Research on Baseflow Separation Based on Single Parameter Digital Filtering Method

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Abstract. Baseflow is the main source of supplement for rivers during dry seasons. The reliable separation methods play an important role in baseflow research and water resources management and utilization. Based on the daily runoff data of Changmabao hydrological station in the upper reaches of Shule River from 1957 to 2016, based on the parameter calibration of the single-parameter digital filter method, the single-parameter digital filter method is used to study the baseflow separation of the study area. The results show that when the optimal parameter combination is when the filtering parameter is 0.975 and the filtering times is 3, the multi-year average BFI value obtained by the single-parameter digital filtering method is 0.742. The high Nash-Sutcliffe efficiency coefficient and the average relative error is less than 10%, indicating that the baseflow estimation results of this method is stable, reliable and accurate.

1. Introduction
The baseflow is the most stable part of the runoff. The baseflow is the main source of supplement for the river during the dry season. The variation of baseflow can reflect the changes of groundwater level and water volume [1]. At the same time, it is also important for basin flow calculation and hydrological simulation [2]. Baseflow plays an important role in water resources evaluation and investigation, water conservancy project construction, pollution evaluation, and rainfall-runoff relationship analysis [3]. The volume of the baseflow is closely related to the basin area, hydrogeological and landform conditions, soil, vegetation, climate, and underlying surface conditions [4]. Baseflow is the lower part of the hydrological process line, with small inter-annual and intra-annual changes, and the baseflow accounts for a large proportion of the total annual flow. Baseflow research not only plays an important role in stable water supply for production and life, farmland irrigation, and river environmental protection, but also helps water resources planning and management and maintaining a benign hydrological cycle. At the same time, baseflow segmentation research can provide reference for hydrological model research. In the arid and semi-arid regions of Northwest China, inland rivers are partially frozen at the end of winter and early spring, and the rivers are mainly supplied by groundwater. Therefore, the baseflow plays an important role in maintaining the continuous flow of the river, the stability of the water source and the stability of the ecosystem [5]. Studying the temporal and spatial changes of the baseflow of the inland river basin in the arid zone is helpful to understand the characteristics of water resources and the characteristics of the water cycle and their transformation relationships in the basin, and has practical guiding significance for the efficient use of water resources [6].

The formation process of baseflow is complicated so it is difficult to obtain data through observation methods. Baseflow can only be estimated by certain methods. Therefore, baseflow
separation has always been the focus and difficulty of hydrology and ecohydrology research [7]. The traditional baseflow separation method has low efficiency, cumbersome calculations. Thus, traditional methods are inconvenient to analysis the long-term series data and it is difficult to guarantee accuracy [8]. Therefore, automatic separation technology is often used for baseflow separation in actual research. In recent years, the automatic separation technology which uses mathematical methods to separate the flow process line has been rapidly developed. The widely used methods mainly including Minimum Smoothing Method, HYSEP (Hydrograph separation), Digital Filter Method, BFI (Baseflow Index Method) and PART Method [9]. The above methods are highly objective, easy to operate, and can be realized by computer programs. So it can obtained a continuous baseflow process quickly and effectively.

Researchers have done a lot of research on runoff changes in arid and semi-arid areas, but they all focus on analyzing runoff trends and different factors affecting runoff and less research on base flow. In order to further study of the variation law of baseflow, discuss influencing factors and other technical support, provide a basis for the hydrological simulation of the basin and the rational distribution of water resources. The paper used single-parameter digital filtering method to separate the base flow aiming to find the suitable separate methods and the estimation results are stable, reliable and accurate.

2. Research Site
The Shule River Basin, one of the three biggest inland river basins in the Hexi Corridor of Gansu Province, is located in the western Qilian Mountains on the northeastern margin of the Tibetan Plateau. The upper Shule River basin (96°51′, 39°49′), above Changmabao hydrologic station, has an area of 1.14×10^4 km^2 and the mean elevation of 3885 m (Figure 1). The study region has a continental arid climate and is mainly controlled by westerly winds, with low precipitation and annual mean air temperature and high evaporation. The annual mean precipitation and annual mean air temperature varied from 200 to 400 mm and -4.0 to -19.4°C over the period of 1960-2010. The annual evaporation was about 1200 mm [10]. The annual average runoff of the upper reaches of the Shule River is 10.83×10^8 m^3. The annual runoff is unevenly distributed that 53% of the annual runoff is concentrated in July to September. The runoff in winter and spring only accounts for 8.5% and 10% of the annual runoff.
3. Methods

3.1. Single-Parameter Digital Filter Method
The single-parameter digital filtering method is a mathematical method for separating the flow process proposed by Nathan firstly in 1990 [11]. This method is derived from signal analysis and processing technology. In recent years, it has become the most widely used method in the world in baseflow separation calculation research. The principle of the method is to regard daily runoff as the superposition of high-frequency signal (surface runoff) and low-frequency signal (base flow). When separate the high-frequency signal and low-frequency signal through signal analysis and processing technology, thereby correspondingly dividing the runoff into surface runoff and base flow. Arnold selected 6 representative watersheds in the eastern and western United States to verify the method. The results show that the method has the advantages of fewer parameters, fast execution, easy operation, and good objectivity and repeatability [12]. The filter equation is:

\[ q_t = \beta q_{t-1} + \frac{1 + \beta}{2} (Q_t - Q_{t-1}) \]  

(1)

After the surface runoff \( q_t \) is calculated, the base flow is calculated by the following formula:

\[ b_t = Q_t - q_t \]  

(2)

Where \( q_t \) and \( q_{t-1} \) are the fast responses filtered at \( t \) and \( t-1 \) respectively (that is, surface runoff), \( m^3 \cdot s^{-1} \); \( \beta \) is filtering parameter; \( Q_t \) and \( Q_{t-1} \) are the measured river runoff at time \( t \) and \( t-1 \), \( m^3 \cdot s^{-1} \); \( b_t \) is the base flow at time \( t \), \( m^3 \cdot s^{-1} \); \( t \) is time, Unit is day.

3.2. Evaluation Index
The low water index is an important indicator reflecting the runoff of groundwater recharge rivers. The Q90 and Q50 represent the baseflow when the frequency of occurrence is greater than 90% and 50% within a period which is determined by the flow duration curve. In the study, the product of low water index (Q90/Q50) and the total annual runoff was used as the actual observed value of the annual base flow for comparison with the estimated results of the baseflow separation. The Nash-Sutcliffe

![Figure 1. Map showing the location of study area](image-url)
efficiency coefficient is used in the research to evaluate the simulation effect of observations and estimation [13]. The formula is:

\[ NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{mi} - Q_{ni})^2}{\sum_{i=1}^{n}(Q_{mi} - Q_{a})^2} \] (3)

Where NSE is the Nash-Sutcliffe efficiency coefficient; \( Q_{mi} \) is the observed annual baseflow in the i-th year, 10^8 m³; \( Q_{ni} \) is the annual baseflow calculated in the i-th year, 10^8 m³; \( Q_{a} \) is the observed average annual baseflow, 10^8 m³. The value of NSE is between 0 and 1. The larger the value of NSE which is closer to 1, the simulation effect is better. Conversely, the simulation effect is worse. Use average relative error for accuracy evaluation. The formula is:

\[ RE = \frac{Q_{na} - Q_{a}}{Q_{a}} \times 100 \] (4)

Where RE is the average relative error, %. The smaller the RE, the better the estimation effect. \( Q_{na} \) is the estimated average annual baseflow, 10^8 m³. The accuracy of the estimated baseflow is good when the Nash-Sutcliffe efficiency coefficient is greater than 0.6 and the average relative error is less than 10%.

4. Results

4.1. Annual Distribution of Runoff

The daily runoff data from 1957 to 2016 of Changmabao hydrological station in the upper reaches of the Shule River is analyzed. It can be seen that the runoff process curve during the year presents an obvious unimodal distribution in the upper reaches of Shule River (Figure 2). The multi-year average monthly runoff in the upper reaches of the Shule River varied from 10.24 to 91.25 m³·s⁻¹, with maximum value in August and the minimum value in January. The runoff changed little and remained stable, fluctuating around 10.5 m³·s⁻¹. As the temperature gradually rises, the snow gradually melts, and the supply of melted ice and snow increases the runoff from March to April. Due to rainfall and a large amount of supplement of melted ice and snow, the runoff increased again and increased greatly, reaching the peak in August. With the decrease of melt water and precipitation, the runoff also decreased and stabilized from September to December.
4.2. Multi-Year Changes of Runoff

The multi-year change process of runoff in the upper reaches of the Shule River from 1957 to 2016 is shown in Figure 3. The average annual runoff of the upper reaches of the Shule River is 31.74 m³·s⁻¹. The maximum runoff was 54.67 m³·s⁻¹ in 2006 and minimum runoff was 18.83 m³·s⁻¹ in 1976. The slope of the runoff trend line is 0.32. It can be seen that the runoff in the upper reaches of the Shule River is increasing, especially increased significantly after 2000. The temperature has increased significantly in recent years which accelerate the melting rate of glaciers. Therefore, the runoff increased owing to the supplement of melted glaciers has increased [14].
Figure 3. Annual runoff variation process in the Upper Shule River basin

4.3. Calibration of Separation Parameters of Single Parameter Digital Filtering Method

The use of single-parameter digital filtering method requires calibration of the filtering parameters and filtering times. The suitable filtering parameters and filtering times for the study area can improve the accuracy of base flow estimation. In order to explore the influence of filter parameters and filter times on the results of base flow separation, this paper separate the baseflow from daily runoff in upper reaches of Shule River basin from 1957 to 2016, with filter parameters are 0.8, 0.85, 0.9, 0.925, 0.95, 0.975 and the filter times are 1, 2, 3, 4, 5, respectively. The results show that when the filter passes through the positive-obverse-positive three times, the baseflow separation results change greatly. When the number of filtering increases again, with the fourth and fifth passes through the filtering, the base stream changes slightly during the flood season with the increase of the number of filtering, but there is basically no change in the non-flood season. The Figure 4 and Table 1 shown that when the filtering times is constant, the divided baseflow gradually decreases and baseflow process line is smoother with the increase of filtering parameters. This is because increasing the filter parameters will increase the pass rate of high-frequency signals, mid- and low-frequency signals, thereby increasing the pass rate of high-frequency signals, that is, surface runoff, thus reducing the baseflow.
The Nash-Sutcliffe efficiency coefficient and average relative error are calculated for the baseflow separation results under different filtering parameters and filtering times. When $\beta=0.8$ and $\beta=0.85$, the baseflow is closer to the runoff, and the peak of the baseflow rises sharply with the runoff which is inconsistent with the hysteresis and stability of the baseflow. When the filtering times is 4 and 5, the baseflow only changes slightly during the flood season. Therefore, only calculate the Nash-Sutcliffe efficiency coefficient and the average relative error when the filtering times is 1, 2, 3 and the filtering parameters are 0.9, 0.925, 0.95, 0.975. The reliability of the separation results under different filtering parameters and filtering times is verified. The results show that when the filtering parameter is 0.975 and the filtering times is 3, the Nash-Sutcliffe efficiency coefficient is the highest. The Nash-Sutcliffe efficiency coefficient is 0.69 and the average relative error is 9.1%. It shows that the estimation result is good and the accuracy is high. Therefore, the combination of this filtering parameter and filtering times is the optimal parameter of the single parameter digital filtering method.

Figure 4. Single parameter digital filtering method of baseflow separation under different filter parameters and times
Table 1. NSE and RE of baseflow separation under different filter parameters and filter times

| Filtering parameter | 0.9  | 0.925 | 0.95  | 0.975 |
|---------------------|------|-------|-------|-------|
| filtering times     | 1    | 2     | 3     | 1     | 2     | 3     | 1     | 2     | 3     |
| NSE                 | 0.45 | 0.34  | 0.36  | 0.50  | 0.52  | 0.54  | 0.53  | 0.50  | 0.60  | 0.59  | 0.50  | 0.60  | 0.69  |
| RE/%                | 21.3 | 31.6  | 30.6  | 14.9  | 23.7  | 23.1  | 14.1  | 11.1  | 10.2  | 13.3  | 11.8  | 9.1   |

Baseflow is relatively stable process of groundwater runoff. Its stability and the applicability of the baseflow separation method can be discussed from its interannual and intra-annual changes. Due to the long time series of daily runoff data, it is difficult to quantitatively compare the baseflow separation results from the separated baseflow process line. It is necessary to introduce the baseflow index in order to deeply analyze the difference of estimation results. Baseflow index (BFI) refers to the ratio of the baseflow to the total runoff during a period of time, reflecting the size of the river baseflow. The multi-year average BFI value obtained by the single-parameter digital filtering method is 0.742. The Changmabao hydrometric station baseflow separation results from 1957 to 2016 are shown in Figure 5.

Figure 5. The monthly baseflow process estimated by single-parameter digital filtering method from 1957 to 2016.

5. Conclusions
By analyzing the distribution process and multi-year changes of runoff from 1957 to 2016, the characteristics of runoff changes in the upper reaches of the Shule River are obtained. Based on the parameter calibration of the single-parameter digital filter method, the single-parameter digital filter method is used to study the baseflow separation of the study area. The results show that the runoff process curve of the upper reaches of the Shule River presents an obvious unimodal distribution. The average annual runoff of the upper reaches of the Shule River is 31.74 m³·s⁻¹. The filtering parameters and filtering times of the single-parameter digital filtering method are calibrated, and the results show
that the optimal parameter combination is when the filtering parameter is 0.975 and the filtering times is 3. The multi-year average BFI value obtained by the single-parameter digital filtering method is 0.742.

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7. References
[1] Yang Z and Wang W J 2009 Arid Land Geogr 325 739-745.
[2] Hu X J 2003 Hydrol 231 32- 36.
[3] Xu L, Liu J, Jin C, Wang A, Guan D, Wu J and Yuan F J J Appl Ecol 2211 3073-3080.
[4] Arnold J and Allen P J 1999 J. Am Water Resour As 352 411–424.
[5] Lan Y and Kang E J 2000 J. gla and Geo 222 147-152.
[6] Chen L, Liu C, Hao F, Liu J and Dai D J 2006a J. Glacio. Geocry 282 141-148.
[7] Koskelo A, Fisher T and Utz R J 2012 J. Hydrol. 451 267-278.
[8] Mcnamara J, Kane D and Hinzman L J 1997 Water Resour Res 337.
[9] Jiao W, Zhu Z and Song X J 2017 Arid Zone Res 341 26-35.
[10] Jiaxin Z, Jinkui W and Shiwei L J 2015 Adv Meteorol 2015 1-10.
[11] Nathan R and Mcmahon T. J 1990 Water Resour Res 267.
[12] Arnold J, Allen P, Mutthia R and Bernhardt G J 1995. Groundwater 336 1010–1018.
[13] Nash J and S J J 1970 J. Hydrol. 10 282-290.
[14] Song X, Zhu Z, Jiao W and Xi X J 2016 Arid Land Geog 396:1319-1326.