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Automated Methods for Estimating Baseflow from Streamflow Records in a Semi Arid Watershed

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Abstract

Understanding of the runoff generation processes is important in understanding the magnitude and dynamics of groundwater discharge. However, these processes continue to be difficult to quantify and conceptualize. In this study, two digital filter based separation modules, the Recursive filtering method (RDF) and a generalization of the recursive digital filter (GRDF) were1991–2002 in the Hableh Roud River at the stream gauge of Bonkuh, Semnan province. A technique for assessing the recession constants of the sub flows based on calibration the average value of the inverse of the value of the inverse of the slope of the linear path in the recession periods of an Ln (q)-time graph is presented. The result show that, the GRDF method gave higher (Baseflow index) BFI values than the RDF method with less variability and the mean baseflow calculated on an annual basis, ranged from 3.27 m^3/s to 4.04 m^3/s over period of study by RDF and GRDF, respectively. Since the true values of the baseflow index are unknown, it cannot be said, which one of the methods gives the best estimates.

Keywords: Base flow; Automated estimation; Digital filter; Hydrograph seperation

1. Introduction

Baseflow is a streamflow component which reacts slowly to rainfall and is usually associated with water discharged from groundwater storage. Understanding of the runoff generation processes is important for the prediction of water quantities However, these processes continue to be difficult to quantify and conceptualize (Gonzales, 2009). Baseflow separation from streamflow hydrographs has long been a topic interest in hydrology (see, Hall, 1968; Birtles, 1978; Tallaksen, 1995; Chapman, 1999; Arnold and Allen, 1999; Piggot et al., 2005; Eckhardt, 2008; Gonzales, 2009) since the baseflow recession curve itself contains valuable information about the aquifer properties, understanding the magnitude and dynamics of groundwater discharge, assessment of water quality, water supply allocation, and low-flow conditions. It can also be used to calibrate or validate hydrological models (Eckhardt, 2005). However, there is no direct way to continuously measure base flow throughout a basin or processes that affect baseflow such as overland flow, evapotranspiration, interflow, and groundwater recharge (Furey and Gupta, 2001). Consequently, many approaches have been developed to estimate or separate baseflow from streamflow continuously in time (e.g., see Birtles, 1978; Rutledge, 1998; Wittenberg, 1999; Chapman, 1999; Arnold and Allen, 1999; Piggot et al., 2005; Eckhardt, 2005).

Baseflow separation techniques use the time-series record of streamflow to derive the baseflow signature. The common separation methods are either graphical which tend to focus on defining the points where baseflow intersects the rising and falling limbs of the quick flow response, or involve filtering where data processing of the entire stream hydrograph derives a baseflow hydrograph.

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Many techniques for separating baseflow based on measured streamflow discharge have been developed and can be categorized into two groups (Chen et al. 2006). One is those that assume that baseflow responds to a storm event concurrently with surface runoff (curve a–b–c in Fig. 1). The other is those that account for the effects of bank storage and assume that the baseflow recession continues after the time when surface runoff begins (Nathan and McMahon, 1990) (curve a–d–e–c in Fig. 1). For the second type of separation techniques, the general shape of a baseflow hydrograph that accounts for the effect of bank storage may be characterized as follows (Nathan and McMahon, 1990): (1) baseflow recession continues after the rise of the total hydrograph due to the initial outflow from the stream into the adjacent banks (curve a–d); (2) baseflow will peak after the total hydrograph peak due to the storage-routing effect of the subsurface storage (curve d–e); (3) the baseflow recession will recess (curve e–c) and will rejoin the total hydrograph as surface runoff ceases, which most likely follows an exponential decay function. Kulandaiswamy and Seetharaman (1969) indicated that point d is often assumed to occur under the hydrograph peak and point e represents where the groundwater recession curve coincides with the timing of the hydrograph inflection point. Until now, techniques for identifying the baseflow peak time and the end of surface runoff are empirical and arbitrary. As pointed out by Tallaksen (1995), the existence of a large number of baseflow separation techniques and the lack of a scientific basis for selecting an appropriate technique prove that substantial subjectivity is usually involved in baseflow analysis and the baseflow process is yet to be fully understood.

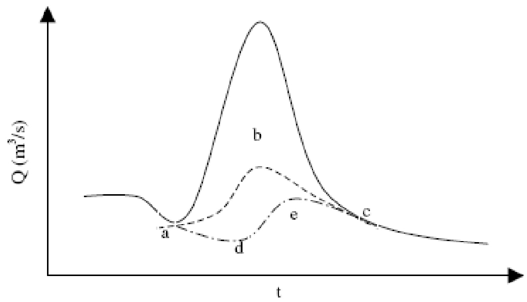

Fig. 1. Streamflow and baseflow hydrographs

None of these approached are physically based under all streamflow conditions and consist of only a few parameters. As a result, they rely heavily on calibration which masks the physics behind baseflow estimation particularly during times when streamflow is rising (Furey and Gupta, 2001).

Gonzales and et al. (2009) were compared tracer-based hydrograph separation methods with the following nontracer-based methods: (i) simple graphical approach (Linsley et al., 1982), (ii) filtering methods (Sloto and Crouse, 1996), (iii) recursive filtering (Eckhardt, 2005), (iv) unit hydrograph method (Su, 1995), and (v) rating curve method (Sellinger, 1996). They concluded that recursive filtering gives the best results if compared to the separation using dissolved silica. However, tracer based methods may not be practical and economic in the long run and it is not possible to apply them to past discharge time series if no chemical/isotopic data of stream water and main source areas are available, which is usually the case. Therefore, it is necessary to use non tracer-based baseflow separation methods that still give meaningful insights in to the groundwater discharge of a catchment.

Graphical methods are commonly applied in Iran to plot the baseflow component of a flood hydrograph event, including the point where the baseflow intersects the falling limb. These techniques aim mainly to separate quick flow from slow flow for the purposes of flood analysis and prediction. In reality however, groundwater outflow is considerably higher than slow flow although in many cases, baseflow is the dominant discharge component even during flood events (Herrmann, 1997). In this sense, the graphical separation techniques appear to be problematic as baseflow does not follow the recession. Also, when two or more rainfall events overlap (Linsley et al., 1982), consequently it is not that useful for baseflow separation over long periods of time.

The baseflow component of the streamflow time series can also be separated using data processing or filtering procedures. These methods tend not to have any hydrological basis but aim to generate an objective, repeatable and easily automated index that can be related to the baseflow response of a catchment (Nathan and McMahon, 1990).

Different types of filters to disaggregate the daily streamflow into quickflow and baseflow components are available from many researchers. The well known one is recursive digital filter (RDF) algorithm attributed to Lyne and Hollick (1979) and used, among others, by Nathan and McMahon (1990), Arnold and Allen (1999), Chapman (1999), Eckhardt (2005). In the present study, we compared baseflow indices that are mathematical filters by the methods of the Arnold and Allen (1999) and Willems (2009) which have been implemented in BFLOW and WETSPRO program respectively. Here, the baseflow separation involves to partitioning the streamflow in two components, direct runoff and baseflow.

2. Materials and methods

2.1. Study area

Hableh Roud Basin is located in the north-central Iran and lies between 51°39' to 53° 08' east longitudes and 34°26' to 35° 57' north latitudes. It has an area of 12,667 km^2. It is bound by the Alborz Mountains in the North and Central Desert of Iran in the South. The basin is cold in the mountains and has an arid climate in the outlet which is a fertile alluvial fan. The average temperature in the basin ranges from 35°C in the summer to -10 °C during winters. The basin altitude ranges from 818 m a.s.l. in the lowlands to about 4075 m a.s.l. in the highlands. Annual precipitation is variable and ranges from 358 mm to 88 mm and averages about 150 mm in the agricultural area. Evaporation especially in the lower parts is high throughout the year and estimated as 1284 mm/year.

Bonkuh gauging station is used to test the baseflow filters because it is located at the most downstream of the Hableh Roud Basin which covers parts of Semnan and Tehran provinces and can therefore be considered representative for the whole basin. Eleven years of daily streamflow data for the 1991–2002 hydrological years were used. The hydrological year in Iran starts in September 23rd of the previous year and ends in September 22nd of the current year. Statistical characteristics calculated for the streamflow at annual scale are presented in Table 1. It is seen that the standard deviation of the average streamflow is as large as its average resulting in a unit coefficient of variation. In Fig. 2, it is seen on average that daily mean streamflow increases through the period starting with February to the end of May, and then the flow decreases gradually until July where it reaches the summer constant flow. As examples for wet and dry years, Fig. 2 can also be examined.

Table 1. Statistical characteristics of the Hableh Rod River at Bonkuh river daily streamflow data (units are in SI system)

Number of values	4015	Autocorrelation	56.49	Q_1	3.25
Mean	6.53	Skewness	3.05	Median	5.96
St. Dev.	5.04	Max	81.72	Q_3	8.15
Coeff. of Var.	0.77	Min	0.11		

2.2 Base flow separation methods

2.2.1 Recursive filtering method (RDF)

The recursive digital filter (RDF) derived from the signal analysis studies. The general approach proposed by Arnold and Allen (1999) is used to perform low pass filtering on the hydrograph in order to separate base flow (see Eq. 1). The program BFLOW (Arnold and Allen, 1999) uses a method, which was apparently first suggested by Lyne and Hollick (1979). Baseflow is usually associated with water discharged from groundwater storage. This process provides considerable smoothing. Hence, in the frequency spectrum of a hydrograph, long waves will be more likely to be associated with baseflow while the high frequency variability of the streamflow will primarily be caused by direct runoff. It should therefore be possible to identify the baseflow by low pass filtering the hydrograph.

Lyne and Hollick (1979) proposed the filter equation

$$b_k = \alpha \times b_{k-1} + \frac{1-\alpha}{2}(y_k + y_{k-1}) \qquad (1$$

Subject to $b_k \leq y_k$.

Most acceptable results were obtained when the filter parameter was in the range 0.90–0.95 with the optimal value 0.925 (Nathan and McMahon, 1990). The time series is filtered three times: forward, backward, and forward again. The output of the filter is constrained such that the separated flow cannot take negative values and is not greater than the total flow. This equation, with a value of 0.925 for the filter parameter α, is implemented in BFLOW.

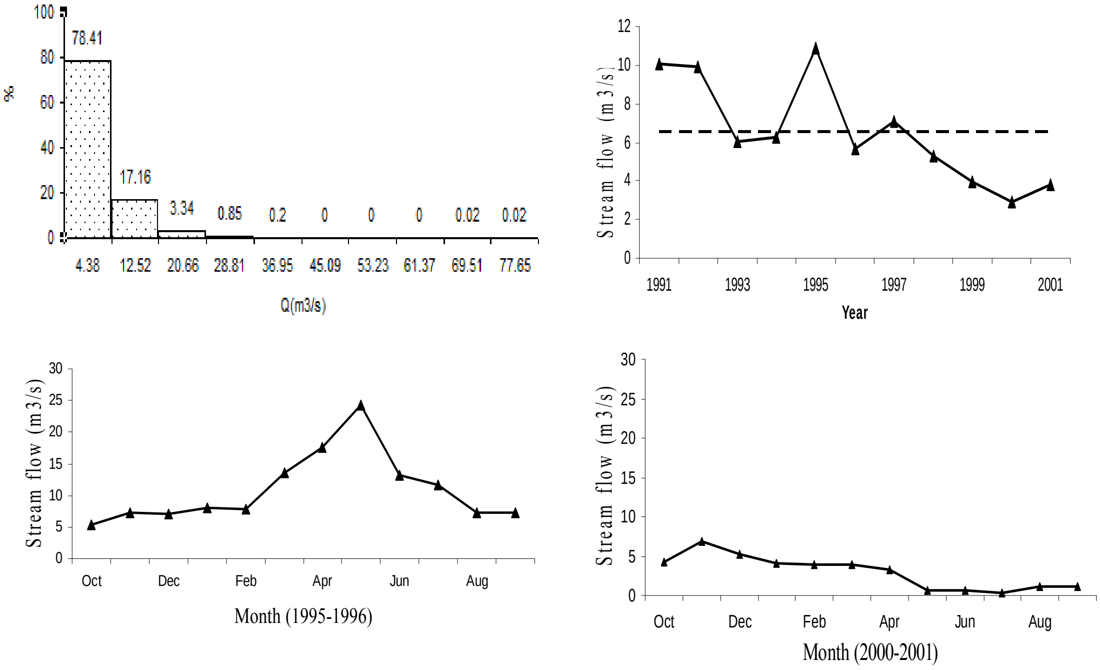

Fig. 2. Frequency of the Bonkuh river daily stream flow data from 1991-2002 of the Hableh Rod River at the streamgauge of Bonhkuh (Upper left panel): daily mean streamflow, average of 11 years (Upper right panel), wet year 1995-96 (Lower left panel), dry year 2000-2001 (Lower right panel)

2.2.2 A generalization of the recursive digital filter (GRDF)

Chapman (1991) criticized the Lyne-Hollick algorithm as providing theoretically incorrect results and presented another filter equation. It physical interpretation is based on the linear reservoir modeling concept. Chapman's modification is the only attempt that has been made to give a streamflow filter some physical meaning. The filter was applied forward, backward, and then forward in time to daily mean streamflow data, and baseflow estimates from this filter compared favorably with base flow data. The original filter by Chapman (1991) has one parameter: the recession constant k of the subflow to be separated. It is shown in Willems (2000) that in the original form of that filter the intrinsic assumption is made that the total long-term volumes of the slow and quick flow series are identical (each 50% of the total runoff). The slow and quick runoff fractions, however, strongly vary between catchments depending on their (topographical, soil type, etc) characteristics (Willems, 2009). Therefore, a generalization of the original Chapman-filter was proposed by Willems (2009), where a new filter parameter w is introduced that represents the case-specific average fraction of the quick flow volumes over the total flow volumes. After this generalization, the filter equations become:

$$f(t) = af(t-1) + b(q(t) - \alpha q(t-1)) \qquad (2$$

$$b(t) = \alpha b(t-1) + c(1-\alpha)(f(t-1) + f(t)) \qquad (3$$

$$with: \alpha = \exp(-\frac{1}{k}) \qquad (4$$

$$c = 0.5 \qquad b = \frac{2}{3-\alpha} \; a = \frac{3\alpha - 1}{3-\beta}$$

Where:

q(t)= the total time series, *b(t)*: the time series of the filtered component (with recession time *k*), *f(t)*: the higher frequency components

As the total time series *q(t)* is the sum of the filtered component *b(t)* and the higher frequency components *f(t)*, and as the higher-frequency components are routed through the reservoir model to derive the filter subflow, it can be easily seen that the filtered components and the higher-frequency components have the same cumulative values in Chapman-filter. This means in rainfall-runoff applications that the rainfall fractions which contribute to the filtered subflow (e.g. baseflow) and the higher frequency subflows (e.g. overland flow and interflow) are assumed identical. This is an important assumption that may not be valid. Therefore, a generalization of the filter was developed. The generalization consists of a time-variability in the fraction w of the cumulative values in the total time series that is related to the filtered component. After introduction of a new filter parameter v (Willems, 2009):

$$v = \frac{1-w}{w} \quad (5$$

And after adoption of the filter parameters:

$$a = \frac{(2+v)\alpha - v}{2+v-v\alpha} \quad (6$$

$$b = \frac{2}{2+v-v\alpha} \quad c = 0.5v \quad (7$$

The filter equations (2) and (3) can still be used in the generalization.

In the Chapman-filter, v equal1, as the filtered component contributes for 50% to the cumulative volumes.

The fractions w are unknown in practical applications. However, their values can be estimated by numerical calibration. In this calibration, the agreement between the total time series and the filtered component is maximized for the recession periods, as the higher- frequency components are diminished to very small values during these periods. Between two such recession periods, the fraction w varies in time.

The recession constants (κ of the subflows can calibrated as the average value of the inverse of the slope of the linear path in the recession periods of a Ln (q)-time graph. When s is a number of time steps considered during the recession periods, the recession constant can be calculated as follows (Willems, 2009):

$$\frac{\ln(q(t-s) - \ln(q(t))}{s} = \frac{1}{k}$$

By visual inspection of this slope for a number of recession periods, an average value for the recession constant can be estimated. The second parameter w can be calibrated by optimizing the height of the sub flow during the recession periods. Also this calibration is done by trial-and-error through visual inspection in the time series.

For comparison of two methods, the direct runoff ratio is defined by BFI. BFI is defined as the ratio of baseflow volume in the time interval $\Delta t = t_2 - t_1$ to the total streamflow volume at the same time interval and is calculated by Aksoy et al. (2009).

$$BFI = \frac{\int_{t1}^{t2} Q_{baseflow}(t)dt}{\int_{t1}^{t2} Q_{totalstreamflow}(t)dt} \quad (9$$

The BFI was calculated for the two methods. Summary statistics were given in Table 2.

3. Results

Data used for this study are daily average discharge. Figs. 3 shows the assessment of the slow flow recession constant and of the slow flow filter result obtained for the daily river flow series observed in the Hableh Rod River at a flow gauging station downstream the catchment at the location Bonkuh by GRDF method. The calibrated filter parameters (κ and W) equal κ =120 days for the baseflow or slowflow and the second parameter was estimated by optimizing the height of the subflow during the recession periods and is equal to 0.15. As mentioned by Willems (2009) the visual inspection based calibration of the V and W parameters involves some subjectivity and uncertainty in the estimation. Upper and lower limits were identified as being (80-150 days) for $\kappa_{baseflow}$. Note that in figure 1 the left slanting lines represents approximately the recession coefficient V; assumed constant for the entire duration. Theoretically, it is known that the W-parameter and the recession coefficient are dependent on both storm and catchment characteristics. A more realistic sub filtering technique would be to use seasonally varying filter parameters. Therefore, more work is required on the seasonal variation of w-parameter. The results of the two separation methods are shown in Fig. 4. Finally, the mean baseflow calculated on an annual basis, ranged from 3.27 m^3/s to 4.04 m^3/s over period of study by RDF and GRDF, respectively (Table 2).

Results are discussed below by considering the baseflow sequences and the baseflow index (BFI) values. Summary statistics were given in Table 2 from which it is seen, on average, that the GRDF method gave higher BFI values than the RDF method with less variability. The coefficient of skewness and variation of the RDF method are higher than GRDF method. RDF and GRDF methods resulted in almost same standard deviation. The GRDF provide extensively smooth time series of baseflow. Fig. 4 shows an example.

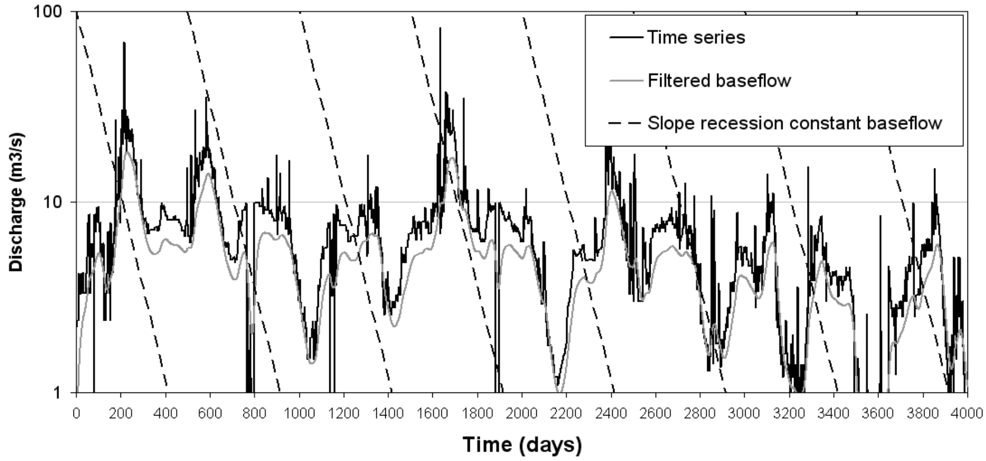

Fig. 3. Assessment of the baseflow recession constant and baseflow filter results based on daily river flow series of Bonkuh station by GRDF, first 4000 days after 01.07.1992

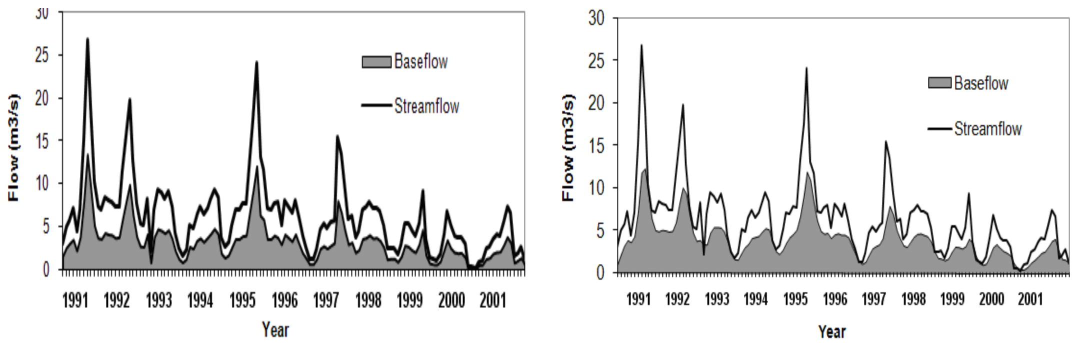

Fig. 4. Comparison of the baseflow separation methods: RDF (Left panel), GRDF (Right panel)

Table 2. Summary statistics- RDF and GRDF methods

Method	Average (m^3/s)	Standard Deviation (m^3/s)	Coefficient of variation	Coefficient of skewness	Q_{min}	Q_{50}	Q_{25}	Q_{max}	BFI
RDF	3.27	2.37	72.60%	2.03	0.11	2.96	4.05	22.78	0.49
GRDF	4.04	2.39	59.09	1.36	0.40	3.77	4.90	12.96	0.61

3. Discussion and Conclusion

The results of these two methods are not very different. However, Eq. (8) has the advantage of being hydrologically more plausible than Eq. (4), which is used in BFLOW (Chapman, 1991). On the other hand, compared with the RDF algorithm, the flexibility to control characteristic baseflow response explicitly – through manual parameter selection – enables consistent automated baseflow separation when applications require the incorporation of a priori judgment in defining ''baseflow'' response.

It is not yet practical to measure baseflow in the field. For instance, it has been shown by Nathan and McMahon (1990) that the RDF baseflow approximates well the baseflow sequence calculated by the matching strips manual separation technique. The RDF filters (smoothes) the sharp peaks and troughs observed in the fast component of the streamflow such that the separated flow represents the delayed component of the streamflow (baseflow). Of a fundamental problem is that the true values of the BFI are unknown. Therefore, one cannot say, which one of the methods approximates reality best (Eckhardt, 2008).

The accuracy of baseflow separation depends on the length of stream-gauge record data that is processed. Longer periods of data provide more reliable separation than shorter periods. Thus, the calibration period should be longer (eight years or more) (Linsley1982, Yapo et al. 1996) and the data used to calibrate should be standardized to account for the temporal variability of runoff that is caused by changes in rainfall and land-use conditions.

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