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Estimation of base flow using flow–sediment relationships in the Chinese Loess Plateau

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ABSTRACT

A common practice to separate base flow from surface flow is to partition the streamflow into the high-frequency and low-frequency components. Instead, this study attempted to partition the streamflow into the erosive and non-erosive components and used the latter as an estimation of base flow. Previous work (Zheng et al., 2012) has reported a linear runoff–sediment yield relationship at the watershed scale in the Chinese Loess Plateau. It was found that the intercept term of this linear relationship represents the non-erosive-flow component of streamflow. We test this hypothesis using the long-term data (1950s to 1980s) of eight tributaries in the middle Yellow River, which are intentionally selected to represent various land surface compositions in the middle Yellow River. The estimated long-term mean, annual and monthly base flows using the flow–sediment relationship are reasonably comparable with those derived from the Lyne and Hollick filter method, whether the watershed management for soil conservation was implemented or not. Moreover, our method is arguably more accurate than the filter method, which tends to overestimate base flow by including all delayed components, not just groundwater flows, as base flow. Thus, our method does not only provide a new way to obtain base flow, but also has the potential to provide validation data in assessing the performance of other base flow separation methods.

1. Introduction

Base flow is a streamflow component which is considered as the outflow of the groundwater feeding a river especially during rainless periods (Aksoy et al., 2009). Base flow time series are not only of great importance for water resource management, but also are helpful for hydrologists to understand the spatial and temporal variability of runoff processes in river basins (Aksoy et al., 2009; Furey and Gupta, 2001; Huyck et al., 2005; Santhi et al., 2007). Direct and continuous measurements of base flow throughout a basin are practically impossible (Furey and Gupta, 2001; Gonzales et al., 2009). The separation of base flow from surface flow has long been a concern in hydrology (Fang et al., 2011; Gonzales et al., 2009; Hall, 1968; Huyck et al., 2005; Tallaksen, 1995; Yan et al., 2013). There have been numerous base flow separation methods, which can be categorized into three groups: graphical methods, digital filtering and separation based on chemical composition (Spongber, 2000). Graphical methods and chemical mixing techniques are labor intensive, especially when applied for long time periods (Chapman, 1999; Huyck et al., 2005). The digital filtering technology is objective and reproducible and is well applicable to long time series of discharge though it does not have physical or hydrological bases (Arnold et al., 2000; Huyck et al., 2005).

The digital filtering technology is currently most commonly used. The technology works on the observation that base flow reacts slowly to rainfall relative to surface flow. As a result, the “slow” or low-frequency component of streamflow can be interpreted to be base flow and the “fast” or high-frequency component of streamflow can be attributed to surface flow. Base flow is clear and non-erosive. In contrast, surface flow is sediment-laden and erosive. As a result, the base flow can be presumably associated with the non-erosive-flow component of streamflow, which forms the cornerstone of our method to estimate base flow.

The object of this study is to estimate base flow by partitioning the streamflow into components of erosive flow and non-erosive flow using the runoff–sediment yield relationship in the middle Yellow River basin of China. We first established the runoff–sediment yield relationships for eight tributaries of the middle Yellow River. Then, we estimated the amount of base flow using both the runoff–sediment yield relationship and a common filter method. Finally, we examined the discrepancy between the two methods.

2. Study area and data

The middle stream of the Yellow River passes through the Loess Plateau (Fig. 1), where a thick loess mantle (>100 m) forms the most spectacular landscape. As an eolian deposit, the loess is silty (0.005–0.05 mm) in texture and loosely compact (Zheng et al., 2013). The

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Nomenclature

BFI (%) the ratio of base flow to total streamflow;
SSY_a (t km^{-2}) specific sediment yield for a single year;
h_a (mm) runoff depth for a single year;
SSY_m (t km^{-2}) specific sediment yield for a single month;
h_m (mm) runoff depth for a single month;
$\overline{q_d}$ (m^3 s^{-1}) daily mean flow discharge;
$\overline{SD_d}$ (kg s^{-1}) daily mean sediment discharge;
$\overline{q'_{dB}}$ (m^3 s^{-1}) daily mean base flow discharge estimated using the Lyne and Hollick filter method;
$\overline{h_{aB}}$ and $\overline{h'_{aB}}$ (mm a^{-1}) the calculated mean annual base flow using the flow–sediment relationship and the Lyne and Hollick filter method, respectively;
h_{aB} and h_{aB}' (mm) the calculated annual base flow using the flow–sediment relationship and the Lyne and Hollick filter method, respectively;
Q_{mB} and Q_{mB}' (10^4 m^3) the calculated monthly base flow using the flow–sediment relationship and the Lyne and Hollick filter method, respectively.

climate is generally semi-arid and temperate with a mean average annual precipitation ranging from 400 mm in northwest to 600 mm in southeast (Liu et al., 1994). Vegetation cover is generally sparse. Soil erosion is largely driven by localized short-duration, high-intensity convective rainstorms. A single rainstorm can commonly cause a soil loss over 10000 t km^{-2}.

Data observed at nine gauging stations in eight tributaries of the middle Yellow River were used (Table 1). Besides loess, eolian sand and bedrock also appear in the middle Yellow River (Fig. 1). The eight rivers are intentionally selected to consist of various land surface compositions (see Table 1). The data used involves three time scales: annual specific sediment yield (SSY_a, t km^{-2}) and annual runoff depth (h_a, mm), monthly specific sediment yield (SSY_m, t km^{-2}) and monthly

Table 1
Gauging stations in eight tributaries of the middle Yellow River.

Station no.[a]	River	Gauging station	Area (km^2)	Data period	n[b]	Surface materials[c]
41	Huangfuchuan	Huangfu	3199	1956–1989	33	1 + 3
42	Kuyehe	Wenjiachuan	8645	1956–1989	32	1 + 2 + 3
43	Tuweihe	Gaojiachuan	3253	1956–1989	33	1 + 2
44	Wudinghe	Chuankou	29662	1975–1989	15	1 + 2
45	Wudinghe	Dingjiagou	23422	1960–1989	29	1 + 2
46	Qingjianhe	Yanchuan	3468	1956–1989	32	1
47	Yanhe	Ganguyi	5891	1956–1989	33	1
48	Pianguanhe	Pianguan	1915	1958–1989	31	1 + 4
49	Qiushuihe	Lingjiapin	1873	1956–1989	32	1 + 4

[a] The numbers correspond to those given in Fig. 1.
[b] *n* represents the number of recorded years.
[c] The given numbers represent land surface materials appearing upstream of the stations. "1" represents the loess, "2" represents the eolian sand (i.e. the MU US Sandy Land in Fig. 1), "3" represents the weathered bedrock (mainly sandstone and silty sandstone), and "4" represents the hard bedrock. The surface material "3" is widely exposed in upper parts of the northern rivers (e.g. #41 and #42). The surface material "4" generally corresponds to well-vegetated mountains (e.g. the Lvliang Mountain in Fig. 1).The surface materials 1-3 generally correspond to sparse vegetation coverage.

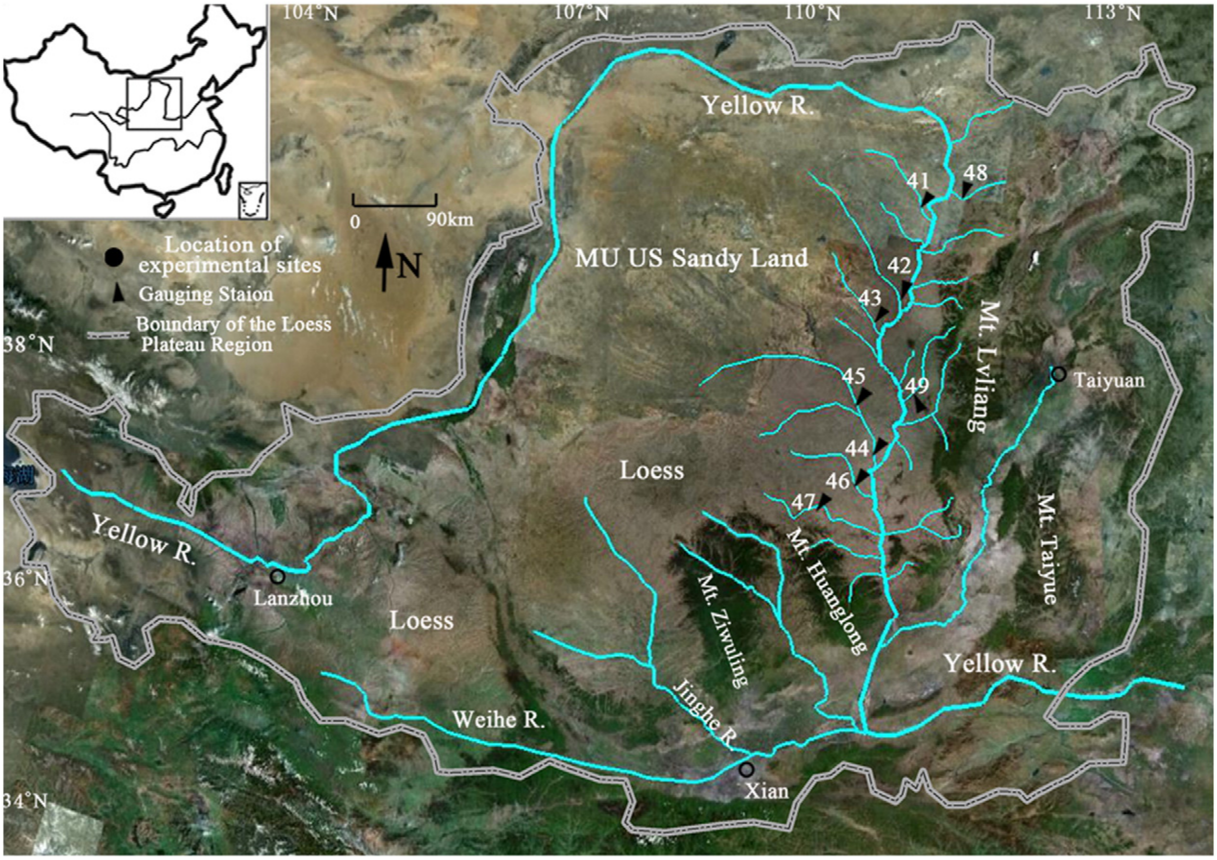

Fig. 1. Location of study areas. The numbers, corresponding to those used in Table 1, indicate the locations of the examined gauging stations. The image was derived from the Google Earth.