Analysis of baseflow index based hydrological model in Upper Wei River basin on the Loess Plateau in China

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Abstract The baseflow is the drainage from the groundwater and soil water to the streamflow. As one important source of the streamflow, the baseflow could be the main source of the streamflow in the dry season. The Wei River, located in the semi-arid region of the Loess Plateau which is overlain by deep and loose soil, is the largest tributary of the Yellow River. According to former research, most of the streamflow in the dry season in the headwater of the Yellow River is baseflow. For the whole Yellow River basin, the baseflow is an important component of the streamflow, and accounts for about 44% of the annual runoff. Physically-based distributed hydrological models can simulate the runoff components separately, and are important tools to analyse the runoff components. Given the importance of the baseflow in the dry season for drought relief to support the ecological water requirement and irrigation, especially in the Wei River, the baseflow is analysed in this study. To investigate the baseflow in the Upper Wei River basin, a semi-distributed hydrological model based on a Representative Elementary Watershed approach (THREW) is employed to investigate the runoff generation process. To compare the results, an automatic baseflow separation method proposed by Arnold is used to separate the baseflow from the daily streamflow at Beidao hydrological station in Upper Wei River basin from 2001 to 2004. Based on the hydrological modelling and the Arnold separation method, the average annual baseflow index, i.e. the ratio of baseflow to the total runoff, is estimated as in the range of 0.30–0.36. The average intra-annual monthly baseflow index represents the seasonality of the baseflow due to the seasonality of the precipitation and evapotranspiration, and is also analysed.

Key words baseflow, hydrological model, Wei River basin, Loess Plateau

INTRODUCTION

Baseflow is considered to be the groundwater contribution to streamflow (Arnold *et al.*, 1995) and is one important component of the runoff in a river, especially in arid and semi-arid regions. The Wei River is located in the semi-arid region of the Yellow River basin in China. Due to the increase of the water withdrawal to supply agricultural irrigation and urban water consumption in Shaanxi, which is in the lower reach of the Wei River basin, baseflow is playing a more and more important role to satisfy the instream ecological water demand in the Wei River. According to research, most of the streamflow in the dry season in the headwaters of the Yellow River is the baseflow (Chen *et al.*, 2006). Even for the whole Yellow River basin, the baseflow is an important component of the streamflow, and accounts for about 44% of the annual runoff (Wang *et al.*, 2008). The quantification of the baseflow in the Wei River is an interesting topic.

The traditional method to separate the baseflow is to analyse the discharge records (Arnold *et al.*, 1995; Aksoy *et al.*, 2009; Wang and Cai, 2010). At the same time, a distributed physically-based distributed hydrological model could simulate the runoff components separately, and could be another option to analyse the runoff components. Previous hydrological modelling (Liu *et al.*, 2012) has shown some results about the proportion of the baseflow in the Upper Wei River. Given the importance of the baseflow in the dry season for drought relief to support the ecological water requirement and irrigation, especially in the Wei River, the baseflow is analysed using a distributed physically-based hydrological model and baseflow separation method.

STUDY AREA AND DATA

The Wei River, located in the semi-arid region of Loess Plateau which is overlain by deep and loose soil, is the largest tributary of the Yellow River. The study area is the upstream of Beidao hydrological station (105.905°E, 34.569°N) in the Wei River basin and it is hereafter denoted as Upper Wei River basin (UWRB). The drainage area of UWRB is about 24 800 km^2. The mean annual precipitation is 512 mm and the mean annual potential evaporation is 893 mm.

The data used in the study include DEM, soil data, leaf area index (LAI), fraction of vegetation cover, meteorological data and discharge data. The spatial resolution of the DEM is 84 m × 84 m and the elevation of the UWRB is shown in Fig. 1. The soil data were obtained from the 1:1 000 000 China Soil Database (from Institute of Soil Science, Chinese Academy of Sciences). LAI is extracted from MODIS/Terra Leaf Area Index/FPAR 8-Day L4 Global 1km SIN Grid V005 (MOD15A25), and the fraction of vegetation cover comes from MODIS/Terra Vegetation Indices Monthly L3 Global 1km SIN Grid V005 (MOD13A3). The meteorological data of 18 weather stations were obtained from the meteorological agency and the location of the rainfall stations are shown in Fig. 2. Daily discharge data at Beidao hydrological station from 2001 to 2004 were collected from the hydrological agency.

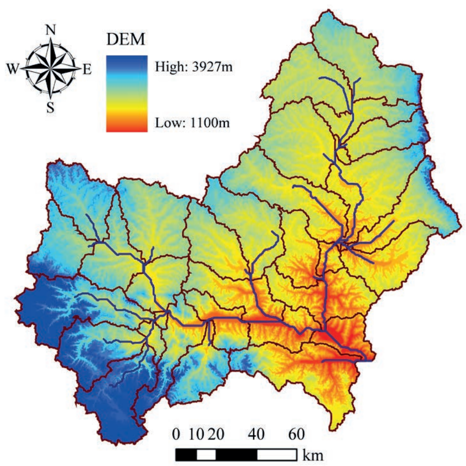

Fig. 1 The DEM of the Wei River Basin in China.

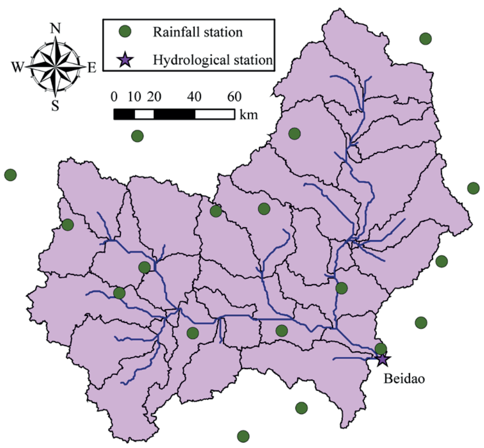

Fig. 2 Location of the rainfall stations and hydrological stations in the Wei River basin.

HYDROLOGICAL MODEL

The Tsinghua Hydrological Model based on REW (THREW model) is a semi-distributed physically-based hydrological model which uses Representative Elementary Watersheds (REWs) as the hydrological response unit. In THREW, each REW is subdivided into several sub-zones (Tian *et al*., 2006). There are the vegetated zone, bare soil zone, and main channel zone above the land surface, and the saturated zone and unsaturated zone under the land surface. For more details about THREW model, please refer to Tian *et al*. (2006).

After the development of THREW in 2006, it was successfully applied in many river basins, such as the Chabagou River basin of China (Tian, 2006), the headwaters of the Urumqi River, China (Mou *et al*., 2008), the Upper Sangamon River basin in Illinois State of USA (Liu *et al*., 2009; Li *et al*., 2010), the test watersheds in the Distributed Hydrologic Model Intercomparison Project – Phase 2 (DMIP2) (Li *et al*., 2012; Tian *et al*., 2012) and the Wei River Basin in China (Liu *et al*., 2012). The performance of THREW proved its ability to simulate the runoff component in the runoff generation process. In the model, four runoff components are simulated in the runoff generation processes: Hortonian runoff, Dunne runoff, quick subsurface flow, and slow subsurface flow. Hortonian runoff and Dunne runoff are surface runoff generated on the land surface during the rainfall. Quick subsurface flow and slow subsurface flow are the subsurface flow from the shallow soil layer and deep soil layer, respectively.

In the study, the Tsinghua Hydrological Model based on REW (THREW) is used to simulate the baseflow in the Upper Wei River basin. Based on the DEM of the Upper Wei River basin, the study area was divided into 35 sub-watersheds, i.e. Representative Elementary Watersheds (REWs) as shown in Fig. 1. The average area of the REWs is 708 km^2. The daily meteorological data (precipitation and potential evaporation) of 18 weather stations within or adjacent to UWRB (Fig. 2) from 2001 to 2004 were interpolated using Tessellation Polygons. The THREW model was run at daily temporal resolution for the period from 2001 to 2004.

BASEFLOW SEPARATION METHOD

The methods to separate baseflow from the flow have been investigated by many researchers, such as Arnold *et al*. (1995), Aksoy *et al.* (2009), Wang and Cai (2010), and others. Arnold *et al.* (1995) developed an automated baseflow separation method using a digital filter and tested it against three other automated techniques and manual separation methods. Since then the automated baseflow separation method has been widely used to separate baseflow from the streamflow. Aksoy *et al*. (2009) coupled the smoothed minima baseflow separation method of the United Kingdom Institute of Hydrology (UKIH) with the recursive digital filter (RDF) to develop the filtered smoothed minima baseflow separation (FUKIH) method, in which a smooth hydrograph representing the baseflow generating mechanisms is obtained. Wang and Cai (2010) provided an analytical baseflow recession equation to discuss the impact of human interferences, which include groundwater pumping, water diversion and return flow, on the determination of the recession slope curve. In the study, the automatic baseflow separation method proposed by Arnold *et al.* (1995) (hereafter noted as Arnold separation method) is used to separate the baseflow of the daily streamflow at Beidao hydrological station in Upper Wei River basin from 2001 to 2004. The baseflow index is defined as the ratio of the baseflow to the total runoff. With the daily baseflow from the Arnold separation method, the average intra-annual monthly baseflow index and annual baseflow index are calculated.

RESULTS

The THREW model for the Upper Wei River basin in China was calibrated and evaluated by Liu et al. (2012). The Nash-Sutcliffe efficiency coefficient (*NSEC*) and the coefficient of determination (R^2) were applied to evaluate the performance of the model quantitatively. In the simulation period of 2001−2004, *NSEC* reached 0.63 and R^2 reached 0.65 for the total period of 2001−2004. The hydrograph of the simulation period in the Upper Wei River basin was shown in Liu *et al*. (2012). As the continuous hydrological model for the semi-arid region, THREW has a reasonable performance in modelling the rainfall−runoff process in the Upper Wei River basin.

In the THREW model, fast subsurface flow can quickly respond to the change of the water storage in the upper soil layer due to rainfall infiltration, and more or less represents the interflow in the upper layer soil near the river channel (Liu *et al.*, 2012). The slow subsurface flow is the outflow of the groundwater. The baseflow consists of the fast subsurface flow and slow subsurface flow in the modelling.

Annual baseflow index

The result of the modelling shows that the max annual baseflow index is 0.460 in 2003 and the min annual baseflow index is 0.184 in 2002. The average annual baseflow index from the THREW model is 0.303, as shown in Table 1.

The baseflow at the Beidao Station from Arnold separation method is shown in Fig. 3, and annual baseflow index from the Arnold separation method is shown in Table 1. The average annual baseflow index is 0.360. The baseflow index from THREW is close to that from the Arnold separation method. The baseflow separation from the hydrological model is based on the runoff generation processes and the baseflow separation from the traditional baseflow separation method is based on the hydrograph at the outlet of the watershed with some assumptions. So the baseflow index from the hydrological model and traditional baseflow separation method may be a bit different. Based on the baseflow index from THREW and the Arnold separation method, the average annual baseflow index in Upper Wei River basin is in the range of 0.30−0.36.

Table 1 The comparison of annual baseflow index.

Period	THREW model	Arnold separation method
2001	0.248	0.347
2002	0.184	0.271
2003	0.460	0.367
2004	0.322	0.457
Average	0.303	0.360

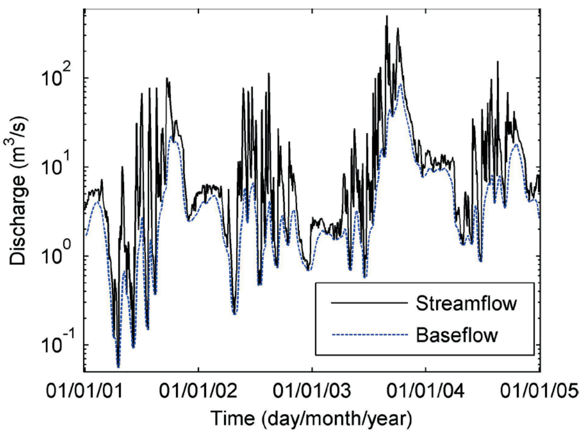

Fig. 3 The hydrograph of the streamflow and the baseflow from the Arnold separation method.

In the upstream of Tangnaihai station in Yellow River, Chen *et al*. (2006) found that the average annual baseflow index is 0.652 based on the streamflow data from 1956 to 2000. Compared with the upstream of Tangnaihai station in the Yellow River, the baseflow index in the Upper Wei River is smaller and the drainage to the streamflow is less. Qian *et al.* (2004) analysed the baseflow index of seven rivers in the middle reach of Yellow River, all of which are on the Loess Plateau, and found that the average baseflow index of the seven rivers, i.e. Huangfu, Gushan, Qingjian, Kuye, Jialu, Wuding and Tuwei, was 0.11, 0.18, 0.29, 0.33, 0.40, 0.55 and 0.68, respectively. It suggests that the annual baseflow indices of the rivers on the Loess Plateau are quite different because of the underlying conditions. The baseflow index of Upper Wei River basin is within the range of the baseflow index of the seven rivers and should be reasonable. In the future, the baseflow index will be investigated based on long-term discharge data.

Monthly baseflow index

The average intra-annual monthly baseflow index represents the seasonality of the baseflow due to the seasonality of precipitation and evapotranspiration. The monthly baseflow index from the hydrological modeling is shown in Fig. 4. The monthly baseflow index from April to September is in the range 0.065−0.276, and that is in the range 0.527−0.893 from October to March of the next year, when the main source of the streamflow is the baseflow. The maximum is 0.893 in December and the minimum is 0.065 in July. From October to March, the subsurface flow, i.e. the sum of the fast subsurface flow and the slow subsurface flow, dominates the runoff with a proportion of more than 53%, and more than 69% from November to February, especially. Dunnian runoff still dominates the runoff from April to September with the proportion of more than 72%.

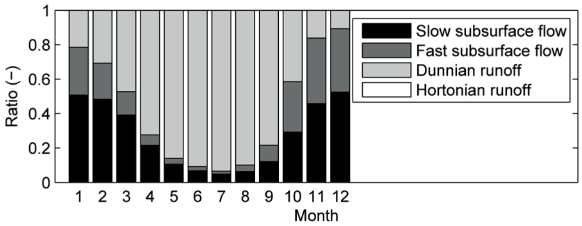

Fig. 4 The monthly ratio of the subsurface flow to the streamflow from THREW model.

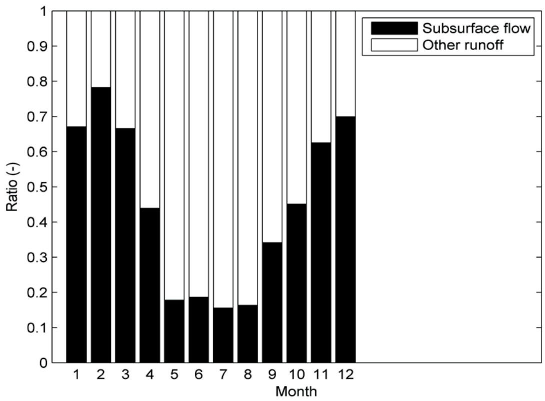

Fig. 5 The monthly ratio of the subsurface flow to the streamflow from Arnold separation method.

The monthly baseflow index calculated by the Arnold separation method is shown in Fig. 5. The monthly baseflow index from October to March is in the range of 0.451−0.782. From April to September, the baseflow index is 0.155−0.439, larger values than that from hydrological modeling. The maximum is 0.782 in February and the minimum is 0.155 in July.

The baseflow index from Arnold separation method has a similar pattern to the baseflow index from THREW model, as shown in Figs 4 and 5. The minimum monthly baseflow index is in July. The index from May to August is markedly smaller than that of other months, in the range 0.065−0.140 from hydrological modeling and 0.155−0.186 from the Arnold separation method. The result of the two methods shows that, the main source of the streamflow is the baseflow from October to March. The monthly baseflow index for November to March is in the range 0.527−0.893 and 0.625−0.782 from hydrological modeling and the Arnold separation method, respectively. The results suggest that the dominant runoff generation mechanism is different in different months and the subsurface flow dominates the runoff generation processes from November to March.

CONCLUSION

Given the importance of baseflow in dry season for drought relief to support the ecological water requirement and irrigation, especially in the Wei River, the baseflow was analysed. To investigate the baseflow in the Upper Wei River basin, a semi-distributed hydrological model based on the Representative Elementary Watershed approach (THREW) was employed to investigate the runoff generation process. To compare the result, an automatic baseflow separation method proposed by Arnold was used to separate the baseflow of the daily streamflow at Beidao hydrological station in Upper Wei River basin from 2001 to 2004.

Based on the hydrological modelling and the Arnold separation method, the average annual baseflow index, i.e. the ratio of baseflow to the total runoff, is estimated as approximately in the range 0.30−0.36. The average intra-annual monthly baseflow index represents the seasonality of the baseflow due to the seasonality of the precipitation and the evapotranspiration, and was also analysed. The hydrological modelling shows that, the monthly baseflow index from April to September is in the range 0.065−0.276, and in the range 0.527−0.893 from October to March of the next year. From the results of the Arnold separation method, the monthly baseflow index from April to September is in the range of 0.155−0.439, and t 0.451−0.782 from October to March of the next year. The monthly baseflow index from May to August is 0.065−0.140 from the hydrological modelling and 0.155−0.186 from the Arnold separation method, very small values.

In the study, the 4-years discharge data are used and in the future, the baseflow index will be investigated based on long-term discharge data and other baseflow separation methods will be applied.

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