

Rainfall, spring discharge and past human occupancy in the Eastern Mediterranean

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Abstract In ancient times human activities were tightly related and sensitive to rainfall amounts and seasonal distribution. East Mediterranean settlements were concentrated around numerous small to large springs, such as the Judean Mountains area. The goals of this study were to determine (a) the sensitivity of total discharge, recession curve, and response time of such springs to annual precipitation patterns, and (b) how spring hydrology responds to series of drought or wet years and to transitions from drought to normal and/or wet episodes (and vice versa). These goals were achieved by setting a finite-element hydro-geological flow model for selected perched springs that characterize the numerous springs throughout the carbonate karst terrain in the Judean Mountains. In addition, we estimated the effect of proposed regional past climate changes on the springs; in so doing, we transfer climate change to community size, livelihood and economic strength that were highly dependent on agricultural productivity. The results of the hydro-geological model revealed that these mountainous communities had the potential to prosper during historically wetter episodes and were probably adapted to short-term variability in annual rainfall. However, moderate to extreme droughts lasting only a few years could have led to a partial or even total abandonment of the springs as focal sites of intensive agricultural production. Spring drying eliminated the primary cause for the location of settlement. This occurred simultaneously in numerous settlements around the mountains of the southern Levant and therefore, must have caused dramatic economic and societal changes in the entire region, perhaps even resonating afar.

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1 Introduction

Synchronous past climate and cultural changes are observed in the Eastern Mediterranean and the Near East [e.g., Bookman et al. (2006); Bookman et al. (2004); Enzel et al. (2003); Faust and Ashkenazy (2007); Issar and Zohar (2007); Migowski et al. (2006); Neumann et al. (2010) and elsewhere]. These temporal associations use paleoclimatic indicators of reduced and increased rainfall that can directly affect this Mediterranean environment (with the emphasis on the dry climates). Enzel et al. (2003) indicated that the variations of the Dead Sea level are indicative of the climate variation in the region, while Bookman et al. (2004) suggest that the lake's high and low stands are correlated with large cultural shifts during the Holocene (e.g., the high stand of the second century BC coincides with the Roman period). Migowski et al. (2006) documented the presence of two major wet phases (~10–8.6 and ~5.6–3.5 kyr BP) during the Holocene; these phases are also characterized by the enlargement of smaller settlements, suggesting a parallelism between climate and Near East settlement development. Faust and Ashkenazy (2007) proposed that increased precipitation during the third millennium BC was the cause for small settlement decline along the Israeli coastal plain. Pollen analyses show that agricultural intensity, manifested in the frequency of olive vs. drought-resistant pine pollen, varied in phase with Dead Sea levels (Neumann et al. 2010). Either both the pollen and the lake levels could have been the same direct response to the changes in rainfall or the pollen/vegetation changes could have been responses to other anthropogenic responses indirectly connected to the change in climate. The transformation of climate into a regional drought was not quantified and only intuitively used. The mechanism involved in transforming the climate into the anthropologic realm, for example, transforming a meteorological drought into hydrological and/or agricultural drought, was less discussed for the entire southern Levant. Here we take this effort further and model response of spring discharge as a function of rainfall and their possible influence on small mountainous settlements in the Eastern Mediterranean.

The reason for focusing on springs is their crucial role in water resources in this region. Before groundwater pumping from deep aquifers became a common practice in buffering water supply shortage in the Levant, local historical and prehistorical societies were more susceptible to extreme dry episodes. Direct precipitation was the main water source for the livelihood of communities—for irrigation, livestock and drinking water. For increased societal resilience and compensating for seasons and years of lower rainfall, major efforts were made to utilize natural and later, manmade water storage. For this purpose, natural springs in the Mediterranean climate act best: (a) they extend water availability from individual rainstorms and wet winters well into the drier months of the year, and (b) they allow irrigation for a longer duration in individual years, thereby permitting intensive agriculture. This extension of spring-based activities can extend for up to a few years following a wet season. Where recharge areas and underground natural storage capacities of such springs are limited, these water resources are increasingly more sensitive to rainfall variations.

In this study, we focus on the mechanism that can transform fast regional changes in precipitation into large excesses or deficits in spring discharge. The strong seasonality of the Mediterranean climate in the Levant with its characteristically high variability in annual to multiannual precipitation strongly affects the springs' discharge. Deficits in discharge, together with the respective changes in rainfall, can drastically distract the economy of the local spring-based communities. As these communities are widespread all around the carbonate mountain terrains of the Levant and the Mediterranean in general, their response to increases and decreases in water availability can transfer impacts of climate changes to the society scale.

1.1 Past climate variations

Past Dead Sea lake levels are the major source of information on past climate in the Levant. The Dead Sea is considered “an enormous rain gauge” (Huntington 1911) and already in 1911 Huntington proposed that its level variations have the potential of representing past climate changes and explaining civilization shifts in the region [see discussion by Issar and Zohar (2007)]. Based on modern measured data Enzel et al. (2003) showed that past mean annual precipitation must have been reduced or increased at the scale of approximately $\pm 1\sigma$ of present-day mean annual precipitation of the respective stations throughout the southern Levant. For example, the mean annual rainfall in Jerusalem (Fig. 1) was $\sim 650 \text{ mm yr}^{-1}$ and $\sim 450 \text{ mm yr}^{-1}$ during Dead Sea lake level rising or falling, respectively, in comparison with its long-term (1847–2000) mean of 554 mm yr^{-1} ($\sigma \sim 120 \text{ mm}$). Such changes in regional mean annual rainfall for multi-year long episodes would have generated wet episodes or long devastating droughts (Enzel et al. 2003). Therefore, contemporaneity between shifts in civilizations and Holocene Dead Sea level changes [e.g., Bookman et al. (2006); Neev and Emery (1967)] and changes in the type of Holocene sediments in Dead Sea drilled cores (Migowski et al. 2006) were used to support Huntington’s proposal.

In addition to the obvious responses to rainfall excess and deficits, the questions raised are: How, and how fast, can such annual to multi-years hydroclimatic changes be transformed from the regional rainfall changes to the practical scale of local food producing communities that are the basis for the society?

1.2 Springs and settlements in the mountain ridge

We based our efforts on the assertion that historical settlements in the Levant, and especially in its mountainous areas, were at least in part dependent on springs for irrigation and drinking water supply [e.g., Frumkin (1999); Ron (1966); Ron (1985)]. Evidence of past engineering solutions for extracting more water from the springs (e.g., large-volume water storage or excavation of short sub-horizontal tunnels towards the springs’ reservoir) is found near many historical settlements in the region. Approximately 160 small springs [maximum discharge of $4,020 \text{ m}^3 \text{ day}^{-1}$ was measured for the Haniye Spring (Israel Hydrological Service 2010)] are scattered relatively densely around the Judean Mountains alone (Fig. 1). Most of these springs are based on local perched aquifers in this karst environment [e.g., Harsha, Delbah, and Matwi Springs; (Weiss and Gvirtzman 2007)]; i.e., the spring discharges small aquifers positioned on top of aquitards, within the unsaturated zone. These numerous perched springs are fed by small recharge areas, not connected to a regional aquifer, and therefore they are sensitive to rainfall amounts (Burg 1997; Peleg and Gvirtzman 2010). These perched aquifers are recharged during the wet season (October to May) of each year, with December–February usually the wettest months. Rainfall is not expected in the summer time (June–August) in this Mediterranean climate. The springs’ discharge falls from a maximum peak in the early to late spring to a minimum in the autumn. These springs are often at the basis of small to large village livelihood, agriculture and culture. Their water production directly affects the life of all inhabitants of the area.

2 Objectives and approach

The objectives of this paper are to (a) examine the effect of changing regional precipitation amounts at the local scale of individual springs, and (b) provide insights into and

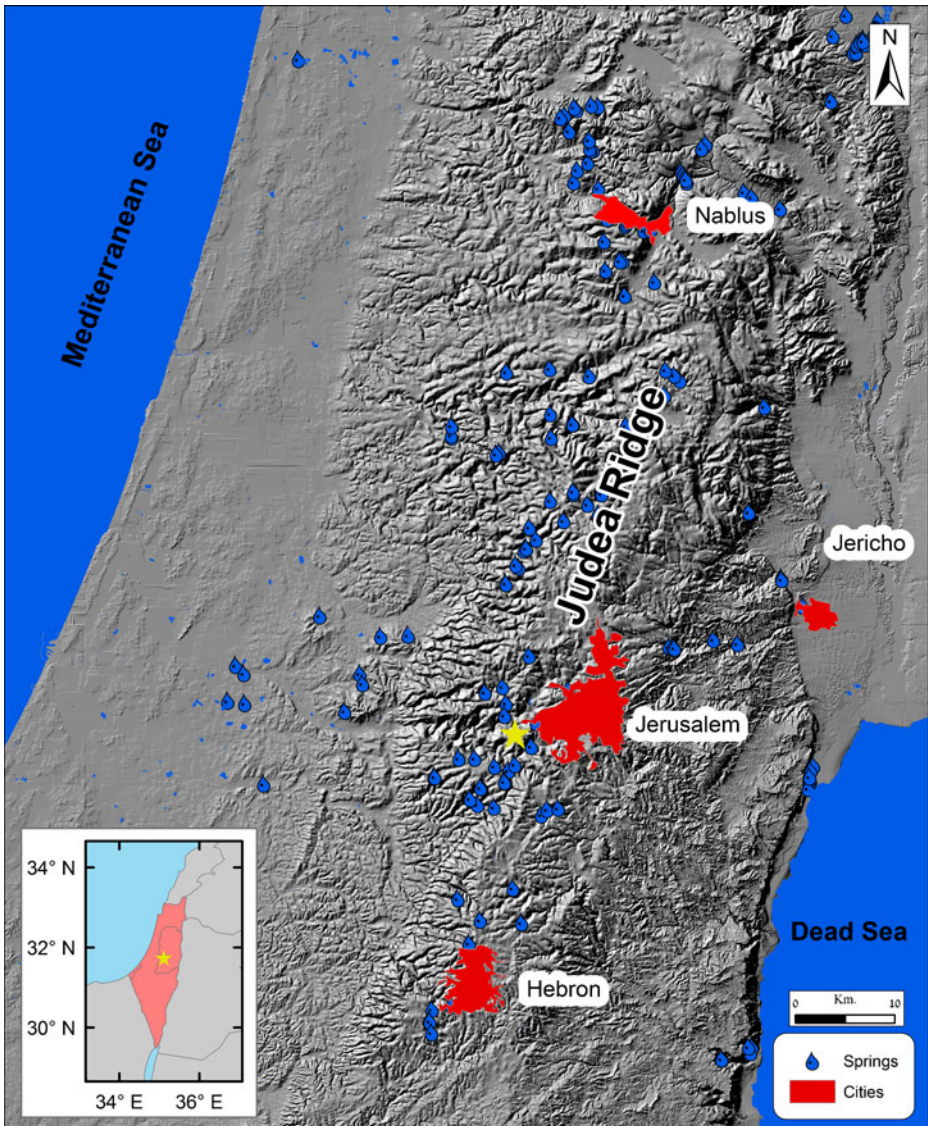


Fig. 1 A shaded relief map of the Judean Mountains in central Israel and the Palestinian Authority. The shaded relief map is from Hall (2008) Approximately 160 springs are scattered at the main ridge of the Judean Mountain. Yellow star marks the location of Batir and Jamia Springs

quantitative estimations of the ways such regional hydro-climatic changes transform and impact the local scale of a village and/or a community. For this, we will estimate (a) the effect of rainfall changes on amounts and seasonal distribution patterns of springs discharge, and (b) the response time of springs to propose past climate changes. This estimation will be carried out by setting a finite-element hydro-geological flow model for selected perched springs, exemplifying the numerous springs throughout the carbonate karst mountainous terrain. Then, we will discuss the main hydrological trends that result from the

modeling efforts, mainly in terms of water resource availability to ancient communities and societies in this region.

3 Hydro-geological modeling of spring discharge

To estimate the effect of precipitation on the spring discharge, a finite-element hydro-geological flow model was constructed. The model was calibrated based on present-day rainfall and discharge data to identify the hydrologic parameters controlling the spring discharge. These parameters were then used to reconstruct long-term spring discharge. Below, we describe the specific springs selected for our research. Their sensitivity and response patterns to precipitation are mimicked by many other springs. The spring hydrological modeling used here follows that of Peleg and Gvirtzman (2010) and the details are presented therein. Therefore, here we present only a short description of the model and its features that are relevant for understanding the results.

3.1 Batir and Jamia Springs

The Judean Mountains are mainly composed of limestone and dolomite lithology of the Judean group that is characterized by intense karst systems (Arkin et al. 1976; Arkin and Hamaoui 1967). Within this group, there are many local aquifers perching on the relatively thin and largely impermeable Motza Marls Formation or on the Soreq Formation (Figs. 2 and 3). The Batir and Jamia Springs were selected because they are located only some five kilometers southwest of Jerusalem (Fig. 1), enabling the use of Jerusalem rainfall data, which can be associated, as noted above to the Dead Sea lake levels. These springs do not only have continuous discharge data, but also represent the main lithologic, structural and hydrologic settings of many other springs in the region [additional spring data are presented in Burg, (1997); Peleg and Gvirtzman (2010); Weiss and Gvirtzman (2007)].

The Batir and Jamia Springs drain a two-level perched aquifer system with the specifics of the geological cross section presented in Figs. 2 and 3. The Batir Spring discharges at the contact between the permeable Aminadav Formation and the underlying impermeable of the Motza Marls Formation (Figs. 2 and 3) with the beds dipping toward the spring source. The Jamia Spring discharges at the contact between the permeable Kesalon Formation and the impermeable Soreq Formation, both dipping moderately toward the spring. The maximum recharge area for both springs is delineated in Fig. 3. The Batir Spring recharge area covers the entire exposure of the Aminadav Formation and is larger than the Jamia Spring recharge area that is only covered by the Kesalon Formations. That is, precipitation recharges the lower perched Jamia Spring only in the area that is not recharging the Batir Spring (Compare Figs. 3 and 2 and the respective permeability of the different formations); this results in the Batir Spring discharging more than the Jamia Spring.

3.2 Model construction and calibration

The FEFLOW software was used to simulate the groundwater flow in the aquifer and springs. The code solves the hydrological flow equations using a finite element method as described by Diersch (2002). In all, 25 years of measured hydrographs were used in the calibration process (Fig. 4) along with corresponding 25 years of daily-rain data. “Trial-and-error” techniques were applied, as no automation process can be fitted for the calibration. A total of four parameters were calibrated in four different hydro-geologic layers (Fig. 2): (1) the storativity,

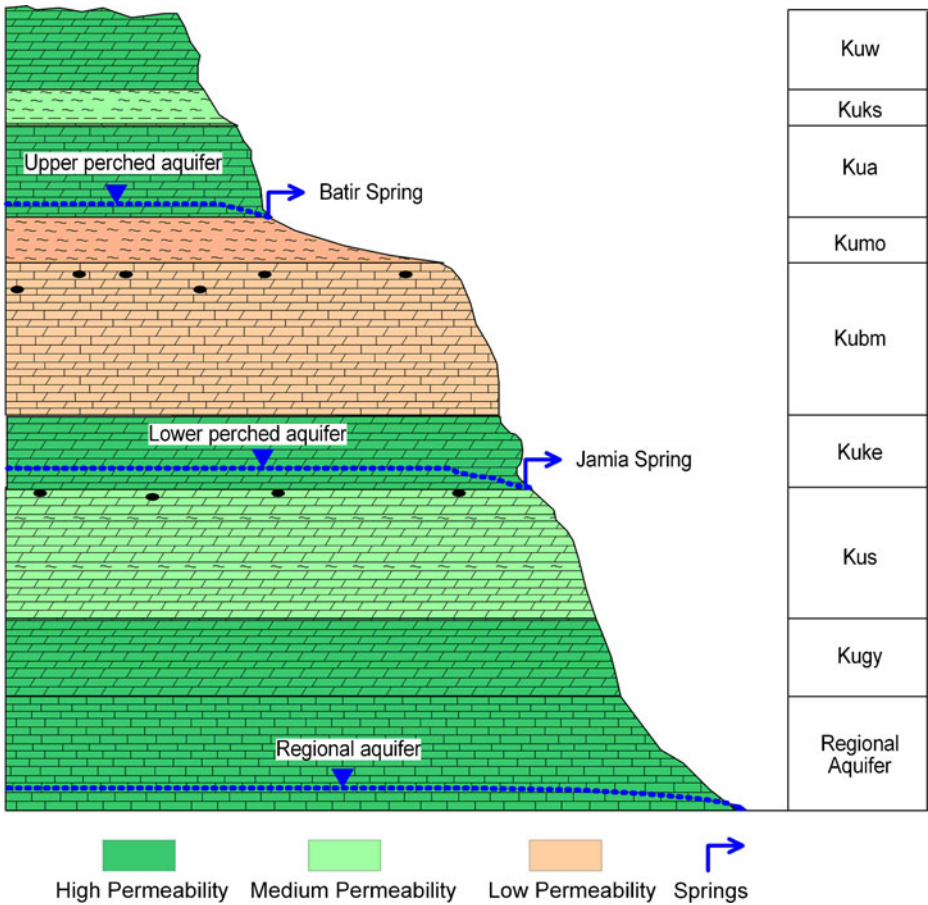


Fig. 2 Schematic hydrogeology cross section of the Batir and Jamia Springs (following Peleg and Gvirtzman 2010). The formations divided by their permeability characteristics: High permeability for Kuw, Kua, Kuke, and Kugy (dark green); Medium permeability for Kuks and Kus (light green); and Low permeability for Kumo and Kubm (light orange). The geologic formations following Arkin et al., 1976

S; (2) the horizontal hydraulic conductivity, K_h ; (3) the vertical hydraulic conductivity, K_v ; and (4) the hydraulic conductivity of the karst conduits, K_k . Sensitivity analyses were also preformed for the above parameters with details in Peleg and Gvirtzman (2010). Table 1 summarizes the values assigned for the calibrated hydro-geological parameters.

4 Sensitivity of spring discharge to precipitation pattern

4.1 Reconstruction of the 83-years hydrographs

The 25-year discharge data were used for the calibration. However, to estimate how precipitation affects spring discharge a longer discharge record is required. Furthermore, relatively long rainfall time series are required to capture the diversity of sequences of wet, normal, or dry years. Such sequences should include, for example, a wet year followed by a

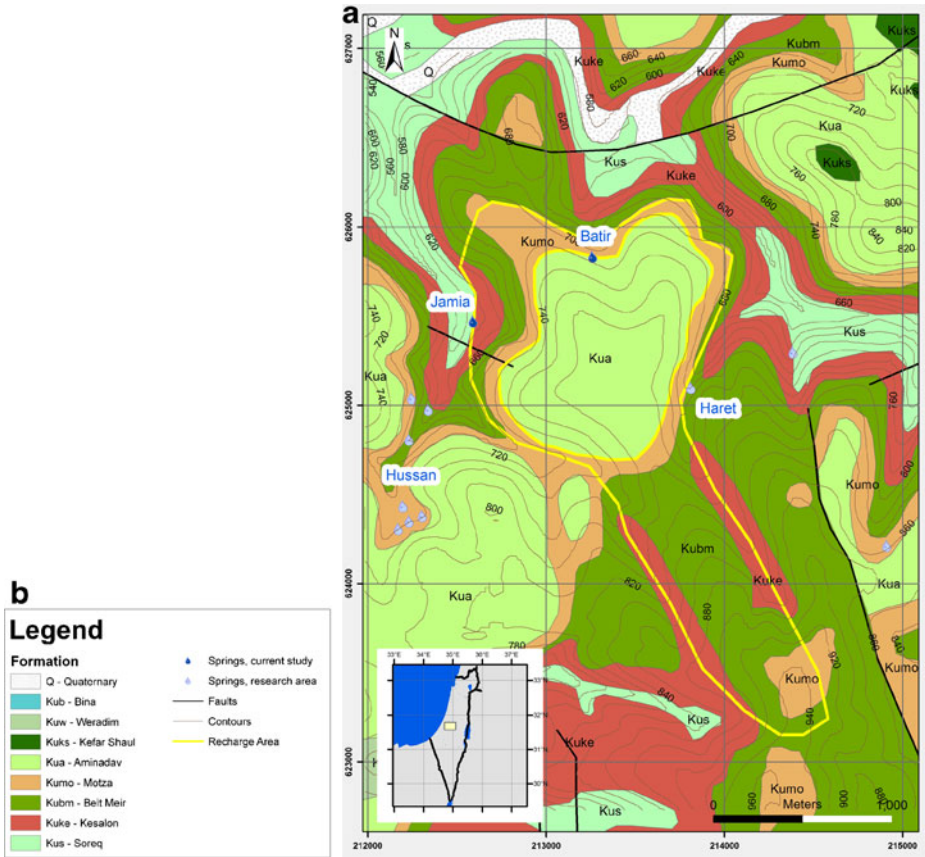


Fig. 3 Geologic map of the Batir (1.06 km²) and Jamia (2.63 km²) area (a) and legend (b) (following Arkin et al., 1976). Yellow line marks the springs’ recharge area (after Peleg and Gvirtzman 2010)

normal year (with approximately the mean annual precipitation) or a dry spell (several consecutive dry years) followed by an extremely wet year. Such rainfall data are available from rain stations in the Jerusalem area within the studied region (Fig. 5), and therefore a synthetic rainfall series is not needed. Nevertheless, no complete rainfall time series could be found at one rain station and therefore the 83-year-long daily rainfall series was prepared using an Inverse Distance Weighted (IDW) interpolation technique from 20 rain stations within 10 km from the studied springs (Table 2). The resulted annual rainfall series is presented in Fig. 5. Rain-recharge functions [see Peleg and Gvirtzman (2010) for details] were calculated for both springs (Fig. 6) and were used here to determine the 83-year-long recharge time series, which served as model input.

The calibrated model was rerun for the 83-year-long daily recharge series, resulting in spring hydrographs for 83 years (Fig. 7). Validation of the results has been conducted by comparing the 25 years measured hydrographs to the corresponding 25 years calculated hydrographs (Fig. 4). The yearly discharge volumes of the springs were estimated by cubic Spline technique, as the springs were regularly measured once a month. The difference in the volume of the calculated versus the measured data is as low as 4% for the upper-perched

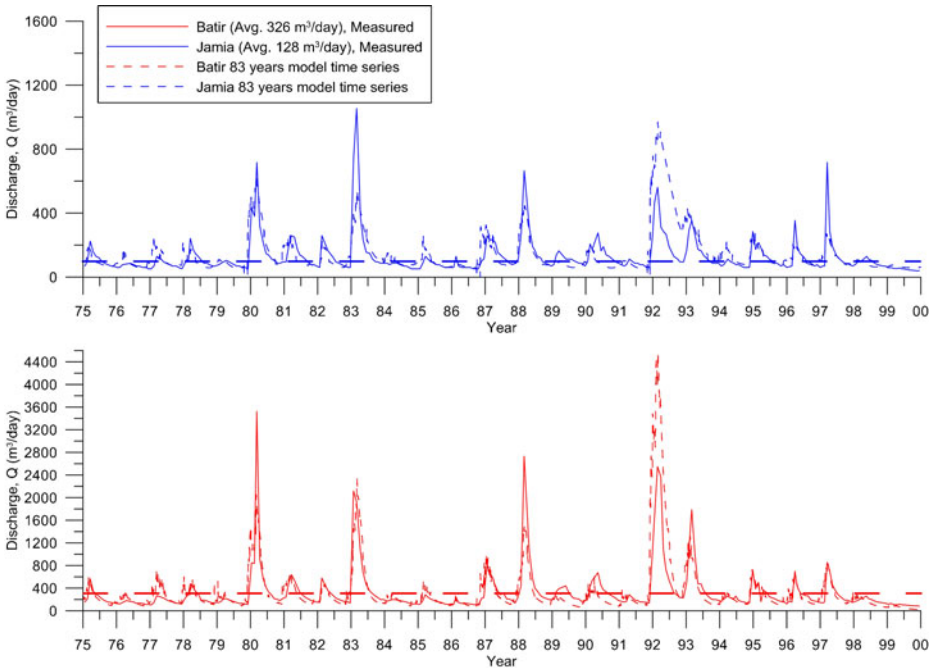


Fig. 4 The Batir (red solid line, lower graph) and Jamia (blue solid line, upper graph) Springs measured hydrographs and their average discharges (stripped lines, corresponding colors). Dashed lines (same colors) refer to the 83 years time series hydrographs (model results) for the corresponding time period

Batir Spring, and 9% for the lower perched Jamia Spring. While the calculated mean volume discharges are close to the measured mean volume discharges, the corresponding standard deviation values do not concur. This is explained by the extremely wet year of 1991–92 (see next section for more details); for that wet year, the calculated discharges volumes compared to the measured ones are as high as 190% for the upper spring and 270% for the lower spring. Excluding this extreme year outlier from the validation worsens the match for Batir Spring to 8% (instead of 4%) and improves the match for Jamia Spring to 2% (instead of 9%). Additionally, excluding this extreme year improves the standard deviation of the measured versus the calculated data, as can be seen in Table 3. As the lower spring is much smaller than the upper one, smaller changes in its discharge volume are relatively larger in term of percentage. The validation appears to be satisfying for any hydrologic study and more so for the purpose of this study.

Table 1 Calibrated parameters (after Peleg and Gvirtzman 2010)

Formation	K_h (m/s)	K_v (m/s)	K_k (m/s)	S
Aminadav	$7 \cdot 10^{-5} \pm 2 \cdot 10^{-5}$		$1.1 \cdot 10^{-1} \pm 0.4 \cdot 10^{-1}$	0.009 ± 0.001
Motza		$3 \cdot 10^{-11} \pm 0.3 \cdot 10^{-11}$		0.024
Kesalon	$7 \cdot 10^{-5} \pm 1 \cdot 10^{-5}$		1–0.1	0.008 ± 0.001
Soreq		$7.5 \cdot 10^{-10} \pm 0.1 \cdot 10^{-10}$		0.01

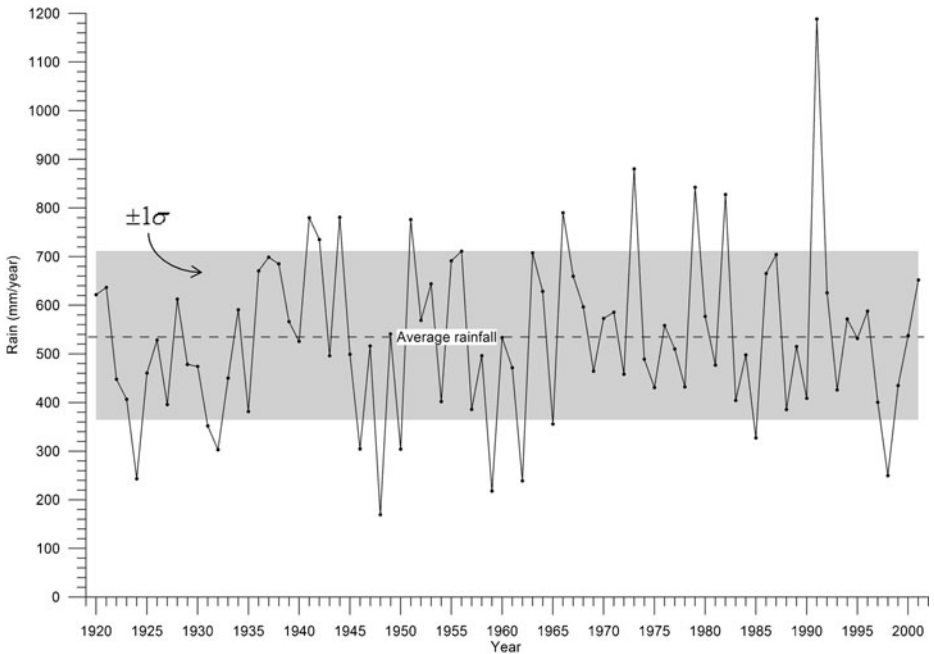


Fig. 5 Measured annual rain data for the Jerusalem vicinity (black dots and line) with the average linear rainfall (stripped line) and one standart deviation gap (dark area)

4.2 Discharge amplification and attenuation

Two discharge-precipitation functions were created, one for the upper spring and one for the lower spring (Fig. 8). A third degree polynomial curve was fitted in both cases, with very high coefficients of determination [$R^2=0.98$ for the upper spring (a), and $R^2=0.92$ for the lower spring (b)]:

- (a) $D = -100586.1 + 361.7 * P + 0.566 * (P - 533.6)^2 + 0.0002 * (P - 533.6)^3$ for $200 < D < 900$
- (b) $D = -23642.5 + 119.4 * P + 0.2 * (P - 533.6)^2 + 8e-5 * (P - 533.6)^3$ for $200 < D < 900$

Where D is the annual spring discharge ($m^3 yr^{-1}$) and P is the annual rainfall ($mm yr^{-1}$) over the recharge area. A lower threshold set for $200 mm yr^{-1}$ and an upper threshold set for $900 mm yr^{-1}$ as only two measurements (one for each threshold) found beyond those limits. The very small coefficient of the third degree implies that a second polynomial regression also might be taken into consideration, with a higher lower-threshold. There is a non-linear relation between the precipitation and the springs' discharge (Fig. 8). The year of 1992–93 falls out of the polynomial fit (e.g., Jamia graph, yearly precipitation of 625 mm with total discharge exceeding $107,000 m^3 yr^{-1}$) as it follows the extremely wet year of 1991–92 (1,188 mm). The second highest annual precipitation record for the last 83 years in the region is 890 mm. In the annual rainfall range of 100–200 mm the discharge from both springs is almost constant (annual volumes are around $24,000 m^3 yr^{-1}$ for both springs), whereas in the rainfall range of 300–1,100 $mm yr^{-1}$ the discharge follows a polynomial process and ascends. The discharge response steepens with increased precipitation and an increasingly larger proportion of precipitation which recharges the perched aquifers. These *discharge*

Table 2 Rain stations within 10-Km from the springs' recharge area used to create the 83-years long daily rainfall series

ID	1st measured year	Last measured year	East ¹	North ¹	Elevation (m)	Distanc ² (km)
1	1920	2003	222	632	740	10.0
2	1922	2003	211	635	700	9.5
3	1923	1987	220	630	750	7.2
4	1920	1977	221	631	760	8.6
5	1948	2003	211	632	722	6.7
6	1949	2003	221	631	815	8.6
7	1951	2003	210	625	760	4.1
8	1947	1996	218	625	825	4.1
9	1924	1970	221	633	760	9.9
10	1944	1990	219	623	750	5.8
11	1952	1997	217	630	810	5.0
12	1924	1963	218	632	800	7.2
13	1954	1993	217	629	760	4.2
14	1920	1948	220	632	810	8.5
15	1924	1952	219	633	830	8.6
16	1953	1981	215	630	660	4.1
17	1961	1988	220	631	800	7.8
18	1930	1956	214	633	710	7.0
19	1959	1985	218	631	780	6.4
20	1924	1947	217	621	775	5.8

¹ Projection—New Israel TM coordinates (data in km.)

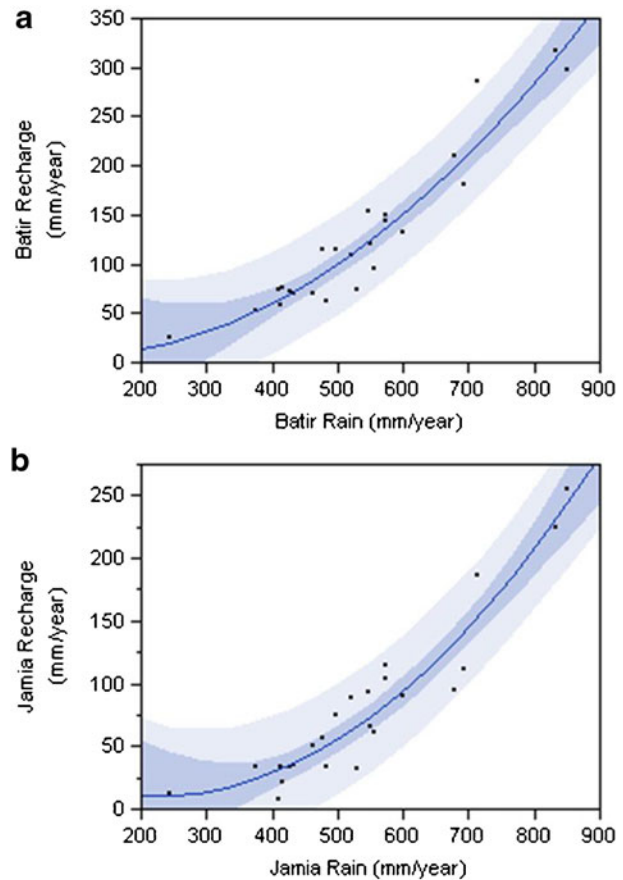
² Distance from the recharge area

amplification and attenuation effects have an important role in understanding how changing climate can influence springs. For example, during a transition from a multi-year drought (e.g., $\mu=300 \text{ mm yr}^{-1}$) to a relatively wet spell ($\mu=700 \text{ mm yr}^{-1}$) the annual precipitation is enhanced by a factor of 2.3 whereas the discharge of the upper and lower springs is enhanced by >5 and 3, respectively. This amplification effect not only increases the total volume of water accessible for the settlements, but has another crucial positive effect: it extends the wet season and high spring discharge well into the summer months, as discussed below.

4.3 Spring recession curve from winter to summer

The springs discharge increases during the winter and decreases during the summer to middle autumn. The yearly recession curve of the springs' discharge is different for wet and dry years. This is illustrated by three cases based on the hydrology model results (Fig. 9): (1) the mean of the 83-year discharge of the two springs and its standard deviation; (2) the spring discharge during the wettest year (1991/2) in the >150-year Jerusalem rainfall record, and (3) the springs' discharge during a moderately dry year [1969/70 (464 mm, $\sim 1\sigma$ below long-term annual average)] and an extremely dry year [the

Fig. 6 Rain-recharge functions for the Batir (a) and Jamia (b) Springs. Blue polygon marks the 95% confidence interval range for the regression and light blue polygon marks the same confidence interval for the individuals



year of 1959/60 (218 mm, $>2\sigma$ below long-term annual average)]. These cases were chosen to match Enzel et al.'s (2003) assertions of the annual precipitations amounts in the Jerusalem area capable of raising, stabilizing, and dropping modern and past Dead Sea levels or causing a devastating meteorological drought in the region. In addition to the obvious differences between total annual discharges and their maxima, an important observation is that the wetter the year the longer the duration of the recession of the discharge from winter into the summer (Table 4).

Increased direct precipitation during wet years improves agriculture yield in Mediterranean areas. Moreover, the above-observed longer duration of naturally stored water supply extended water availability precisely at the crucial time of the growing season and therefore at the time of the highest water demand. This allowed irrigation of larger areas and larger yields in crops and stocks. A dry spell, the other extreme in precipitation, poses a great hazard to the settlement water supply and its agriculture yield as the spring discharge fast diminishes and the manmade water storage rapidly dries out. In the most extreme scenarios, these three sources of water (direct rainfall, springs, and cisterns) are acting in-phase and almost simultaneously (within 1–2 seasons) and can obliterate the spring, probably the main reason of the establishment of settlement in the first place.

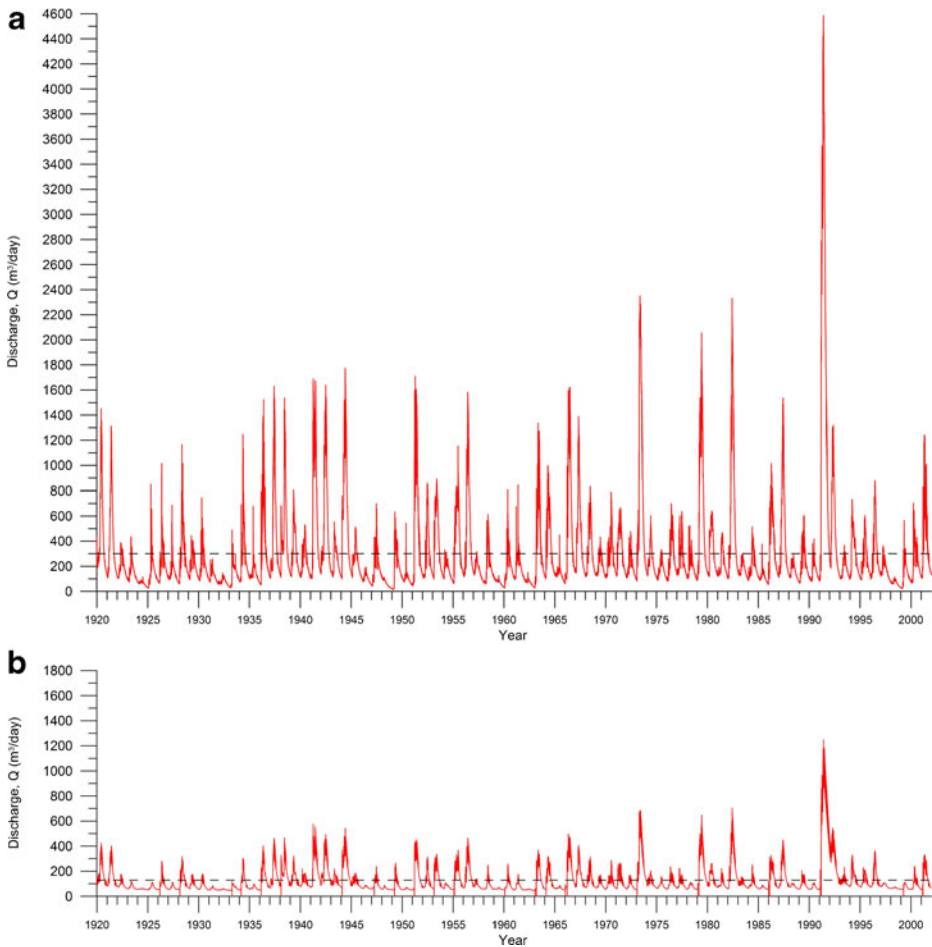


Fig. 7 Batir (a) and Jamia (b) Springs calculated hydrographs for the 83-years time series

4.4 Springs' response time

A wet spell following a dry spell will increase the springs' discharge. This can be demonstrated with the winter of 1983–84, as 68,000 m³ discharged from Batir Spring (410 mm of rainfall were measured in this winter), while in the winter of 1999–2000 the measured discharge was only 53,000 m³ (with similar amounts of 413 mm of rainfall measured). Those differences in the spring discharge are explained by examining the previous-winter precipitations: the winter of 1982–83 was very wet (852 mm), while the winter of 1998–99 was exceptionally dry (245 mm). These discharge changes are buffered by the storativity of the perched aquifer. As a result, the annual changes in the springs' discharge are smaller than expected. The time interval between the formation of a new rainfall pattern and a new spring discharge maximum (or minimum) is described as the springs' response time.

Fiorillo (2009), among others, recently showed that springs that discharge large karst systems have a relatively short-term “memory effect” (response time) lasting only a few

Table 3 Validation data

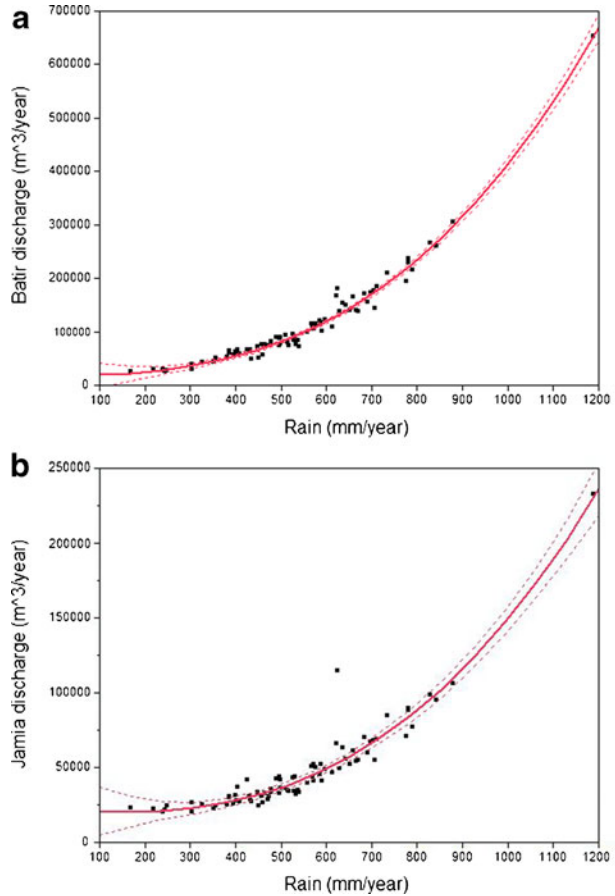
Year	Batir			Jamia		
	Measured ¹ (m ³ yr ⁻¹)	Calculated (m ³ yr ⁻¹)	Difference (%)	Measured ¹ (m ³ yr ⁻¹)	Calculated (m ³ yr ⁻¹)	Difference (%)
1975	54,000	61,031	113%	27,000	29,978	111%
1976	64,000	96,345	151%	30,000	38,763	129%
1977	89,000	91,562	103%	39,000	35,112	90%
1978	60,000	63,895	106%	29,000	27,720	96%
1979	251,000	258,143	103%	85,000	94,474	111%
1980	121,000	113,423	94%	52,000	48,988	94%
1981	104,000	80,071	77%	46,000	34,811	76%
1982	266,000	263,502	99%	109,000	98,002	90%
1983	68,000	63,943	94%	30,000	36,077	120%
1984	62,000	76,113	123%	29,000	35,073	121%
1985	47,000	41,625	89%	24,000	24,440	102%
1986	135,000	137,492	102%	54,000	53,792	100%
1987	268,000	175,468	65%	83,000	67,449	81%
1988	108,000	57,734	53%	39,000	29,287	75%
1989	136,000	78,259	58%	55,000	34,294	62%
1990	73,000	55,693	76%	32,000	26,069	81%
1991	348,000	651,914	187%	87,000	231,985	267%
1992	214,000	178,966	84%	63,000	113,798	181%
1993	73,000	64,146	88%	31,000	41,039	132%
1994	111,000	107,780	97%	50,000	51,194	102%
1995	96,000	89,937	94%	42,000	42,809	102%
1996	115,000	114,936	100%	59,000	51,670	88%
1997	70,000	60,835	87%	34,000	30,900	91%
1998	42,000	24,780	59%	21,000	23,698	113%
1999	53,000	46,423	88%	26,000	26,175	101%
All data						
Mean	121,120	122,161	96%	47,040	53,104	109%
Std.	82,582	126,182		23,100	44,302	
Data excluding 1991–1992						
Mean	111,667	100,088	92%	45,375	45,650	102%
Std.	69,174	62,483		22,011	24,471	

¹ Estimated using cubic spline technique

years. This, in turn, results in spring discharge amplifying the effect of poor rainfall seasons. In this paper, we examined the response time of springs and the discharge amplification and attenuation effect for small-perched springs, but with a stronger quick flow component than that described by Fiorillo (2009).

Identifying the respective response time of the springs (Table 5) was conducted by using synthetic rain series which are based on rain statistics that impose changes in Dead Sea levels (Enzel et al. 2003). Three cases were tested here: (1) a change from dry to wet; (2) a change from wet to dry; and (3) a change from a dry spell to an episode characterized by the mean of

Fig. 8 Rain-discharge functions for the Batir (a) and Jamia (b) Springs, with the 95% confidence interval for the individuals (red dots). A third degree polynomial curve was fitted in both cases [$R^2=0.98$ for the upper spring (a), and $R^2=0.92$ for the lower spring (b)]: (a) $D=-100586.1+361.7 * P+0.566*(P-533.6)^2+0.0002 *(P-533.6)^3$, (b) $D=-23642.5+119.4*P+0.2*(P-533.6)^2+8e-5 *(P-533.6)^3$



modern rainfall. Cases 1 and 2 characterize the maximum duration of response time of the springs, and case 3 will identify the common responding time of the springs. In every simulation, the year 0 represents the starting year prior to the artificially imposed climatic change. The simulations for each of the situations ended when the maximum or minimum discharge values were achieved, i.e., when a new steady state of annual discharge was attained.

The simulation results are summarized in Table 5 and in Fig. 10. The results indicate that for the upper spring it took (a) four years to reach the maximum discharge when the recharge area experiences a transition from a drought to a wet episode, as in case 1, (b) three years to reach the minimum discharge following a transition into drought, as in case 2, and (c) two years to recover from a drought to the maximum values associated with mean precipitation conditions, as in case 3. For the lower spring, it took (a) 10 years to reach the maximum discharge, as in case 1, (b) five years to reach the minimum discharge, as in case 2, and (c) two years to reach the maximum values for case (3).

It seems that the response time of the lower spring is much longer than that of the upper spring. It is also clear that both springs react faster to the aquifers' depletion than to their recharge. This is expected as: (1) the depletion of the perched aquifer is a perennial process while the recharge process occurs mainly during the winter; and (2) the depletion rate is not constant, and is depended on the water head in the

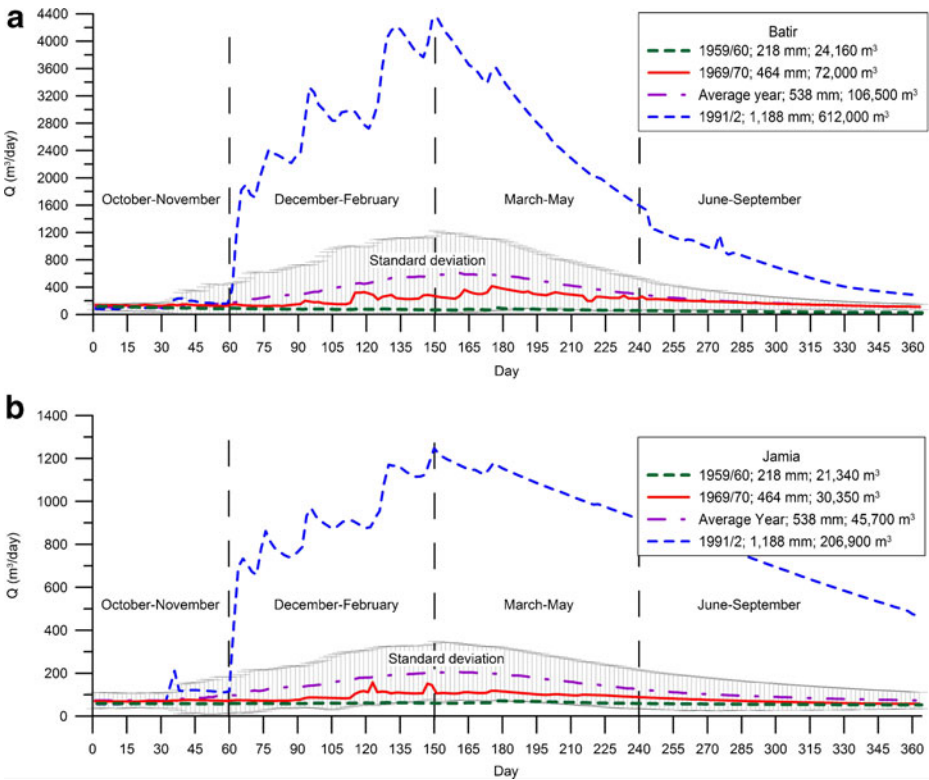


Fig. 9 The yearly winter to summer recession curve of the Batir (a) and Jamia (b) Springs: The mean of the 83-years discharge of the two springs and its standard deviation (purple dashed line); The spring discharge during the wettest year (blue dashed line); The springs discharge during the dry year of 1969/70 (red solid line); and the springs discharge during an extremely dry year (green dashed line)

perched aquifer (higher pressure—higher leak downward the aquitard and higher spring discharge). Negative feedback occurs as a higher recharge rate leads to a higher depletion rate. The results also imply that a moderately positive change in precipitations ($\leq 120 \text{ mm yr}^{-1}$, approximately 1σ in the Jerusalem area) has an almost immediate effect on aquifer storativity and spring discharge.

Table 4 Rain, max discharge, total discharge and decay time for selected years following Fig. 9

	Year	Rain (mm)	Max discharge (m^3/day)	Total discharge (m^3)	Duration from max-to-min discharge (days)
Batir Spring	1991–2	1,188	4,374	612,000	256
	Avg.	588	743	106,500	210
	1969–70	464	414	72,000	203
	1959–60	218	123	24,160	–
Jamia Spring	1991–2	1,188	1,248	206,900	268
	Avg.	588	239	45,700	211
	1969–70	464	173	30,350	188
	1959–60	218	71	21,340	–

Table 5 Synthetic rain data and the springs response time

	Batir			Jamia		
	Year	Rain (mm/year)	Discharge (m ³ /year)	Year	Rain (mm/year)	Discharge (m ³ /year)
A	0	245 (Year 1924/5)	1,440	0	245	16,630
	1	677 (Year 1936/7)	118,670	1	677	69,750
	2		169,050	2		86,580
	3		177,260	3		93,950
	4		180,010	4		101,290
				5		109,740
				6		127,390
				7		144,130
				8		151,840
				9		157,480
B	0	677 (Year 1936/7)	184,200	0	677	163,210
	1	374 (Year 1935/6)	50,780	1	374	60,190
	2		41,020	2		44,260
	3		38,910	3		40,630
				4		38,180
C	0	462 (Year 1925/6)	52,660	0	462	41,160
	1	556 (Year 1976/7)	65,690	1	556	48,860
	2		71,100	2		50,200

The springs' discharges react within a few years to inter-annual or even longer droughts. Even the modeled 10-year response of the lower spring (case 1) seems to be an over-estimation as the synthetic rain series simulates very dry to very wet transition. This response, faster than the decadal-century resolution of proposed regional climate changes, makes the numerous spring-dependent settlements sensitive to rainfall, although they may be adapted even to the extremes in the inter-annual variability. When dry spell duration increases beyond a few years its impact on such settlements can be catastrophic.

5 Rainfall discharge and possible cultural changes

The annual rainfall at the research area ranges from 360 mm yr⁻¹ to 700 mm yr⁻¹ for the years 1920–2002 ($\pm 1\sigma$ from the mean, square box at Fig. 11a), with analog changes for the Batir Spring discharge ($\pm 80\%$ from the mean discharge) and the Jamia Spring discharge ($\pm 60\%$ from the mean discharge). An increase in annual rainfall by an amount equivalent to over one standard deviation (i.e., 40–60% above the average rainfall in respective stations in the region) will amplify the springs discharge; it will result in an increase of 90–190% and 80–120% from the average discharge of the Batir (case A, Fig. 11a) and Jamia (case B, Fig. 11a) Springs, respectively. This effect is manifested by the extended duration of spring flow (considering only flow above baseflow). The threshold for the baseflow of Batir and

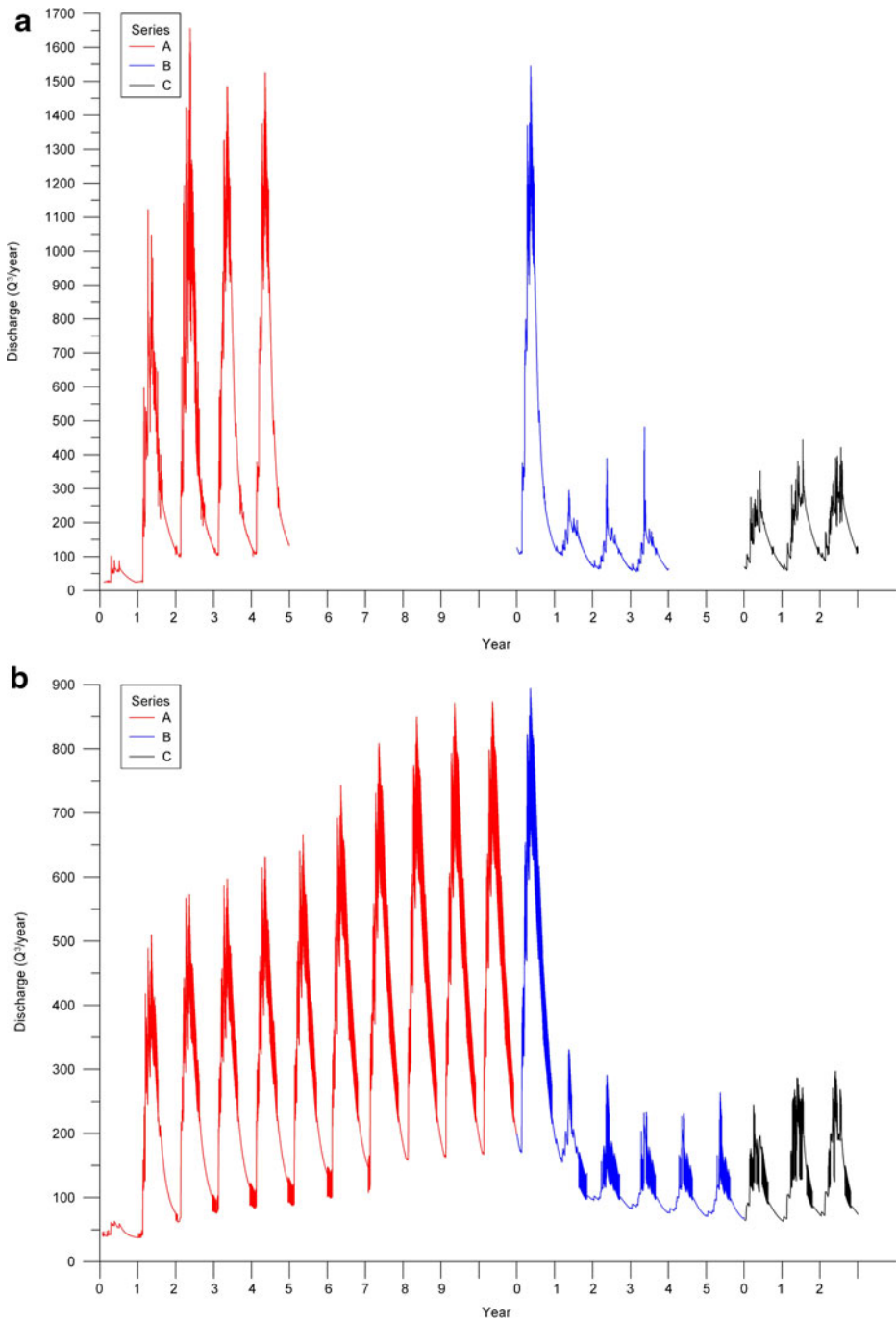
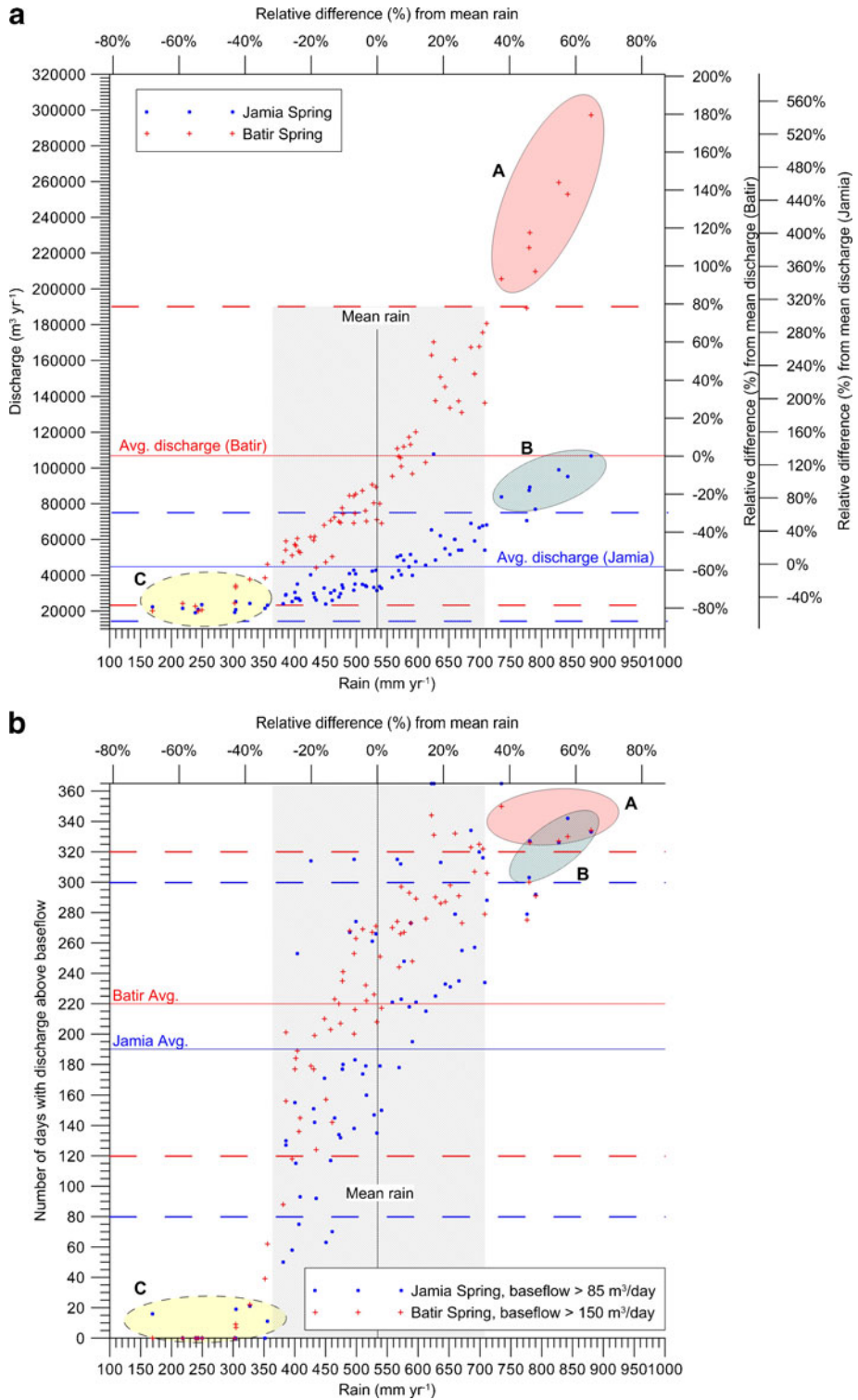


Fig. 10 The response time of the Batir (a) and Jamia (b) Springs. Three cases were tested: a change from dry to wet (red); a change from wet to dry (blue); and a change from a dry spell to an episode characterized by the modern rainfall mean (black)



◀ **Fig. 11** **a** Annual measured rain vs. annual discharge, and **b** annual measured rain vs. the number of days above baseflow for the Batir (*red plus*) and Jamia (*blue point*) Springs. The black line marks the mean rainfall for the region ($\pm 1\sigma$ delimited by square box). Continuous lines (red for Batir and blue for Jamia) represent the average discharge (**a**) or baseflow (**b**), while the discontinuous lines represent the $\pm 1\sigma$ for the relevant data. Very wet period marked with pink ellipse for Batir Spring (A) and grey ellipse for Jamia Spring (B). Very dry period for both springs marked with yellow dotted ellipse (C)

Jamia Springs defined as $150 \text{ m}^3 \text{ day}^{-1}$ and $85 \text{ m}^3 \text{ day}^{-1}$, respectively. In the wet scenario (Fig. 11b, cases A and B) both springs exceed the threshold for most of the year (Batir Spring >320 days; Jamia Spring >300 days), and even partly in the dry months of the summer time. However, shifts toward drier climatic period (case C, Fig. 11), with a decrease of 40–60% of the average rainfall, will result in similar spring discharge decrease (for both springs), and significant reduction in the number of days exceeding the baseflow threshold (up to 20 days).

Shifts toward drier climates probably reduced the direct rain-dependent agriculture production, and during the first few years would have made the spring-dependent agriculture more dominant. However, within a few years, the total volume of water would be reduced and the duration of the spring discharge would be shortened to such a low level that settlements could no longer rely on it and the abandonment of settlements would accelerate. As the season shortened drastically from its mean (211 days from max-to-min discharge to 188 days, or even less) in drier episodes (Fig. 9 and Table 3) the villagers may adjust by irrigating smaller areas or may change crop types. Reducing irrigated agriculture areas might also lead to economic crises as the goods were not only self-consumed but were also used for trading and taxes.

The springs that discharge the large regional aquifers [such as the Yarqon Springs in coastal Israel, historically discharging about 227 million cubic meters per year (Dafny et al. 2010)] have longer memory duration than the small perched springs discussed above. Therefore, these ‘regional’ springs may have served their communities for longer and perhaps as a regional backup during short droughts to the rest of population. These small perched vs. large regional springs raise additional complications for traditional, cross-region water use and management. It is actually difficult to quantify the amount of water needed for small settlements to maintain their production. However, we suggest that mountainous settlements, which were dependent on perched springs alone, were among the first to respond to shifts in climate and even more so to shifts to drier conditions. Even a partial climatic-induced dispersal of villagers from the mountainous areas has the capacity of dramatically disturbing regional organized and unorganized societies.

6 Conclusions

Early on, human activities were focused around the numerous small to large springs found in the mountainous areas of the Levant. The Batir and Jamia Springs, studied here, represent the numerous small-perched springs scattered in the Judean Mountains. A hydro-geologic flow model was set for these two springs to explore the sensitivity of total discharge, discharge recession curves, and response time of mountainous, perched karst springs to annual precipitation patterns. Additionally, we examined how spring hydrology responds to clusters of drought or wet years and the transitions between them.

Spring discharge is largely influenced by 3–5 years of dry or wet spells in precipitation; annual rainfall variability can be easily buffered by the storativity of the perched aquifers. It appears that it takes only several years for a change in precipitation (>120 mm/year) to have a full effect on the springs' discharge, and thus on the surrounding dependent communities. These mountainous communities can flourish and prosper during historically wetter and normal episodes; they are probably adapted to short-term variability in seasonal rainfall. However, moderate to extreme droughts lasting only a relatively short duration has the potential to disrupt local communities' dependence on springs. Such droughts may have led to partial or total abandonment of the springs as water resources and as focal sites of agricultural production (livestock and irrigated orchards and fields). Our results demonstrate that hydrological parameters that are important for a village's livelihood are sensitive to climatic changes due to the amplification and reduction effects in the discharge of springs.

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