Changes in streamflow regimes and their response to different soil and water conservation measures in Loess Plateau watersheds, China

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Abstract

Investigating the changes in streamflow regimes is useful for understanding the mechanisms associated with hydrological processes in different watersheds and for providing information to facilitate water resources management. In this study, we selected three watersheds, i.e., Sandu River, Hulu River, and Dali River on the Loess Plateau, to examine the changes in the streamflow regimes and to determine their responses to different soil and water conservation measures (terracing, afforestation, and damming). The daily runoff was collected continuously by three hydrological gauges close to the outlets of the three watersheds from 1965 to 2016. The eco-surplus, eco-deficit, and degree of hydrological change were assessed to detect hydrological alterations. The Budyko water balance equation was applied to estimate the potential impacts of climate change and human activities on the hydrological regime changes. Significant decreasing trends ($P < 0.05$) were detected in the annual streamflow in the Sandu and Dali River watersheds, but not in the Hulu River watershed where afforestation dominated. The annual eco-surplus levels were low and they decreased slightly at three stations, whereas the eco-deficit exhibited dramatic increasing trends in the Sandu and Dali River watersheds. In the Sandu River watershed (dominated by terraces), the runoff exhibited the most significant reduction and the eco-deficit was the highest among the three watersheds. The integral degrees of hydrological change were higher in the Sandu River watershed than the other two watersheds, thereby suggesting substantial variations in the magnitude, duration, frequency, timing, and rate of change in the daily streamflow. In the Dali River watershed (dominated by damming), the changes in the extreme flow were characterized by a decreasing number appearing in high flow. In these watersheds, human activities accounted for 74.1%

and 91.78% of the runoff reductions, respectively. In the Hulu River watershed (dominated by afforestation), the annual runoff exhibited an insignificant decreasing trend but with a significant increase in the low flow duration. Rainfall changes accounted for 64.30% of the runoff reduction.

Keywords: climate variability; human activities; indicators of hydrologic alteration (IHA); streamflow regime

1. Introduction

Streamflows are essential for environmental health, economic prosperity, and human well-being. They provide the water required to produce energy, crops, and industrial products, and for maintaining terrestrial and aquatic environment systems (Curmi et al., 2013). The water resources in rivers determine the size, shape, structure, and dynamics of aquatic ecosystems. The streamflow regime in a river is considered to be mainly responsible for the variations in many other components of a river ecosystem, e.g., fish populations and nutrient cycling (Richter et al., 2003). Streamflow variability influences hydrological functions and it is important for maintaining biodiversity in rivers and the integrity of ecosystems (Arthington et al., 2006; Jovanovic et al., 2016; Vogel et al., 2007).

Recent studies have demonstrated that streamflow regimes have exhibited obvious changes in many rivers around the world. Approximately 24% of the world's large rivers appear to have exhibited significant changes in the water flux according to observations of the streamflow in 4399 rivers (Li et al., 2020). Forest clearing and large-scale agricultural activities have led to dramatic changes in the streamflow in Amazonian rivers over the last 40 years (Aldrich et al., 2012; Latrubesse et al., 2009; Souza-Filho et al., 2016). Milly et al. (2002) predicted increased streamflows for some areas of equatorial Africa, the La Plata Basin, and high-latitude North America and Eurasia, but decreases in southern Africa, southern Europe, the Middle East, and mid-latitude western North America by the year 2050. The global mean annual temperature has increased by 0.8°C since 1880 (Flato et al., 2013), and the humidity and precipitation increased by around 2% in the last century (Huntington, 2006; Wise, 2010), which may have altered the balance of the global water circulation and energy cycle, thereby resulting in changes in the magnitude and spatiotemporal distribution of streamflows (Nam et al., 2015). Climate change affects streamflow regimes by increasing temperatures but also by altering precipitation patterns, rates of evaporation, transpiration, and soil moisture contents (Merritt et al., 2006). Human activities may alter streamflow regimes through land use changes, large-scale infrastructure such as reservoirs, water abstraction, urbanization, and ecological restoration projects (Dey et al., 2017; Liang et al., 2015; Tamm et al., 2018; Wang et al., 2016b). Both of these possible causes of changes in streamflow regimes have been investigated widely (Li et al., 2021; Ellis, 2011; Guo et al., 2019; Munoz et al., 2018; Zhang et al., 2017; Smith et al., 2016). It is necessary to explore streamflow variations and related factors to better understand the mechanisms associated with streamflow changes (Li and Fang, 2017; Wang et al., 2020), thereby providing useful reference data to facilitate climate adaptation and improved water resources management.

Hydrologic alterations represent the changes in streamflow regimes at different temporal and spatial scales due to regulation and water extraction via human activities. Over recent decades, numerous methods have been developed to assess the streamflow variations in rivers. The Newtonian and Darwinian approaches are currently applied widely from microscopic and macroscopic perspectives, respectively (Omer et al., 2020; Wang et al., 2020). Hydrological models (e.g., SWAT, TOPMODEL, and VIC) are mainly categorized as Newtonian approaches, and they are useful tools for hydrologic alteration assessment and decision making (Tamm et al., 2018). A representative Darwinian approach is the Budyko-based method, which has been widely applied to quantify how climate change and human activities might affect streamflow changes (Liang et al., 2015; Wang et al., 2019).

Many methods have been developed to assess streamflow regime changes. In particular, Richter et al. (1996) proposed the indicators of hydrologic alteration (IHA) method for quantifying streamflow regime changes using long-term observed daily flows in the Roanoke River in North Carolina, USA. Furthermore, the range of variability approach (RVA) was developed to meet the water requirements of ecosystems and achieve ecological sustainability, where the degree to which the shape of a river's natural flow regime can be altered is a well-established approach for quantifying flow regime alteration (Olden and Poff, 2003).

Many studies have demonstrated that hydrologic regimes are associated with dam construction (Yang et al., 2008). Lai et al. (2013) and Wang et al. (2016b) found that the operation of the Three Gorges Project aggravated hydrological droughts downstream, thereby leading to extremely low water levels and environmental flow deficits, with substantial effects on the streamflow regimes downstream of the Yangtze River. By contrast, Du et al. (2020) suggested that the construction of dams can stabilize hydrological regimes and reduce the flood peaks.

The Yellow River is one of China's largest rivers and the water it carries is utilized by 8% of the population. The lower reaches of the Yellow River appeared to have zero flows for 21 of the 27 years from 1972 to 1998, which contributed to the severe ecological damage to the river (Chen et al., 2020). Droughts, water shortages, and soil and water losses are the most severe environmental problems that have affected the social and economic development of the Yellow River basin (Wu et al., 2004). The Loess Plateau is located in the middle reaches of the Yellow River basin. Over 20 rivers flow into the Yellow River and they contribute nearly 9% of the sediment and 40% of the streamflow into the river basin. Due to severe soil erosion, various soil and water conservation measures have been implemented on the Loess Plateau since the 1970s (Zhao et al., 2014). The main measures comprise afforestation, check dam construction, and terracing, which have increased rainfall infiltration and reduced the flood peaks, soil erosion, and sediment transported into the rivers. Many studies have been conducted on the Loess Plateau to estimate the changes in runoff and the sediment load, as well as their potential causes (Gao et al., 2015; Guo et al., 2020; Zhang et al., 2017; Zhang et al., 2018; Zhou et al., 2020). These studies have clarified the effects of climate changes and human activities on runoff and sediment load reductions. However, few studies have assessed the alterations in the streamflow regimes and their responses to different soil and water conservation measures. Due to the limited availability of information regarding conservation measures, few studies have also compared the hydrological responses of river flows to individual conservation measures. Therefore, the objectives of this study were: (1) to examine the changes in the streamflow regimes in three watersheds with different conservation measures; and (2) to quantify the effects of climate variability and human activities on the streamflow changes.

2. Study area and data

2.1. Study area

More than 20 tributaries in the middle reaches of the Yellow River flow through the Loess Plateau and they discharge approximately 90% of the sediment that enters the Yellow River. Since the 1950s, extensive soil and water conservation measures have been implemented in these watersheds to control severe soil erosion, including afforestation, grass planting, terracing, and check dam construction. According to the spatial distribution and types of soil and water conservation measures on the Loess Plateau, we selected the following three different watersheds and analyzed the changes in their streamflow regimes: Sandu River watershed (dominated by terracing), Hulu River watershed (affected by afforestation), and Dali River watershed (dominated by check dams). Figure 1 shows the locations of the watersheds and hydro-meteorological gauges.

2.1.1. Sandu River watershed

The Sandu River watershed is located upstream of the Wei River basin and it covers an area of 2484 km^2. This watershed is characterized by a continental monsoon climate, with a mean annual temperature around 10.2°C and average annual precipitation of approximately 467.3 mm. The average annual streamflow and sediment yields are 0.45 billion m^3 and 8560 t/km^2, respectively. Since the 1970s, many terraces have been constructed on the hill slopes. Terraces with a total area of 1807.45 km^2 were built by 2017, which covered 72.7% of the whole watershed.

2.1.2. Hulu River watershed

The Hulu River is a tributary of the Beiluo River (a tributary of the Wei River, Figure 1), with a drainage area of 4715 km^2. The mean annual precipitation and evaporation in this watershed are 494 mm and 1147 mm, respectively. The streamflow from July to September accounts for about 50% of the annual total. The catchment is covered by dense forest, where *Pinus tabuliformis* Carr. and *Platycladus orientalis* (Linn.) Franco are the major forest species present in this watershed. More than 90% of the sloping arable land was converted into forest or grassland after 1999 as part of the “Grain for Green” project launched by the Chinese government. The vegetation cover has reached approximately 80% and the sediment yield decreased significantly from 107 × 10^4 t in the 1960s to 76.8 × 10^4 t in 2016.

2.1.3. Dali River watershed

The Dali River is the largest tributary of the Wuding River, with an area of 3906 km^2 and length of 170 km. The average annual streamflow was 1.31 billion m^3 from 1960 to 2016. The average annual precipitation is 429 mm and high-intensity rainstorms cause considerable soil erosion in this watershed during the summer. Since the beginning of the 1980s, many check dams have been built in the watershed to trap sediment transported from hill slopes to the Yellow River. In 2017, 11602 check dams were present in the Wuding watershed, i.e., 1155 large sized check dams and 10174 medium to small sized check dams (Han et al., 2018). Due to the implementation of large-scale soil and water conservation measures in the Dali River watershed, the sediment load decreased from 0.64 × 10^8 t/a in the 1970s to 0.15 × 10^8 t/a from 2000 to 2016 (Zhang et al., 2019).

<Figure 1>

2.2. Data set

The daily streamflows at the Gangu (Sandu River), Zhangcunyi (Hulu River), and Suide (Dali River) hydrological stations (Figure 1) were obtained from the Hydrological Year Book of the Yellow River, which was published by the Ministry of Water Resources of China. In total, the daily discharge measurements for 52 years from 1965 to 2016 were collected for investigation. Table 1 shows general information for the three stations in the watersheds. Monthly rainfall, air temperature, relative humidity, sunshine duration, and wind speed meteorological data at 11 climate stations were obtained from the China National Climate Center. The potential evapotranspiration was calculated using the Penman–Monteith equation (Allen et al., 1998). The basin-averaged precipitation and potential evapotranspiration data were estimated, and then interpolated with the inverse distance weighted method in ArcGIS 10.6 (http://www.esri.com). The spatial distributions of soil and water conservation measures, including terraces, check-dams, and reservoirs, in each catchment during 2017 were interpreted with Google Earth and validated based on a field survey. The homogeneity and continuity of all the measured data were checked to guarantee the data integrity and consistency before their release.

<Table 1>

3. Methodology

The Mann–Kendall test and accumulated anomaly method were applied to detect the changing trends and abrupt changes in the annual streamflow at the three hydrological stations. These methods have been used widely to examine changing hydro-meteorological time series (Kendall, 1975; Mann, 1945; Sagarika et al., 2014; Zhao et al., 2014), so they are not described in detail. The detailed estimation procedures were described in previous studies (Weber et al., 2010; Zhao et al., 2019). The IHA method (Richter et al., 1996) was employed to analyze the streamflow regime changes according to the daily streamflow, and the effects of climate change and human activities on streamflow variations were assessed by using the Budyko equation (He et al., 2019; Yang et al., 2014).

3.1. Changes in hydrological regimes

The IHA method was first developed by the Nature Conservancy and it has been applied widely. The IHA method employs 32 parameters (we excluded “the number of zero-flow days” because zero flows were never observed at the three hydrological stations) related to hydrological extremes and averages, which can be classified according to five major categories (Table 2).

The RVA method proposed by Richter et al. (1996) was used to quantify the hydrological changes in terms of the 32 indicators. The target range for the RVA comprises IHA values that fall within the thresholds between the 25th and 75th percentile values (Huang et al., 2019). The degree to which the RVA does not reach the target range denotes the degree of hydrological change, and can be expressed as (Di) for each indicator. Cheng et al. (2019) and Zhang et al. (2016) described the calculation method in detail. Therefore, the following three equal sized categories were employed: (1) $\left(\left|D_i\right| < 33\%\right)$ indicating little or no alteration; (2) $\left(33\% < \left|D_i\right| < 67\%\right)$ denoting a moderate degree of alteration; and (3) $\left(67\% < \left|D_i\right| < 100\%\right)$ representing a large change.

The nondimensional eco-flow metrics comprising the eco-deficit and eco-surplus were estimated based on the flow duration curve (FDC) using the daily flow data (Vogel et al. 2007) in order to provide intuitive representations of the hydrological impacts and to supplement those characterized by the IHA. The annual FDC can be regarded as a function of the excess of the daily streamflow over the probability in each year. The eco-flow metrics were estimated in the following four steps. (1) According to the change point, the daily streamflow series covering the period from 1965 to 2016 was subdivided into two sections. In the baseline period, human activities were regarded as having limited effects on the streamflow regimes. (2) The 25% and 75% FDC quantiles were taken as threshold values, and the values in the intervals were the adaptive range for the river ecosystem. (3) The eco-flow was determined by comparing the annual FDC in other years with the previously obtained 25% and 75% FDC quantiles. The area above the 75% quantile FDC was the eco-surplus, whereas the area below the 25% quantile FDC was the eco-deficit. Full details of the calculation procedure were provided by Gao et al. (2012) and Vogel et al. (2007).

<Table 2>

3.2. Impacts of climate variability and human activities

The Budyko equation is important in hydrology because it provides a concise and accurate representation of the relationship between the annual evapotranspiration and long-term average water and energy balance at catchment scales (Sposito, 2017). In a natural basin, the long-term average annual water and energy balance at the catchment scale can be expressed as follows.

$$R = P - E - \Delta S \quad (3)$$

The Budyko hypothesis (Budyko, 1974) considers the balance for precipitation (P) between potential evapotranspiration (E_0) and actual evapotranspiration (E). Based on the long-term catchment water balance equation, ΔS is assumed to be zero. By combining dimensional analysis and physical principles, Fu (1981) analytically derived the water–energy balance function at the mean annual time scale, which is expressed as:

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^{\omega}\right]^{\frac{1}{\omega}}, \qquad (4)$$

where E_0 is the mean annual potential evapotranspiration and the parameter ω represents the catchment landscape characteristics. The long-term $\frac{E}{P}$ is mainly controlled by the water–energy balance $\frac{E_0}{P}$ (the dryness index). Changes in the catchment streamflow can be expressed as the sum of three components defined by Schaake (1990) as the precipitation, potential evapotranspiration, and catchment landscape elasticity of the streamflow, and thus the new equation is expressed as:

$$\Delta R = \varepsilon_P \frac{R}{P}\Delta P + \varepsilon_{E_0}\frac{R}{E_0}\Delta E_0 + \varepsilon_{\omega}\frac{R}{\omega}\Delta\omega = \Delta R_P + \Delta R_{E_0} + \Delta R_{\omega}, \qquad (5)$$

where the elasticities of the streamflow are given as:

$$\varepsilon_P = \frac{\left[1 + \left(E_0/P\right)^{\omega}\right]^{\frac{1}{\omega}+1} - \left(E_0/P\right)^{\omega+1}}{\left[1 + (E_0/P)^{\omega}\right]\left\{\left[1 + \left(E_0/P\right)^{\omega}\right]^{\frac{1}{\omega}} - \left(E_0/P\right)\right\}} \qquad (6)$$

$$\varepsilon_{E_0} = \frac{1}{\left[1 + (E_0/P)^{\omega}\right]\left\{1 - \left[1 + \left(E_0/P\right)^{-\omega}\right]^{\frac{1}{\omega}}\right\}} \qquad (7)$$

$$\varepsilon_{\omega} = \frac{\ln\left[1+(E_0/P)^{\omega}\right] + (E_0)^{\omega}\ln\left[1+(E_0/P)^{-\omega}\right]}{\ln\left[1+(E_0/P)^{\omega}\right]\left\{1-\left[1+(E_0/P)^{-\omega}\right]^{\frac{1}{\omega}}\right\}}, \qquad (8)$$

where ω is a model parameter denoting the non-climatic effects on the water–energy balance attributed to the soil properties, topography, and vegetation (Gunkel et al., 2017; Wang et al., 2016a).

Changes in the observed mean annual runoff depth ΔR^T can be estimated between the baseline period and changing period, and they can be attributed to climate variability ΔR^C and human activities ΔR^h. The streamflow change due to climate variation (ΔR^C) includes the streamflow changes due to precipitation variation (ΔR_P) and potential evaporation variation (ΔR_{E_0}) (Koster & Suarez, 1999; Milly & Dunne, 2002). The contributions to annual streamflow changes due to climate change and human activities, respectively, can be approximated as follows.

$$\eta_C = \frac{\Delta R^C}{\left|\Delta R^C\right| + \left|\Delta R^h\right|} \times 100\% \qquad (11)$$

$$\eta_h = \frac{\Delta R^h}{\left|\Delta R^C\right| + \left|\Delta R^h\right|} \times 100\% \qquad (12)$$

4. Results

4.1. Changes in annual streamflows

4.1.1. Temporal variations in annual streamflows

Figure 2 shows the linear trends in the annual streamflows in the three watersheds. Overall, the annual streamflows tended to decrease at all stations, with relatively high reductions at Gangu station (0.159 mm/10a) and Suide station (0.138 mm/10a) during 1965–2016. For example, at Gangu station, the annual average streamflow was only 0.21×10^8 m^3/a from 1995 to 2016, which was much lower than that during 1965–1994 (0.629×10^8 m^3/a). The Mann–Kendall test showed that the annual streamflows at Gangu (Figure 2a) and Suide stations (Figure 2c) decreased significantly ($P < 0.01$), but not significantly at Zhangcunyi station (Figure 2b). Comparisons of the annual streamflow fluctuations at the three stations showed that the variability in the annual streamflow was higher at Zhangcunyi ($C_V = 0.34$).

<Figure 2>

4.1.2. Abrupt changes in annual streamflows

As shown in Figure 3, abrupt changes in the annual streamflows mostly occurred during the mid-1990s and they were mainly attributable to the large-scale soil and water conservation measures implemented in the middle reaches of the Yellow River. Abrupt changes were detected during 1994 at Gangu station (Figure 3a), 1990 at Zhangcunyi station (Figure 3b), and 1996 at Suide station (Figure 3c). Therefore, the total time series at each station were divided into two periods based on these breakpoints. The first period represented the baseline period with very limited human activities or none. The second period represented the change period when the watershed experienced substantial changes in land use, afforestation/deforestation, and dam construction.

<Figure 3>

4.2. Changes in IHA metrics

The IHA indicators in group 1 (G1) represent the magnitudes of the average monthly median streamflow, which clearly varied at the three gauging stations. Significant decreases were found in all of the areas, but particularly at Gangu station, with average change rates lower than –50% (P < 0.001). The median 1-, 3-, 7-, 30-, and 90-day annual minimum/maximum flows (Group 2, G2) tended to decrease. The highest reduction in G2 was detected at Gangu station and the lowest at Zhangcunyi station. In addition, the 1- and 3-day minimum flows increased at Suide station but not significantly. The Group 3 (G3) indicators represent changes in the timing of extreme flows. The minimum and maximum dates tended to increase at all three stations, thereby suggesting time lag effects of the soil and water conservation measures. In particular, at Gangu station, the low flow date changed most greatly and reached up to 90.9%. In the Group 4 (G4), the durations of the low pulses tended to increase at all stations during the changing period, but especially at Gangu and Zhangcunyi stations, with higher change rates (P < 0.05) that increased from 3 to 6.5 days and 3.5 to 7.25 days, respectively. The durations of the high pulses remained relatively stable at all stations. Different trends were found at Suide station where the median duration of high pulses during the change period decreased to 2.5 days and by 9.09% compared with that of 2.75 days before the baseline period. The flow fall rates all decreased significantly at three stations ($P < 0.05$).

The variations in the hydrologic indicators tended to differ among the stations, as shown in Figure 4b. We found that 13 indicators exhibited moderate alterations at Suide station, 18 indicators had low-degree alterations at Zhangcunyi station, and 75% of the indicators had high degree alterations at Gangu station. Clearly, the fall rates exhibited the greatest changes ($|D_i|>67\%$) in the three watersheds and they indicated declines in the streamflows, where more of the conditions in the post-period were below the lower limit of the RVA threshold than those in the pre-period. At Suide station, the D_i value was related to the flood season. Indicators such as the duration of low pulses $(D_i = -78.57\%)$, baseflow index $(D_i = -70\%)$, and number of reversal stations were assigned to the high-degree alteration category at Zhangcunyi.

<Figure 4>

4.3. Changes in eco-flow metrics

In Figure 5, the blue and red curves correspond to the 25th percentile and 75th percentile FDC, respectively, during the baseline period at each station. Compared with the daily streamflow indices in the baseline period, the high and low flows decreased significantly at the three stations, where the reductions in the low flow (Q_{90}) rates were lower than those in the high flow (Q_{10}) rates at Gangu and Zhangcunyi stations. In particular, the low flow declined greatly by 69.57% at Gangu station. By contrast, the daily streamflow remained relatively stable at Zhangcunyi station, where the Q_{10} and Q_{90} components decreased by

23.48% and 18.4%, respectively. At Suide station, the reduction in the low flow component (44.64%) was higher than that in the high flow (23.33%) during the changing period.

<Figure 5>

Figure 6 shows the annual eco-flow metrics (eco-surplus and eco-deficit) obtained based on the annual FDC and temporal variations in the annual precipitation anomaly at the three stations. Overall, the annual eco-surplus and annual eco-deficit tended to fluctuate greatly. Remarkably, the variations in the annual eco-deficit were more substantial than those in the annual eco-surplus. Figures 6b, 6d, and 6e show the eco-surplus and eco-deficit results for the three stations in different decades. From the 1990s, the annual eco-deficit increased dramatically at Gangu station (a), but there was no apparent variation at Zhangcunyi (b) and only a slight increase at Suide station (c). The eco-surplus tended to decrease at the three stations. At Gangu station, persistent and high peaks were detected in the eco-deficit and eco-surplus during the early baseline period and later changing period. In addition, the negative deviation in the precipitation explained the eco-deficit during 1994–2002. At Zhangcunyi station, the eco-flow metrics varied consistently with the changes in precipitation, thereby suggesting that afforestation did not change the eco-flow metrics in the watershed and climate change may have contributed more to the streamflow changes. At Suide station, the eco-flow metrics and precipitation were strongly correlated. During the changing period, the eco-deficit increased because of the implementation of soil and water conservation measures, although the precipitation increased. According to Figure 6, the low flow rate contributed more to the eco-surplus whereas the high flow rate contributed more to the eco-deficit. These results are similar to those reported by Du et al. (2020).

<Figure 6>

4.4. Attribution of streamflow variations to climate variability and human activities

Significant reductions in the annual streamflow could be attributed to climate change and human activities. We employed the Budyko equation to quantify the effects of climate change and land surface changes on the streamflow variations. After comparing the annual runoff rates in the changing period and baseline period, we found that the streamflow decreased by 16.83 mm, 4.16 mm, and 9.95 mm at Gangu, Zhangcunyi, and Suide stations, respectively. Thus, the annual streamflow reduction was lowest at Zhangcunyi station in the forest dominated watershed. As shown in Table 3, climate change only accounted for 25.9% and 8.22% of the reductions in the Sandu and Dali River watersheds, respectively. Human activities were mainly responsible for the runoff reductions, particularly in the Dali River watershed (91.78%). In contrast to the Sandu and Dali River watersheds, the streamflow reduction in the Hulu River basin was attributed primarily to climate change (64.30%), and human activities (mainly afforestation) were only responsible for the other 35.70%.

<Table3>

5. Discussion

5.1. Impacts of climate change and human activities on streamflows

Using hydro-climatic data, the elasticity/sensitivity method based on the Budyko equation has been widely applied to quantify the effects of climate variability and human activities on streamflow changes. Wang et al. (2020) found that human activities accounted for over 50% of the runoff reductions in four catchments in the Yellow River basin from 1960 to 2015. Gu et al. (2019) showed that precipitation and human activities contributed approximately 20% and 80%, respectively, to the runoff reductions in both river sources and the middle reaches of the Yellow River basin. Similar results were obtained in our analyses of watersheds dominated by terraces and check dams, but different results in the afforested watershed (Hulu River watershed).

To further verify our results, we applied the double mass curve method to quantify the effects of climate change and human activities on the runoff changes (Chang et al., 2015; Gao et al., 2017). Figure 7 shows that changes were found in the cumulative annual runoff curves and precipitation at Suide and Gangu stations, thereby indicating that the runoff changes were more significant in these two watersheds. The estimates indicate that human activities accounted for 86.85% of the runoff reduction at Gangu station and 97.11% at Suide station. For the Hulu River watershed, human activities accounted for 35.70% of the streamflow reduction and the remaining 64.30% was attributed to climate change. Thus, the results obtained using the double mass curve were consistent with those produced by the Budyko method.

<Figure 7>

5.2. Impacts of soil and water conservation measures on streamflow regime changes

Soil and water conservation measures have been implemented in the upper and middle reaches of the Yellow River basin since the late 1950s (Zhang et al., 2018). These measures include biological measures comprising afforestation and grassing, and engineering measures comprising terracing and check dams. Approximately 58000 check dams have been built, including 5546 large sized dams. The area covered by terraces is 5.5×10^4 km^2, mostly upstream of the Wei River and in the middle reaches of the Yellow River basin.

The proportion of vegetation cover in the study area was 28.6% in the 1980s and it increased to 63.2% by 2018. These obvious changes in the land surface cover were responsible for the significantly reduced river streamflow. Vegetation plays a vital role in regulating terrestrial water flows, where forests can fix and store carbon as well as regulating water functionalities (Bai et al., 2020; Ellison et al., 2017; Farooqi et al., 2020). The "Grain for Green" project launched in 1999 greatly increased the vegetation cover and reduced soil erosion on the Loess Plateau (Zhou et al., 2015). Figure 8 shows the vegetation cover at different levels (high, medium, and low vegetation cover) in the three watersheds. Changes in the medium and high vegetation cover levels occurred in the three watersheds. In general, the Hulu River watershed had a high vegetation cover rate, and transformations occurred from medium vegetation to high vegetation cover in the other two watersheds from 1998 to 2016 (Figures 8b and 8c). These results are consistent with previous reports of great increases in the vegetation cover in the middle reaches of the Yellow River basin (Wang et al., 2019), and the vegetation cover has increased significantly since 2002 (Xin et al. 2008).

<Figure 8>

The hydrological responses to afforestation differed among the three river basins. We found significant reductions in the runoff in the Sandu and Dali River watersheds, and a constant increase in the eco-deficit values after the abrupt change. The results suggest that engineering measures had more significant effects on runoff reduction. A non-significant decrease in the annual runoff was found in the forest-dominated basin (Hulu River basin), thereby confirming that afforestation affected the river streamflow by increasing terrestrial interception and evapotranspiration (*ET*). Moreover, large differences in the eco-flow metrics and degree of hydrologic alteration according to most of the IHA indicators were found between the Hulu River basin and other watersheds. Previous studies by Zhou et al. (2015), Ellison et al. (2017), and Evaristo et al. (2019) showed that afforestation can effectively moderate floods by storing or recycling substantial amounts of water via interception, infiltration, transpiration, evaporation, and groundwater recharge. Vegetation cover can help to maintain a low flow by moderating the streamflow and conserving water. The change in precipitation was also an important factor that affected the variations in vegetation cover. Thus, the relatively stable streamflow regime in the Hulu River basin was caused by afforestation.

However, compared with the changes in the annual runoff in the humid region, the dry region tended to decrease due to both climate variability and afforestation. Zhou et al. (2020)

reported that the water conserving effects of afforestation were higher than those of increased terrestrial interception and evapotranspiration in a humid region. However, this is the opposite of the effect found in dry areas, such as the Hulu River watershed. Afforestation can increase low flows and reduce high floods through more interception and infiltration, but it also results in higher evapotranspiration. This may explain the decreased runoff at Zhangcunyi station.

<Figure 9>

Terraced fields are essential measures for reducing the transport of soil eroded from upstream to downstream areas by reshaping the microtopography and increasing the slope length (Tarolli et al., 2014), as demonstrated by Zhang et al. (2008) and Chen et al. (2017). An experimental study conducted by Ran et al. (2006) suggested that terraces could reduce the runoff by 60.7% and sediment yield by 58.0% in the Wei River Basin. In the Sandu River basin, about 72.7% of the watershed is covered by terraces (Table 4), which is much higher than the coverage rates found in the Dali and Hulu River basins. The change in the streamflow regime in the Sandu River basin differed from those in the other watersheds. The annual streamflow and eco-deficit decreased most in the Sandu River basin watershed, thereby demonstrating the significant effect of terraces on the surface runoff. The Budyko method indicated that the evaporation was 40 mm higher during the changing period than the baseline period. Moreover, the duration of the low flow increased, whereas the number of high flows clearly decreased.

<Table 4>

Check dams were initially built to trap sediment and produce fertile agricultural land in the gully-dominated region of the Loess Plateau. According to Li et al. (2016), check dams are vital engineering measures for retaining flood water, trapping upstream sediment, increasing the availability of farmland for agricultural production, and reducing downstream sediment transport. In the Dali River watershed, 46.7% of the total area was controlled by check dams and reservoirs in 2017. By contrast, far fewer check dams were present in the other two watersheds. Dams and reservoirs can effectively reduce flood peaks and increase their slow time, as indicated by the IHA metrics. Dam construction significantly increases the seepage of soil water into groundwater, thereby leading to an increase in low flows. According to Martin-Rosales et al. (2007), check dams increased the infiltration of runoff by 3–50% in a semiarid region of Spain. Unlike vegetation measures, engineering measures can immediately regulate surface runoff, especially in high flow events. Furthermore, the hydrological alteration degree in the Dali River watershed changed significantly in terms of the streamflow regime among the watersheds, thereby demonstrating the strong influence of dams on hydrological processes.

Previous studies employed the IHA/RVA approach to analyze the hydrological alterations in the middle reaches of the Yellow River. Zhang et al. (2016) determined the effects of reservoir construction and operation in the upper Yellow River basin on alterations in the ecological flow regimes, and found decreases in high flows and increases in low flows at mainstream stations. Indicators of low flow and rising and falling water conditions changed greatly, and they were consistent with our results. However, we obtained more detailed results regarding the streamflow regime changes related to different soil and water conservation measures.

6. Conclusion

In this study, we applied the IHA/RVA method and eco-flow metrics to estimate streamflow regimes based on the daily discharge in three watersheds where different soil and water conservation measures were implemented from 1965 to 2016 on the Loess Plateau. The Budyko equation was employed to quantify the effects of climate change and human activities on the streamflow variations. Our main conclusions can be summarized as follows.

(1) The annual streamflows decreased significantly at Gangu station (Z = –6.75) in the Sandu River watershed and Suide station (Z = –3.28) in the Dali River watershed. The decrease in the annual streamflow was not significant at Zhuangcunyi station (Z = –1.75) in the Hulu River watershed. Abrupt change points were mostly detected in the 1990s for all watersheds.

(2) The hydrological indicators obtained with the IHA/RVA method showed that the degrees of hydrological change in the Sandu River, Dali River, and Hulu River basins were at high, medium, and low levels, respectively, thereby suggesting that the streamflow regimes varied under different soil conservation measures. On the microscale level, the low flow duration and the number of high flows had great influences at the three stations.

(3) The changes in the eco-deficit were more remarkable than those in the eco-surplus at all stations. The annual eco-deficit increased dramatically after the 1980s at Gangu station, but there was no obvious change at Zhangcunyi and it only increased moderately after the

1990s at Suide station. The annual eco-surplus tended to decrease slightly at all three stations.

(4) The significant annual runoff reductions were primarily attributed to human activities in the Dali River watershed (91.7%) and Sandu River watershed (74.1%). Climate change accounted for 64.30% of the annual streamflow decrease in the Hulu River watershed where afforestation dominated.

The streamflow at Gangu station changed greatly due to the significant effect of numerous terraces, which apparently led to an eco-deficit. The flow regime was altered in the forest dominated watershed but the overall streamflow was relatively weaker and vulnerable to climate change. Moreover, human activities made the greatest contribution to the reduced runoff in the Suide watershed. The results obtained in this study provide novel insights into hydrological regime changes and their responses to different soil and water conservation measures.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (grant number 42077076). We also thank the National Climatic Centre and the Hydrology Bureau of the Yellow River Water Resources Commission for providing valuable climatic and hydrological data.

Data Availability Statement

Data available on request due to privacy/ethical restrictions.

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