**Attribution of runoff changes in the main tributaries of the middle Yellow River, China, based on the Budyko model with a time-varying parameter**

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**Abstract**

Discerning the controlling factors of spatial and temporal changes in runoff is critical for water resources management. This study investigated runoff changes and related them to climate change and human activities in 14 sub-catchments of the middle Yellow River basin, China. The spatio-temporal variations in contributions of factors to runoff change were examined using a Budyko-based framework with a time-varying catchment characteristic parameter *n* in a 9-year moving window and by a comparison of northern and southern sub-catchments. The results show that runoff changes induced by climate change had an increasing trend firstly and then gradually decreased over the period 1982–2015, whereas human activities associated with soil and water conservation measures had a greater impact in the northern parts of the study area. We found that the parameter *n* in Choudhury-Yang’s equation is significantly correlated to climatic and artificial factors. The influence of climatic factors on runoff includes changes both in hydrological inputs and catchment characteristics while the impacts of artificial factors are mainly achieved by the alteration of catchment characteristics. In addition to vegetation cover, the engineering measures for soil and water conservation, mainly including terraces and check-dams, played an important role in runoff reduction in the middle Yellow River basin. Inclusion of such features is therefore important when undertaking runoff attribution analysis.

**Key words:** runoff change; climate change; vegetation cover; soil and water conservation measures; Budyko model

1. **Introduction**

Recent observations from many rivers suggest streamflow has been seriously disturbed in many parts of the world due to climate variation, land use/cover change (LUCC), check-dam construction and re-afforestation (Walling and Fang, 2003; Liu et al., 2008; Naik and Jay, 2011; Salmoral et al., 2015). Climate variation will alter the spatio-temporal distribution of global water resources (Jiang et al., 2010) and LUCC can transform the water balance of a watershed by affecting rainfall interception and actual evapotranspiration (Zhan et al., 2014). Li et al. (2020) found that 24% of the world’s large rivers have experienced significant changes in streamflow. By assembling long-term records of annual streamflow for 10 large rivers across China, Liu et al. (2008) concluded that there was little change in average annual runoff in the southern rivers but runoff in the northern rivers showed significant evidence of reduction. Hydrological processes in arid and semiarid regions are especially vulnerable to environmental change (Li et al., 2017; Zhou et al., 2015a) and it is a grand challenge to manage water resources in these ecologically fragile areas. Hence, scientific understanding of watershed hydrology has important practical significance for improving water resources management. For sustainable utilization of water resources, the attribution of climate variation and human activities to changes in runoff has been the focus of more research over recent years (Zhai and Tao, 2017; Hasan et al., 2018; Wang et al., 2016).

The middle Yellow River basin (MYRB) in China is a water-scarce area under arid and semiarid climate. With population growth and urbanization, water shortage has become an important bottleneck for economic progress. During the past 30 years, the runoff from sub-catchments (e.g., Huangfu, Jinghe, Wuding and Weihe) located in the MYRB has decreased dramatically. Many previous studies have assessed the impacts of climate change and human activities on catchment annual runoff in the MYRB as a whole or in specific tributaries of the basin. For example, Gao et al. (2011), using double mass curves, showed that human intervention was the main driving factor controlling runoff of the MYRB. By using the Soil & Water Assessment Tool (SWAT) hydrological model, Shi et al. (2019) found that the impact of human activities accounted for 75% of the declining runoff in the Wuding River and check-dams for 12% over the period 1980–2010. Han et al. (2019) concluded that soil and water conservation measures, comprising building check-dams, terracing, and large-scale ecological restoration, are the critical factors causing runoff reduction in the Wuding River. Zuo et al. (2016) reported that land use types including grassland, farmland and forest explained 25.3% of the water yield decrease whereas climate change gave rise to a runoff reduction of 53.7% in the Huangfu River. Wang et al. (2012) assessed the contributions of precipitation and human activities in the Huangfu River using a new statistical method based on the slope change ratio of accumulative quantity (SCRAQ), and reported that the contribution of human activities to decreasing runoff was 63.57% (1980–1997) and 83.19% (1998–2008), respectively. As can be seen from these examples of previous work, different approaches (process-based and statistically-based) have been used in conjunction with available time series for runoff, resulting in different, and sometimes contradictory, conclusions being reached. Here, process-based hydrological models require a large quantity of input data, meaning that many previous studies using such models are limited to specific catchments/regions of the MYRB. As a result, it remains necessary to clarify the main reasons for declining runoff in the MYRB using a consistent method applied at whole basin scale. The work reported in this paper addresses this research need and evidence gap.

The Budyko framework is a rational method linking water and energy in a catchment (Donohue et al., 2007). Because of its simplicity and effectiveness, it has been widely applied to assess impacts of climate forcing and land surface characteristics on water and energy cycles at catchment scales (Xu et al., 2013). In recent years, the Budyko methods have been introduced into the attribution analysis of runoff changes in the MYRB (Zhao et al., 2014; Li et al., 2017; Liang et al., 2015; Ning et al., 2017). Fu’s (Fu, 1981) and Choudhury-Yang’s functions (Yang et al., 2008) are the most popular for describing catchment water-energy partitioning (Zhou et al., 2015b; Ning et al., 2019). The controlling parameters *w* in Fu’s equation and *n* in Choudhury-Yang’s equation reflect the influence of catchment characteristics and determine the shape of the Budyko curve (Yang et al., 2008). It is necessary to develop an empirical form for quantifying the contributions of the main factors to the parameter variations, so as to better interpret hydrological changes induced by human activities (Li et al., 2017). There have been some previous studies to establish the relationship of catchment parameters to the factors such as climate, vegetation, topography, irrigated area, population and gross domestic product (Yang et al., 2007; Jiang et al., 2015; Ning et al., 2019). However, the effects of soil and water conservation measures, especially check-dams and terraces, on the controlling parameters are often only analyzed qualitatively (Li et al., 2017; Liang et al., 2015), and importantly, they are rarely separated from other factors in the attribution of runoff changes. In addition, these influencing factors and the controlling parameters have conventionally been regarded as constants, but are known to vary with time.

In the context of the above background and research gaps, the work reported in this paper examined the impacts of climate change and soil and water conservation measures on catchment water balance in the main tributaries of MYRB. More specifically, the relationship of the parameter *n* in Choudhury-Yang’s function with climatic factors and soil and water conservation measures, including check-dams and terraces, was established to reveal the time-varying nature of *n* by using a 9-year moving window.

**2. Data and methods**

***2.1. Study area***

The MYRB is located between the Toudaoguai and Huayuankou hydrological stations (Fig. 1). It is bounded by the Taihang Mountains in the east, the Qin Mountains in the south, and the Mu Us desert in the northwest (Shi et al., 2013). On the west side of the Yellow River mainstream is the Loess Plateau, and on the east side is the Lvliang Mountains. The MYRB covers a drainage area of ~362,000 km2 and the total length of the mainstream channel is ~1234 km, with elevations ranging between 85–3917 m (Sun et al., 2020). The MYRB is characterized by a semi-humid and semi-arid continental monsoon climate. From north to south, mean annual precipitation ranges from 320 mm to 830 mm, 70% of which falls in the flood (June to September) season (Zhao et al., 2014). The mean annual temperature ranges from about 6 °C to 11 °C southwards, with a basin wide average annual potential evapotranspiration of 1055 mm.

The MYRB is the main sediment source for the Yellow River (Zhang et al., 2019). It occupies 48.1% of the total area of the Yellow River Basin, but its sediment yield accounted for nearly 90% of the total sediment load of the Yellow River gauged at Huayuankou station over the period 1950–2019 according to hydrological records. To control soil erosion, the Chinese government has implemented a series of soil and water conservation projects since the 1950s, which include both biological (“Grain to Green” project) and engineering (terraces and check-dams) measures (Ning et al., 2017). The area affected by soil and water conservation measures increased from 2.9×103 million m2 in the 1950s to 1.02×105 million m2 by 2006, including 2.85×104 million m2 of terraces, 5.86×104 million m2 of afforestation, 1.41×104 million m2 of planted grassland and 1.3×103 million m2 of check-dams (referring to the silted land behind dams) (Zhao et al., 2014). As a result, the hydrological processes and responses of the MYRB have undergone significant changes.

***2.2. Data***

Annual runoff data over the period 1982–2015 were collected from the Yellow River hydrological yearbook issued by the Yellow River Conservancy Commission. Daily meteorological data for the same years were acquired from the National Meteorological Information Centre (<http://data.cma.cn/>), comprising daily precipitation, maximum and minimum temperatures, atmospheric pressure, sunshine duration, wind speed, and relative humidity. For all the hydroclimatic data, missing values were replaced with the arithmetic mean of the neighbouring stations. Potential evapotranspiration () at each meteorological station was estimated using the Penman-Monteith equation recommended by the Food and Agriculture Organization (FAO; Allen et al. 1998). Mean annual runoff, precipitation and potential evapotranspiration in each of the 9-year moving windows were calculated from the annual data. The Normalized Difference Vegetation Index dataset 3 (NDVI3g) in the framework of Global Inventory Modelling and Mapping Studies (GIMMS) was obtained from the National Aeronautics and Space Administration (NASA) Ames Ecological Forecasting Lab, and the NDVI data covering the growing season (June to September) were converted to the fraction of photosynthetically active radiation () for the purposes of our study. Digital elevation models (DEMs) with a spatial resolution of 90 m were downloaded from the Loess Plateau Data Center, National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (http://loess.geodata.cn). The implementation history of soil and water conservation measures (including terraces, trees, pasture and check-dams) was reconstructed from Zhang (2016), Liang et al. (2015) and Shi et al. (2013). Missing data for soil and water conservation measures were obtained by interpolation and extension from the adjacent years. All the primary data used in this study were quality assured by the corresponding agencies before being made publicly available.

***2.3. Methods***

To analyze the spatial variations in runoff changes, 14 sub-catchments in the MYRB were selected for our study area (Fig. 1 and Table 1). To investigate the temporal changes in runoff and causal attribution, a 9-year moving window was chosen to divide the whole study period spanning 1982–2015 into subperiods. The selection of this moving window paid due consideration to the fact that water storage change is zero for periods longer than 5–10 years based on the findings of Li et al. (2017) and Zhang et al. (2001). In the study reported herein, we first assigned impacts of climatic and artificial factors on catchment characteristic parameters, and then we quantified the impacts of climate change and human activities on the water balance equation.

*2.3.1. The Budyko function*

The Budyko hypothesis (Budyko, 1974) treats the distribution of precipitation () between actual evapotranspiration () and runoff () as a function of water supply and energy demand from the atmosphere. In this study, the Choudhury-Yang equation (Roderick and Farquhar, 2011) was used to describe catchment water-energy partitioning:

(1)

where  represents potential evapotranspiration and  refers to catchment landscape characteristics which are considered to be governed both by land surface and climate conditions (Zhang et al., 2016; Ning et al., 2019). is defined here as the difference between precipitation and runoff by ignoring the changes in water storage over the long term.

*2.3.2. Estimating the parameter*

The parameter  was calibrated at the catchment scale by minimizing the mean squared error between the modelled and water-balance-based 9-year moving mean . Stepwise regression analysis was used to relate the parameter and catchment attributes and build the semi-empirical formula of  in the 14 sub-catchments of the MYRB. Here, expresses the 9-year moving mean of catchment characteristic parameter (for instance, in 1986 equals the average of for 1981–1989). Following Ning et al. (2019), three catchment attributes were considered: vegetation coverage (the fraction of Photosynthetically Active Radiation was chosen in our study, ), climate seasonality index (*S*), and the fraction of precipitation falling as snow (). We also considered the following four catchment attributes: precipitation (), potential evapotranspiration (), temperature (), and the ratio of engineering measure area to the total catchment area (). is very similar to the NDVI, and we selected it because it is a biophysical attribute that directly links vegetation with surface energy and water fluxes (Donohue et al., 2008). The climate seasonality index is an important factor that controls the catchment scale water balance and the inclusion of *S* can improve water balance simulations on the Budyko curve (Yang et al., 2012). Berghuijs et al. (2014) proved that the changes of would significantly affect catchment hydrological processes. The value of each sub-catchment was derived from soil and water conservation data provided by Liang et al. (2015), Zhang (2016) and Shi et al. (2013). As the capacity of runoff interception by terraces and check-dams is different (Zhang et al., 1994; Shi et al., 2013; 0.07 m3/m2 and 0.45 m3/m2, respectively), we assumed a weight of 1 for check-dams and 0.07/0.45 for terraces. With these weights, the ratio of engineering measure area for soil and water conservation () to the total sub-catchment area can be calculated. and were also chosen as critical climatic factors that would have a profound impact on the parameter . Jiang et al. (2015) showed that could affect runoff through altering the parameter and should therefore be considered explicitly. The detailed calculation procedures of , *S*, and are described in the Supplementary information.

*2.3.3. Separating the impacts of climate change and human activities on runoff*

The Choudhury-Yang equation with the parameter was employed as the physical basis to separate the impacts of climate change and human activities on runoff. In the baseline period (), the precipitation, potential evapotranspiration and runoff were denoted by , and with the parameter . In the post-baseline period (), the precipitation, potential evapotranspiration and runoff were = , , with the parameter . According to Roderick and Farquhar (2011), the total differential of runoff can be expressed as:

(2)

where the partial derivatives in the three terms on the right-hand side of the equation are the sensitivity coefficients of runoff to , and , respectively (see Supplementary information). With the differences of the conditions of climate and human activities in the baseline period and the post-baseline period, Eq. (2) can be expressed as:

(3)

In some previous studies (e.g., Xu et al., 2014), the change of the parameter was attributed to human activities. However, it might be unreasonable to attribute the change of the parameter just to human activities as climatic factors could also play an important role in affecting this parameter (Ning et al., 2019; Yang et al., 2007). Therefore, the causes of the change in should include not only artificial factors but also hydroclimatic variables. The contributions of climatic and artificial factors to the change in parameter were estimated by using the total differential method. Ignoring the higher orders of the Taylor expansion, the total differential equation for parameter *n* can be written as:

(4)

With the individual relative contributions of climatic and artificial factors to the change in parameter , the contribution to the change in runoff induced by climate change can be calculated:

(5)

Finally, the contribution to the change in runoff induced by human activities can be expressed as:

(6)

*2.3.4. Trend analysis*

To detect the long-term variations in runoff and influencing factors in the MYRB, the nonparametric Mann-Kendall test-based index (Kendall slope; Mann, 1945; Kendall, 1975) was employed to estimate the significance of the trends in runoff together with climate factors and human activities.

**3. Results**

***3.1. Trend analysis of the annual hydroclimatic variables and artificial factors***

As summarized in Table 2, annual runoff showed a significant downward trend for most sub-catchments, except for the Fenhe sub-catchment. The rate of changes in runoff ranged from –0.02 to –1.45 mm·a–2, with an average of –0.65 mm·a–2. Annual presented a significant upward trend in most sub-catchments (apart from the Wuding sub-catchment) of 1.76 mm·a–2. In contrast, no significant trends in *P* and were detected for any of the sub-catchments. Annual in three sub-catchments exhibited decreasing trends while the remaining sub-catchments exhibited increasing trends. Statistically significant (p < 0.1) trends in were only detected for the Dali, Qingjian, Yanhe and Beiluo sub-catchments. Significant increases in annual were identified for all sub-catchments. For artificial factors, the annual and increased drastically and passed the Mann-Kendall trend test at the 0.05 significance level in all 14 sub-catchments.

***3.2. Changes in and its relationship with climatic and artificial factors***

The annual values of the time-varying parameter from 1986 to 2011, were computed with mean annual , and in each time window as inputs. Fig. S1 depicts the evolution and linear trend of in each sub-catchment. It was found that in most sub-catchments (apart from the Wuding and Dali sub-catchments) showed significant upward trends at the 0.01 significance level, meaning that the evapotranspiration would increase and the runoff would decrease for the same hydrological inputs.

Jiang et al. (2015) and Ning et al. (2019) found that the catchment characteristic parameter was significantly sensitive to the combined effects of both climatic and artificial factors. Hence, we first focused on the relationships between and climatic and artificial factors with respect to their temporal variations. Here, soil and water conservation measures were included in the artificial factors. Power and exponential regressions were performed for each of the influencing factors (Fig. 2). For climatic factors, was positively correlated with (R2 = 0.54, p < 0.001), (R2 = 0.12, p < 0.001) and (R2 = 0.19, p < 0.001) but negatively correlated with (R2 = 0.29, p < 0.001) and (R2 = 0.40, p < 0.001). This suggested that the runoff change caused by variation in catchment characteristics decreased with increasing , and but increased with increasing and . For artificial factors, was positively correlated with (R2 = 0.70, p < 0.001) and (R2 = 0.19, p < 0.001). Due to the existence of collinearity between influencing factors, the stepwise regression method was used for selecting significant factors and building the relationship for the 14 sub-catchments over the study period (1982–2015). The dataset from the 14 sub-catchments was used to fit the relationships between and influencing factors. Considering the relationships in Fig. 2, the general form of the time-varying parameter can be expressed as:

(7)

Using the linear least square regression method, the time-varying parameter was derived as follows:

(F = 379.7, p < 0.0001) (8)

The simulated *E* was estimated with the modelled based on Eq. (8). Figure 3 shows that the simulated *E* is close to the “measured” *E* (based on water balance) with low MAE (mean absolute error), RMSE (root-mean-square error) and RE (relative error) values and a NSE (Nash-Sutcliffe efficiency) coefficient greater than 0.9. Thus, , and explained the time-varying parameter of the sub-catchment water balance in the Choudhury-Yang equation.

***3.3. Quantitative attribution of runoff variation***

For apportioning controls on runoff variation in this study, the initial nine years (1982–1990), centered at 1986, was treated as the base-line period while the other time windows were regarded as the post-baseline periods. The individual relative contributions of climatic and artificial factors to the parameter were derived by applying Eq. (4) to Eq. (8). Fig. 4 shows the evolutions of climate-induced runoff change and human-induced runoff change by altering the sub-catchment characteristic parameter over the period 1982–2015. Compared to the baseline period of 1982–1990, played an important role in total runoff changes in all 14 sub-catchments during most time windows. In the Jialu, Qingjian, Yanhe, Weihe and Fenhe sub-catchments, some time windows showed that by altering catchment characteristic parameters, artificial factors promoted runoff decline while climatic factors inhibited runoff decline, meaning that the contribution rate of artificial factors to runoff change exceeded 100%. However, it should be noted that climate change and human activities were commonly both driving factors for the decline in runoff within the MYRB.

Figure 5 summarizes the runoff change  induced by the change of vegetation cover and runoff change induced by the change in the ratio of engineering measure area to the total sub-catchment area. It can be seen that has a larger impact on than in most sub-catchments during most time windows. However, the effects of on runoff reduction increased over time in all 14 sub-catchments. Here, the engineering measures for soil and water conservation accounted for a large proportion of in the Beiluo, Jinghe, Fenhe and Xinshui sub-catchments.

***3.4. Spatio-temporal variations of climatic and anthropogenic runoff changes***

The runoff changes induced by climate change and human activities are shown in Fig. 6. It can be seen that runoff changes induced by climate change had an increasing trend first and then decreased. Accordingly, the role of human activities has increased over time. Also, it is clear that the contribution rates of climate change and human activities were highly variable in the 14 sub-catchments of the MYRB during the period 1991–2015. A close inspection of Fig. 6 reveals a distinct contrast between the contribution rates for the northern and southern sub-catchments. Here, based on the long-term hydroclimatic characteristics (Table 1), we divided the MYRB into northern and southern parts and examined the impact of climate change and human activities on runoff in five selected time windows; i.e., 1982–1990, 1991–1999, 2000–2008, 2007–2015 and 1991–2015. The northern part of the MYRB consists of the Huangfu, Gushan, Kuye, Tuwei, Jialu, Wuding, and Dali sub-catchments, characterized by low vegetation cover ( < 0.45, the mean over 1982-2015, the same below), low mean precipitation ( < 500mm), high potential evapotranspiration ( > 1000mm) and high climate seasonality. The southern part includes the Qingjian, Yanhe, Beiluo, Jinghe, Weihe, Fenhe, and Xinshui sub-catchments with higher vegetation cover (> 0.45), higher mean precipitation (> 500mm), low potential evapotranspiration (< 1000mm) and low climate seasonality.

Compared with 1982–1990, the impacts of climate change and human activities on runoff for all the sub-catchments varied over different periods (Table 3). During 1991–1999, human activities in the Huangfu, Kuye, Jialu and Dali sub-catchments played a significant role, whereas climate change was more important in the Gushan, Tuwei and Wuding sub-catchments in the northern part. In the southern part of the MYRB, except for the Qingjian and Xinshui sub-catchments, the contributions of climate change in most sub-catchments were more than 90%. The contribution of climate change to runoff variation in the Qingjian sub-catchment was slightly lower than that of human activities. In the period 2000–2008, the contribution rates of human activities to runoff variation gradually decreased from the Huangfu sub-catchment to the Dali sub-catchment in the northern part and the contribution rates of climate change exceeded 100% in the Wuding and Dali sub-catchments. Similarly, climate change had a greater impact in the southern part of the MYRB, except in the Qingjian and Yanhe sub-catchments located in the transition zone between the northern and southern parts of the MYRB. In the period 2007–2015, the impact of human activities on runoff change in all 14 sub-catchments increased. Only in the Jinghe, Weihe and Fenhe sub-catchments, in the southern part of the MYRB, were the effects of climate change stronger than human activities. For the whole period spanning 1991–2015, the results were similar to those for 2000–2008. In the four most northern sub-catchments (Huangfu, Gushan, Kuye and Tuwei), the contribution of human activities was more than 100%. The impact of climate change on runoff in the southern part was more significant than that in the northern part of the MYRB.

**4. Discussion**

***4.1. Why are soil and water conservation measures included in the sub-catchment characteristic parameter?***

In previous studies, the catchment characteristic parameter was reported to be mainly affected by soil types, topographic factors and vegetation cover. Soil and topography were generally included as constants and the parameter variation thereby came from vegetation change. The assumption of some static parameters is clearly dependent on some catchment characteristics included in the Budyko framework being free from human interference. This approach is suitable for some case studies but the opportunities for taking this simplistic approach are becoming more limited. Xu et al. (2014), for example, chose 33 catchments with low human impacts in the Haihe basin, China, when attributing runoff decline based on the Budyko hypothesis. However, catchments without direct influence of local human activities are increasingly rare in most parts of the world, including in the MYRB, since large-scale soil and water conservation measures have been implemented, initiated by government-sponsored conservation programmes and ecological restoration campaigns since the 1950s (Sun et al., 2019). The resulting different land use patterns have great impacts on the water cycle. By interception and dissipation, hillslope-targeted measures, such as vegetation cover and terraces, reduce runoff into river channels. In-channel measures including check-dams influence the runoff change by controlling flooding and increasing infiltration during wet seasons (Polyakov et al., 2014). In addition, water diversion for irrigation and potable consumption has significantly influenced the hydrological cycle and should be included in the catchment characteristic parameter when applying the Budyko hypothesis. Liang et al. (2015) analysed the relationships between the catchment characteristic parameter and the affected area of ecological restoration measures and revealed that the parameter could be captured by the relative area. Furthermore, a high correlation was detected between the parameter and the accumulative areal fraction of different land use types for most regions in the case study reported by Li et al. (2017). Hence, in our study reported herein, the effects of terraces and check-dams on the parameter *n* were taken into explicit consideration in terms of their accumulative areal fractions and their runoff-detaining efficiency. Figure 2 shows that the parameter was positively correlated with the ratio of engineering measure area to the total corresponding sub-catchment area (, p < 0.001) and Fig. 5 also demonstrates that the impact of engineering measures associated with soil and water conservation on runoff variation cannot be ignored. Vegetation cover (denoted as ) also has a significant relationship with the parameter (Fig. 2). With regards to irrigation, Ning et al. (2019) found that vegetation could represent the effects of the effective irrigated area ratio in water-limited areas and that the effective irrigated area ratio for 30 catchments on the Loess Plateau, China, showed a weak relationship with the catchment characteristic parameter. Thus, irrigation information was not included in the parameterization scheme of the present study. According to the above analysis, changes in the catchment characteristic parameter are related to changes in soil and water conservation measures, not vegetation cover alone. It is therefore informative to develop an empirical formula to include these factors explicitly when apportioning controls on runoff change.

***4.2. Causes for spatio-temporally variable attribution of runoff changes***

The above results show that the human contribution rates in the northern sub-catchments tended to be higher than those in the southern ones. This regional discrepancy in human contribution rates is likely to result from the contrasting climate conditions between the northern and southern sub-catchments. A comparison between the northernmost (Huangfu, Gushan, Kuye and Tuwei) and southernmost (Beiluo, Jinghe, Weihe and Fenhe) sub-catchments supports this reasoning. The of the four northernmost sub-catchments ranged from 2.13 to 2.63 and their corresponding ranged between 0.25–0.43. The corresponding contribution rate of human activities for all the time windows was 24.2%–185.9% in these four sub-catchments. In contrast, the corresponding contribution rate of human activities for all the time windows varied between 12.4% and 65.5% in the southernmost sub-catchments, which had a lower value in the range of 0.51 to 0.70 and a much larger value in the range of 0.49–0.75. The more important role of human activities in runoff variations in the northern sub-catchments on the Loess Plateau suggests again that in the areas under arid or semi-arid climate, the river runoff is more sensitive to human interferences as argued by Zhou et al. (2015a) and Ukkola et al. (2016).

Besides the effects of climate change and human activities, previous studies have argued that the transformation from precipitation to streamflow is highly scale dependent (Li et al., 2017). The following analyses suggested that sub-catchment scale may be also responsible for the diverse contributions of climate change and human activities to runoff change in the study area. Three sub-catchments (Beiluo, Jinghe and Xinshui) with similar climate were selected to assess the role of scale. Their values fall in a narrow range from 1.72 to 1.77, but their are different; 0.716, 0.519 and 0.687 for the Beiluo, Jinghe and Xinshui sub-catchments, respectively, Correspondingly, their values are 0.058, 0.057 and 0.039, respectively. It can be seen that the vegetation cover of the Xinshui sub-catchment is within the range of those of the Beiluo and Jinghe sub-catchments but that the Xinshui sub-catchment has a lower runoff coefficient than the latter two sub-catchments. This may be a reflection of the scale effects in that each of the Beiluo and Jinghe sub-catchments has a much larger drainage area than the Xinshui sub-catchment (Table 1). Furthermore, we performed a Pearson correlation test between the contribution rates of human activities () and the sub-catchment area. The result showed that was negatively related with sub-catchment area at the 0.01 significance level.

Disclosed by the attribution of temporal runoff change at a yearly time step in this study (Fig. 4), the contribution rates of climate change to runoff change in most sub-catchments generally experienced an initial rise before decreasing, reaching the maximum in the time windows of the 1990s. Both the upward and downward trends were very sharp, and the trend has stabilized in the last decade. This temporal pattern is consistent with the implementation of the Integrated Management of Small Watersheds programme after 1982 and the Grain-for-Green programme since 1999 (Sun et al., 2020 and Liang et al., 2015). In addition, human activities in some sub-catchments (Jialu, Wuding, Dali, Qingjian, Beiluo, Jinghe, Fenhe and Xinshui) increased runoff in some time-windows. This was related to the decline in vegetation cover and the destruction of some check-dams due to extreme weather in the corresponding year. In the early stages of small watershed management in the study area, inappropriate afforestation including the selection of unsuitable tree species and overly high afforestation densities, resulted in the emergence of only small trees which had a low effect on runoff reduction (Jia et al., 2019). This phenomenon gradually alleviated after the implementation of the Grain-for-Green programme.

Clarifying the detailed response of runoff changes to climate change and human activities over time can not only test the effects of ecological restoration and soil and water conservation in the past, but also provide a solid evidence base for decision makers in the future. Given the potential for soil and water conservation measures to impact runoff in tributaries, it is important to assess the likely impacts of these measures when planning their implementation for maintaining the healthy development of river catchments at regional scale.

***4.3. Limitations***

It is important to acknowledge some uncertainties and limitations in the attribution of runoff changes. Yang et al. (2014) indicated that climate elasticity estimated from a first-order Taylor expansion generates a potential error, when an increasing or decreasing underestimates the climatic contributions and a decreasing or increasing overestimates climatic contributions. Table 2 shows that the trend of was not significant and increased significantly in all sub-catchments, meaning that the contribution rates of climate change may be overestimated in our study. Similarly, errors were induced from the developed empirical formula for the controlling parameter . In addition, may be affected by additional factors. For instance, Zhang et al. (2001) reported that different vegetation types have different impacts on catchment water balance, and Jiang et al. (2015) claimed that population and gross domestic product could change the runoff of rivers. Therefore, further exploration of factors influencing the controlling parameter remains a goal for future work.

**5. Summary**

In this paper, we applied a two-step framework based on Choudhury-Yang’s equation with a time-varying parameter to separate the impacts of climate change and human activities on runoff in 14 sub-catchments of the MYRB. Firstly, the relationship of the parameter *n* in Choudhury-Yang’s equation with climatic and artificial factors was built to reveal its temporal variations using a 9-year moving window. Secondly, the impacts of climate change and human activities on runoff were estimated using a sensitivity method. The results show that soil and water conservation measures, such as terraces and check-dams in the study area, should be taken into account in the artificial factors that affect the controlling parameter *n.* Similarly, the influence of climatic factors on the parameter *n* could not be ignored. The contributions of climate change and human activities were spatio-temporally variable. The impacts of human activities on runoff in the northern and southern parts were significantly different and the relative contributions from climate change were generally decreasing over time after an initial increase. The changes in precipitation and temperature accounted for the main runoff change induced by climate change, while the increasing vegetation cover contributed to the main anthropogenically-induced runoff change. The use of the methods described in this paper can help inform improved management of water resources in areas where water stress is increasing.

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Table 1 Long-term (1982–2015) hydroclimatic characteristics.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | Long-term mean annual value | | | | | | |
| ID | Sub-catchment | Gauging Station | Area (km2) | (mm a-1) | (mm a-1) | (mm a-1) | (10-2 a-1) | (a-1) | ( a-1) | *n* |
| 1 | Huangfu | Huangfu | 3,230 | 21.94 | 1001.70 | 419.99 | 3.42 | 0.51 | 8.72 | 2.32 |
| 2 | Gushan | Gaoshiya | 1,260 | 29.33 | 1012.33 | 443.07 | 3.32 | 0.44 | 9.34 | 2.20 |
| 3 | Kuye | Wenjiachuan | 8,621 | 40.62 | 1037.81 | 429.14 | 3.85 | 0.52 | 8.54 | 1.83 |
| 4 | Tuwei | Gaojiachuan | 3,307 | 69.00 | 1043.97 | 448.32 | 3.43 | 0.48 | 9.25 | 1.49 |
| 5 | Jialu | Shenjiawan | 1,138 | 30.10 | 1040.94 | 460.09 | 3.21 | 0.44 | 9.78 | 2.23 |
| 6 | Wuding | Dingjiagou | 24,682 | 29.49 | 1050.21 | 422.13 | 3.28 | 0.61 | 9.45 | 2.02 |
| 7 | Dali | Suide | 3,861 | 31.27 | 1033.22 | 472.99 | 3.11 | 0.44 | 10.32 | 2.28 |
| 8 | Qingjian | Yanchuan | 3,600 | 32.92 | 1009.31 | 510.59 | 3.14 | 0.27 | 10.92 | 2.50 |
| 9 | Yanhe | Ganguyi | 5,857 | 30.14 | 989.71 | 530.11 | 3.16 | 0.22 | 10.71 | 2.78 |
| 10 | Beiluo | Zhuangtou | 25,723 | 32.22 | 957.97 | 552.56 | 4.75 | 0.12 | 10.05 | 2.97 |
| 11 | Jinghe | Zhangjiashan | 43,106 | 30.45 | 937.37 | 529.53 | 4.57 | 0.15 | 9.98 | 2.92 |
| 12 | Weihe | Linjiacun | 30,122 | 46.34 | 865.50 | 543.90 | 6.44 | 0.13 | 7.19 | 2.76 |
| 13 | Fenhe | Hejin | 38,728 | 13.88 | 961.88 | 529.29 | 3.75 | 0.14 | 11.24 | 3.77 |
| 14 | Xinshui | Daning | 4,186 | 22.21 | 965.82 | 562.50 | 3.65 | 0.19 | 11.32 | 3.49 |

Note: , , , , , , and *n* are runoff, potential evapotranspiration, precipitation, the fraction of precipitation falling as snow, climate seasonality index, temperature and catchment characteristic parameter, respectively.

Table 2 Summary of the trend analysis for the hydroclimatic variables and artificial factors using the Mann-Kendall trend test (1982–2015).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sub-catchment | (mm a-2) | (mm a-2) | (mm a-2) | (10-3 a-2) | (10-3 a-2) | ( a-2) | (10-3 a-2) | (10-2 a-2) |
| Huangfu | -0.99(\*\*\*) | 1.85(\*\*\*) | 1.23(ns) | 0.40(ns) | 2.12(ns) | 0.06(\*\*\*) | 3.06(\*\*\*) | 1.31(\*\*\*) |
| Gushan | -1.07(\*\*\*) | 1.86(\*\*\*) | 1.52(ns) | 0.30(ns) | 0.29(ns) | 0.06(\*\*\*) | 4.40(\*\*\*) | 3.60(\*\*\*) |
| Kuye | -1.45(\*\*\*) | 0.98(\*) | 0.92(ns) | 0.36(ns) | 2.39(ns) | 0.06(\*\*\*) | 3.26(\*\*\*) | 1.52(\*\*\*) |
| Tuwei | -1.03(\*\*\*) | 1.36(\*\*) | 1.46(ns) | 0.34(ns) | -0.32(ns) | 0.06(\*\*\*) | 3.87(\*\*\*) | 2.28(\*\*\*) |
| Jialu | -0.51(\*\*) | 1.41(\*\*) | 1.95(ns) | 0.25(ns) | -8.54(ns) | 0.05(\*\*\*) | 5.14(\*\*\*) | 4.74(\*\*\*) |
| Wuding | -0.23(\*\*\*) | 1.08(ns) | 0.63(ns) | 0.25(ns) | 1.81(ns) | 0.04(\*\*\*) | 3.17(\*\*\*) | 3.32(\*\*\*) |
| Dali | -0.30(\*\*) | 1.11(\*) | 1.43(ns) | 0.23(ns) | 5.00(\*) | 0.03(\*\*) | 4.40(\*\*\*) | 4.34(\*\*\*) |
| Qingjian | -0.50(\*) | 1.48(\*) | 2.13(ns) | 0.06(ns) | 4.85(\*) | 0.02(\*\*) | 6.36(\*\*\*) | 6.71(\*\*\*) |
| Yanhe | -0.45(\*\*\*) | 2.25(\*\*) | 1.52(ns) | 0.11(ns) | 4.26(\*) | 0.03(\*\*\*) | 4.67(\*\*\*) | 3.06(\*\*\*) |
| Beiluo | -0.49(\*\*\*) | 2.69(\*\*) | 0.78(ns) | -0.45(ns) | 1.94(\*) | 0.04(\*\*\*) | 1.76(\*\*\*) | 2.40(\*\*\*) |
| Jinghe | -0.66(\*\*\*) | 2.64(\*\*\*) | 0.52(ns) | -0.21(ns) | 0.97(ns) | 0.05(\*\*\*) | 2.81(\*\*\*) | 6.27(\*\*\*) |
| Weihe | -1.08(\*\*\*) | 2.59(\*\*\*) | -0.23(ns) | -0.21(ns) | -0.06(ns) | 0.05(\*\*\*) | 1.45(\*\*) | 1.06(\*\*\*) |
| Fenhe | -0.02(ns) | 1.81(\*\*) | -0.26(ns) | -0.08(ns) | 1.47(ns) | 0.05(\*\*\*) | 2.89(\*\*\*) | 5.30(\*\*\*) |
| Xinshui | -0.34(\*\*) | 1.51(\*\*) | 0.41(ns) | -0.16(ns) | 1.36(ns) | 0.03(\*\*\*) | 2.81(\*\*\*) | 3.34(\*\*\*) |

Note: , , , , , and are the same as those in Table1. refers to the fraction of Photosynthetically Active Radiation and refers to the ratio of engineering measure area to the total catchment area. “\*” *p* < 0.1, “\*\*” *p* < 0.05, “\*\*\*” *p* < 0.01; “ns” means insignificant.

Table 3 and in different time windows estimated by the Choudhury-Yang equation for the 14 sub-catchments in the MYRB. and for each time window are estimated with the mean annual runoff in the time window of 1982–1990 as the benchmark.

| Sub-catchment | Time window | (mm) | (mm) | (%) | (%) | Sub-catchment | Time window | (mm) | (mm) | (%) | (%) |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Huangfu | 1982-1990 | - | - | - | - | Qingjian | 1982-1990 | - | - | - | - |
|  | 1991-1999 | 5.5 | -11.6 | 0 | 100 |  | 1991-1999 | 8.2 | 9.9 | 45.3 | 54.7 |
|  | 2000-2008 | 1.8 | -12.4 | 0 | 100 |  | 2000-2008 | -2.7 | -6.1 | 30.4 | 69.6 |
|  | 2007-2015 | 1.8 | -10.1 | 0 | 100 |  | 2007-2015 | 6.5 | -14.6 | 0 | 100 |
|  | 1991-2015 | 2.8 | -13.4 | 0 | 100 |  | 1991-2015 | -1.5 | -0.93 | 61.0 | 39.0 |
| Gushan | 1982-1990 | - | - | - | - | Yanhe | 1982-1990 | - | - | - | - |
|  | 1991-1999 | 4.7 | -4.1 | 100 | 0 |  | 1991-1999 | 9.5 | -7.8 | 100 | 0 |
|  | 2000-2008 | 0.1 | -13.2 | 0 | 100 |  | 2000-2008 | -2.6 | -4.1 | 39.4 | 60.6 |
|  | 2007-2015 | 4.0 | -15.3 | 0 | 100 |  | 2007-2015 | 4.4 | -11.2 | 0 | 100 |
|  | 1991-2015 | 2.4 | -14.1 | 0 | 100 |  | 1991-2015 | -1.8 | -2.2 | 44.7 | 55.3 |
| Kuye | 1982-1990 | - | - | - | - | Beiluo | 1982-1990 | - | - | - | - |
|  | 1991-1999 | 4.0 | -10.3 | 0 | 100 |  | 1991-1999 | -13.2 | 7.4 | 100 | 0 |
|  | 2000-2008 | -0.6 | -16.8 | 3.3 | 96.7 |  | 2000-2008 | -7.9 | 0.9 | 100 | 0 |
|  | 2007-2015 | 4.6 | -21.5 | 0 | 100 |  | 2007-2015 | -3.4 | -6.3 | 34.9 | 65.1 |
|  | 1991-2015 | 1.8 | -18.5 | 0 | 100 |  | 1991-2015 | -7.8 | 0.46 | 100 | 0 |
| Tuwei | 1982-1990 | - | - | - | - | Jinghe | 1982-1990 | - | - | - | - |
|  | 1991-1999 | -1.3 | 1.0 | 100 | 0 |  | 1991-1999 | -14.8 | 6.6 | 100 | 0 |
|  | 2000-2008 | -3.4 | -13.5 | 20.2 | 79.8 |  | 2000-2008 | -9.6 | -2.5 | 79.3 | 20.7 |
|  | 2007-2015 | 11.9 | -26.3 | 0 | 100 |  | 2007-2015 | -6.2 | -5.9 | 51.1 | 48.9 |
|  | 1991-2015 | 1.5 | -12.8 | 0 | 100 |  | 1991-2015 | -9.7 | -1.0 | 90.4 | 9.6 |
| Jialu | 1982-1990 | - | - | - | - | Weihe | 1982-1990 | - | - | - | - |
|  | 1991-1999 | -26.2 | 31.1 | 0 | 100 |  | 1991-1999 | -24.7 | -1.96 | 92.7 | 7.3 |
|  | 2000-2008 | -3.7 | -4.8 | 43.5 | 56.5 |  | 2000-2008 | -17.4 | -7.7 | 69.3 | 30.7 |
|  | 2007-2015 | 8.0 | -9.9 | 0 | 100 |  | 2007-2015 | -14.2 | -11.1 | 56.1 | 43.9 |
|  | 1991-2015 | -1.2 | -1.3 | 48.1 | 51.9 |  | 1991-2015 | -17.4 | -8.3 | 67.7 | 32.3 |
| Wuding | 1982-1990 | - | - | - | - | Fenhe | 1982-1990 | - | - | - | - |
|  | 1991-1999 | -8.1 | 7.6 | 100 | 0 |  | 1991-1999 | -8.5 | 4.1 | 100 | 0 |
|  | 2000-2008 | -6.3 | 1.4 | 100 | 0 |  | 2000-2008 | -4.4 | -1.8 | 70.7 | 29.3 |
|  | 2007-2015 | 1.7 | -6.2 | 0 | 100 |  | 2007-2015 | -2.1 | -0.9 | 70.8 | 29.2 |
|  | 1991-2015 | -4.4 | 1.1 | 100 | 0 |  | 1991-2015 | -5.0 | 0.3 | 100 | 0 |
| Dali | 1982-1990 | - | - | - | - | Xinshui | 1982-1990 | - | - | - | - |
|  | 1991-1999 | -9.7 | 14.6 | 0 | 100 |  | 1991-1999 | -11.9 | 12.3 | 0 | 100 |
|  | 2000-2008 | -5.7 | 4.6 | 100 | 0 |  | 2000-2008 | -5.4 | 2.7 | 100 | 0 |
|  | 2007-2015 | 4.7 | -10.3 | 0 | 100 |  | 2007-2015 | -0.04 | -5.5 | 0.6 | 99.4 |
|  | 1991-2015 | -3.0 | 2.1 | 100 | 0 |  | 1991-2015 | -5.7 | 2.7 | 100 | 0 |



Figure S1. Evolution and linear trend of the time-varying parameter in each sub-catchment. *Y* denotes the Year.



Figure 1. Location of 14 sub-catchments in the middle Yellow River basin (MYRB), China (1, Huangfu; 2, Gushan; 3, Kuye; 4, Tuwei; 5, Jialu; 6, Wuding; 7, Dali; 8, Qingjian; 9, Yanhe; 10, Beiluo; 11, Jinghe; 12, Weihe; 13, Fenhe; 14, Xinshui).



Figure 2. Relationships between the time-varying parameter and (a) , (b) , (c) , (d) , (e) , (f) , and (g) *REM.*



Figure 3. Relationship between water-balance-based *E* (-) and simulated *E* using the Choudhury-Yang equation with modelled in the 14 sub-catchments. NSE, RMSE, RE and MAE stand for Nash-Sutcliffe efficiency coefficient, root-mean-square error, relative error and mean absolute error, respectively.



Figure 4. Contributions of climate-induced runoff change and human-induced runoff change by altering the sub-catchment characteristic parameter over the period 1982–2015.



Figure 5. Two components of based on the sensitivity method under the Budyko framework, i.e., induced by the change of vegetation cover, and induced by the change in the ratio of engineering measure area to the total sub-catchment area. and were estimated with the mean annual runoff in the time window of 1982–1990 as the benchmark.

Figure 6. Contributions of climate change () and human activity () to runoff change estimated by the Choudhury-Yang equation over the period of 1982–2015 for each sub-catchment.