ground water

Interpretation of Spring Recession Curves

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Abstract/

Recession curves contain information on storage properties and different types of media such as porous, fractured, cracked lithologies and karst. Recession curve analysis provides a function that quantitatively describes the temporal discharge decay and expresses the drained volume between specific time limits (Hall 1968). This analysis also allows estimating the hydrological significance of the discharge function parameters and the hydrological properties of the aquifer. In this study, we analyze data from perennial springs in the Judean Mountains and from others in the Galilee Mountains, northern Israel. All the springs drain perched carbonate aquifers. Eight of the studied springs discharge from a karst dolomite sequence, whereas one flows out from a fractured, slumped block of chalk. We show that all the recession curves can be well fitted by a function that consists of two exponential terms with exponential coefficients α_1 and α_2. These coefficients are approximately constant for each spring, reflecting the hydraulic conductivity of different media through which the ground water flows to the spring. The highest coefficient represents the fast flow, probably through cracks, or quickflow, whereas the lower one reflects the slow flow through the porous medium, or baseflow. The comparison of recession curves from different springs and different years leads to the conclusion that the main factors that affect the recession curve exponential coefficients are the aquifer lithology and the geometry of the water conduits therein. In normal years of rainy winter and dry summer, α_1 is constant in time. However, when the dry period is longer than usual because of a dry winter, α_1 slightly decreases with time.

Introduction

The spring hydrograph is the curve that shows its temporal discharge variation (Figure 1). The recession curve is that part of the hydrograph that extends from a discharge peak to the base of the next rise. The analysis of the curves has been useful in many areas of water resource administration, including discharge forecasting and waste disposal (Eisenlohr et al. 1997). Such analyses are also useful for rainfall/runoff mathematical models, graphical separation of different flow components, estimation of discharge statistics, and indexing the storage capacity of catchment areas (Tallaksen 1995).

The purpose of the present study is to identify, in recession curves, parameters that characterize specific springs and to interpret their hydrological significance. For that

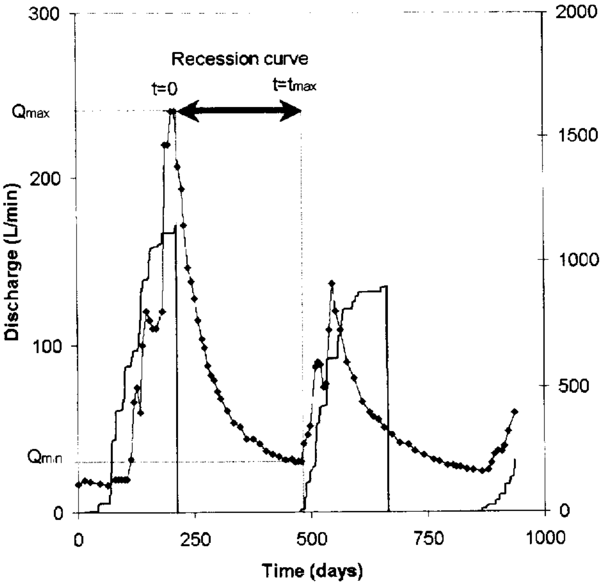

Figure 1. A typical hydrograph. The recession curve (line with markers—'En Yael spring) is defined from the point of maximum discharge until the beginning of the next rise. Heavy line represents the cumulative rain (Jerusalem station).

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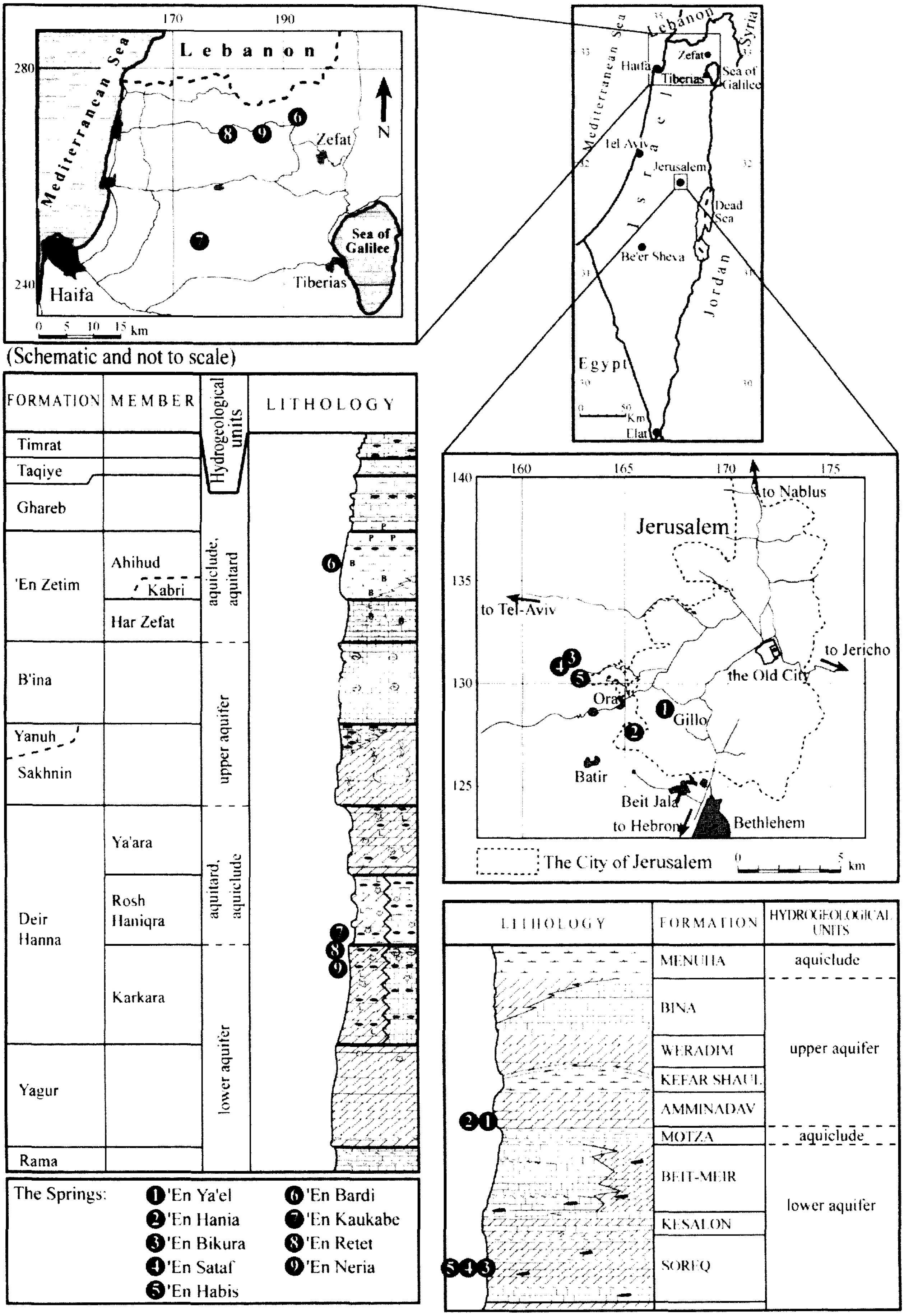

Figure 2. Top left: a general location map of the studied springs. Bottom left: a location map and a composite columnar section of the Judea Mountains (Sass and Bein 1978). Right: a location map and a composite columnar section of the Galilee (Burg 1998).

purpose, we use the data collected by Burg (1998) during two normal years (rainy winters and dry summers) in 1992 and 1993, as well as new data collected during the extremely dry period of 1999–2000. Five perennial springs in the Judean Mountains and four others in the Galilee Mountains, northern Israel, were studied (Figure 2a).

The studied springs are distributed along the mountainous backbone of the country, within Upper Cretaceous carbonate rock formations, draining different perched carbonate aquifers in the unsaturated zone. The thickness of the carbonate rock sequence is on the order of several hundred meters. The strata comprise mainly dolomite and limestone layers alternating with marl. The marls provide the necessary aquicludes to support the springs, explaining the large number of springs in such formations. The dolomite rocks display cracking, faulting, and karst phenomena.

The environment of the investigated springs is presented in Figure 2. Three of the Judean springs—'En Sataf (590 m mean sea level [MSL]), 'En Bikura (580 m MSL), and 'En Habis (550 m MSL)—discharge from the dolomitic Soreq Formation. Two springs—'En Hania (650 m MSL) and 'En Yael (670 m MSL)—discharge at the base of the Aminadav Formation dolomite near its contact with the marly Motza Formation. Three Galilean springs—'En Retet (520 m MSL), 'En Neria (820 m MSL), and 'En Kaukabe (345 m MSL)—discharge from dolomite. All the aforementioned springs discharge from the Judea group. One spring, 'En Bardi (695 m MSL), discharges from the chalky 'En Zetim Formation.

The investigated area has a moderate, Mediterranean-type climate with a wet winter season between November and March, followed by a dry summer from April through October. The average annual temperatures are 15° to 17°C and 17° to 18°C in the Galilee and Judea mountains, respectively. Some 850 to 900 mm/year rain falls on the Galilee area, whereas only 500 to 550 mm/year falls in the Judea area.

The selected Judean and Galilean springs, the local distribution of precipitation and the sampling program adopted by us facilitate a new insight into the interpretation of recession curves. This is demonstrated by the following points:

1. The absolutely dry Israeli summer results in classically shaped hydrographs, which in turn allow a high level of accuracy in model fitting.
2. Our data sets include two recession curves collected during two seasons for the same spring. A comparison of these curves makes it possible to resolve whether the curve parameters depend on the amount of precipitation or reflect spring properties.
3. The sampling of a "dry" winter (1999–2000) enabled us to evaluate a part of the recession curve that is usually undistinguishable in spring hydrographs.
4. The inclusion of one chalk aquifer, previously investigated by Burg and Heaton (1998), into our sampling program of mainly dolomite aquifers, allowed us to compare recession parameters that were obtained from springs in slightly different geological settings; however, these are influenced by identical climatic conditions as the dolomite springs.

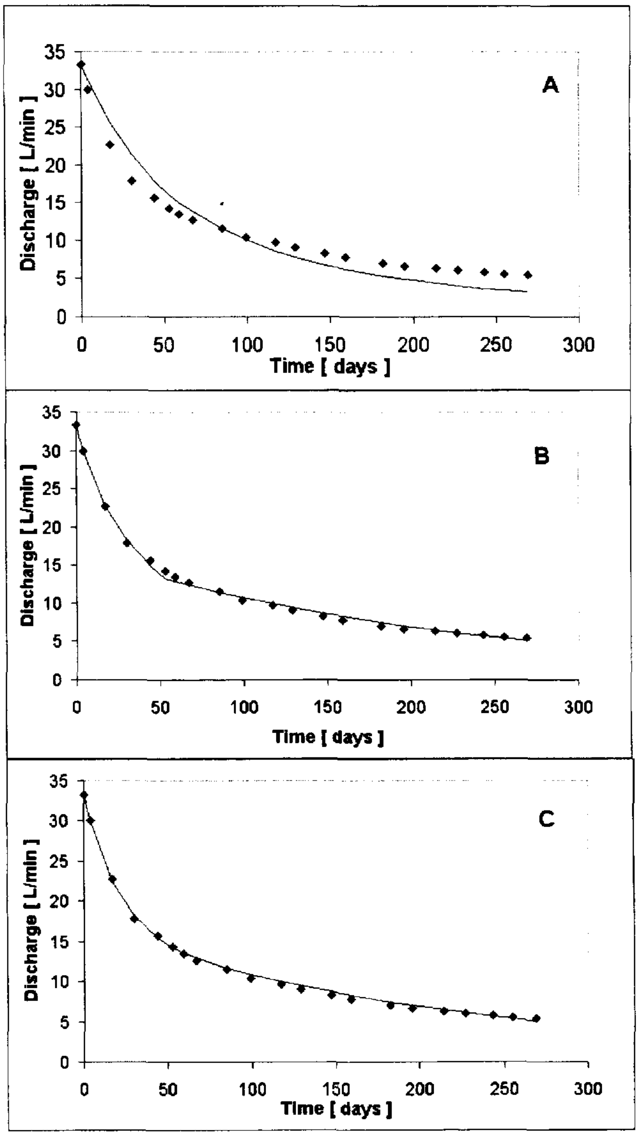

Figure 3. A comparison between three methods of data fitting: (a) Coutagne, (b) Mangin, and (c) Boussinesq.

Theoretical Background

The first attempt to fit a quantitative expression to a recession curve was probably made by Boussinesq (1904). Assuming a moderate hydraulic head gradient, homogeneity, isotropy, and one-dimensional flow, Boussinesq (1904) proposed a fitting by a sum of two exponential components. Several researchers (Mero 1964; Forkasiewicz and Paloc 1967) modified Boussinesq's approach and proposed that the discharge, Q(t), as a function of time, t, during the recession can be represented as a sum of N exponential components

$$Q(t) = \sum_{i=1}^{N} Q_i \cdot e^{-\alpha_i t} \qquad (1)$$

where α_i is the slope of the i-th component of the recession curve on a logarithmic scale. Q_i is the initial amplitude of the ith component at time t = 0, which corresponds to the beginning of the recession. Tallaksen (1995) concluded that

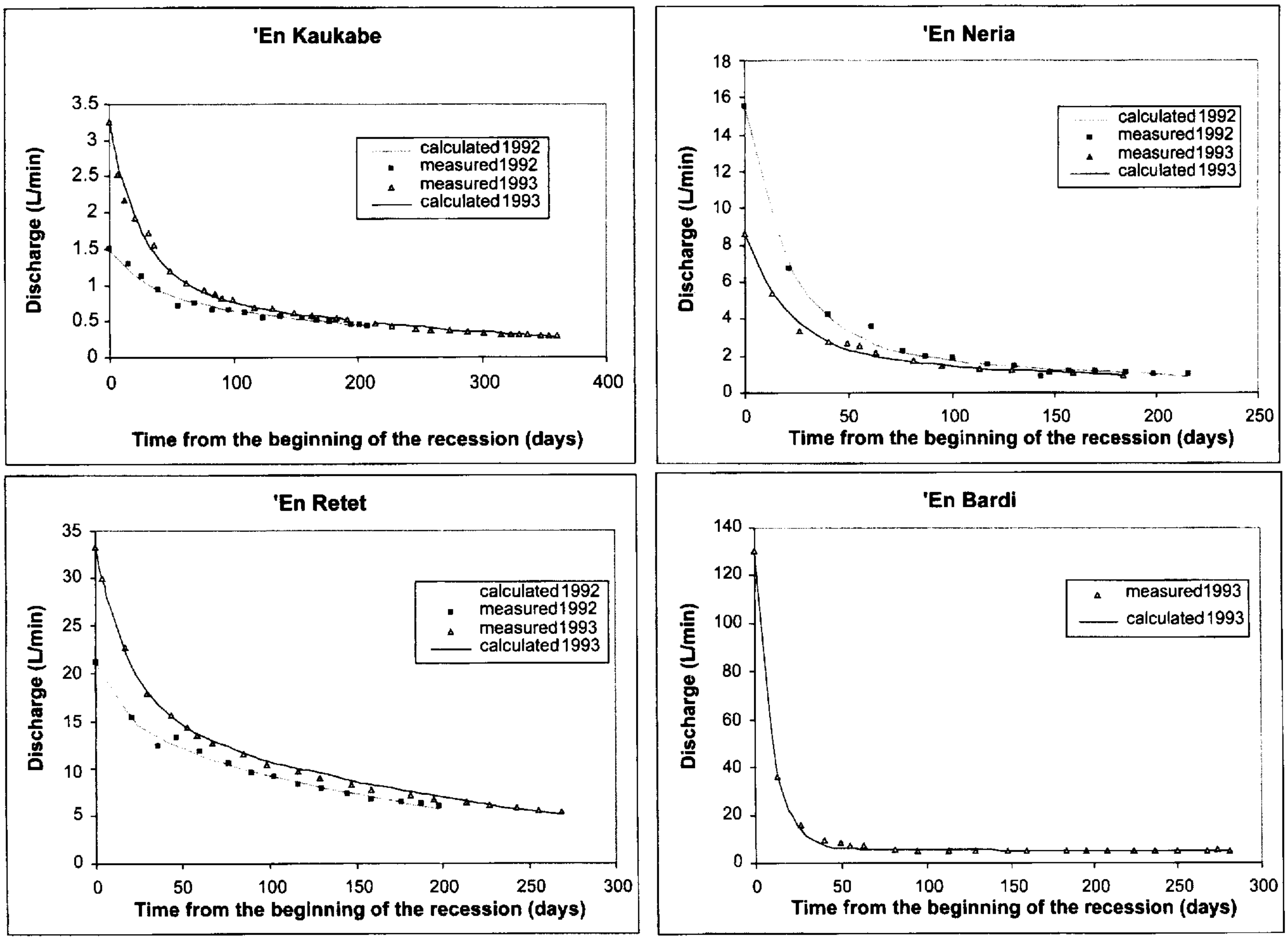

Figure 4. The recession curves of the Galilee springs and their curve fits according to Boussinesq's approach.

Table 1

Summary of the Main Parameters Characterizing the Recession Curves According to Boussinesq's Approach

Location	Spring, year	Lithology	α_1 [1/day]	Q_b [L/min]	α_2 [1/day]	Q_q [L/min]	α_2/α_1	V_{0b}/V_0
Galilee	Neria 1992	Dolomite	0.0052	2.8	0.0475	12.7	9.1	0.67
Galilee	Neria 1993	Dolomite	0.0044	2.18	0.048	6.45	10.9	0.79
Galilee	Kaukabe 1992	Dolomite	0.0034	0.89	0.0341	0.61	10	0.94
Galilee	Kaukabe 1993	Dolomite	0.0033	1.07	0.0415	2.19	12.6	0.86
Galilee	Retet 1992	Dolomite	0.0049	15.1	0.0601	6.14	12.3	0.97
Galilee	Retet 1993	Dolomite	0.0044	16.7	0.0514	16.6	11.7	0.92
Judea	Yael 1992	Dolomite	0.0048	96.1	0.0283	143.9	5.9	0.80
Judea	Yael 1993	Dolomite	0.0036	70.6	0.0284	65.8	7.9	0.89
Judea	Habis 1993	Dolomite	0.004	8.9	0.0641	31.1	16	0.82
Galilee	Bardi 1993	Chalk	0.0006	5.86	0.1052	124.5	175.3	0.90

All the dolomite aquifers show a great similarity in their α_1 values. α_2 values differ from spring to spring but are similar for consecutive recessions in the same spring. 'En Bardi has a smaller α_1 value and a larger α_2 value in comparison with the dolomite springs.

The volume ratio, V_b/V_0, indicates that a significant part of the water volume is stored in the bulk rock volume rather than in the cracks, even for low-porosity rocks such as chalk.

each exponential term, in a recession curve that comprises a sum of exponents, represents the depletion of a specific reservoir, where the hydraulic conductivity of the reservoir is proportional to α_i. Accordingly, the exponential term with the largest slope, α_2, represents the rapid depletion of flow channels with the highest hydraulic conductivity. The largest α-value is probably a measure of the degree of fracturing and intrakarst connectivity. The exponential term with the smallest slope, α_1 corresponds to the baseflow, i.e., to the slow depletion of the flow network with low hydraulic conductivity. Thus, the slope of the baseflow may reflect a matrix porosity and porosity-related permeability. The numerical models of Darcy's flow equation confirm that the baseflow represents the depletion of the low hydraulic conductivity aquifer volumes (Eisenlohr et al. 1997). Likewise, a change in the slope of the recession curve has been attributed to the heterogeneity of the aquifer (Riggs 1964; Petras 1986), whereas recession curves that can be expressed by one exponent represent homogeneous conductivity and storage properties.

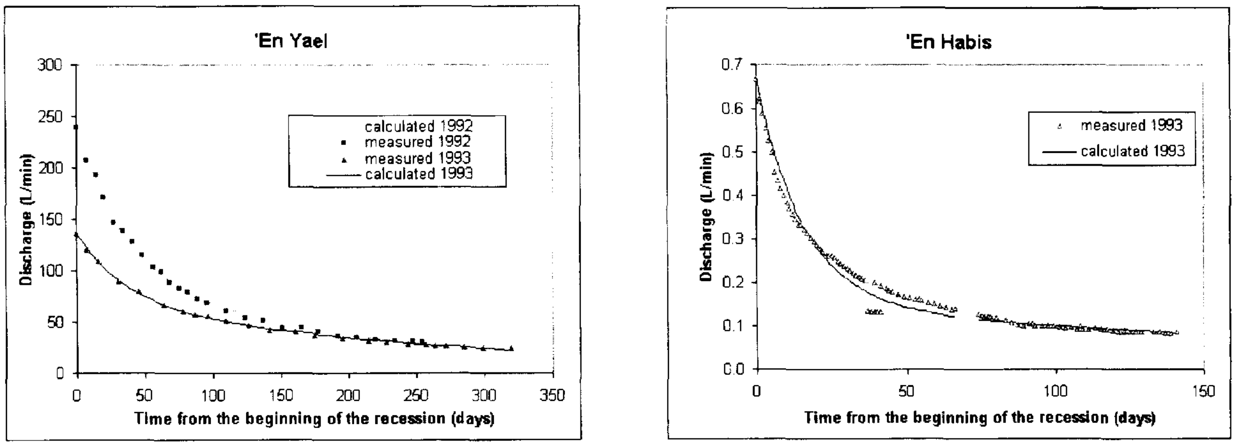

Figure 5. The recession curves of the Judea springs and their curve fit according to Boussinesq's approach.

Other investigators have provided additional fitting models to spring recession curves. Mangin (1975) suggested that the recession curve is composed of a nonexponential component and an exponential baseflow component. Coutagne (1968) visualized the recession as a response of a single reservoir, the discharge of which obeys a power law of the drained volume. Analysis of all the collected data (Amit 2000) showed that Coutagne's approach regularly underestimates the baseflow component, whereas the results of Mangin's approach could hardly be distinguished from the function presented in Equation 1. Figure 3 shows one example of comparison between the three aforementioned curve fits, applying for that purpose our 1993 data from the 'En Retet spring. It can be seen that Coutagne's model (Figure 3a) slightly overshoots the data until about 80 days, dropping later below the actual measurements, attaining a 40% difference toward the end of the recession. The splitting of the recession to a nonexponential and an exponential baseflow component according to Mangin's approach (Figure 3b) provides a good fit for the entire range, except for a small kink around the 53rd day. The kink occurs at the transition from the nonexponential component to the exponential one. It is only Boussinesq's model that provides a smooth and high-quality fit throughout the whole range of data (Figure 3c). Consequently, the curve fits for all the spring recession curves analyzed are based on Boussinesq's approach and performed as described later. The slope of the semilogarithmic (Q vs. t) curve during late (baseflow) periods yields the lowest exponential coefficient, where its intercept represents the initial discharge of that component. The slowest component can then be subtracted and the procedure repeated to reveal the larger components. If the discharge is composed of only two components, the component with the smaller exponential coefficient is defined as the baseflow, and the other is the quickflow (Padilla et al. 1994). Whether or not the exponential coefficients (α_i) represent inherent aquifer characteristics can be tested by comparing their values obtained from two recession curves in the same spring. Variations in α values between springs would indicate that α is a local hydrological characteristic. On the other hand, similar α values in several or all springs would imply that α is a common aquifer property, such as material porosity.

Table 2
Values of the Exponential Coefficient of the 1999 Recession

Spring	'En Hania	'En Sataf	'En Bikura
α_{dry} [1/day]	0.001	0.0008	0.001

A quantitative treatment of the recession curve allows calculating the amount of water drained through a particular spring from the beginning of the recession. It also enables estimating the total spring storage volume. These characteristics are important for evaluating water resources, especially in water-deficient regions. Once a discharge function (Equation 1) is established, the amount of water, V(t), drained through the particular spring from the beginning of the recession (t = 0) until the moment t = t can be calculated by integrating the discharge function:

$$V(t) = \int_0^t Q(t)dt = \sum_{i=1}^{N} \frac{Q_i}{\alpha_i}(1 - e^{-\alpha_i t}) \tag{2}$$

Provided that no recharge takes place, the total spring storage volume from t = 0 to t = ∞ is defined by V_0:

$$V_0 = \int_0^\infty Q(t)dt = \sum_{i=1}^{N} \frac{Q_i}{\alpha_i} \tag{3}$$

Results

The fitting procedure described previously was applied to the hydrographs of all the springs under study. Tables 1 and 2 include the summary of the parameters characterizing the discharge during 1992–1994 and the extremely dry period of 1999–2000. Comparison of the α values for different recession curves permits dividing them into three groups:

Type 1—Curves from dolomite springs representing a year with "normal" precipitation (amount and distribution). This group holds four springs, with two recession curves each.

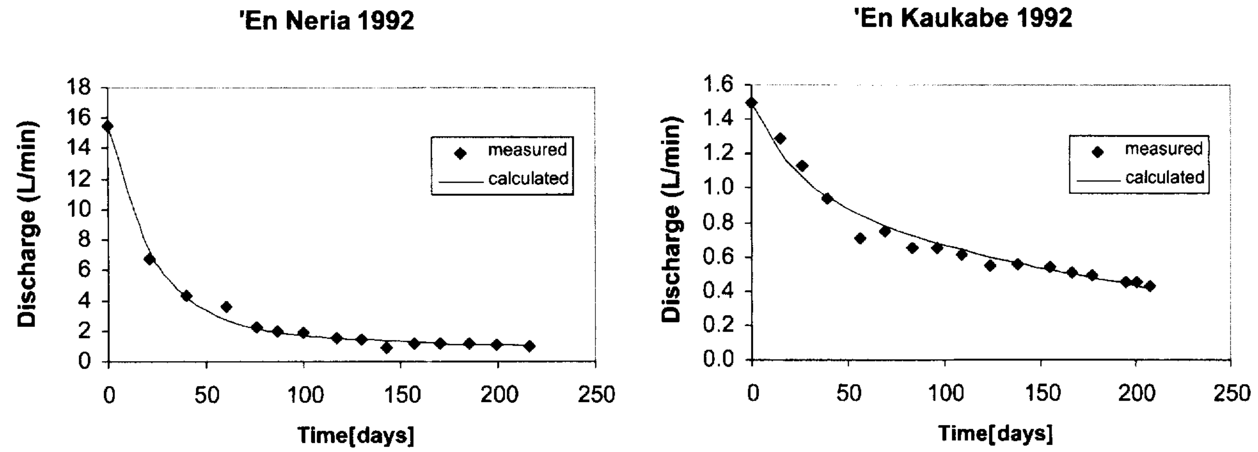

Figure 6. Fitting recession curves by substitution with average α_1. To prove that the α_1 values of the springs in dolomite are practically the same, their α_1 values were substituted with the average value. The two selected recession curves shown in the figure are the ones with the largest and smallest α_1 values.

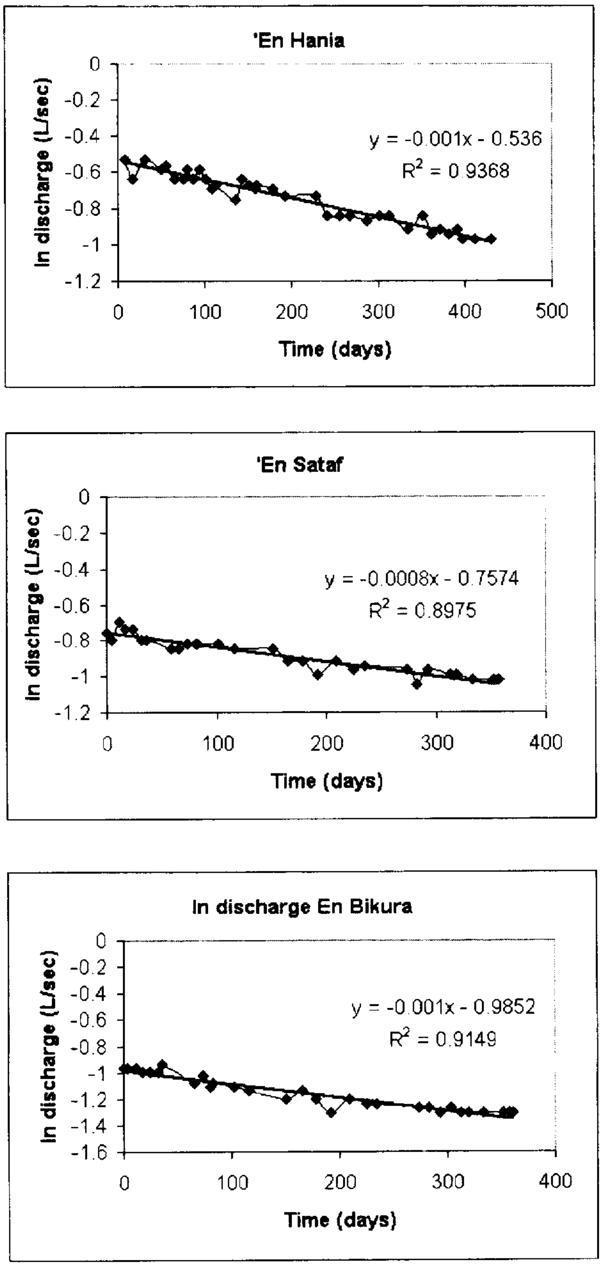

Figure 7. Recession curves (semilog scale) in the "dry" year (1999).

Type 2—Curves representing dolomite springs sampled during an extremely dry year. This group comprises three springs, each with one curve.

Type 3—One recession curve of a chalk spring samples during a "normal" year.

Two exponential components were found to be adequate to fit a normal year's data, within experimental error, from the first and the third type (Figures 4 and 5). An attempt to fit the curves with more than two components did not improve the fitting quality. The amplitude of a third component falls within the fitting scatter and is negligible relative to the amplitudes of the first two components. Hence, the initial discharge of each component is Q_b for the baseflow and Q_q for the quickflow. Together with the exponential coefficients, α_1 for the baseflow and α_2 for the quickflow, these parameters provide a complete quantitative description of the discharge decay (Table 1). It should be noted that the first data points in the 'En Kaukabe and 'En Retet springs in 1992 have been ignored (Figure 4), because the time interval between these and subsequent measurements was too long (one month). The data used to plot these springs was obtained at a two-week or less frequency.

The temporal variability of α_1 and α_2 within a given spring is much smaller than that observed between different springs. At the same time, the initial discharges, Q_b and Q_q, significantly change from year to year in the same spring. These observations imply that the geological environment and crack geometry are the decisive factors dictating the values of α_1 and α_2, whereas the initial discharges, Q_b and Q_q, depend on the amount of precipitation.

Baseflow

The α_1 values derived from recession curves of all dolomite springs during normal years range from 0.0033 (day^{-1}) to 0.0052 (day^{-1}). Moreover, fitting these recession curves using an average value of $\alpha_1 = 0.0042$ (day^{-1}) does not cause any deviation beyond data accuracy. The resultant curves displaying the largest deviation from the averaged value of α_1 are presented in Figure 6. Thus, all the recession curves of dolomite springs in normal years are combined into one group (type 1). In sharp contrast, the value $\alpha_1 = 0.0006$ (day^{-1}) for 'En Bardi is approximately

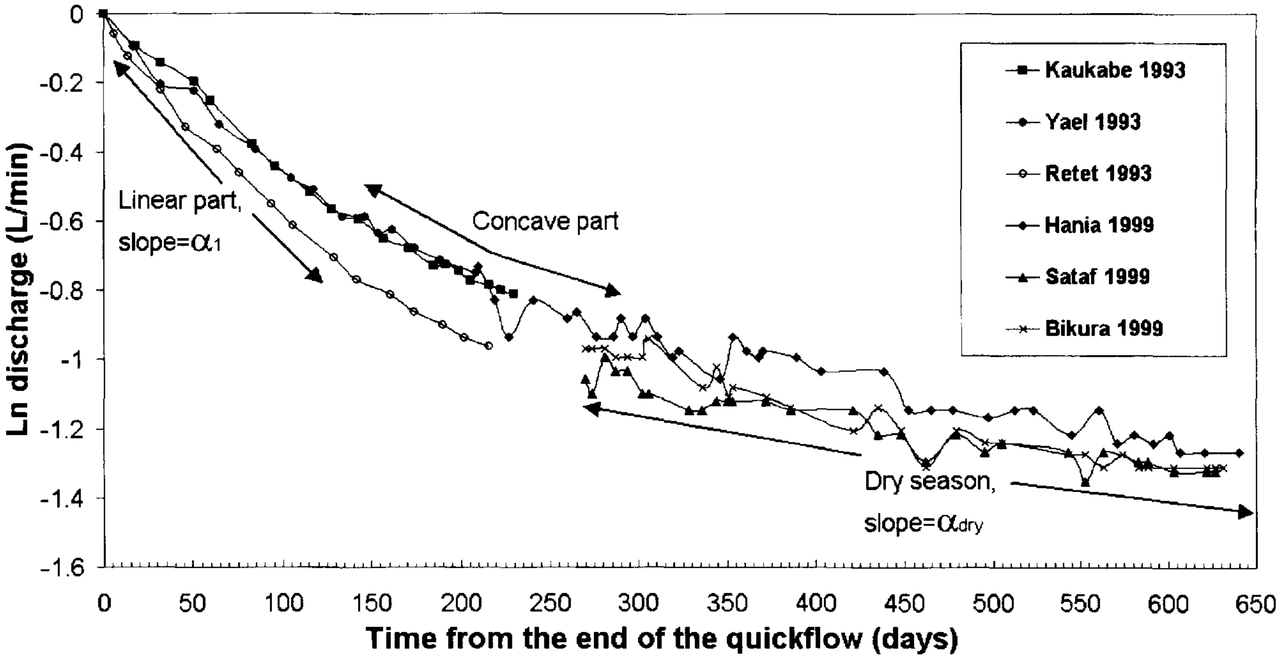

Figure 8. Normalized baseflows of long recession. This figure demonstrates the variation of the slope with time and shows the continuation of the "dry" year curves for the long recessions of the "normal" year.

one order of magnitude smaller than the α_1 value for the type 1 springs. Although the data for the 'En Bardi recession curve was collected for only one year, the significant difference in the slope of the baseflow excludes poor statistics as a source of error. In other words, all dolomite springs have a similar α_1 value that significantly differs from the value obtained for the chalk spring. It can therefore be concluded that the local lithology with the same petrographic characteristics and probably similar permeability dictate the similar baseflow exponential coefficient, α_1, whereas a much lower permeability would be reflected in significantly lower baseflow exponential coefficient.

Quickflow

Table 1 shows similar α_2 values obtained from discharge measurements taken during two seasons in the same spring. This, however, is not the case with α_2 values calculated for different springs in the same season, which show significant variability. Hence, it may be concluded that the quickflow, despite being a spring characteristic, is meaningless for spring classification. This is in agreement with the assumption that the quickflow represents the drainage through local cracks and is a consequence of geometry of local fractures and their connectivity, which varies from spring to spring.

The "Dry" Year

The year 1999 was extremely dry in Israel. Very small amounts of precipitation (< 300 mm) during the 1998–1999 winter were insufficient to produce the typical hydrograph shape with recession curve. Rather, the spring discharge can be interpreted as a continuous baseflow representing a recession period spanning two years. Had this been the case, one would expect a slope similar to the baseflow of type 1 springs. However, the recession curves of the three type 2 springs (i.e., dry year dolomite springs) are well fitted by one exponential component (Figure 7) with a slope that is significantly smaller than the slope of the baseflow of type 1 springs (α_1 values in Tables 1 and 2). This contradicts our previous expectation of the continuous baseflow with a constant slope and is discussed in the next section.

Discussion

Our results show that, during normal years, the type 1 dolomite springs have similar α_1 values and that each spring is characterized by a specific α_2 value. The normal year (type 3) chalk spring significantly differs in its α_1 exponential coefficient values from the corresponding values derived from type 1 hydrographs. This conclusion is in concert with the model that relates the exponential coefficients to the specific hydrological properties prevailing in each aquifer rather than to the amount of precipitation. A comparison of the α_1 values obtained here to α_1 values from other environments is essential for a reliability test. For that purpose, α_1 values of four karst springs studied by Padilla et al. (1994), amounting to 0.006, 0.007, 0.013, and 0.025 (day^{-1}), have been considered. It can be seen that two of the values reported by Padilla et al. (1994) are larger by an order of magnitude relative to our data. The fact that our approach yields significantly different α_1 values for different lithologies lends support to its reliability. Thus, under otherwise equal climatic conditions and geological environments (similar distribution of precipitation and recharge), the exponential coefficient of the baseflow reflects the hydrological characteristics of the spring area.

The similarity in all α_1 values of type 1 hydrographs stems from the fact that, under similar climate, the water in all the examined springs flows through dolomite. The baseflow has the same drainage rate for different springs of the same geological environment. The 'En Bardi 1993 spring (type 3) forms an exception because here the water flows through chalk. Lower α_1 value for this spring reflects that the hydraulic conductivity of chalk is considerably lower than in dolomite.

The observation that two recession curves in a given spring display similar α_2 values indicates that α_2 also is a spring-characteristic constant. Its value depends on the specific geometry, size, and connectivity of the local conduits. The α_2 value of 'En Bardi spring (type 3) in 1993 is half an order of magnitude larger than in the other springs, in good agreement with field observations of well-developed fracturing in the recharge area of that spring (Wust et al. 1997; Wust-Bloch and Wachs 2000).

A quantitative description of recession curves also allows estimating total spring storage volumes and individual contributions of the quickflow and the baseflow components. For fractured porous media, the ratio between the volume of water drained by the baseflow to the total spring storage volume is expected to be high (Freeze and Cherry 1979), provided the baseflow and quickflow really represent porous flow and local conduits, respectively. This ratio was calculated for every recession curve in each spring, using the expressions for the volumes (Equations 2 and 3), and the spring parameters (Table 1). The analysis shows that this ratio is >0.8 for almost all recession curves, including 'En Bardi with the largest quickflow and smallest baseflow exponential coefficients, in which most of the water volume (90%, Table 1) is drained by the baseflow. These calculations confirm that the baseflow should be related to the porous flow mechanism, whereas the quickflow depends on the structure of fractures in the medium.

The shape of the hydrographs obtained from the dry year data (Figure 8) is different from that of a normal year (Figure 1). Actually, in Figure 8 a semilogarithmic scale had to be used to contain the wide data range and better express the shape of the curves. The hydrographs can be visualized as long-term extensions of the hydrographs from the preceding year, 1998. The three springs have only one exponential component with a similar slope, α_{dry}, of ~0.001 (day^{-1}) (Table 2). This value is approximately four times smaller than the slope of the baseflow in normal years of ~0.004 (day^{-1}). This observation can be explained if we assume that the baseflow exponential coefficient, α_1, slowly decreases in time. Figure 8 enhances the validity of this interpretation. Even in a normal year, the normalized semilogarithmic curves tend to become slightly concave after ~100 days. The dry year data (Figure 7 and the later part in Figure 8) seem to be natural extensions of the normal year curves. Our previous analyses, which contained only normal year data, leads to the high-quality curve fits using two exponential components with constant exponential coefficients. For nine-month-long recession curves, slow variations in the slope of the baseflow could hardly be recognized. Only the dry year data provided sufficient time to make the change visible. The change in the slope of the baseflow is probably related to the change in the hydraulic conductivity of a partly saturated medium which decreases with a decrease in the moisture content (Freeze and Cherry 1979; Fetter 1988).

An alternative interpretation, relating the low slope to the emergence of a third exponential component, was discussed by Mero (1964), Forkasiewicz and Paloc (1967), and others. In this case, the baseflow decays faster than the third component because α_1 is larger than α_{dry}. After some time, the baseflow decreases, leaving the third component dominant and visible during the dry year. This is impossible during normal years in which the minute amplitude of the third component is totally masked by that of the baseflow. Our attempts to approximate the one-and-a-half-year-long recession curve with three constant-slope exponential components have failed. To reasonably fit a recession curve during the dry season with a third component, its amplitude should be large enough to be recognizable during the normal year. Alternatively, reducing the amplitude of the third component sufficiently during the normal year fails to provide a good fit for the dry period. Hence, one is left with the choice that the baseflow should slightly decrease in time.

Summary and Conclusions

The main factors that affect the recession curve exponential coefficients are the aquifer lithology and the geometry of the water conduits therein, as detailed in the following:

1. For normal rainy seasons, the discharge from dolomite springs is fitted by two exponents: the quickflow and baseflow. The exponential coefficients are approximately constant. The larger coefficient may reflect the fast flow through cracks (quickflow), whereas the lower one may represent the slow flow through the porous medium (baseflow).
2. The study of one spring, discharging from a chalk aquifer under the same climate as the dolomite springs, displays parameters of different magnitude. The lower α_1 and higher α_2 values of the chalk spring indicate a considerably lower hydraulic conductivity and well-developed fracturing of chalk relative to the adjacent dolomite.
3. Dry winters point to a weak temporal change of α_1. In normal seasons, this dependency can hardly be distinguished, but a long recession that occurs only after dry years clearly shows that α_1 decreases with time.

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