Recession Flow Analysis for Assessment of Springs

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ABSTRACT:
Water security of mountainous basins is mainly dependent on the springs water supply as the main source of drinking water. Sustainable development of springs to ensure water security requires the proper assessment of the flow characteristics of the spring flows. Thus, measurement and prediction of spring flows from aquifers are critical to water resources managers to maintain flows. As the springs integrate the signal of geological and hydrological processes over large spatial areas and long periods of time, they are an indirect source of information. Therefore, spring hydrograph recession analysis is widely used for the assessment of spring flow instead of data intensive physically based models. This paper presents a detailed analysis and explanation of break points on master recession curve (MRC) via various values of recession coefficient α in Maillet's equation. For this purpose the application of fully automatic objective-based method for MRC separation has been demonstrated with use of spring flow time-series data observed at Rupado Village in Danda Watershed of Tehri Garhwal district, Uttarakhand, India. Daily time series from 11 August, 1999 to 2 March, 2001 and two daily time series from 5, March 2001 to 31, December 2004 have been used in the analysis. The obtained recession constants when MRC separated in three segments are k_1= 0.893, k_2 = 0.936 and k_3 = 0.949 for fast flow, intermittent flow and recession spring flow components, respectively. Here, high value of recession constant k_3 tends to indicate the dominance of recession flow in the spring flow. Similarly seasonal MRC's for rainy, winter and summer season are generated. The recession constants values for separated MRC segments 1-3 are closely matching with the recession constant values obtained from MRC's for rainy, winter and summer season, respectively. The analysis of seasonal flow duration curves (FDCs) suggest that attention should be given for water storage during rainy season which could be used during water scarcity period.

1. INTRODUCTION

Across Indian Himalayan mountainous basins, the dwellers are facing the severe problem of water scarcity, especially of drinking water which is mainly fulfilled by spring's water supply. In such areas, generally the springs are of small orders which become dry during summer months. Flow/discharges in such springs vary considerably depending on the catchment characteristics (e.g. area, hydrogeology) and recharge in the catchment. The knowledge about the number of springs as well as their flow characteristics is important for sustainable development of the water resources of these areas (Goyal, 2001). Measurement and prediction of spring flows from aquifers are critical to water resources managers to plan and manage the water supply from these sources.

For more than a century, hydrologist and hydro-geologists have been investigating the processes of stream and springs baseflow recession. The assessment of spring flow using physically based model requires the knowledge of fundamental input parameters such as hydraulic conductivity, specific yield and effective hydraulic conductivity describing the subsurface hydrology. Among the typically used hydraulic parameters, hydraulic conductivity or transmissivity is the most problematic to obtain, in part because the variability of observed values spans many orders of magnitude than other parameters. Springs integrate the signal of geological and hydrological processes over large spatial areas and long periods of time; they are an indirect source of information for this purpose. Thus, spring hydrograph recession analysis has a wide application in the forecasting of low flows, estimating groundwater resources in the catchment and base flow augmentation (e.g. Amit et al., 2002; Arnold et al., 2005; Birk and Hergarten, 2010; Tallaksen, 1995). A report from Vogel and Kroll (1996) study in central western Massachusetts indicate that recession flow statistics are highly correlated with the product of watershed area, average watershed slope, and the baseflow recession constant. They further state that the baseflow recession constant can be used as a surrogate for both watershed hydraulic conductivity and drainable soil porosity.

The objective of the present paper is to present a methodology for construction of MRC and optimally separating MRC into user defined two or three segments based on the flow duration curve analysis. Three separate MRC has also been generated using the time series of spring flow during the three seasons (rainy, winter and summer seasons). Based on these analyses, comparative assessment of reliability and availability of the existing spring flow during the three seasons through flow duration curves (FDC) has been demonstrated. The main focus of the study is on the demonstration of MRC separation technique using fully automated objective based method with observation gap in time-series data.

2. STUDY AREA AND DATA USED

Danda watershed is located in Hindolakhal block of Devprayag Tehsil in Tehri Garhwal district of Uttarakhand. The Danda watershed lies at an elevation 777-1810 m above MSL, between latitude 30° 13' 36" N to 30° 14' 46" N and longitude 78° 37' 04" E to 78°38' 56" E (Fig. 1). The area falls in Survey of India (SOI) Toposheet No. 53 J/12. The Danda watershed has an area of 450.44 hectare at the gauging site near Dugyar village. The Watershed has a highly undulating topography with steep slopes and scanty vegetation. The major land use/land cover classes for the catchment under the study area can be classified as agricultural area (small % is irrigated), degraded forest, dense forest, fallow, grass with shrubs, waste land and settlement area. The main source of water is numerous springs and a few perennial streams (NIH, 2003).

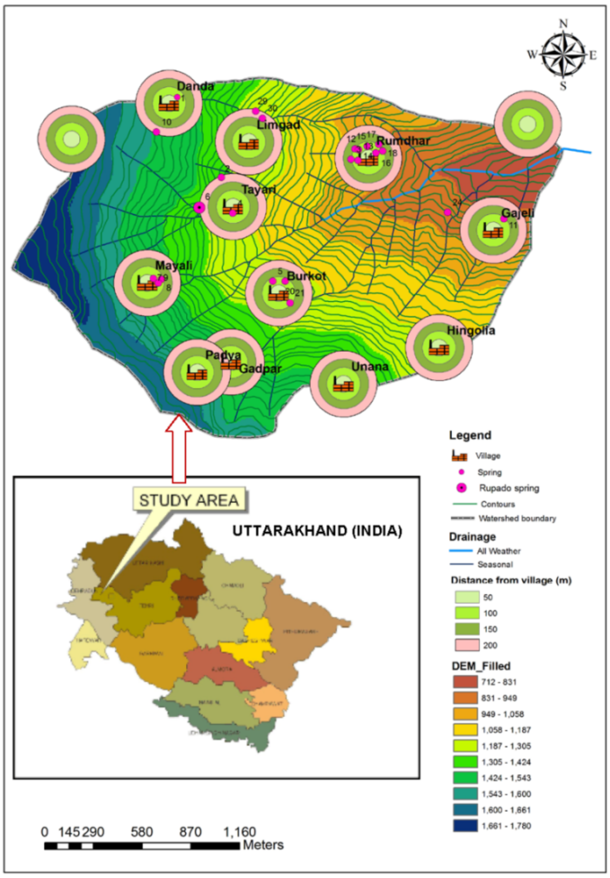

Figure 1. Study area map showing locations of spring, distance from village, catchment divide and contours (m)

The rock type of the area is low grade metamorphic rock with slates, which are highly fractured and foliated. Regular foliation, bedding and fractures in these rocks act as a preferential pathways for the recharge of the springs in the area. The watershed falls under subtropical (cool temperate) climate zone in lesser Himalayan mountain ranges of India. This watershed area falls in rain shadow zone of mountains with moderate rainfall with annual average of 900 mm. The rainfall occurs in almost all the month of the years except in October and November which receives scanty rainfall. The bulk of rainfall occurs in the month of July, August and September.

In this watershed, around 30 springs with varying discharge are identified which are shown in Figure 1 (Kumar et al., 2003). Out of these 30 springs, the Rupado spring (Spring ID No. 6) has been used in this study. The springs in this physiographic setting result from gravity drainage from the unconfined aquifer with or without contribution from surface runoff. Fractures and joints are the main source of spring water in the watershed (Goyal and Kumar, 1996-97). For Rupado spring (ID No. 6), daily time series from 11 August, 1999 to 2 March, 2001 and two daily time series from 5, March 2001 to 31, December 2004 have been used for the recession flow analysis (Fig. 2). There are some observation gaps in data series due to unavoidable circumstances.

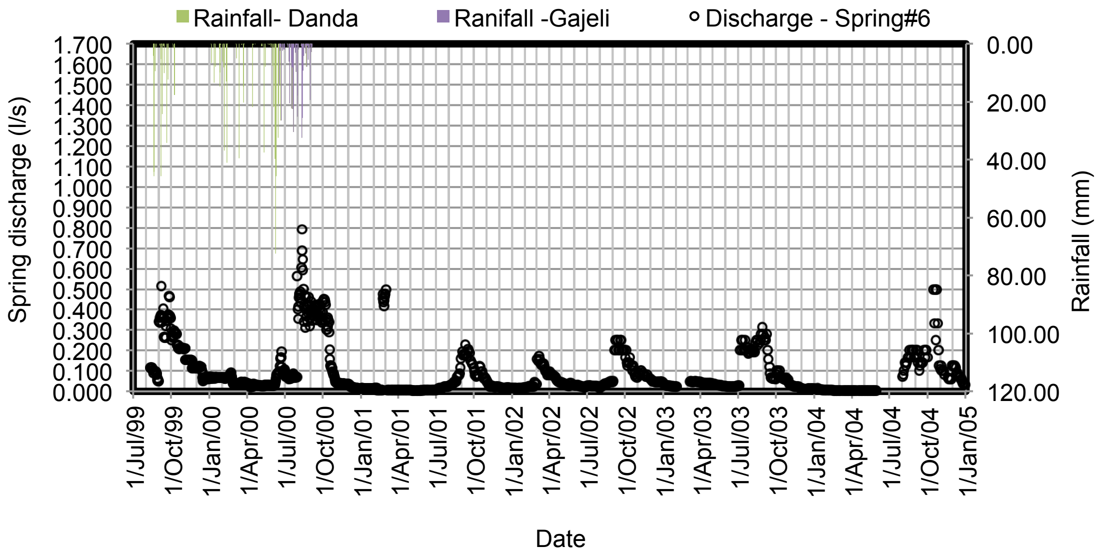

Figure 2. Observed daily spring discharge hydrograph at Rupado spring and daily rainfall in Danda Watershed

3. METHODOLOGY

Recession flow analysis focuses on the recession curve which is specific part of spring flow hydrograph following the flow peak when flow recedes. Generally, the total recession curve can be represented as the sum of two, three or more exponential functions for ground water flow in the porous or fractured medium, which is given as

$$Q(t) = \sum_{i=1}^{N} Q_{0_i} e^{-\alpha_i t} = \sum_{i=1}^{N} Q_{0_i} k^t \tag{1}$$

Where $Q(t)$ is discharge of spring at any time *t*, Q_{0i} are the initial discharges of spring at *t* = 0; t is time since start of recession, α_i are the recession coefficients for each exponential recession, k_i is known as recession constant or depletion factor, which is commonly used as an indicator of the extent of base flow. One of the advantage of a solution in Eq. 1 is that a flow "half life", "$t_{1/2}$" can be determined independently from the flow at any given time, which can be given as (Malvicini et al. 2005)

$$t_{1/2} = \frac{0.69}{\alpha_i} \tag{2}$$

3.1 Master Recession Curve (MRC)

The exponential function of spring flow hydrograph depicted in Eq. 1 implies that the plot of In *Q(t)* vs *t* is a straight line on a semi-logarithmic axis, and slope of line equal to the recession parameter k_i. The individual recession segment may have different slopes due to variability in storage, evaporation loss, and recharge rates (Posavec, 2006). Determining recession constant for a spring representing a particular aquifer/catchment is difficult because of many factors that can affect each individual recession. This variability makes it difficult to infer, physically or conceptually, meaningful underlying processes from recession data. To overcome the problem, a master recession curve (MRC) that normally is defined as an envelope of various individual recession curves could be constructed. As antecedent conditions of the drainage basin have strong influence on the recession rate, the MRC represents the most probable recession scenario under a given condition (Nathan and McMahon, 1990). As stated earlier, in well developed aquifer systems, three straight-line segments of ln Q vs t with different value of α_i occur in the recession. Therefore, separation of spring flow recession hydrograph into two or three segments is necessary in understanding the magnitude and dynamics of groundwater discharge. In practice, however, the transition from one line to the next is very gradual; hence it is difficult to select point of change in the slope as well as the slope itself.

The two most commonly used methods for the Master Recession Curve (MRC) construction are the matching strip method and the correlation method. In the matching strip method, which is based upon the simple exponential model, individual recession segments are plotted and adjusted horizontally using five different linear/nonlinear regression models until they overlap in the main parts (Posavec et al., 2006). Subsequently, Posavec et al. (2010) presented a fully automatic objective based method for separation of MRC into two or three segments on the basis of FDC analysis. The program used in this manuscript can be applied to long time-series data sets with in-between measurement gaps due to unavoidable circumstances or generating MRC for multi-year time-series data for particular season *viz*. rainy, summer or winter.

The hydrological investigations as well as instrumentation in the Danda watershed were carried out by National Institute of Hydrology Roorkee under DST, Government of India sponsored project (NRDMS, 2008; NIH, 2003). The data collected under this project has been used in this paper. To understand the annual and seasonal variability and availability of spring discharge through time, the flow duration curves (FDC) have been plotted for Rupado spring (Figs. 3 and 4). The FDC plotted for the entire time series has been used to select two probable ranges of percent of flow rate in order to facilitate optimal separation of MRC into three recession segments. FDC for different months were grouped into three seasons: (1) Summer or pre-monsoon season (March to 15th June) (2) Monsoon or rainy season (June 2nd half to September), and (3) winter season (October to February), for seasonal analysis of the daily discharge data. Characterization of springs in study area was done through spring flow variability and low flow variability index using FDC.

Recssion analysis was carried out for the winter and summer seasons. In case of separated MRC in three segments, it is assumed that out of these three segements, first segement represents MRC of rainy season, second segement epresents MRC of winter season and third segement represents MRC of summer season. The MRCs have been also constructed using the exponential decay function for grouped months for three seasons. The recession equation in the form of Eq. (1) for MRCs of the three seasons and separated MRCs of the entire time series have been used to estimate average value of recession coefficient and recession constant for each season. The recession coefficients are used to provide the half life period of spring for various seasons (each seprated segement).

4. RESULTS AND DISCUSSION

The minimum, maximum and average value of discharges with their date of observation of the Rupado spring for the entire period (August 1999 to December 2004) and seasonal time series for this period are given in Table 1. Discharge of the spring varied between 0.0027 and 0.794 lps with average value of 0.0998 lps. Spring flow time-series presented in Fig. 1 shows that this spring shows more pronounced increase or decrese in discharge with rapid recession characteristics after rainfall which indicates that the spring is fed by an aquifer with storage dominated by large discontinuties i.e. pronounced foliations and large fractures with high permeability. The flow duration curve of the spring for entire period and selected separation criteria ranges are shown in Fig. 3. Similarly, the seasonal FDCs for rainy, winter and summer seasons are shown in Fig. 4.

Table 1. Observed Minimum, Maximum and Average Discharge Values for Different Periods of Time-Series

Time-series observation period	Min. discharge (lps)	Date	Max. discharge (lps)	Date	Average discharge (lps)
Entire	0.0027	28-Apr-04	0.7937	11-Aug-00	0.0998
Rainy season	0.0066	21-Jun-01	0.7937	11-Aug-00	0.1856
Winter season	0.0040	28-Feb-04	0.5000	15-Oct-04 19-Oct-04 23-Oct-04	0.0824
Summer season	0.0027	28-Apr-04	0.5000	2-Mar-01	0.0350

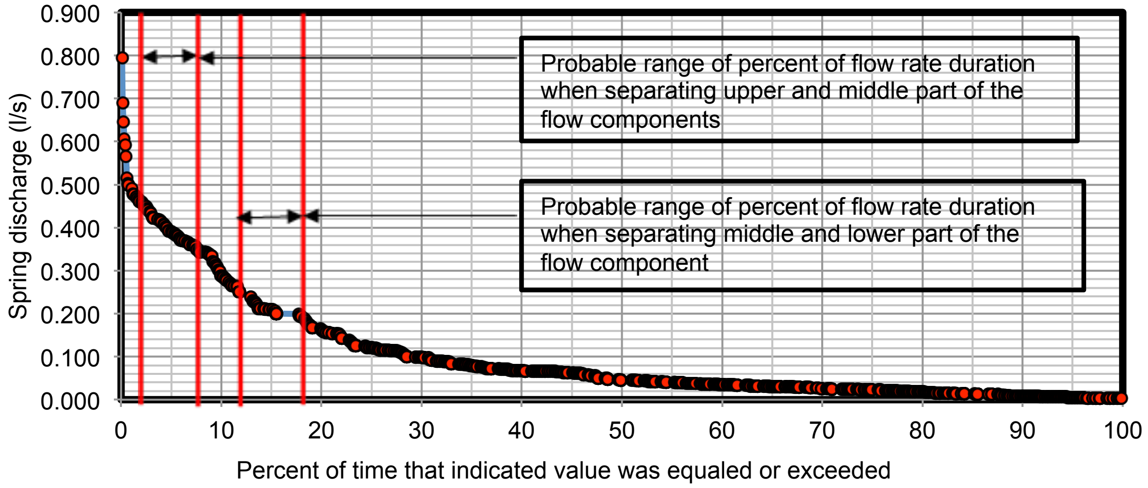

Figure 3. Flow duration curve of Rupado Spring when separation is performed on three MRCs

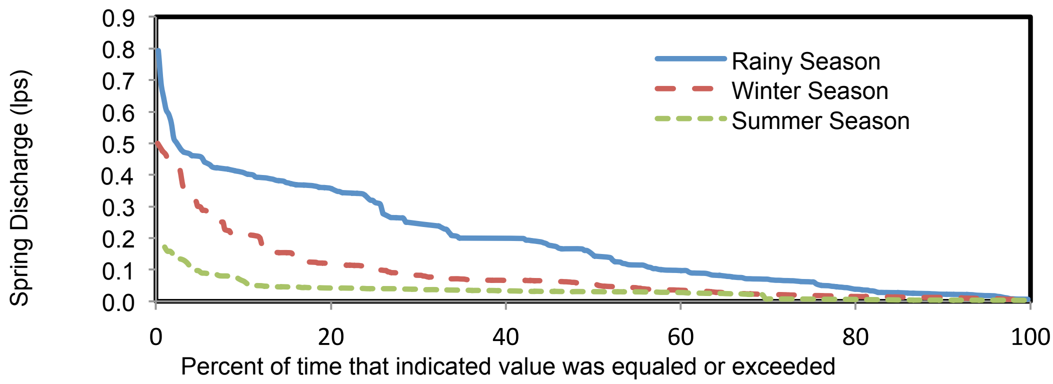

Figure 4. Seasonal flow duration curve of Rupado spring for the period 1999-2004

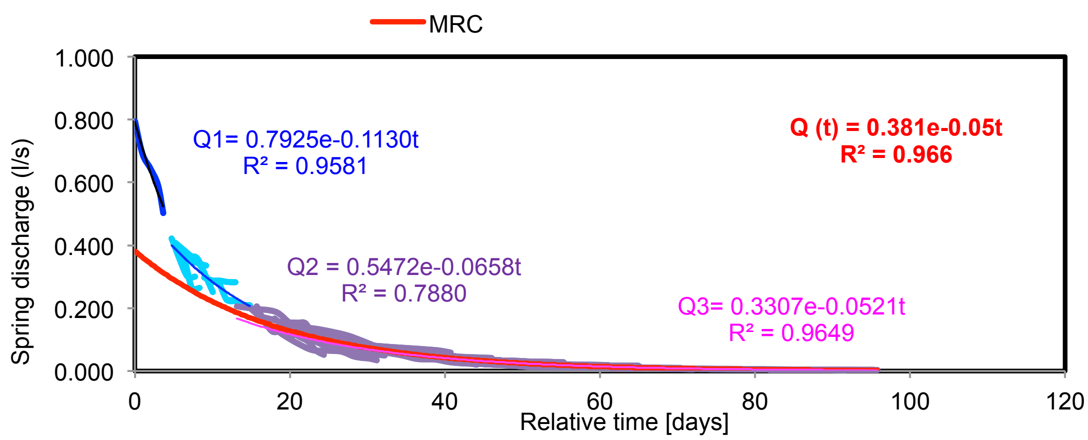

Figure 5. Separated MRCs of the Rupado spring for the period 1999-2004

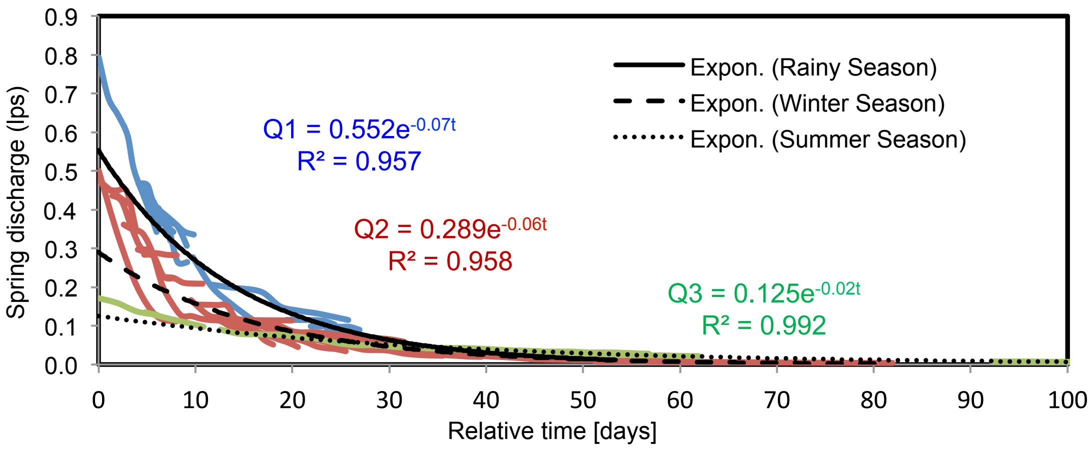

Figure 6. Seasonal MRCs of Rupado spring for the period 1999-2004

From FDC for the entire period (Fig. 3), the breaking points on a plot result from the decrease in the catchment area i.e. underground hydro-geological catchment area and also from the decrease in the effective porosity of the aquifer. The last section of the recession curve (the third segment) actually represents the master recession curve. The importance of this latter section of the recession curve is significant and its function is to define and predict the behaviour of the remaining ground water reserves during drought periods (Bonacci, 1993). It reveals that the spring is largely contributed by interflow and baseflow. Further, it can be seen that a steep slope of the spring indicates a fast response of the catchement to rainfall. To measure the variability of spring flow, the ratio of (Q_{10}/Q_{90}) proposed by Netopil (1971) is being used. The (Q_{10}/Q_{90}) value for Rupado spring is 37.4, which indicates high flow variability. The low flow variability measured by (Q_{50}/Q_{90}) ratio is 5.88, which indicates relatively low variability of Rupado spring. The highest availability of spring outflow is during monsoon season, which is followed by winter season and summer season, respectively (Fig. 4). The rainy season FDC reveals that the surplus water is available for 80-90% time exceedence for the monsoonal period. The assessment of surplus water as well as lean period water availability is very important for sucessful management water resources in hilly area. The optimum design capacity of storage structure to store spring water during unutilized period can be based on design low flow value i.e. the flow within the 10-50% time exceedence.

For separation on three MRCs, separation criteria were estimated between 1% and 7% and 13% and 18% of time (Fig. 3) that indicates flow rate was equaled or exceeded. Stated separation criteria of estimation are those of authors. Fig. 5 represents the separated MRCs for the Rupado spring having optimal separation criteria, calculated as 3% and 15% of the flow rate duration, respectively. Similarly, the plot of MRCs using exponential delay function is shown in Fig. 6. The average values of recession coefficient (α_i), recession constant (k_i), flow half life period in days ($t_{1/2}$) and spring flow at the start and end of MRC recession segement/ seasonal MRC are shown in Table 2. Since the rainfall occurs in almost all months of the year except in October and November, the winter season provides a longer period of recession curve compared to summer season. Winter season characteristics are very important as they are outcome of yearly occurance of monsoonal recharge and significantly impacts the summer outflow (Tarafdar, 2011).

Subsequently, although the value recession α_i values for MRCs represented by segement 1 and 2 are slightly higher and, hence lower values k_i , $t_{1/2}$ as comapered to those values for MRCs of rainy and sumer seasons, respectively. Further, it is noted from Fig. 5 and Table 2 that the MRC for entire time series (i.e. average) is well fitted for the lower portion of recession curve, which suggests that the exponential decay equation is well suited for base flow recession.

Table 2. Different Recession Parameters and Spring Flow for Rupado spring

MRC		Recession coefficient (α_i)	Recession constant (k_i)	Coefficient of determination (R^2)	Flow half life, (days) ($t_{1/2}$)	Spring flow discharge values (lps)	
						Start of recession period	End of recession period
Entire time-series	Segment 1	0.113	0.893	0.96	6	0.794	0.502
	Segment 2	0.066	0.936	0.79	10	0.422	0.209
	Segment 3	0.052	0.949	0.97	13	0.206	0.003
	Average	0.055	0.946	0.97	13		
Rainy season		0.072	0.930	0.96	10	0.794	0.500
Winter season		0.061	0.941	0.96	11	0.500	0.172
Summer season		0.029	0.971	0.99	24	0.172	0.003

5. CONCLUSIONS

The main focus of the study is on construction of MRC and optimally separating MRC into user defined three segments based on the flow duration curve analysis using fully automated objective based method. The obtained average values of recession coefficient, recession constant and half life period for three separated segments of MRC for the entire period are close to those obtained for the seasonal MRCs. The fully automatic objective based method is simple, reliable and easy to use method for spring recession flow analysis. Based on these analyses, comparative assessment of reliability and availability of the existing spring flow during the three seasons through flow duration curves (FDC) has been demonstrated. The analysis can serve guidelines to water resource manager to undertake short-term or long-term measures to address water scarcity problem and to ensure the water security for dwellers in the vicinity of spring. The FDC analysis exhibits its importance to understand its variability and assess the reliability of the low yielding perennial springs. Seasonal FDC could be used for assessment of water availability during lean period and surplus water during rainy season. This information is very useful in design the water storage structure of optimum capacity.

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