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ArticleTitle	A Complementary Streamflow Attribution Framework Coupled Climate, Vegetation and Water Withdrawal	
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Article CopyRight	The Author(s), under exclusive licence to Springer Nature B.V. (This will be the copyright line in the final PDF)	
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Schedule	Received	5 May 2023
	Revised	
	Accepted	2 Aug 2023
Abstract

Quantifying the contributions of climate change (CC) and human activities (HA) to streamflow alteration is significant for effective water resources management. However, numerous studies fail to differentiate the individual impacts of various HA on streamflow. In this study, a comprehensive streamflow attribution framework that incorporates climate, vegetation, and water withdrawal (WW) was proposed. In this framework, traditional streamflow attribution methods such as statistical analysis (Double Mass Curve and Slope Change Ratio of Accumulative Quantity), elasticity (Budyko), and modeling simulation (Variable Infiltration Capacity and Long Short-term Memory) are employed to separate the influence of meteorological factors (MF) on streamflow. Subsequently, the impacts of WW on streamflow are assessed using global WW data. The Residual Analysis method is utilized to quantify the effects of vegetation alteration caused by both CC (Lcc) and HA (Lha) on streamflow alteration. To demonstrate the applicability of our proposed framework, two stations, Xianyang and Huaxian, located within the Weihe River Basin in Northwest China were selected as the case study area. The results demonstrated that compared to the baseline period (1961–1990), the average contributions of MF, Lcc, Lha, and WW to streamflow reduction during the variation periods (1991–2019) were as follows: for the Xianyang station, 26.0%, 13.5%, 30.9%, and 29.6% respectively; and for the Huaxian station, 28.9%, 5.5%, 17.7%, and 47.9% respectively. Additionally, during the variation periods, the contributions of CC and HA to vegetation variation were 30.5% and 69.5% respectively in Xianyang, and 23.7% and 76.3% respectively in Huaxian. The framework developed herein also provides a solution for quantifying the indirect effects of CC on streamflow through vegetation.
Keywords (separated by '-') Climate change - Vegetation change - Attribution analysis - Residual analysis - Water withdrawal

Footnote Information

Journal : SmallCondensed 11269	Article No : 3582	Pages : 17	MS Code : 3582	Dispatch : 7-8-2023

Water Resources Management
https://doi.org/10.1007/s11269-023-03582-1

A Complementary Streamflow Attribution Framework Coupled Climate, Vegetation and Water Withdrawal

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Received: 5 May 2023 / Accepted: 2 August 2023

Abstract

Quantifying the contributions of climate change (CC) and human activities (HA) to streamflow alteration is significant for effective water resources management. However, numerous studies fail to differentiate the individual impacts of various HA on streamflow. In this study, a comprehensive streamflow attribution framework that incorporates climate, vegetation, and water withdrawal (WW) was proposed. In this framework, traditional streamflow attribution methods such as statistical analysis (Double Mass Curve and Slope Change Ratio of Accumulative Quantity), elasticity (Budyko), and modeling simulation (Variable Infiltration Capacity and Long Short-term Memory) are employed to separate the influence of meteorological factors (MF) on streamflow. Subsequently, the impacts of WW on streamflow are assessed using global WW data. The Residual Analysis method is utilized to quantify the effects of vegetation alteration caused by both CC (Lcc) and HA (Lha) on streamflow alteration. To demonstrate the applicability of our proposed framework, two stations, Xianyang and Huaxian, located within the Weihe River Basin in Northwest China were selected as the case study area. The results demonstrated that compared to the baseline period (1961–1990), the average contributions of MF, Lcc, Lha, and WW to streamflow reduction during the variation periods (1991–2019) were as follows: for the Xianyang station, 26.0%, 13.5%, 30.9%, and 29.6% respectively; and for the Huaxian station, 28.9%, 5.5%, 17.7%, and 47.9% respectively. Additionally, during the variation periods, the contributions of CC and HA to vegetation variation were 30.5% and 69.5% respectively in Xianyang, and 23.7% and 76.3% respectively in Huaxian. The framework developed herein also provides a solution for quantifying the indirect effects of CC on streamflow through vegetation.

Keywords Climate change · Vegetation change · Attribution analysis · Residual analysis · Water withdrawal

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1 Introduction

Streamflow plays a crucial role in the overall water resources system (Grill et al. 2019). However, the streamflow of many rivers worldwide has undergone substantial changes since the mid-20th century as a result of climate change (CC) and human activities (HA) (Rani and Sreekesh 2019; Melo et al. 2023). On the one hand, CC, particularly variations in precipitation patterns, directly impacts the trends of streamflow (Ahmed et al. 2022; Gholami and Sahour 2022). On the other hand, HA, including land cover changes and water withdrawals (WW), exert direct or indirect influences on streamflow (Krajewski et al. 2021; Zhu et al. 2021). Consequently, accurately quantifying and attributing the contributions of climate, vegetation, and WW changes to alteration in streamflow is crucial for developing effective water resources management strategies (Alehu and Bitana 2023; Wang et al. 2023).

Currently, various approaches have been employed to differentiate the contributions of CC and HA to streamflow alteration, including statistical analysis, elasticity, and modeling simulation methods (Sharifi et al. 2021). Statistical analysis approaches, such as the double mass curve (DMC) and slope change ratio of accumulative quantity (SCRAQ), utilize statistical techniques to isolate the influence of meteorological factors (MF), specifically precipitation, on streamflow as an indicator of CC-induced streamflow alteration (Wang et al. 2012). Elasticity approaches are primarily based on Budyko's hypotheses, using sensitivity coefficients of MF to streamflow and catchment-specific parameter n to isolate the impacts of CC and HA on streamflow (Sharifi et al. 2021). Modeling simulation methods involve hydrological models like the Variable Infiltration Capacity (VIC) model and machine learning models like long short-term memory (LSTM) that can simulate natural streamflow (Sahour et al. 2021; Zhang et al. 2022). By comparing the simulated streamflow with observed streamflow, these models can differentiate the contributions of CC and HA to streamflow alteration, assuming that the difference between observed and natural streamflow is attributable to HA (Jiang et al. 2019; Gholami and Khaleghi 2021).

Different methods or perspectives may exhibit disparities or contradictions in the same area (Luan et al. 2021). For instance, Swain et al. (2021), employing three complementary approaches, discovered that the DMC and SCRAQ methods alleviate the effects of CC compared to hydrological models. Sharifi et al. (2021), using nine methods, indicated that non-parametric attribution methods are unsuitable for streamflow attribution in the Ghaleh-Shahrokh watershed when compared to Budyko and hydrological model methods. Therefore, an increasing number of researchers are adopting multiple combination approaches to isolate the contributions of CC and HA to streamflow alteration in order to mitigate the uncertainty associated with a single method (Swain et al. 2021). However, there is a lack of research regarding the differentiation of the impacts of different HA on streamflow. Currently, the Budyko method and the reduction streamflow method are utilized to differentiate the effects of land cover changes and WW on streamflow alteration (Li et al. 2022). For example, Bao et al. (2021) employed the disparity between natural streamflow restored by water resource evaluation and natural streamflow restored by a hydrological model to represent the impact of land cover changes on streamflow. Nevertheless, this method failed to consider WW and land cover data. Therefore, a complementary streamflow attribution framework coupled climate, vegetation, and WW was proposed. In this framework, the impacts of MF on streamflow were separated using traditional streamflow attribution methods such as statistical analysis, elasticity, and modeling simulation. Subsequently, the impacts of WW on streamflow were distinguished based on global WW data.

Journal : SmallCondensed 11269	Article No : 3582	Pages : 17	MS Code : 3582	Dispatch : 7-8-2023

The remaining impacts were attributed to land cover changes. Finally, the effect of CC and HA on streamflow through land cover was substituted with the effect of CC and HA on vegetation changes using the residual analysis (RA) method. Moreover, the RA method, which predicts the changing trend of multi-grid climate variables, is widely employed to attribute alterations in vegetation's Normalized Difference Vegetation Index (NDVI) and determine the contributions of CC and HA to vegetation changes (Zhou et al. 2022).

In this study, a complementary streamflow attribution framework that integrates climate, vegetation, and WW was proposed, which can assess the effects of MF, vegetation alteration caused by CC (Lcc), vegetation alteration caused by HA (Lha) and WW on streamflow. The Weihe River Basin (WRB) in Northwest China, a typical area with a heavy hydrological alteration, was selected as the case study area to perform the complementary streamflow attribution framework. We aimed (1) to isolate the contributions of CC and HA on streamflow and vegetation alteration, and (2) to quantify the impacts of climate, vegetation and WW alterations on streamflow and characterize the response between streamflow and vegetation.

2 Material and Methods

In this section, a comprehensive streamflow attribution framework that integrates climate, vegetation, and WW was proposed (Fig. 1). The framework consists of four steps. The first step involves determining baseline and variation periods using the Pettitt test (P-test) and the Accumulative Anomaly Method (AAM), as previously described by Wang et al. (2012). The second step focuses on separating the contributions of CC and HA to streamflow and vegetation alterations. To achieve this, traditional approaches such as statistical analysis (DMC and SCRAQ), elasticity (Budyko), and modeling simulation (VIC and LSTM) are used for streamflow attribution caused by MF. Additionally, the RA method is utilized for attributing changes in vegetation. Third, there are three schemes for streamflow attribution that incorporate

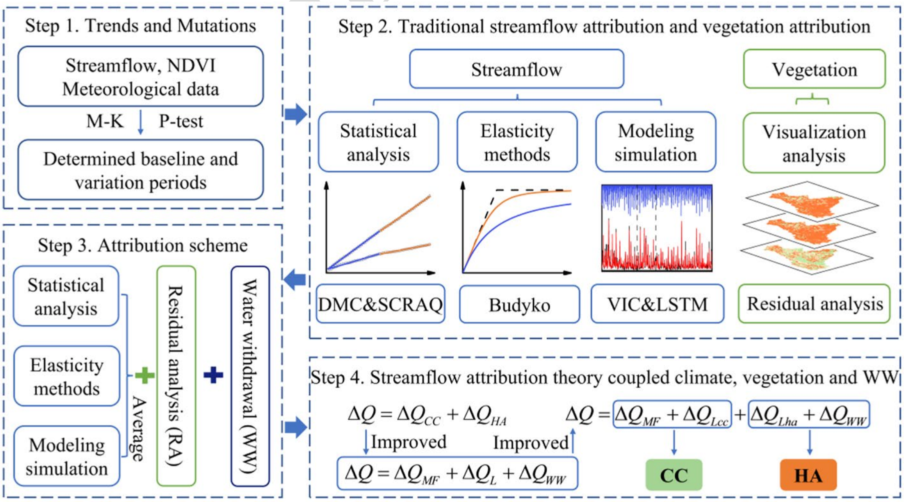

Fig. 1 Proposed complementary streamflow attribution framework coupled climate, vegetation and water withdrawal

Journal : SmallCondensed 11269 | Article No : 3582 | Pages : 17 | MS Code : 3582 | Dispatch : 7-8-2023

climate, vegetation, and WW. These schemes include: (1) coupling statistical analysis, RA, and WW; (2) coupling elasticity methods, RA, and WW; and (3) coupling modeling simulation, RA, and WW. By averaging the results obtained from the three schemes, the findings of this study can effectively reduce uncertainty and enhance the robustness of the analysis. Finally, an improved streamflow attribution method coupled climate, vegetation and WW was proposed. AQ1

2.1 Traditional Streamflow Attribution

2.1.1 Statistical Analysis

The DMC and SCRAQ are two popular linear statistical analysis methods used to separate the influence of precipitation on streamflow, representing the contribution of MF to streamflow alterations (Wang et al. 2012 and Yang et al. 2018).

2.1.2 Elasticity Method

The long-term water balance is as below (Swain et al. 2021):

$$P = E + Q + \Delta S \tag{1}$$

where P, E, and Q, are precipitation, actual evapotranspiration, streamflow, and ΔS is the alteration in water storage which can be assumed to be zero on a multi-year scale. The aridity index (φ)and evaporative index ($F(\varphi)$) are respectively the ratios of the potential evapotranspiration (E_p) and actual evapotranspiration (E) to precipitation as follow:

$$\varphi = E_P / P \tag{2}$$

$$F(\varphi) = E / P \tag{3}$$

The mathematical equations based on Budyko hypotheses have been developed to account for streamflow alteration:

$$Q = P - E = P - \frac{E_P P}{(P^n + E_P^n)^{1/n}} \tag{4}$$

where E_P is potential evapotranspiration, and n is the catchment-specific parameter, such as soil properties, slope, and vegetation cover. The elasticity of streamflow to P and E_P can be computed as (Luan et al. 2021):

$$\Delta Q_{CC} = \frac{\partial Q}{\partial P} \Delta P + \frac{\partial Q}{\partial E_P} \Delta E_P \tag{5}$$

$$\frac{\partial Q}{\partial P} = 1 - \frac{E}{P} \left(\frac{E_P^n}{P^n + E_P^n} \right) \tag{6}$$

$$\frac{\partial Q}{\partial E_P} = - \frac{E}{E_P} \left(\frac{P^n}{P^n + E_P^n} \right) \tag{7}$$

Journal : SmallCondensed 11269	Article No : 3582	Pages : 17	MS Code : 3582	Dispatch : 7-8-2023

$$\Delta Q_{HA} = \Delta Q - \Delta Q_{CC} \tag{8}$$

where ΔQ_{HA} and ΔQ_{CC} are the streamflow alteration caused by CC and HA alteration.

2.1.3 Modeling Simulation

The VIC model is a semi-distributed hydrological model and has been applied in daily-scale hydrological simulation. More model parameters and details can be found in Jiang et al. (2022). The LSTM is an improved recurrent neural network. The information can be stored in an additional cell state, which enables LSTM more advantage for sequential data in machine learning (Zhang et al. 2022). The Nash–Sutcliffe efficiency coefficient (NSE) is used to optimize model parameters.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{sim}(i) - Q_{obs}(i)\right)^2}{\sum_{i=1}^{n}\left(Q_{sim}(i) - \overline{Q}_{obs}\right)^2} \tag{9}$$

where $Q_{obs}(i)$, $Q_{sim}(i)$, and $\overline{Q}_{obs}$ are the observed, simulated, and mean observed streamflow, respectively; m is the number of data points.

The VIC and LSTM can separate the contributions of CC and HA on streamflow through the simulated-observed comparison method which can assume that difference between observed streamflow and natural streamflow was due to HA.

$$\Delta Q = \Delta Q_{HA} + \Delta Q_{CC} = \overline{Q}_{obs,\mathrm{var}} - \overline{Q}_{obs,base} \tag{10}$$

$$\Delta Q_{CC} = \overline{Q}_{sim,\mathrm{var}} - \overline{Q}_{sim,base} \tag{11}$$

$$\Delta Q_{HA} = \Delta Q - \Delta Q_{CC} = \left(\overline{Q}_{obs,\mathrm{var}} - \overline{Q}_{obs,base}\right) - \left(\overline{Q}_{sim,\mathrm{var}} - \overline{Q}_{sim,base}\right) \tag{12}$$

where $\overline{Q}_{obs,\mathrm{var}}$ and $\overline{Q}_{obs,base}$ are the average streamflow in the variation period and the baseline period. $Q_{sim,\mathrm{var}}$ and $Q_{sim,base}$ are the average simulated streamflow by VIC and LSTM in the variation period and the baseline period (Jiang et al. 2019).

2.2 Vegetation Attribution

In this study, the RA approach was employed to isolate the impacts of CC and HA on vegetation alterations. The underlying assumption is that HA's impact on vegetation can be captured by the unexplained variations in the model. To achieve this, precipitation and temperature were selected as the primary MF influencing vegetation. Previous studies have demonstrated that multiple linear regression models can effectively capture the vegetation response to MF. The method utilized in this study consists of four main steps (Zhou et al. 2022), which are as follows:

1. A multiple linear regression model among the maximum annual NDVI, average annual precipitation (P) and average annual temperature (T) was established.

$$NDVI_{CC} = a \times T + b \times P + c \tag{13}$$

Journal : SmallCondensed 11269	Article No : 3582	Pages : 17	MS Code : 3582	Dispatch : 7-8-2023

where $NDVI_{CC}$ represents the effect of CC on vegetation. The a and b are regression coefficients and c is the intercept.

2. The $NDVI_{obs}$ is interannual trend rate of NDVI.

$$NDVI_{obs} = \frac{n\sum_{i=1}^{n}(i \times NDVI_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} NDVI_i}{n\sum_{i=1}^{n} i^2 - \sum_{i=1}^{n} i} \tag{14}$$

where the "i" is the time variable (year), equal to an integer from 1 to n and the "n" is the number of years in the research period. $NDVI_i$ is the maximum NDVI at i year.

3. The difference between the predicted ($NDVI_{CC}$) and observed NDVI ($NDVI_{obs}$) is the residual, which indicates the response of vegetation to HA ($NDVI_{HA}$).

$$NDVI_{HA} = NDVI_{obs} - NDVI_{CC} \tag{15}$$

4. The contributions of CC (η_{CC}) and HA (η_{HA}) to vegetation alteration can be calculated as.

$$\eta_{CC} = NDVI_{CC}/NDVI_{obs} \tag{16}$$

$$\eta_{HA} = NDVI_{HA}/NDVI_{obs} \tag{17}$$

2.3 Improved Streamflow Attribution

The traditional streamflow attribution hypothesis is that the streamflow alteration is caused by MF and HA.

$$\Delta Q = \Delta Q_{CC} + \Delta Q_{HA} = \Delta Q_{MF} + \Delta Q_{HA} \tag{31}$$

where ΔQ, ΔQ_{MF}, and ΔQ_{HA} are streamflow alteration, and streamflow alteration caused by MF and HA.

It can be further assumed that the streamflow alteration is caused by MF, land use and WW.

$$\Delta Q = \Delta Q_{MF} + \Delta Q_{L} + \Delta Q_{WW} \tag{32}$$

where ΔQ_L and ΔQ_{WW} are streamflow alteration caused by land use and WW.

Here the effect of CC and HA on streamflow through land cover was replaced by the effect of CC and HA on vegetation change. Therefore, the new streamflow attribution can be further written as:

$$\Delta Q = \Delta Q_{MF} + \Delta Q_{Lcc} + \Delta Q_{Lha} + \Delta Q_{WW} \tag{33}$$

where ΔQ_{Lcc} and ΔQ_{Lha} are streamflow alteration caused by vegetation alteration caused by CC and HA. ΔQ_{MF} and ΔQ_{Lcc} represent the impact of CC on streamflow alteration. ΔQ_{Lha} and ΔQ_{WW} represent the impact of HA on streamflow alteration.

Journal : SmallCondensed 11269	Article No : 3582	Pages : 17	MS Code : 3582	Dispatch : 7-8-2023

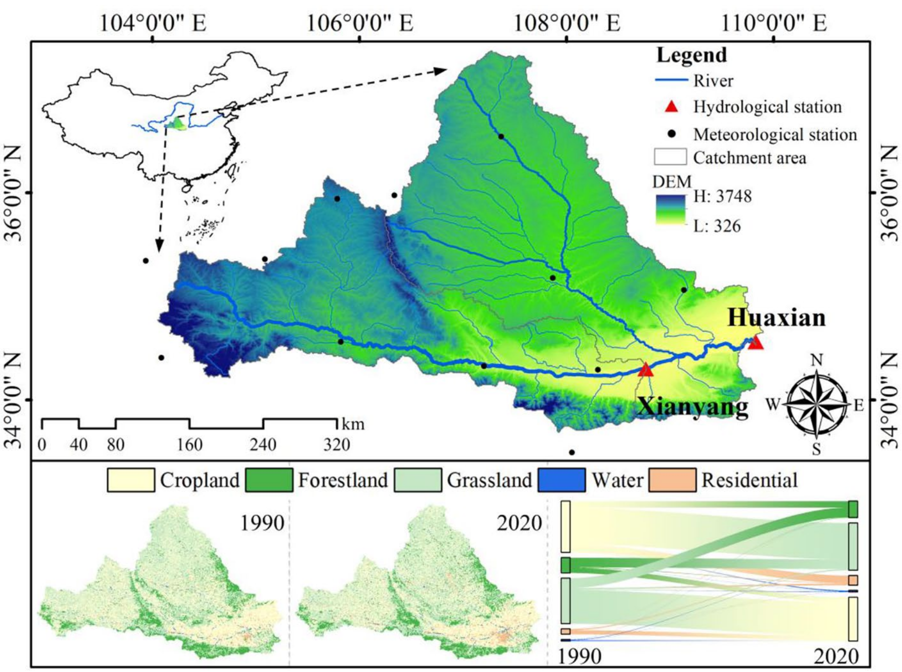

Fig. 2 Location of the Weihe River Basin, the hydrological and meteorological stations, and land use alteration from 1990 to 2020

Table 1 Data used in this study

Data	Time	source
Daily streamflow records	1961–2019	Yellow River Conservancy Commission
Daily meteorological records	1961–2019	China Meteorological Data Sharing Service System
NDVI	1982–2019	National Earth System Science Data Center
WW	1961–2019	Yan et al. (2022) and Yellow River Resource Bulletin
Land cover	1990/2000	Resources and Environmental Science and Data Center, Chinese Academy of Sciences
Global 1-km land cover classification product	2000	University of Maryland

2.4 Study Area and Data

The WRB belongs to the Loess Plateau with an area of 10.6×10^4 km^2, which is the largest tributary of the Yellow River. Two hydrologic stations (Xianyang and Huaxian) (Fig. 2), were selected as the controlling stations. Based on the observed hydro-meteorological records from 1961 to 2019, the mean annual air temperature and precipitation are 9.4 °C and 569.1 mm, respectively. Besides, HA have altered the underlying surface of the WRB by returning cropland to forestland and grassland (Luan et al. 2021). Moreover, specific data can be found in Table 1.

3 Results

3.1 Trend and Mutation Analysis

The results obtained from M–K and linear regression conducted in the WRB indicate that there is no significant trend in precipitation and potential evapotranspiration (Fig. 3c–f). However, a significant downward trend is evident in streamflow (Fig. 3a, b), while temperature and NDVI (Fig. 3g–j) show a significant upward trend ($P < 0.01$). There were distinct mutations in streamflow, temperature, and NDVI in 1990, 1993, and 2000, respectively, at the Xianyang and Huaxian stations (Fig. 3k, l). It is worth mentioning that 1990 marked a prominent turning point for streamflow (Fig. 3a, b). Furthermore, HA in the WRB have experienced significant increases since 1990 (Liu et al. 2022). Therefore, 1990 was identified as the mutation, with the baseline period from 1961 to 1990 and the variation period from 1991 to 2019. Similar research findings have been reached by Liu et al. (2022) using different analysis methods. Moreover, within the variation period, the HA exhibits variations across different stages (Luan et al. 2021). Consequently, the variation period was segmented into three stages: period I (1991–2000), period II (2000–2010), and period III (2010–2019).

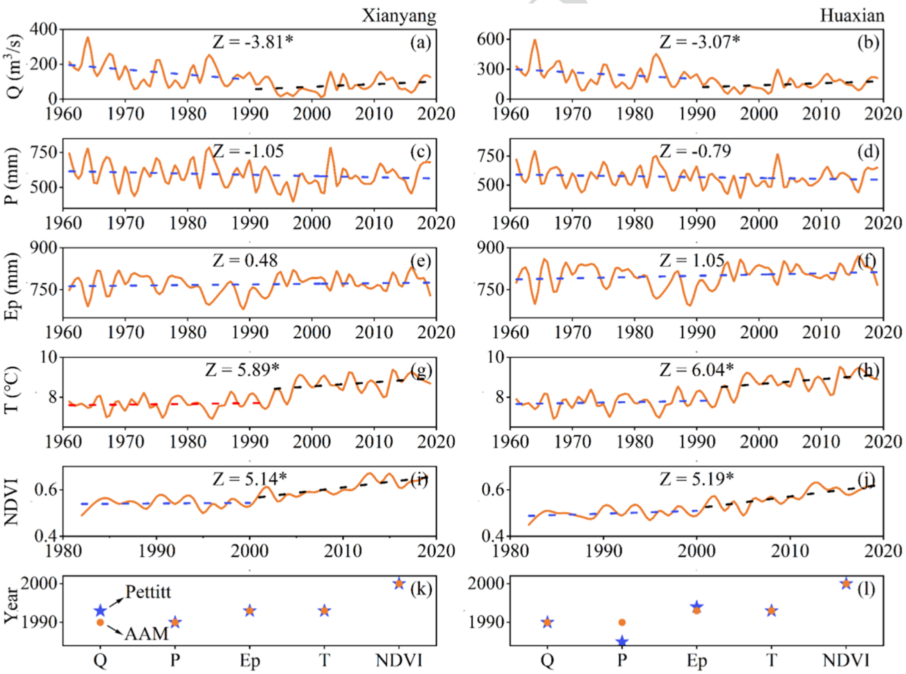

Fig. 3 The trends and mutations of streamflow (Q), precipitation (P), potential evapotranspiration (Ep), temperature (T), and NDVI in the Xianyang and Huaxian stations. (**a**–**j**: trends of Mann–Kendall (M–K) and linear regression; * Significant trends at 1% level; **k**–**l**: mutations of Pettitt test (P-test) and Accumulative Anomaly Method (AAM))

Journal : SmallCondensed 11269 | Article No : 3582 | Pages : 17 | MS Code : 3582 | Dispatch : 7-8-2023

3.2 Relative Contribution Based on Traditional Hydrological Methods

3.2.1 Model Parameters

In the DMC method (Fig. 4a, b), the slopes for the Xianyang and Huaxian stations during the baseline period were 0.15 and 0.11, respectively, which decreased to 0.08 and 0.07, respectively, during the variation period. In the SCRAQ method (Fig. 4c, d), the slope for precipitation and streamflow at the Xianyang station was 0.61 and 0.14 during the baseline period, respectively, which decreased to 0.57 and 0.08 during the variation period. Similarly, at the Huaxian station, the slope for precipitation and streamflow was 0.58 and 0.23 during the baseline period, respectively, which decreased to 0.55 and 0.15 during the variation period.

The calibration of the Budyko using a single parameter in the WRB during the baseline and variation periods showed a strong agreement between the estimated actual evapotranspiration and the values derived from the water balance equation. The NSE values exceeded 0.81, indicating that the parameters of the Budyko equation successfully captured the characteristics of the catchments. The parameter n for the Xianyang catchment were 2.87 and 3.64 in the baseline and variation periods, respectively, which were 3.28 and 3.63 in the Huaxian catchment (Fig. 5).

Figure 6 presents the results of the natural streamflow reconstruction using the VIC and LSTM models. In the calibration period (1961–1980), the NSE values for the Xianyang station were 0.67 (VIC) and 0.92 (LSTM). During the validation period (1981–1990), the NSE values were 0.84 (VIC) and 0.92 (LSTM). For the Huaxian station, the NSE values during the calibration period were 0.75 (VIC) and 0.97 (LSTM), while in the validation period they were 0.89 (VIC) and 0.98 (LSTM). The overall simulation results demonstrated a high level of accuracy.

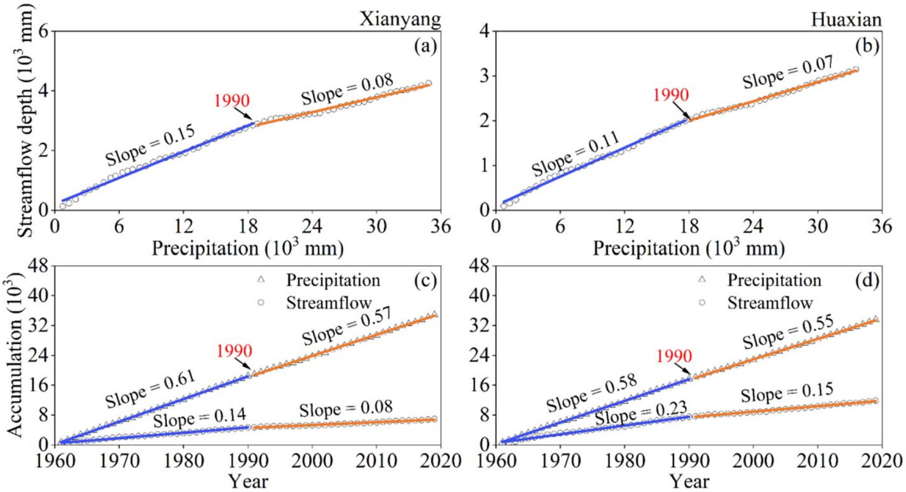

Fig. 4 The parameters of statistical analysis methods including DMC (**a** and **b**) and SCRAQ (**c** and **d**)

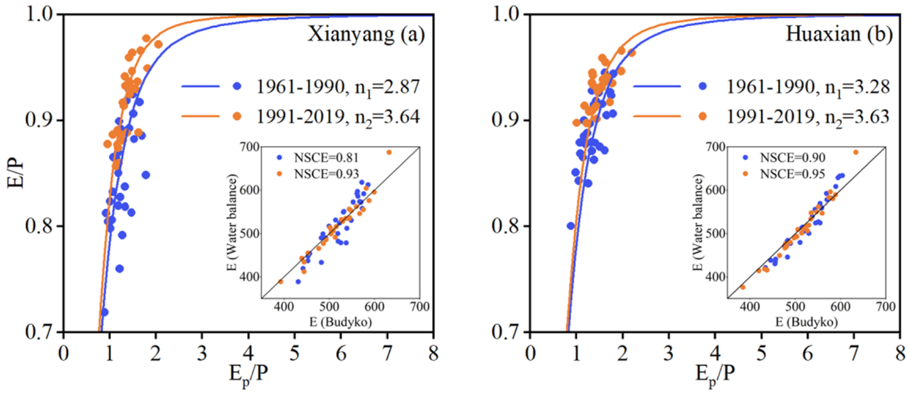

Fig. 5 Determine the catchment-specific parameter *n* of the Weihe River Basin

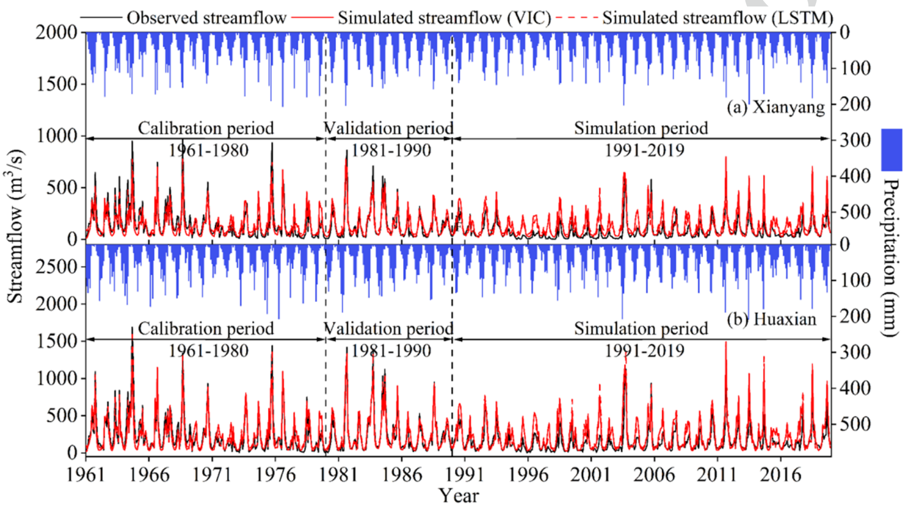

Fig. 6 Reconstruction of natural streamflow using hydrological model (VIC) and machine learning (LSTM) in the Weihe River Basin

3.2.2 Relative Contribution

Figure 7 provides a summary of the contributions of CC and HA to streamflow alteration by traditional hydrological methods. In the Xianyang catchment, the contribution of CC to streamflow alteration varied between 22.0% and 39.0% in period I, 10.8% and 41.0% in period II, 5.1% and 40.6% in period III, and 14.0% and 40.1% in period IV. Additionally, the average contributions of CC and HA to streamflow were 32.1% and 67.9% in period I, 24.1% and 75.9% in period II, 18.4% and 81.6% in period III, and 26.0% and 74.0% in period IV. Similarly, in the Huaxian catchment, the contribution of CC to streamflow alteration ranged from 22.3% to 57.5% in period I, 15.5% to 38.7% in period II, 5.8% to 24.6% in period III, and 15.4% to 39.2% in period IV. The average contributions of CC and HA to streamflow were 39.3% and 60.7% in period I, 25.8% and 74.2% in period II, 15.6%

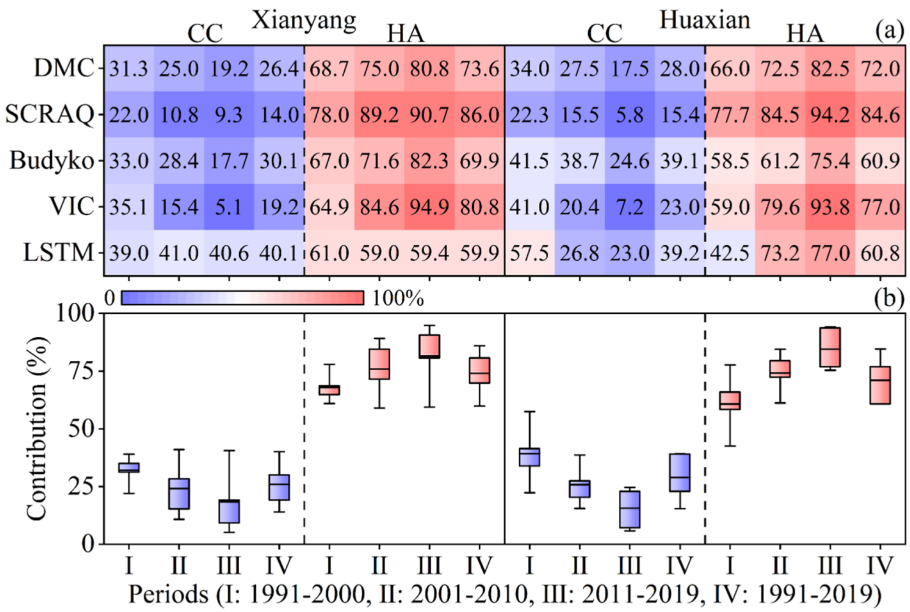

Fig. 7 Summary of the climatic and anthropogenic contributions to streamflow alteration based on traditional hydrological attribution methods in the Weihe River Basin

and 84.4% in period III, and 28.9% and 71.1% in period IV. Furthermore, the impact of CC on streamflow alteration decreased from period I to period III.

3.3 Relative Contribution Based on the RA Method

Figure 8 illustrates the characterization of CC and HA contributions to NDVI alteration using the RA method across multiple periods. During the baseline period, the CC and HA contributions to NDVI variation in the Xianyang catchment were 38.8% and 61.2%, respectively, while in the Huaxian catchment, which were 38.6% and 61.4% respectively. In the variation period (IV), the CC and HA contributions to NDVI variation in the Xianyang catchment were 30.5% and 69.5% respectively, whereas in the Huaxian catchment, which were 23.7% and 76.3% respectively. Compared to the baseline period, the HA contributions were significantly amplified during the variation period. Regions where HA accounted for 75% to 100% of NDVI alteration constituted 69% and 74% of the Xianyang and Huaxian catchments respectively, representing the highest proportions. The contribution of HA to NDVI alteration in the Xianyang and Huaxian catchments from 2001 to 2010 was 80.8% and 86.3% respectively, primarily attributed to the implementation of the Grain to Green Program in 1999 (Luan et al. 2021).

3.4 Relative Contribution Coupled Climate, Vegetation and WW

In the Xianyang catchment, compared to the baseline period, the contributions of MF, Lcc, Lha, and WW to streamflow reduction during the variation periods were 26.0%, 13.5%, 30.9%, and 29.6%, respectively. in the Huaxian catchment, compared to the baseline

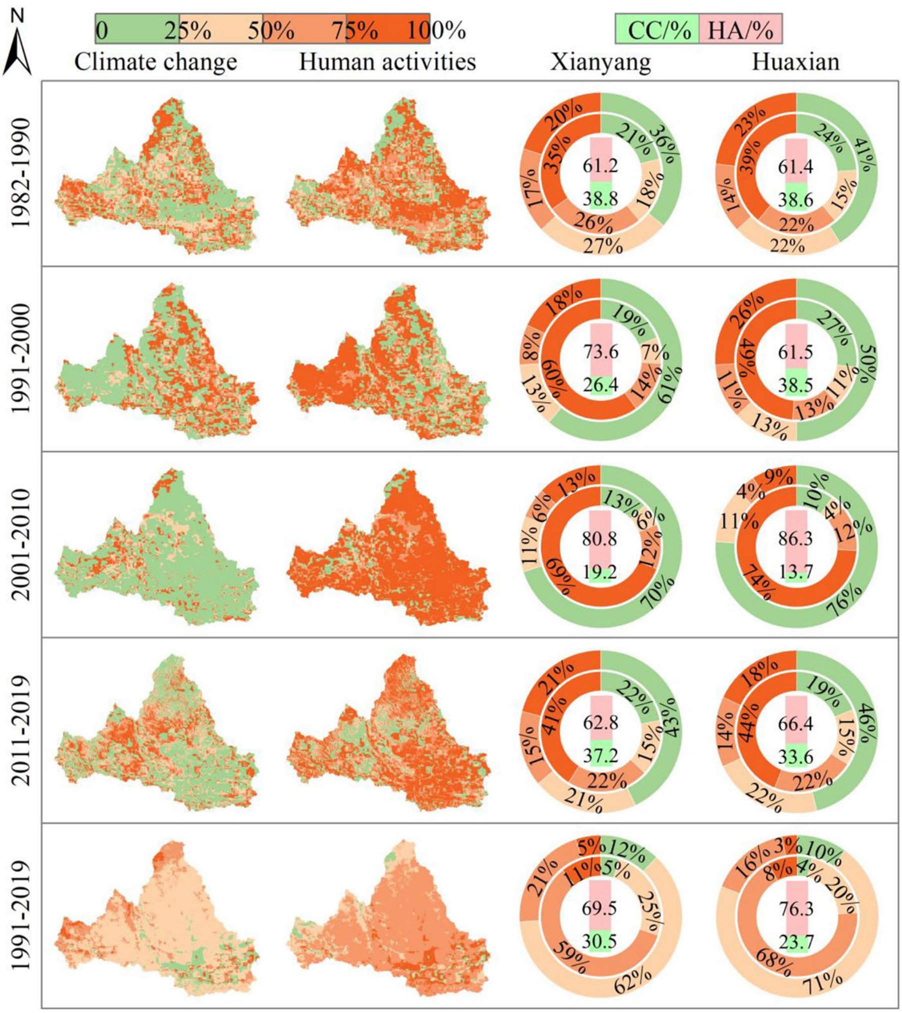

Fig. 8 Quantifying climatic and anthropogenic contributions to NDVI alteration using residual analysis (RA) method over multiple periods in the Weihe River Basin. (The outer and inner circle represents the contributions of the proportion of climatic regions and HA regions and the histogram represents the climatic and anthropogenic contributions to NDVI alteration)

period, the contributions of MF, Lcc, Lha, and WW to streamflow reduction during the variation periods were 28.9%, 5.5%, 17.7%, and 47.9%, respectively (Fig. 9a, b). These findings indicate that the impact of WW on streamflow reduction is more significant in the Huaxian catchment compared to the Xianyang catchment. This is primarily due to the concentration of population and agricultural areas in the lower reaches of the Huaxian catchment (Yan et al. 2022).

Additionally, the average contributions of MF, Lcc, Lha, and WW to streamflow reduction varied across different periods within the variation period (Fig. 9c–j). Specifically, in the Xianyang catchment, the contribution of MF to streamflow reduction decreased from

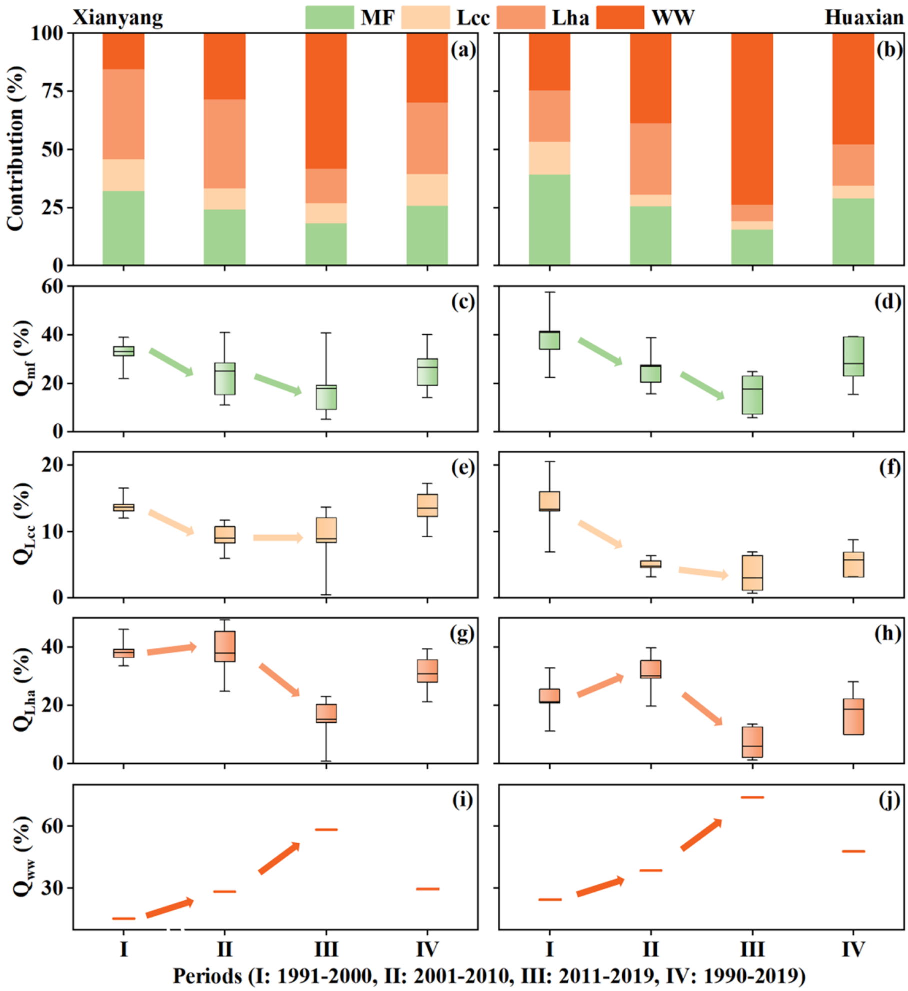

Fig. 9 Relative contribution coupled climate, vegetation and water withdrawal in the Weihe River Basin. The **a**-**b**: contribution of meteorological factors (MF), vegetation alteration due to climate change (Lcc), vegetation alteration due to human activities (Lha), and water withdrawal (WW) to streamflow reduction (average of three schemes). The **c**-**d**, **e**-**f**, **g**-**h**, and **i**-**j** are the variation in contributions of MF, Lcc, Lha, and WW to streamflow reduction in different periods

32.1% in period I to 18.4% in period III. The contribution of Lcc to streamflow reduction decreased from 13.9% in period I to 8.7% in period III. The contribution of Lha to streamflow reduction decreased from 38.7% in period I to 14.6% in period III. The contribution of WW to streamflow reduction increased from 15.4% in period I to 58.3% in period III. In the Huaxian catchment, the contribution of MF to streamflow reduction decreased from 39.3% in period I to 15.6% in period III. The contribution of Lcc to streamflow reduction decreased from 14.0% in period I to 3.6% in period III. The contribution of Lha to streamflow reduction decreased from 22.3% in period I to 7.0% in period III. The contribution of WW to streamflow reduction increased from 24.5% in period I to 73.8% in period III.

There was a significant increase in Lha from period I to period II in the WRB, indicating that the vegetation greening resulting from the Grain for Green Program played a positive role in streamflow reduction (Luan et al. 2021). Moreover, the decrease in Lha from period II to period III in the WRB was primarily caused by a noticeable increase in WW.

4 Discussion

The traditional streamflow attribution methods are widely used for quantifying CC and HA contributions to streamflow alteration (Swain et al. 2021). However, these traditional approaches tend to underestimate the effects of CC and are unable to isolate the individual impacts of multiple HAs on streamflow (Li et al. 2022). In this study, a streamflow attribution framework that serves as an effective tool for evaluating the impacts of MF, Lcc, Lha, and WW on streamflow alterations was proposed. On one hand, in comparison to previous findings regarding the impact of CC on streamflow (Fan et al. 2017), our research corrects the underestimated influence of CC and quantifies the impact of vegetation and WW changes on streamflow. On the other hand, distinct from the Budyko and reduction runoff methods employed to differentiate the effects of land cover and WW on streamflow, our study utilizes the ratio of CC and HA to vegetation change in order to quantify the impacts of CC and HA on streamflow through land cover. This simplification of the method enables a more straightforward distinction between the influences of land cover and WW on streamflow (Li et al. 2022).

Catchment hydrological processes involve intricate interactions among climate, vegetation, and WW (Luo et al. 2020). In recent years, these factors have exhibited heightened temporal variability in response to a changing environment (Ahmed et al. 2022; Gholami et al. 2023). Consequently, the challenge lies in effectively disentangling the impacts of vegetation and WW changes on streamflow (Melo et al. 2023). In this study, firstly, we separate the impacts of MF on streamflow, followed by the separation of the effects of WW on streamflow utilizing global WW data. The remaining impacts are then attributed to land cover change. The contribution of CC and HA to streamflow through land cover is substituted by the proportion of CC and HA on vegetation change. Our findings reveal that the HA-induced greening of vegetation in the WRB during period III had a significant influence on streamflow generation (Fig. 9g, h). Moreover, the impact of vegetation on streamflow was found to be less pronounced compared to the effects of CC and direct HA (Fig. 9). These research conclusions are consistent with the findings of Jin and Duan (2019). The methodology developed in this study provides a solution for quantifying the indirect effects of CC on streamflow via vegetation, serving as a relatively simple scientific tool for attributing streamflow alterations resulting from climate, vegetation, and WW.

Finally, it is important to acknowledge certain limitations of the streamflow attribution framework proposed in this study. Specifically, the framework only takes into account two human activities, vegetation and WW. When applying the streamflow attribution framework to other regions, additional factors such as damming and irrigation should be considered (Swain et al. 2021; Wang et al. 2022). Future research endeavors could aim to develop schemes that optimize the attribution of streamflow alterations caused by land cover, and subsequently integrate them into the streamflow attribution framework. This would enhance the robustness and applicability of the framework in capturing a more comprehensive understanding of the complex interactions between human activities and streamflow.

Journal : SmallCondensed 11269 | Article No : 3582 | Pages : 17 | MS Code : 3582 | Dispatch : 7-8-2023

5 Conclusions

In this study, a complementary streamflow attribution framework coupled climate, vegetation and WW was proposed. Compared with streamflow attribution methods, our approach accounts for the impacts of both vegetation and WW changes on streamflow. When compared to similar approaches, we streamline the simulation of WW by utilizing global WW data, allowing us to quantify the effects of CC and HA on streamflow through land cover. The WRB in Northwest China was selected as the case study area to perform the proposed framework. The results demonstrate that, in comparison to the baseline period, the average contributions of MF, Lcc, Lha, and WW to streamflow reduction during the variation periods were 28.9%, 5.5%, 17.7%, and 47.9% respectively in the WRB. This methodology provides a relatively straightforward scientific tool for attributing streamflow alterations resulting from MF, Lcc, Lha, and WW in various real-world case studies. Furthermore, the impact of WW on streamflow can be further subdivided based on the proportion of water used for industrial, agricultural, and domestic. However, vegetation change alone cannot fully replace the consideration of land cover in streamflow attribution. Future research efforts may focus on developing schemes that optimize the attribution of streamflow alterations caused by land cover, which can then be incorporated into the streamflow attribution framework.

Author Contribution Conceptualization: Shanhu Jiang; Yongwei Zhu; Methodology: Denghua Yan; Hao Cui, Ying Liu, and Menghao Wang; Funding acquisition: Shanhu Jiang, Liliang Ren, and Chong-Yu Xu.

Funding This work was financially supported by the National Natural Science Foundation of China (U2243203, 51979069); the Fundamental Research Funds for the Central Universities (B200204029); the National Natural Science Foundation of Jiangsu Province, China (BK20211202); and the Research Council of Norway (FRINATEK Project 274310).

Data Availability Data will be made available on request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publication Not applicable.

Competing Interests The authors declare that they have no competing interests.

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Journal : SmallCondensed 11269	Article No : 3582	Pages : 17	MS Code : 3582	Dispatch : 7-8-2023

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