Formulating the spring discharge-function for the recession period by analyzing its recession curve: A case study of the Ranichauri spring (India)

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The Greater Himalayan region is witnessing a changing rainfall pattern from the last few decades. Low-intensity longer-duration rainfall events have now been replaced with intense and shorter-duration events that are further responsible for the reduced recharging of the spring catchments. Consequently, the natural springs are either drying up or becoming seasonal. Prediction of spring water availability during the recession period is the key to its proper management. The spring discharge-rate can be forecasted by studying its behaviour for the past recession periods. Expressing recession curve in mathematical terms requires its quantitative analyses *in priori*. It was found that the fitting of recession-curve (of the Ranichauri spring under study) with two exponential components gives accurate results. The maximum value of exponential coefficient (i.e., 0.0206) represents the major contribution to drainage from the spring-catchment's portion with highest permeability, whereas the minimum value (i.e., 0.0016) represents the major contribution to spring discharge from the portion with lowest permeability. Analyses show that the permeability of the porous medium is responsible for discharge rate and its capacity is responsible for perennial or seasonal behaviour of the spring. Using the mean values of the recession parameters, the master discharge-function of the spring for the recession period is formulated for calculating its discharge-rate during the recession period of any year. Apart from the year 2001, its predictions are in close agreement with the actually monitored data. The efficiency of the formulated master discharge function of the spring for the recession period has been evaluated equal to 0.965 using the Nash–Sutcliffe efficiency criterion.

1. Introduction

In recent years, the occurrences of extreme events such as droughts and floods have been on rise almost worldwide (Xu *et al.* 2004). Now it is a proven fact that the climate change is responsible for these hydrological extremes and due to this, availability of freshwater in Asia is projected to decrease as pointed out by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007). The Great Himalayas are also known as Water Tower of Asia (Qiu 2008; Xu 2008). Marked variation in the elevation along with the vegetation creates highly heterogeneous geography in the Himalayan terrain, and because of that this region has great climatic variability (Xu *et al.* 2009). Based on regional studies, it has already been pointed out that the climate impacts are already occurring in the Greater Himalayas (Beniston 2003; Cruz *et al.* 2007). The climatic

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variability in the region has also changed the rainfall pattern and the predictions show that there will be slight increase in rainfall along with greater intensity (Rees and Collins 2006; Singh *et al.* 2008; Tambe *et al.* 2011; Agarwal *et al.* 2012). This changed pattern is further responsible for the reduced recharging of the spring catchments, whose impact is visible through the diminishing and/or drying-up of the springs during the recession period of the year. Being completely dependent on these springs, the long term sustainability of human population in the region is questionable now.

The only feasible answer to this water scarcity problem in recession period is to store it when it is in excess during monsoon and post-monsoon seasons. However, the construction/purchase of water storage tank without optimizing its size requirement may be highly uneconomical. Depending on the knowledge regarding the future water availability from the spring, the difference in demand and availability can be evaluated. This difference will ultimately decide the dimensions of the tank required for storing the water. Hence, the solution to the said problem solely depends on the prediction of spring's discharge-rate in the recession period.

The graphical representation of temporal discharge variation of a spring is known as spring hydrograph. The behaviour of a spring can be administrated and forecasted by studying and analyzing it. Discharge-rate of a spring does not remain constant. Fluctuation in spring discharge-rate can be attributed to the temporal variations in the rate-of-recharge and the prevailing hydrologic and geologic conditions. After attaining a peak (during monsoon or post-monsoon), spring's temporal discharge starts decreasing in general (with minor ups and downs) till the next monsoon. Intermittent rainfall showers due to western disturbances do not affect the spring hydrograph majorly. The part of the spring hydrograph curve that extends from a base to the discharge peak is known as accession curve, whereas the part from discharge peak to the base of the next rise is known as recession curve (figure 1). Rise of accession curve is generally not smooth due to intermittent increase in discharge-rate of the spring. This increase in discharge-rate on irregular basis can be attributed to the irregular increase in head due to intermittent recharging from non-uniform rainfall events. Conversely, drop in recession curve is comparatively uniform (due to lack of any spring catchment recharging) and therefore, is generally opted for study. The study of recession curves is further useful for rainfall/runoff mathematical models, graphical separation of different flow components, estimation of discharge statistics, and indexing the storage capacity of catchment areas

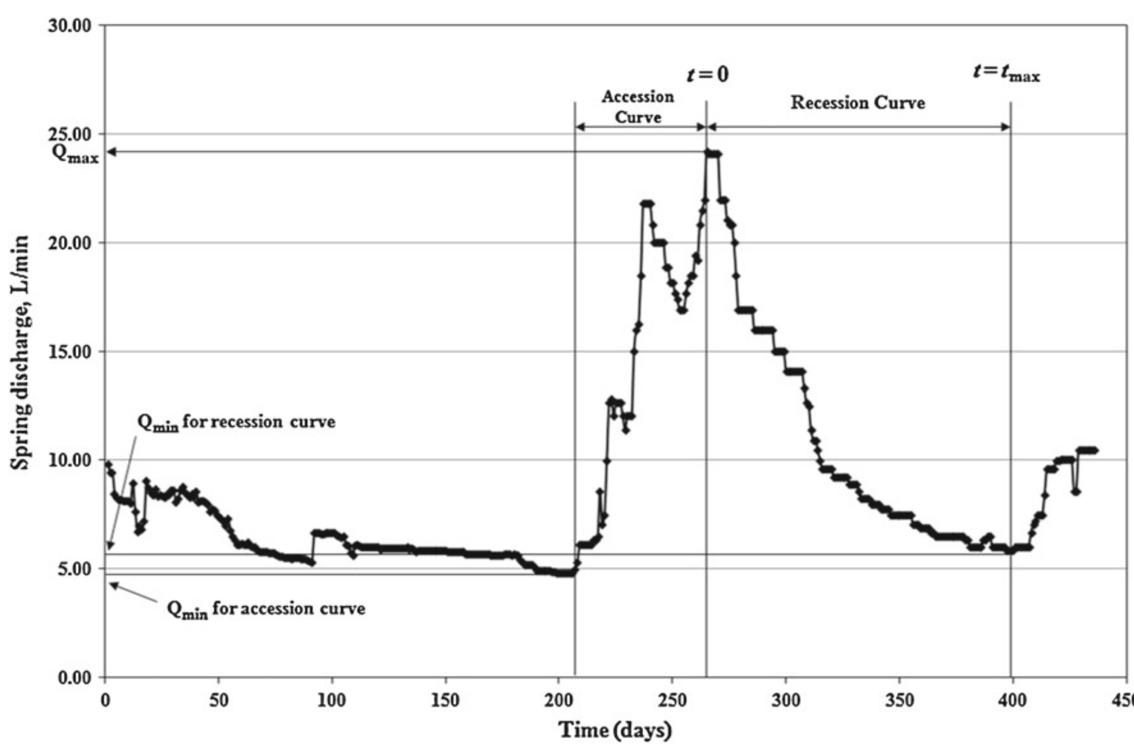

Figure 1. A typical hydrograph of Ranichauri spring. Accession and recession periods are also marked in the figure.

(Tallaksen 1995). Keeping the above-mentioned discussion in mind, the present study is undertaken with the following objectives:

- To study the recession curves for eight years temporal discharge data of a gravity-spring and delineate its quick- and base-flow values.
- To formulate the spring discharge-function for predicting its discharge-rate in the recession period.

2. Description of the study area

Garhwal, in the Western Himalayan region, is drained almost entirely by the Ganga and its tributaries. In comparison to valley areas (near to perennial streams) of the region, the population residing on high reaches face acute water scarcity in summer months. Agarwal *et al.* (2012) after studying the hydrological behaviour of springs in *Chandrabhaga* and *Danda* watersheds of the region, reported that the drying up of springs in early summer can be attributed to the decreased water-retaining capacity of soils which is being degraded by deforestation and thinning of forest cover and/or by a rainfall pattern of increasing high intensity storms and longer dry spells.

The spring selected for the present study is located at the College of Forestry and Hill Agriculture (Uttarakhand University of Horticulture and Forestry), Ranichauri at 30°18′47.09″N latitude and 078°24′33.34″E longitude at an elevation of 1871 m above mean sea level, in Tehri-Garhwal District, Uttarakhand, India. Location of the spring is shown in figure 2. The spring is categorized as gravity spring. Rainfall is monitored from the rain gauge situated in the college itself at location 30°18′44.94″N and 078°24′36.72″E and at an elevation of 1850 m. It measures the rainfall on a daily basis. The temperature of the region ranges between 3° and 28°C. The annual rainfall varies from 1200–1400 mm, of which 70–80% is normally received during the months from June–September (i.e., monsoon season). The region belongs to the *Krol* formation and is having phyllite lithology. The soils of the spring catchment are formed under cool and moist climate from rocks of biotite schist and phyllitic material. These are shallow, gravelly, and impregnated with weathered fragments of stones and parent rock. The soils are brown to greyish-brown and dark grey in colour, besides being generally non-calcareous and neutral to slightly-acidic in reaction. The vegetation of the area is dominated with oak and minor shrubs like *Myrsine Africana*, *Berberis lyceum*, *Rubus ellipticus* and *Sarcococca hookeriana*.

3. Development of spring hydrographs

Spring hydrograph represents the temporal variation of its discharge-rate (Q). For the present study, rainfall data as well as daily discharge-rate of the spring monitored for eight years is procured from the All India Co-ordinated Research Project (AICRP) on Groundwater Utilization, Department of Irrigation and Drainage Engineering, G B Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India. Figure 1 shows that the recession curve generally extends from the month of September/October to April/May next year. Small-scale frequent variations in spring discharge during recession period can be visualized from figure 1. To reduce the sensitivity of these frequent variations, it was decided to plot the spring discharge-rate on the logarithmic scale. The logarithmic transformation of the discharge-rate creates smoothness in the hydrograph. Keeping this in

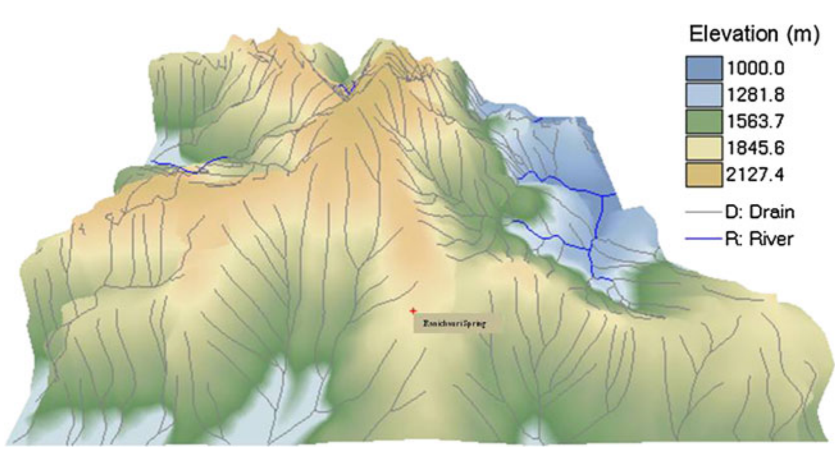

Figure 2. Location map of Ranichauri spring.

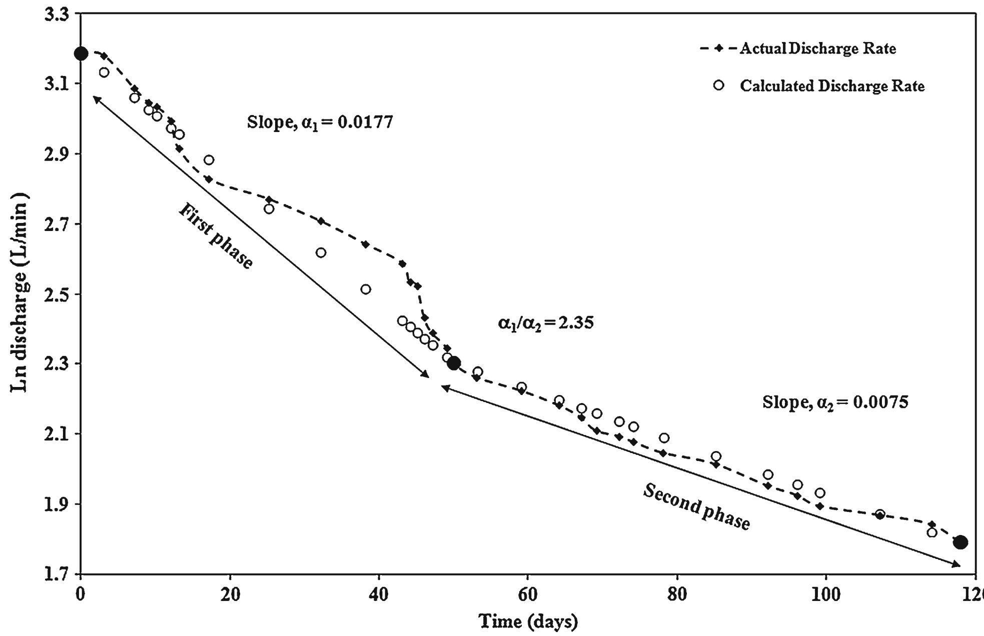

Figure 3. Recession curve for the year 1999.

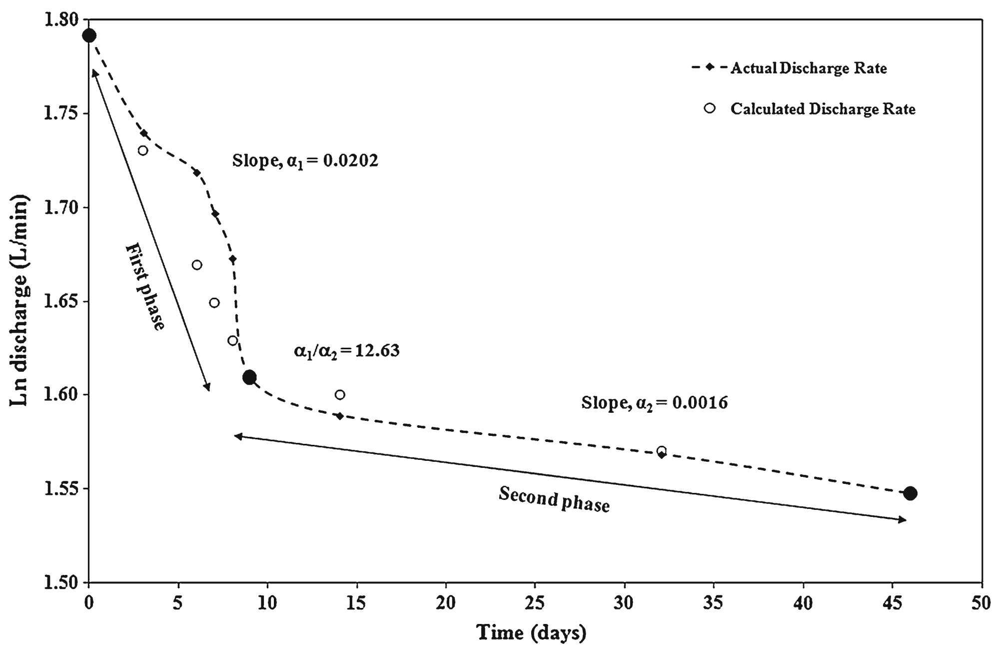

Figure 4. Recession curve for the year 2001. Note that the recession period ends after 46 days and slope-ratio is exceptionally high.

view, spring hydrographs (semi-logarithmic Q *vs.* t) were developed for eight years and the recession curves are demarcated. Among the all eight curves, only four recession curves for the year's, viz., 1999, 2001, 2002, and 2005 are presented in figures 3–6. Because of their typical behaviour, these curves are specifically chosen. First value of the discharge rate (i.e., the discharge peak) is placed against time $t = 0$ and rest of the data is timed consecutively.

4. Exponential component fitting

After demarcating the recession curves, next step is to fit these curves with the number of exponential components so that results near accuracy could be achieved. Considering one-dimensional flow through the homogeneous and isotropic spring catchment under a moderate hydraulic head gradient, Boussinesq (1904) fitted the recession curve by

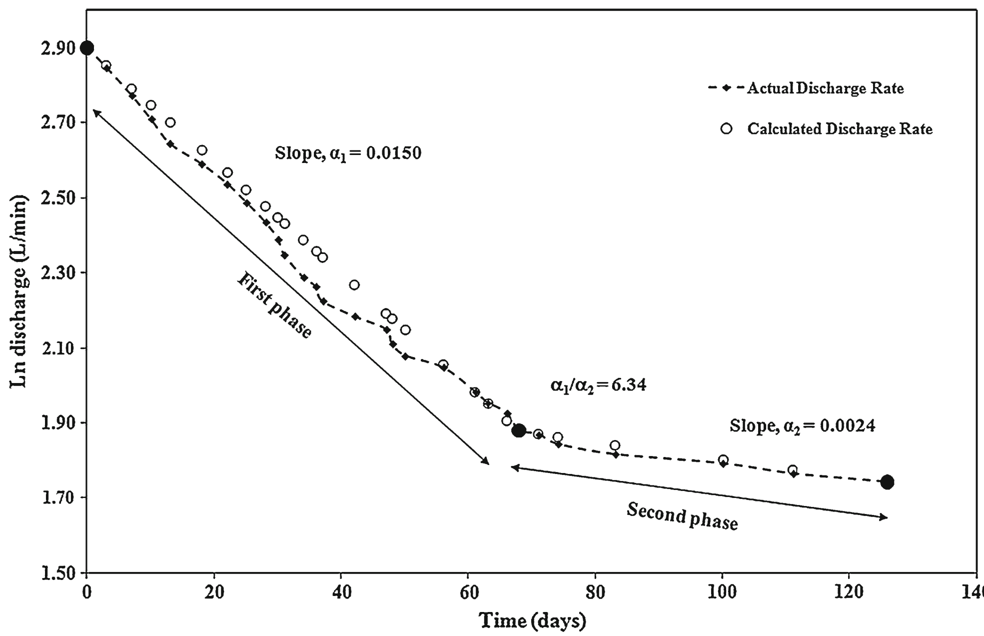

Figure 5. Recession curve for the year 2002.

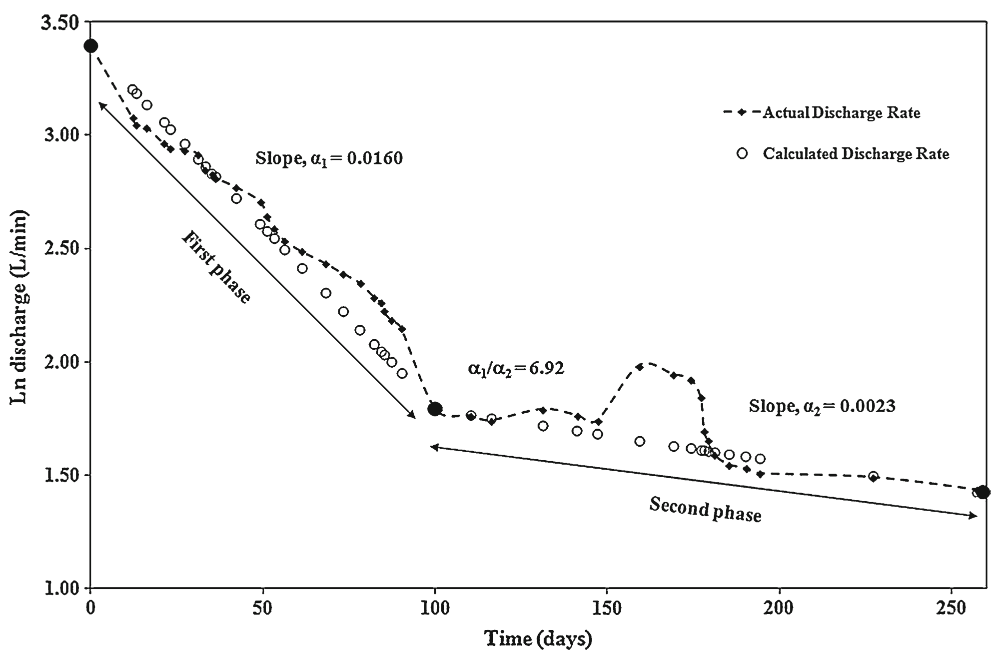

Figure 6. Recession curve for the year 2005. Note the increase in spring discharge in the month of March 2006 due to rainfall in the month of January 2006.

a sum of two exponential components. The original Boussinesq equation describes the flow in unconfined aquifers. Brutsaert and Lopez (1998) have thoroughly discussed the three theoretical solutions of the Boussinesq equation that have the general form of a power function as:

$$\frac{dQ}{dt} = -aQ^b. \tag{1}$$

In equation (1), Q is the recession flow, t is time, and a, b are constant coefficients. The coefficient a can be directly related to the groundwater reservoir's characteristics and b is an exponent whose value depends on the time scale (Malvicini *et al.* 2005). They analyzed the spring flow data by considering it a linear reservoir to determine the dry season spring flow behaviour and half-life of the spring. A more general analytical expression into hydro-technical theory and practice for defining a hydrograph recession curve in a long lasting dry period (with no precipitation) is introduced by Maillet (1905) and that can be written as:

$$Q_t = Q_0 e^{-\alpha t}. \tag{2}$$

In equation (2), Q_t is the discharge at time t, Q_0 is the discharge rate at the start of the recession, and α is a recession coefficient which depends upon the geological and morphological structure of the catchment analyzed.

Alternatively, Mangin (1975) proposed the recession curve fitting into non-exponential component for earlier duration and an exponential component for later duration. Amit *et al.* (2002) supported the Boussinesq results and showed that the recession curves can be well fitted by a function that consists of two exponential terms. However, unless the recession curve decay is very smooth, the number of exponential components required to fit a recession curve depends on the number-of-time it changes slope. Petras (1986) reported that a change in the slope of the recession curve can be attributed to the heterogeneity of the spring catchment. Furthermore, a recession curve also changes slope depending on the quantity of recharge the spring catchment received during the accession period. If the time-lag between rainfall and the spring discharge is more, such changes generally appear during the recession period (see figure 6). An unusual rainfall event (i.e., 29 mm/day) in the month of January 2006 increases the spring discharge in the month of March 2006. Hence, the recession curve changes its general slope pattern for few days and later on adopts the initial trend. While fitting the curves mathematically, such occasional changed slope patterns are not considered for writing a new exponential component. Only when the recession curve is presenting the changing slope pattern for considerable duration every year, a new exponential component is fitted. The changes in recession-curve slopes can be easily interpreted visually from the recession graph before fitting. Due to the site specific nature, all spring catchments have their unique features (especially, from geological point of view). Hence, the number of exponential components required to fit a recession curve for a particular spring may vary. For that reason, before evaluating the spring parameters, it is necessary to compare the results by fitting the recession curve with one, two, and three exponential components. For the purpose, analytical expressions defining the spring-hydrograph's recession curve and its yield for the recession period are required. A modified form of equation (2) that represents the recession curve with N number of exponential components can be written as:

$$Q_{t_i} = Q_{0_i} \cdot e^{-\alpha_i t_i}\,; \quad \text{for } i = 1 \text{ to } N, \ \ t_i = 0 \text{ to } T_i. \tag{3}$$

In equation (3), Q_{0_i} and Q_{t_i} represent the discharge-rates of the ith component of the recession curve at the initial and at time t_i, respectively; T_i is the total number of days in the particular exponential component; and α_i is the slope of the ith exponential component of the recession curve on the logarithmic scale and is termed as exponential coefficient (or occasionally depletion coefficient). Based on equation (3), a general equation for computing spring yield V for the recession period with one exponential component can be expressed as:

$$V = \sum_{t_1=0}^{T_1} Q_{t_1} = \sum_{t_1=0}^{T_1} Q_{0_1} \cdot e^{-\alpha_1 \cdot (t_1 - 0)}. \tag{4}$$

Table 1. *Comparison of discharge calculated by fitting recession curve for the year 1999 by one, two, and three-exponential components.*

Year 1999	One-exponential component	Two-exponential components		Three-exponential components		
Slope	$\alpha_1 = 0.0118$	$\alpha_1 = 0.0177$	$\alpha_2 = 0.0075$	$\alpha_1 = 0.0139$	$\alpha_2 = 0.0411$	$\alpha_3 = 0.0075$
Initial discharge rate (L/min)	24.19	24.19	10.00	24.19	13.33	10.00
Duration (days)	118	50	68	43	7	68
Calculated discharge (million-litres)	2.22	1.99		2.01		
Actual discharge (million-litres)	1.98					
Over (+)/under (−) prediction from actual (%)	+12.00	+0.77		+1.66		

Similarly, the spring yield V for the recession period with N number of exponential components can be obtained by modifying equation (4) as:

$$V = \left[\sum_{t_i = T_{i-1}}^{T_i - 1} Q_{0_i} \cdot e^{-\alpha_i \cdot (t_i - T_{i-1})} \right] \Bigg|_{\text{for } i=1 \text{ to } N-1} + \left[\sum_{t_N = T_{N-1}}^{T_N} Q_{0_N} \cdot e^{-\alpha_N \cdot (t_N - T_{N-1})} \right] \Bigg|_{\text{for } i=N} . \quad (5)$$

As it is already mentioned in section 3 that first value of the recession period is kept against time equal to zero; therefore, in equation (5), T_0 will also be equal to zero. To avoid any confusion to the readers, all the parameters of equations (3–5) are kept same as found in literature. Using the analytical equation (3), the recession curve of the year 1999 is fitted with one, two, and three-exponential components. The evaluated exponential coefficients (i.e., slopes) for the three cases are presented in table 1. From the slope, initial discharge and duration values of various exponential components, three independent expressions based on equations (4) and (5) for calculating spring yield in a recession period of 118 days can be written as:
For one-exponential component:

$$V = \sum_{t_1=0}^{118} Q_{t_1} = \sum_{t_1=0}^{118} 24.19 \times e^{-0.0118 \times (t_1 - 0)}. \quad (6)$$

For two-exponential components:

$$V = \left[\sum_{t_1 = T_0 = 0}^{50-1} 24.19 \times e^{-0.0177 \times (t_1 - 0)} \right] \Bigg|_{\text{for } i=1 \text{ to } 1} + \left[\sum_{t_2 = 50}^{118} 10.00 \times e^{-0.0075 \times (t_2 - 50)} \right] \Bigg|_{\text{for } i=2} . \quad (7)$$

For three-exponential components:

$$V = \left[\sum_{t_1 = T_0 = 0}^{43-1} 24.19 \times e^{-0.0139 \times (t_1 - 0)} + \sum_{t_2 = 43}^{50-1} 13.33 \times e^{-0.0411 \times (t_2 - 43)} \right] \Bigg|_{\text{for } i=1 \text{ to } 2} + \left[\sum_{t_3 = 50}^{118} 10.00 \times e^{-0.0075 \times (t_3 - 50)} \right] \Bigg|_{\text{for } i=3} . \quad (8)$$

Calculated spring yield for the recession period with one-, two-, and three-exponential components from equations (6–8) are computed and tabulated in table 1. Perusal of the table 1 clearly indicates that the fitting of the recession curve by exponential components for all the three cases overpredicts the recession-period discharge of the spring in general; though, the predictions by mathematical expression with two-exponential components is near accuracy (i.e., +0.77%) as compared to one (i.e., +12%) and three-exponential component (i.e., +1.66%) results. Hence, the quantitative analysis for the eight-year recession curves will be based on the mathematical expressions fitted with two-exponential components.

5. Results and discussion

5.1 *Interpretation of slope values*

Recession curves for the eight years are fitted with two-exponential components following the procedure as described in section 4. The exponential coefficients (i.e., the slopes α_1 and α_2) for the two demarcated segments in all the recession curves are presented in table 2 and are also depicted on the selected figures (3–6). The division of recession curve in two segments is demarcated by solid circular markers (i.e., •). Slope-ratios (i.e., α_1/α_2) for the eight recession curves are also tabulated in table 2. Except for the years 2001, 2002, and 2005 with the highest for year 2001 (i.e., 12.63), the values of the slope-ratios in general are comparable. Abrupt change in slope of the recession curve leads to such high value (see figure 4). During the first phase of the recession periods in these three years, rapid depletion in the catchment-storage has occurred. Obviously, it is through the specific porous medium of the catchment that has high permeability. It is worth mentioning that a spring catchment in general, is a complex combination of different geological mediums having marked difference in permeability values. Hence, lesser recharging of the spring catchment is the basic cause for this abrupt change in slope. For better understanding of the concept in simpler way, a hypothetically sketched schematic map of the spring catchment is shown in figure 7. Since, the Ranichauri spring under study is giving accurate results with two-exponential components; the hypothetical sketch in figure 7 is shown with two portions having different permeability values separated by a contact layer. Shaded region of the sketch represents the low permeability region. Depending on the head of water in the particular portion, water movement across the contact layer is possible in both ways (as shown by arrows). In the hypothetical sketch, water movement from the portion 2 to portion 1 is shown at particular time t_1. First phase of recession curves (figures 3–6) represents the contribution of the spring catchment mainly from portion 2. However, it is worth mentioning that the

Table 2. *Slope ratio of recession curves for different years.*

(1) Year	1999	2000	2001	2002	2003	2004	2005	2006	Average
(2) Rainfall (mm)	939.70	1334.40	719.10	1254.60	1173.80	1174.70	1386.90	897.00	1110.03
(3) Q_{0_1} (L/min)	24.19	30.30	6.00	18.18	18.46	20.00	29.85	20.00	20.87
(4) α_1 (day^{-1})	0.0177	0.0123	0.0202	0.0150	0.0133	0.0205	0.0160	0.0206^{+}	0.01695
(5) Number of days for which the slope α_1 is evaluated	50	79	9	68	63	25	100	43	~ 55
(6) Q_{0_2} (L/min)	9.52	11.93	$	7.16	7.27	7.87	11.75	7.87	8.22
(7) α_2 (day^{-1})	0.0075	0.0055	0.0016$^{@}$	0.0024	0.0057	0.0070	0.0023	0.0047	0.0046
(8) Number of days for which the slope α_2 is evaluated	68	108	37	58	90	71	159	93	~ 86
(9) Exponential coefficients (Slopes) ratio (α_1/α_2)	2.35	2.21	12.63$^{\#}$	6.34$^{\#}$	2.34	2.92	6.92$^{\#}$	4.37	3.69

$ Since, the recession period of the spring was for 46 days (i.e., 9 + 37) only that is less than 55 days (i.e., average number of days for which the slope of first exponential component is evaluated). Hence, there is no Q_2 value for this particular case.
+ It indicates the major contribution to spring discharge from the catchment-portion having highest permeability and is termed as quick-flow.
@ It indicates the major contribution to spring discharge from the catchment-portion having lowest permeability and is termed as base-flow.
# Slope ratios with exceptionally high values. Due to abrupt change in slope of the recession curve from first exponential component to second leads to such high values.

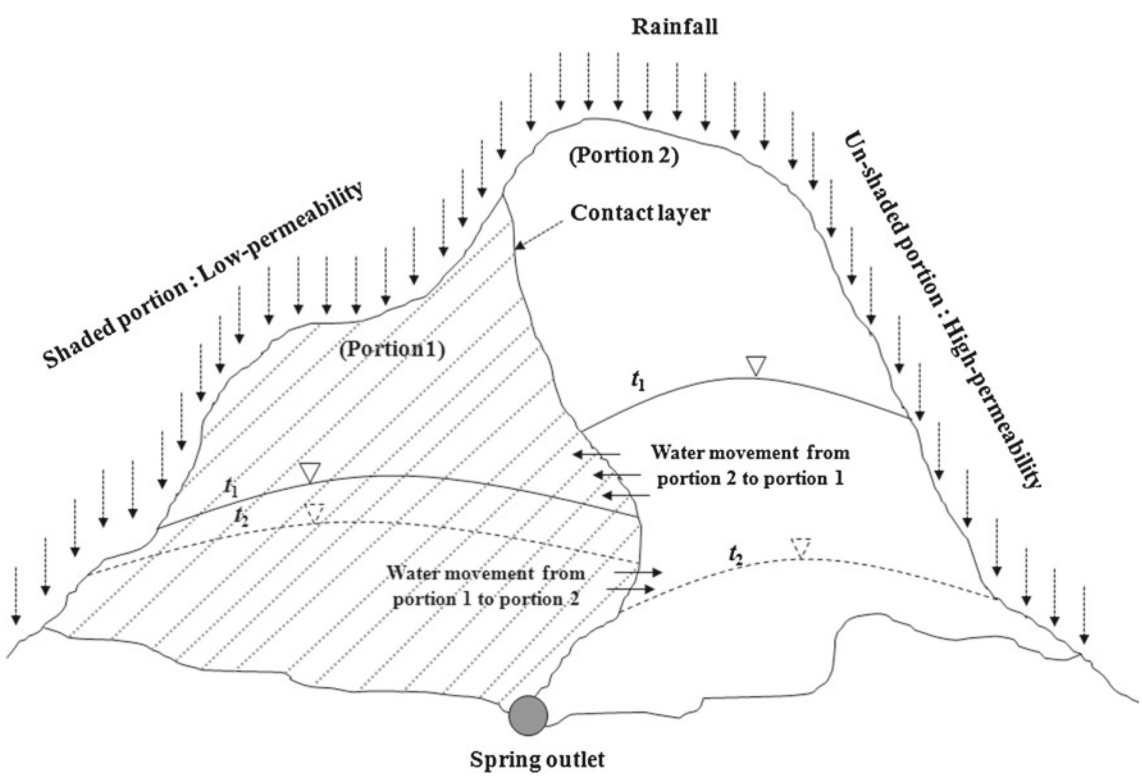

Figure 7. Hypothetically sketched spring catchment showing two portions having different permeability values.

actual spring discharge includes the contribution from both the portions and distinguishing these contributions (to the total discharge-rate) is a very difficult task and needs further study. As soon as the water level (or head) in portion 2 becomes lower than portion 1 (say at time t_2), water will start seeping towards portion 2. From the above discussion, it is clear that the major contribution to spring discharge from portion 2 will steer the recession curve steeply; and if this contribution is further increased by drainage from portion 1, it will flatten the recession curve.

Rainwater after infiltrating through the catchment's surface-soil recharges the two portions of the catchment. The storage-rate (i.e., intake rate) of water in particular portion of the spring catchment depends on its permeability (as is shown in figure 7 by different water levels at time t_1). Volume of water stored in particular portion of the spring depends on its storage capacity. From this justification it is clear that the maximum volume of water in lesser time will be stored in the portion with highest permeability and capacity. Conversely, it is also true that the portion having highest permeability will deplete earlier in comparison to catchment-portions with low permeability (see the water level at time t_2). From the above discussion, it is clear that the 'temporal variation in spring discharge' depends on the capacity and permeability of different spring-portions within the catchment. More elaborately, the permeability of the porous medium is responsible for the discharge rate and its capacity is responsible for perennial or seasonal behaviour of the spring.

The year 2001 received 719.10 mm of rainfall and that was exceptionally lower than the average annual of the region (i.e., 1110.03 mm). Moreover, the major distribution of this rainfall was concentrated in the second half of the monsoon season. Unfortunately, the rainfall intensity was not monitored. However, the rainfall's major concentration in the second half of the monsoon-season strengthens the possibility that the initial moisture content of the surface-soil was high. The mentioned factor was probably responsible for lesser recharging of all portions of the catchment and that was reflected clearly by the spring hydrograph. Steep slope of the recession curve in the first phase of the recession period clearly shows that the spring discharge-rate was dependent on the high permeability portion of the spring catchment (i.e., portion 2) and that was depleted within a period of 9 days only. Conversely, the mild slope of recession curve in the second phase of recession period reflects the dependency of spring discharge-rate on the low permeability portions of the catchment (i.e., portion 1).

In spite of rainfall sufficiency in years 2002 and 2005 (i.e., 1254.60 and 1386.90 mm, respectively), the basic cause for high slope-ratios in these two years is again same (i.e., lesser recharging of the spring catchment). However, the basis of lesser recharging is different for these cases. It can probably be attributed to the lesser infiltration opportunity time, the rain-water got due to high rainfall-intensity than the infiltration rate of catchment-soil. Consequent to this fact, major component of rain water gets converted into overland flow and escaped from the catchment.

The slope values marked with '@' and '+' in table 2 are the two extremes of the recession curves for the eight-year data analyses. Maximum value (i.e., 0.0206) of exponential coefficient (i.e., slope) indicates the major contribution to drainage from the catchment-portion having highest permeability and can suitably be termed as quick-flow. In other terms, we can express that it represents the least recharging of the spring catchment's lesser permeable portion whose contribution flattens the recession curve. Note that the rainfall reception in year 2006 is ∼19% less than the average. Amit *et al.* (2002) in a study reported that the quick-flow represents the drainage through local cracks and is a consequence of geometry of local fractures and their connectivity. However, they have not mentioned about the contribution from the lesser permeable portions of the catchment during quick flow. On the other hand, the minimum value (i.e., 0.0016) indicates the major contribution to drainage from the catchment portion having lowest permeability and is usually termed as base-flow.

5.2 *Formulation of the master discharge function for the recession period*

The mean values of all the parameters of the fitted exponential components are presented in the last column of table 2. Using the mean values of rows (4, 5, 7 and 8), the master discharge function of the spring for the recession period can conveniently be formulated as:

$$V = \sum_{t_1=0}^{55-1} Q_{0_1} \times e^{-0.01695\,\times\,(t_1-0)} + \sum_{t_2=55}^{151} Q_{0_2}\,(=Q_{55}) \times e^{-0.0046\,\times\,(t_2-55)}. \tag{9}$$

In equation (9), Q_{0_1} is the initial discharge-rate for first phase of the recession period with an average duration of 55 days; Q_{0_2} is the initial discharge-rate for second phase of the recession period and is equal to the discharge rate of the spring after 55 days in first phase. It means that the last discharge-rate value of first-phase recession period will be the initial discharge-rate for the second phase. Although, the mean duration for evaluating slope α_2 in second phase of the recession period came equal to 86 days, for the purpose of testing the formulated master discharge-function's performance, the actual durations are considered for the second-phase recession period. It is for the reason that the different duration recession-periods were witnessed during the data collection years.

For evaluating the performance of the formulated master discharge function of the spring for

Table 3. *Comparison of the calculated discharge evaluated using developed discharge-function with the actually monitored results.*

Year	1999	2000	2001	2002	2003	2004	2005	2006	Average
Calculated discharge of the spring (million-litres)	2.02	3.29	0.28	1.58	1.79	1.47	3.80	1.82	1.94
Actual discharge of the spring (million-litres)	1.98	3.60	0.34	1.59	2.00	1.56	3.48	1.69	2.03
Percentage error in calculating discharge over actual	+2.00	−8.76	−16.46	−0.80	−10.31	−5.51	+9.19	+7.67	−4.66
Efficiency of the spring discharge-function, E					0.965				

the recession period, the actually monitored Q_{0_1} (row 3, table 2) and the second-phase recession-period durations (row 8, table 2) are incorporated in equation (9) and the calculated-discharge of the spring for all the eight years is tabulated in table 3. The over- and under-calculated errors from the actually monitored discharge are also presented in the table. The calculated results are comparable with the actual spring yield except for the year 2001. It is already explained in section 5.1 that the monsoon rainfall in year 2001 was significantly below average. However, the winter season of the year 2001–2002 received good amount of rainfall (∼507 mm) starting from the mid-December 2001 to end-March 2002. This unusual rainfall increases the spring discharge that break-off the recession period only after 46 days from the discharge peak (see figure 4). Since, this recession period was even smaller than the average annual-duration of the first exponential component (i.e., 55 days) of the spring, the predicted results notably varied from the actual.

5.3 *Efficiency of the formulated master discharge function for the recession period*

The process of assessing the performance of a hydrologic model requires the hydrologist to make subjective and/or objective estimates of the 'closeness' of the simulated behaviour of the model to the field observations (Krause *et al.* 2005). Alternatively, the efficiency criterion is defined as mathematical measures of how well a formulated-model simulation fits the available observations (Beven 2001). In the present study, the Nash–Sutcliffe efficiency criterion has been used to test the performance of the formulated master discharge-function (equation 9) of the spring for the recession period. In mathematical terms, the criterion can be written as:

$$E = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2}. \qquad (10)$$

In equation (10), E is the efficiency; O_i is the observed and P_i is the predicted value. The symbol $\overline{O}$ represents the average of the observed values. The range of E lies between 1.00 (perfect fit) and $-\infty$. Incorporating the observed and predicted values of spring discharge from table 3 in equation (10), the efficiency E value comes equal to 0.965.

6. Summary and conclusions

Prediction of spring discharge-rate is the key to the proper management of water in the recession period. The behaviour of a spring can be administrated and forecasted by studying its hydrograph. In the present study, therefore, an effort has been made to formulate the master discharge function for computing the spring flow for the recession period based on the present day discharge-rate. For the purpose, eight-year temporal discharge data of Ranichauri spring was procured from the AICRP on Groundwater Utilization, Department of Irrigation and Drainage Engineering, G B Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India. The analyses have been completed after fitting the eight-year recession curves by exponential components. The following conclusions have been drawn from the results:

- It is concluded that the fitting of the recession curves by two-exponential components predicts the spring discharge in the recession period near accuracy (i.e., with error +0.77%) as compared to one- (i.e., with error +12.00%) and three-exponential components (i.e., with error +1.66%) results.
- The values of the slope-ratios (α_1/α_2) are comparable except for the years 2001, 2002, and 2005 with the highest value in the year 2001 (i.e., 12.63). Abrupt change in slope of the recession curve leads to such high value. Lesser recharging of the different portions of the spring catchment (especially having low permeabilities) is the basic

reason for the exceptionally high slope-ratios. Further, the conclusion is drawn that the 'temporal variation in spring discharge' depends on the capacity and permeability of different spring-portions within the catchment. The permeability of the porous medium is responsible for the discharge rate and its capacity is responsible for perennial or seasonal behaviour of the spring.

- The maximum value of slope (i.e., 0.0206 in year 2006) indicates the major contribution to spring discharge from the catchment-portion having highest permeability and can be termed as quick-flow. On the contrary, the minimum value (i.e., 0.0016 in year 2001) indicates the major contribution to spring discharge from the catchment portion having lowest permeability in comparison to high permeable portion and is usually termed as base-flow.
- Based on the average values of evaluated parameters for eight years' recession curves, master discharge-function of the spring for the recession period is formulated with two exponential components. The formulated discharge-function predicted the spring discharge in well agreement with the actually monitored data except for the year 2001. It is because of the fact that the recession period for the said year was only for 46 days and that is even lesser than the fitted average annual-duration of the first exponential component (i.e., 55 days) of the spring.
- The Nash–Sutcliffe efficiency E of the formulated master discharge-function of the spring for the recession period comes equal to 0.965.

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