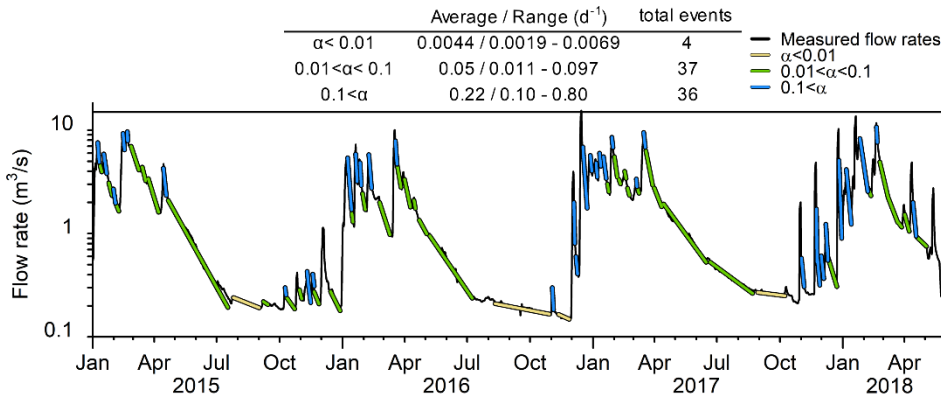


Figure 6: Calibration of the recession coefficients for 77 depletions over the 2015-2018 period.

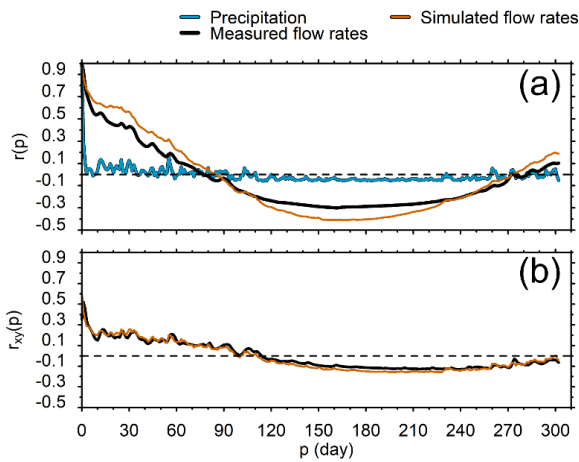
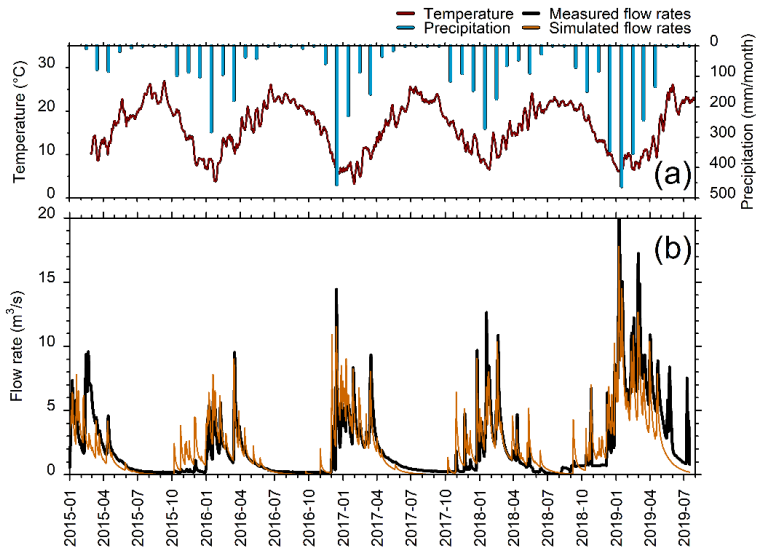


Figure 7: Autocorrelation functions of precipitation, measured flow rates, and simulated flow rates (a) and cross-correlation functions between precipitation (input) and measured or simulated flow rates (outputs) (b). Both were performed on 1/3 of the 2015-2018 period ($m = n/3$).



650 **Figure 8:** Measured meteorological data (a) and observed and simulated spring discharge (b).

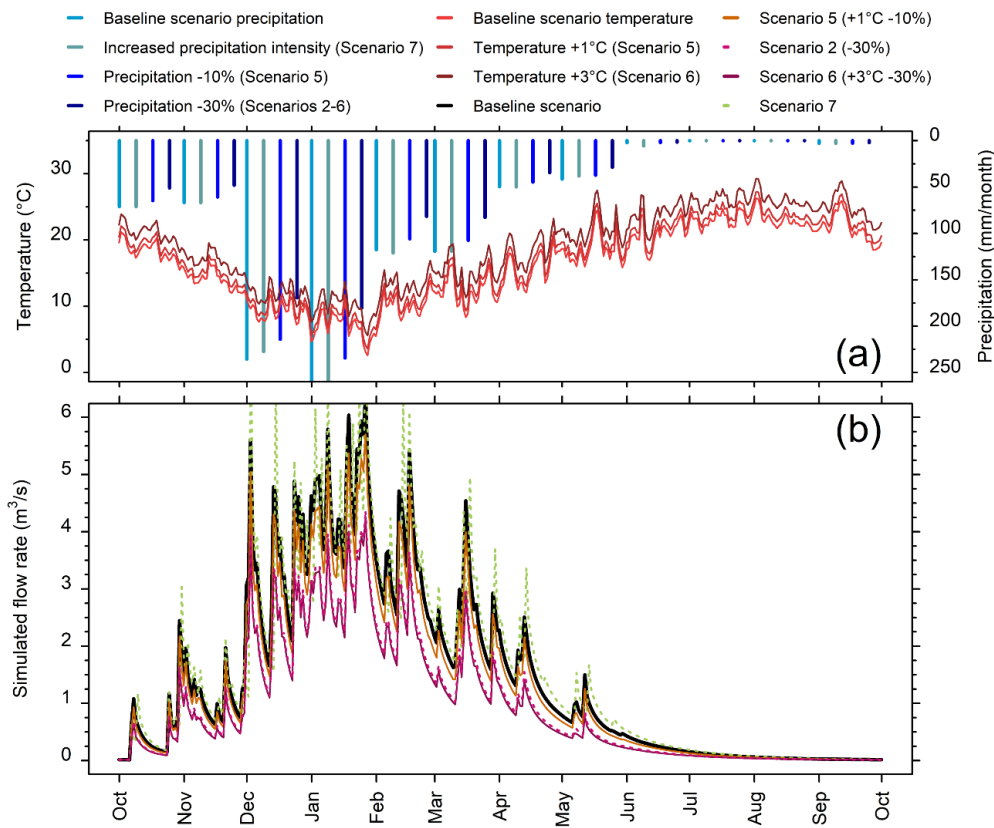


Figure 9: Precipitation and temperature scenarios (a) and simulated flow rates (scenarios 1, 2, 5, 6, 7, and the baseline scenario) for the spring for the 10th hydrological year of the period 2020-2030 (b).

Table 1: Parameterization of the hydrological model (MIKE SHE 2016), final calibration values, and sensitivity tests.

Component	Parameter	Value	Unit	Type of Data	Normalized sensitivity [-]	Ranking of parameters according to sensitivity analysis	
Atmosphere and Surface	Climatic data	Precipitation (P)		Measured	<0.01	9	
		Temperature (T)	-	mm	Measured	<0.01	9
		Potential Evapotranspiration (PET)			Calculated	<0.01	9
		Temperature lapse rate	-0.45	°C/100m	Measured	<0.01	10
		Precipitation lapse rate	6	%/100m	Measured	-0.02	9
	Snow melt	Melting temperature	1	°C	Measured	<0.01	10
		Melting rate	2	mm/°C/day	Calibrated	<0.01	10
	Vegetation	Leaf Area Index (LAI)	1	[-]	Calibrated	0.01	9
		Root Depth- (RD)	5	m	Calibrated	-0.08	7
	Unsaturated Zone (UZ)	Soil	Hydraulic Conductivity at saturation (K _s)	1.10 ⁻⁶	m/s	Calibrated	<0.01
Field capacity			0.2	[-]	Calibrated	<0.01	10
Total porosity			0.3	[-]	Calibrated	-0.19	5
Wilting point			0.05	[-]	Calibrated	<0.01	10
Specific yield			0.01-0.1	[-]	Calibrated	0.03	8
Saturated Zone (SZ)	Interflow reservoirs (1 to 5)	Time constant for percolation	2-5	day	Calibrated	-0.14-0.39	4
		Time constant (1/α)	5	day	Calibrated ^f	0.04-0.11	6
		Fraction of percolation to reservoir 1	0.3	[-]	Calibrated	0.23	4
	Base-flow reservoir 1	Specific yield	0.2	[-]	Calibrated	0.83	2
		Time constant (1/α)	20	day	Calibrated ^f	0.1	6
	Base-flow reservoir 2	Specific yield	0.15	[-]	Calibrated	1	1
		Time constant (1/α)	200	day	Calibrated ^f	0.64	3

^f - Previously calibrated with the analyses of the time series

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Table 2: Simulation results and comparison with the baseline scenario.

#	Name	Condition	Precipitation mm/year	Average annual discharge flow mm/year	Average annual discharge flow in comparison with the baseline scenario	Actual evapotranspiration mm/year	Duration of the summer low flow (days < 0.2 m ³ /s)
-	Baseline	Invariant precipitation, temperature, and ET rates (average climatic year)	966	837	1.49	-	167
1	Precipitation -10 %	Cumulative decrease of precipitation rate over 10 years of 10%	873	745	1.33	-11 %	163
2	Precipitation -30 %	Cumulative decrease of precipitation rate over 10 years of 30%	679	556	0.99	-34%	152
3	Temperature +1°C	Cumulative increase of temperature over 10 years of 1°C and associated evolution of ET rates	966	828	1.47	-1%	176
4	Temperature +3°C	Cumulative increase of temperature over 10 years of 3°C and associated evolution of ET rates	966	811	1.44	-3%	194
5	Precipitation -10 % / temperature +1°C	Combination of 1 and 3	873	736	1.31	-12%	171
6	Precipitation -30 % / temperature +3°C	Combination of 2 and 4	679	532	0.95	-38%	175
7	Increased intensity of precipitation	Sum of the baseline precipitation per 3 days (annual precipitation constant)	960	879	1.57	+5%	118

Table 3: Maximum cross correlation (r_{xy}(p)) values between input and output signals and memory effects of karstic systems reported in the literature.

Reference	System	r _{xy} (p) _{max}	memory effect (day)
This study	Qachqouch karst spring (Lebanon)	0.52	50
Marsaud, 1997	Baget (France)	0.6	15
Larocque et al., 1998	La Rochefoucauld karst aquifer (France)	0.8	80
Ei Hakim, 2005	Anjar, Chamsine (Lebanon)	0.3; 0.35	69; 90
Bailly-Comte et al., 2008	Coulazou river (France)	0.8	<20
Ei-Hajj, 2008	Dalleh, Bziza (Lebanon)	0.45; 0.4	50; 40
Hosseini et al., 2017	Sasan aquifer (Iran)	0.2	90
Li et al., 2017	Guzhou catchment area (China)	0.45	3.5
Petalas et al., 2018	Paradisos Karst aquifer system (Greece)	0.25	125

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