

Attribution of nonstationary changes in the annual runoff of the Weihe River using the de-nonstationarity method

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ABSTRACT

The attribution of nonstationary change of the annual runoff series of the Weihe River is a topic of debate. In order to determine main drivers of nonstationary changes of Weihe River runoff, a de-nonstationarity method is used to remove the nonstationary influence of the potential driving factors and transform the nonstationary annual runoff series into a stationary reconstructed series. Then, the primary causes of the nonstationarity are identified by determining which factor results in the most stationary reconstructed series. The climate change factors (annual precipitation and annual average temperature) and the human activity factors (irrigation area and reservoir index) are selected as the reconstructed factors. The attribution results demonstrate that (1) both temperature rises and human activities have a significant impact on the nonstationary change, (2) the temperature is the most significant contributor to the nonstationary change in the annual runoff, which has a non-linear impact on the first and second moments, (3) the influence of reservoir index is relatively smaller than irrigation area without considering the regulation rule, (4) the stationary precipitation series still exerts some impacts on the second moment of the annual runoff, (5) the temperature and irrigation area have some overlapped influence on annual runoff because the synchronous increase trend in the two series leads to a certain correlation between them, and the temperature rise may also lead to the adjustment of irrigation planning and management.

Key words: annual runoff, attribution, climate change, de-nonstationarity method, human activity, nonstationary

HIGHLIGHTS

- A de-nonstationarity method is used to remove the nonstationary influence and transform the nonstationary annual runoff series.
- The climate change factors and the human activity factors indicate the relative contribution to the nonstationary change observed in the annual runoff.
- The stationarity of the reconstructed series proves that a significant impact on the nonstationary change in the annual runoff.

1. INTRODUCTION

Due to external factors such as climate change and human activity, measured hydrological series exhibit nonstationary changes. Numerous studies have demonstrated the existence of gradual trends, abrupt changes, or other more complex nonstationary changes in hydrological series (Milly *et al.* 2008; Zuo *et al.* 2012; Qin *et al.* 2015; Madsen *et al.* 2017). This nonstationarity creates significant challenges when it comes to hydrological frequency analysis and water resources management. While statistical detection of change is an important scientific endeavor, attribution of change (i.e. determining the most likely cause(s)) is fundamental to developing appropriate management responses and long-term adaptation strategies. Harrigan *et al.* (2014) and Merz *et al.* (2012) also pointed out that the rigorous attribution should be made after the detection of hydrological change.

River runoff is one of the most important components of the hydrological system, and the change of runoff dominates the change of the entire hydrological system. Because of the effects of climate change and human activity, the runoff from many rivers worldwide has changed significantly, which seriously threatens the regional water resource condition (Milly *et al.* 2005). Identifying the driving force behind runoff changes is the key to water resource planning and utilization.

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The most common data-based attribution technique for hydrological time series uses measured hydrometeorological data to statistically analyze the correlation between the hydrological variable and any potential driving factors (Merz *et al.* 2012). After analyzing regional trends in the measured runoff, temperature, and precipitation, Cunderlik & Burn (2004) attributed the changes in the monthly maximum flow in southern British Columbia to the warming of spring air temperatures, which triggers the onset of snowmelt earlier in the spring and ultimately results in significant changes to the intra-annual high-flow regime. Moreover, the increase in summer temperatures leads to a higher soil water deficit, which reduces the maximum flow in autumn. Using the multiple working hypotheses method to construct an attribution framework, Harrigan *et al.* (2014) identified that the change of runoff in Boyne catchment was not only impacted by climate factors, the arterial drainage and field drainage built from 1970 to 1980s were also important driving factors.

Another type of attribution approach is the simulation-based attribution (Merz *et al.* 2012). By simulating and comparing different hydrological scenarios with or without a certain driving factor, it is possible to evaluate the changes imparted by the presence or absence of that factor. Using this technique, Hamlet & Lettenmaier (2007) attributed the flood change in the western US throughout the twentieth century to temperature change. Hundedcha & Merz (2012) attribute the changes in the seasonal extreme flow of varying mesoscale catchments located throughout Germany primarily to changes in precipitation, with temperature playing a minor role. The simulation-based attribution has also been used to assess the effects of human activity factors such as river training (Vorogushyn & Merz 2013) and land use changes (Brath *et al.* 2006).

As the largest tributary of the Yellow River, the Weihe River plays a significant role in the ecology of northwestern China. A number of studies have shown that the runoff from the Weihe River has noticeably decreased in recent years (Song *et al.* 2007; Zhang *et al.* 2009). By conducting hydrologic sensitivity analyses and running model simulations, Guo *et al.* (2014) attributed 59–77% of the decline in the runoff of two sub-basins in the upper reaches of Weihe River to human activity. Wu *et al.* (2012) pointed out that agricultural irrigation would also impact the annual runoff of the Weihe River. Xiong *et al.* (2014) used the generalized additive models in location, scale, and shape (GAMLSS) to analyze the effects of climate change and human activity on the Weihe River runoff and concluded that the runoff is more sensitive to changes in temperature and precipitation than it is to changes in the irrigation area. While previous works agree on the significant change of the runoff of the Weihe River, there is still some debate as to which factor(s) is primarily responsible for these nonstationary changes.

For the data-based attribution method, due to the lack of physical mechanism, it is impossible to avoid the large uncertainty in the analysis of extremely complex hydrological system. While the simulation-based attribution method attempts to model the hydrological process from the perspective of physical mechanism, the reliability of the model itself is the biggest constraint of this attribution method because our understanding of these mechanisms is incomplete. In this study, a de-nonstationarity method proposed by Li *et al.* (2020) was used for the attribution analysis. By identifying the main influencing factors and the relationship between these factors and the hydrological variable, this method can remove the nonstationary influences of these factors, so as to obtain a new stationary de-nonstationarity series. The new stationary series can be used as sample series for hydrological frequency analysis or any other cases where a stationary series is required. Li *et al.* (2020) used this method to remove the nonstationary influence of check dam projects on the flood peak discharge in Mahuyu River Basin in northern Shaanxi, China, and obtained more reasonable design values under nonstationary conditions. Furthermore, by using the de-nonstationarity method, Li & Qin (2022) have analyzed the annual runoff series of the Jialu River Basin in Shaanxi Province, China, and the calculated design annual runoff was more consistent with the measured data.

In the application of this method, we found that according to the stationarity improvement degree of the series reconstructed by different factors, the influence of the selected factor on the nonstationary change can be evaluated. Therefore, we use the de-nonstationarity method in this paper to determine which factor(s) is primarily responsible for the nonstationary change in the annual runoff of the Weihe River. Different from the above attribution methods, the de-nonstationarity method introduces the influence laws of driving factors on hydrological variables on the basis of statistical theory. This approach has the potential to achieve the combination of statistical principle and physical mechanisms.

2. STUDY AREA AND DATA

2.1. Study area

The Weihe River originates from the north of the Niaoshu Mountains in Weiyuan County in Gansu Province. The river flows through the Gansu, Ningxia, and Shaanxi Provinces from west to east, and ultimately feeds into the Yellow River in Tongguan County in Shaanxi Province. The Weihe River Basin (WRB) has an approximate river length of 818 km, a drainage area of

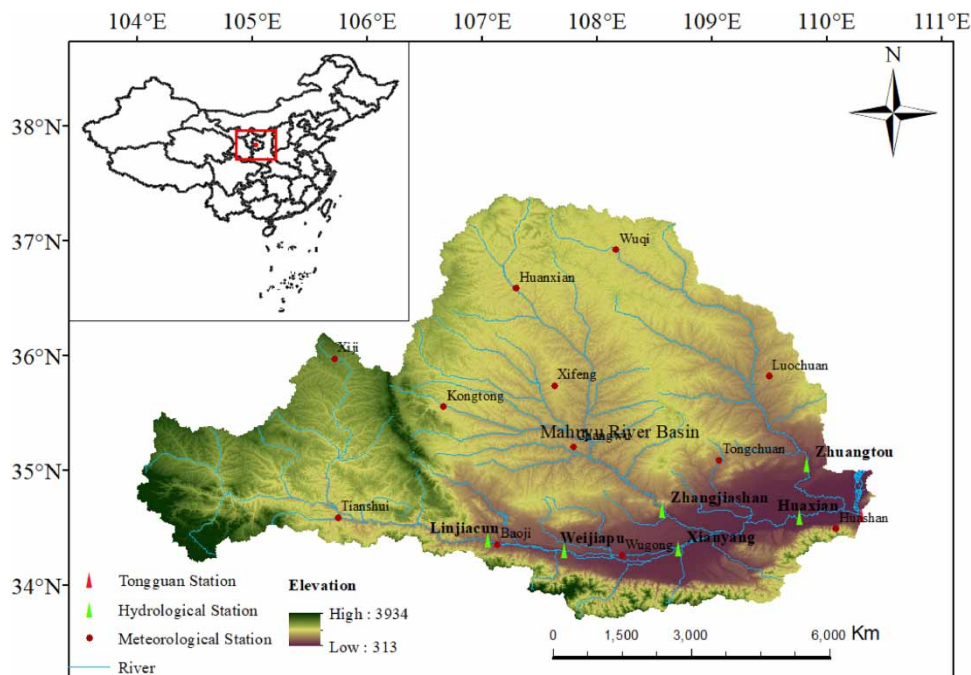


Figure 1 | Distribution of hydrological and meteorological stations in the WRB.

133,800 km², and a geographical extent that lies between 33°40′–37°25′N and 103°55′–110°20′E (Figure 1). The WRB is located in the southwestern part of the Loess Plateau and is characterized by a semi-arid continental climate. The average annual precipitation is 634.9 mm, and the flooding season usually occurs from July to October, which accounts for more than 60% of the annual total precipitation. The Weihe River provides living security for more than 20 million people, including the population of the city of Xi'an. Historically, the WRB has been extensively altered by human activity, such as the construction of reservoirs, agricultural irrigation, and soil and water conservation projects. Due to these anthropogenic factors and global climate change, the annual runoff of the Weihe River exhibits a significant nonstationary change (Xiong *et al.* 2014).

2.2. Runoff and potential drivers

The last control station in the lower reaches of Weihe River, Huaxian hydrological station, has a control area of 105,600 km². The Beiluo River Basin is controlled by the Zhuangtuo hydrological station. The total annual runoff of the Weihe River is the superposition of the measured annual runoff of the Huaxian station and the Zhuangtuo station. We employed the Mann-Kendall (M-K) test (Mann 1945; Kendall 1975) and the Breusch-Pagan (B-P) test (Breusch & Pagan 1979) to detect trends in the first and second moments, respectively, of the annual runoff series of the Weihe River from 1958 to 2015 (Figure 2 and Table 1). For convenience, other types of nonstationarity are not considered in this study. The results show that both the mean and variance of the Weihe River annual runoff series exhibit a significant downward trend. In the past, because the magnitude of the runoff directly impacts the number of available water resources, we were more concerned with changes in the mean of the runoff series. However, with the increasing number of extreme hydrological events in recent years, the importance of understanding and quantifying changes in the variance of a hydrological series is becoming apparent. In this study, we determine the extent to which climate factors and human activity factors contribute to the nonstationary changes observed in the first and second moments of the annual runoff series of the Weihe River.

In assessing the impact of climate change on the Weihe River annual runoff, we employed the annual precipitation (P) and the annual average temperature (T) as potential driving factors. Precipitation has a direct correlation with runoff, and temperature rise is the main manifestation of environmental change, so it is appropriate to select P and T as the climate factors. In addition, a large number of human activities are also an important reason for the nonstationary changes of annual runoff. Among the human activity factors, the continuous construction of irrigation and reservoir projects will lead to increase of water withdrawals of Weihe River, which will lead to the runoff reduction. Therefore, we select the irrigation area (IA)

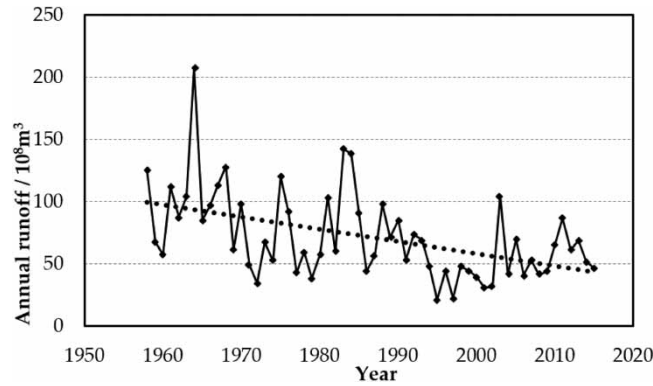


Figure 2 | The temporal variation of the annual runoff series of the Weihe River.

Table 1 | The statistical trends in the first and second moments of the annual runoff and climate driving factors in the WRB

Object	M-K test for mean	B-P test for variance	Result
Annual runoff	-3.52*	6.15*	Significant
<i>P</i>	-1.30	0.54	Nonsignificant
<i>T</i>	5.25*	0.17	Significant in the first moment

* $p < 0.05$.

and reservoir index (RI) as the potential human activity factors. All the four driving factors have an significant correlation with annual runoff, and the correlation between climate driving factors and annual runoff is stronger than that between human activity factors and runoff, which is still significant.

The series of *P* and *T* of the WRB were calculated using observational data from 11 meteorological stations in the WRB using the Thiessen polygon method. The data were obtained from the National Meteorological Information Center (<http://cdc.cma.gov.cn>). Analyzing the trends in the first and second moments of the climatic factors revealed that the precipitation in the WRB did not change significantly (Table 1), an observation that is consistent with the results of previous studies (Guo *et al.* 2014; Xiong *et al.* 2014). However, the temperature exhibited a significant upward trend in the first moment, while the second moment did not change significantly (Figure 3).

The information of irrigation and reservoir projects were obtained from the Shaanxi River Engineering Technology Research Center. The IA of the WRB varies with the construction of the nine large-scale irrigation projects in the WRB (Figure 4(a)). The calculation method of RI (López & Francés 2013) representing the regulating influence of reservoirs is

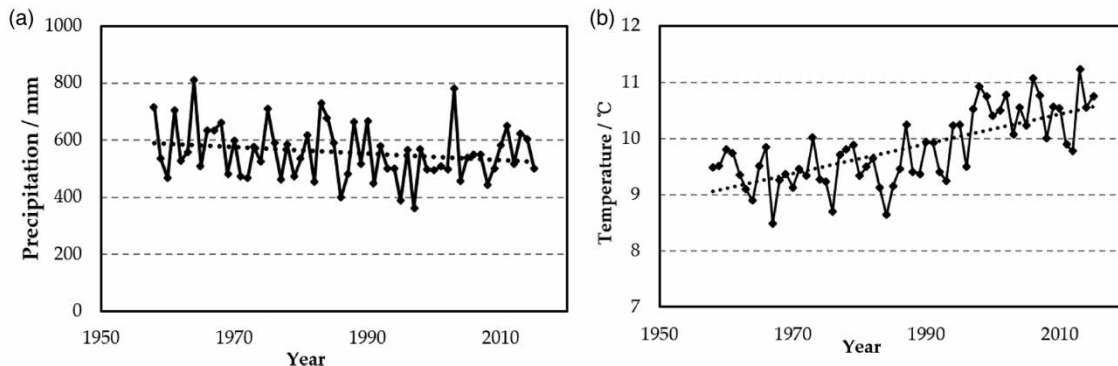


Figure 3 | Time series of (a) the annual precipitation and (b) the annual average temperature in the WRB from 1958 to 2015.

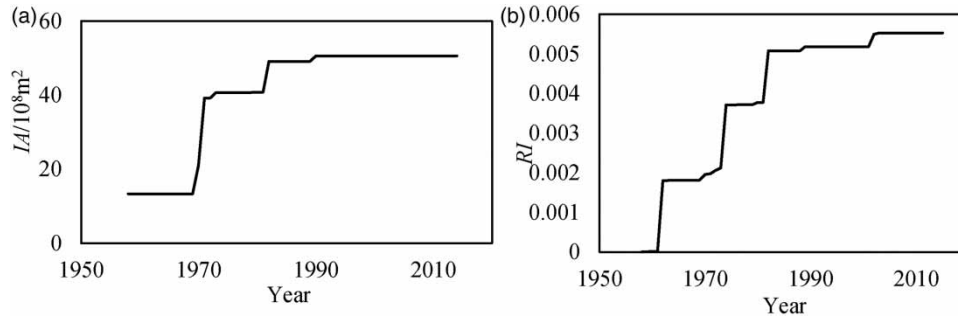


Figure 4 | Temporal evolution of the (a) IA series and (b) the RI series in the WRB.

as follow:

$$RI = \sum_{i=1}^N \left(\frac{A_i}{A_T} \right) \left(\frac{C_i}{C_T} \right) \quad (1)$$

where A_i is the control area of each reservoir, A_T is the basin area, C_i is the capacity of each reservoir, C_T is the average annual runoff of the basin, and N is the number of reservoirs in the basin. We investigated the large and medium reservoirs in the WRB and calculated the RI series (Figure 4(b)). Both the IA and RI series exhibit a monotonic upward trend.

3. METHODOLOGY

3.1. The de-nonstationarity method

The de-nonstationarity method is proposed by Li *et al.* (2020) for the nonstationary frequency analysis. This method can achieve the transformation from an original nonstationary series to a new stationary reconstructed series by removing the nonstationary influence of the driving factors. The influence law of a driving factor of the research variable can be defined as $f_i(X_i)$. In the study of Li *et al.* (2020), the research variable is the flood peak discharge, the influence factor X_i is the effective runoff generation area; the influence law $f_i(\cdot)$ is a power law function.

We can use the following expression to describe the relationship between the hydrological variable Y and its influence factor X_i .

$$Y = f_i(X_i) \cdot \xi \quad (2)$$

where ξ contains the effects of other secondary nonstationary factors, many stationary factors, and even the unrecognized factors. After removing the influence of the most important nonstationary factor X_i , the ξ can be considered as statistical stationary. So the reconstructed series $RS(t)$ can be defined as:

$$RS(t) = \frac{Y(t)}{f_i(X_i(t))} = \xi(t) \quad (3)$$

Obviously, if X_i is indeed the influence factor causing nonstationary changes of the hydrological variable Y , after removing its nonstationary influence from $Y(t)$, the reconstructed series $RS(t)$ represents the comprehensive effect of the remaining factors; the value of $RS(t)$ is equal to $\xi(t)$, so $RS(t)$ is a stationary series. As we know, the nonstationary change in the hydrological variable Y must be caused by the corresponding nonstationary behavior in one or more influencing factors. After removing the nonstationary influence of these driving factors, the reconstructed series is stationary in all aspects. Therefore, the de-nonstationarity method is not limited to a specific type of nonstationary change, which is also one of its major advantages. In order to verify this characteristic, in this paper, various nonstationary tests will be carried out on the de-nonstationary reconstructed series of the annual runoff series of the Weihe River.

In this paper, we use the de-nonstationarity method to attribute the nonstationary change in the annual runoff series of the Weihe River, and construct a stationary hydrological series after accounting for the influence of different driving factors. By

measuring the improvement of the stationarity of the de-nonstationarity series reconstructed by different factors, we can determine the contribution that each factor makes to the overall nonstationarity of the series.

3.2. Attribution process

In order to achieve robust attribution, it is necessary to ensure the accuracy of the influence law $f_i(X_i)$, which reflects the physical mechanism that the factor X_i influences on the hydrological variable Y . This physical mechanism can be determined through theoretical derivation and experimental analysis. However, due to the complexity of hydrological systems, it is difficult to determine a completely accurate expression of a physical mechanism; the exact details of mechanism are hidden in the relationship between the hydrological variable and its influence factors. Therefore, it is an inevitable choice to estimate the influence law through the statistical relation between Y and X_i .

In practice, the influence law of each factor can be approximated using regression analysis. After estimating the influence law of the first influence factor X_1 ($f_1(X_1(t))$) according to the relationship between the variable Y and X_1 , we can remove the influence of X_1 from the time series using the de-nonstationarity method. The influence law $f_2(X_2(t))$ of the second factor X_2 can be determined based on the statistical relationship between the remaining series $(Y(t))/(f_1(X_1(t)))$ and X_2 . This process continues iteratively until the influence law of each factor is established. We set the reconstruction order of each factor according to the strength of the correlation between the hydrological variable and each influence factor.

Although it is difficult to identify all the nonstationary factors that influence the hydrological variable, some of the most important factors can be determined according to hydrological theory and experience. Once the nonstationary factors are identified reasonably, the original nonstationary hydrological series Y_t can be converted into a stationary reconstructed series RS_t by the de-nonstationarity method. Based on the improvement in the stationarity of the first and second moments of the reconstructed series, we can determine which influence factor(s) contributed to the nonstationarity in the first and second moments of Y_t .

To summarize, the attribution process of the de-nonstationarity method is:

1. Select the potential driving factors.
2. Stationarity analysis of the selected factors.
3. Analyze the correlation between each nonstationary factor and the hydrological variable, and carry out the de-nonstationarity process in order of decreasing correlation coefficients.
4. Removing the influence of the first factor X_1 .
5. Analyze the stationarity of the reconstructed series $(Y(t))/(f_1(X_1(t)))$. If it is stationary, the selected factor X_1 is the main influence factor that causing the nonstationary change of Y_t . If it is still nonstationary, we develop another reconstructed series by removing the influence of the second factor X_2 .
6. Repeat steps (4) and (5) until the first and second moments of the reconstructed series are stationary. Then, determine the main influencing factors of the changes in the first and second moments, respectively.

4. RESULTS AND DISCUSSION

4.1. Removing the nonstationarity by different factors

4.1.1. Reconstruction by climate factors

Based on our analysis, the T exhibited a significant increase, while the annual P in WRB did not change significantly. According to the concept of the de-stationarity method, the reconstructed series should still be nonstationary after the reconstruction with P . However, because there is a strong correlation between the annual runoff and P , we still include the P as a potential driver to verify the rationality of our de-nonstationarity attribution method. We use different types of relationships (such as linear, exponential, power law, and logarithm) to conduct regression analysis, and found that the power law relationship between the annual runoff and the P or T was the most significant (Figure 5).

The approximations of the influence law of the P and T on the annual runoff are:

$$R = 3 * 10^{-5} P^{2.3371} \quad (4)$$

$$R = 2 * 10^6 T^{-4.518} \quad (5)$$

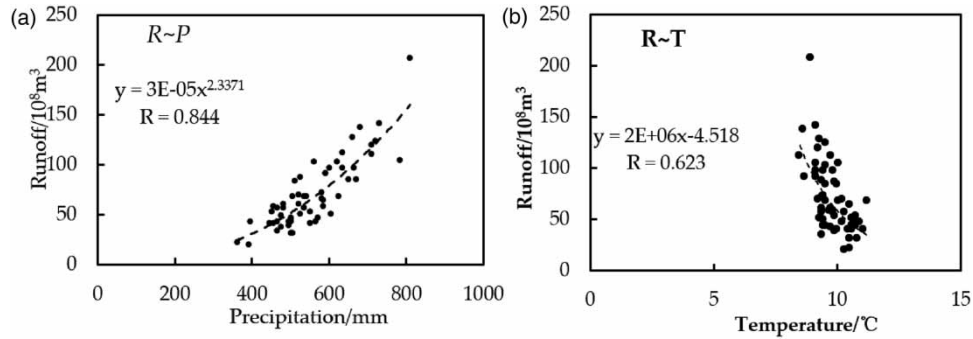


Figure 5 | The estimated influence law of (a) the P and (b) the T on the annual runoff.

According to Equation (2), the reconstructed series generated by the removal of the influence of these factors from the original hydrological series is shown in Figure 6. The statistical results of the M-K test and the B-P test for the first and second moments of this reconstructed series, respectively, are shown in Table 2.

4.1.2. Reconstruction by human activity factors

While assessing the influence of human activity in the WRB is challenging, irrigation and reservoir projects are clearly very important influence factors. The correlation between annual runoff and human activity factors is weaker than that between annual runoff and climate factors, but there is still a significant exponential relationship between annual runoff and IA or RI (Figure 7).

The approximations of the influence laws of IA and RI act on annual runoff are:

$$R = 120.14e^{-0.016IA} \tag{6}$$

$$R = 98.433e^{-107.4RI} \tag{7}$$

The results of applying the de-nonstationarity method to the annual runoff of the Weihe River after removing the influence of IA and RI are shown in Figure 8, while the relevant statistical analyses of the first and second moments of the new reconstructed series are shown in Table 3.

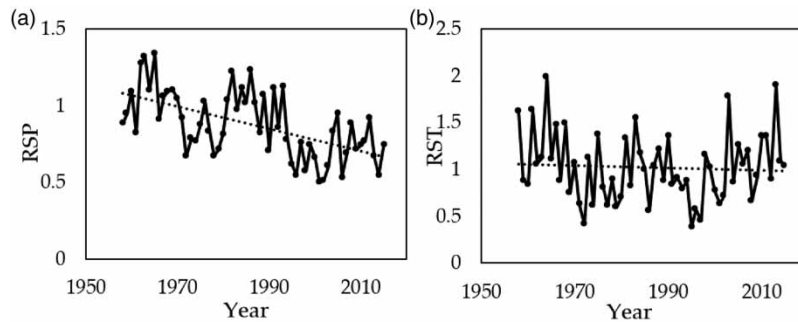


Figure 6 | The reconstructed series of the annual runoff after removing the influence of (a) the P and (b) the T .

Table 2 | Trend analysis of the reconstructed series reconstructed by climatic factors

Object	M-K test for mean	B-P test for variance	Result
Annual runoff	-3.52*	6.15*	Significant in the first and second moments
$RS_{P,t}$	-3.97*	0.60	Significant in the first moment
$RS_{T,t}$	-0.35	0.12	Nonsignificant

* $p < 0.05$.

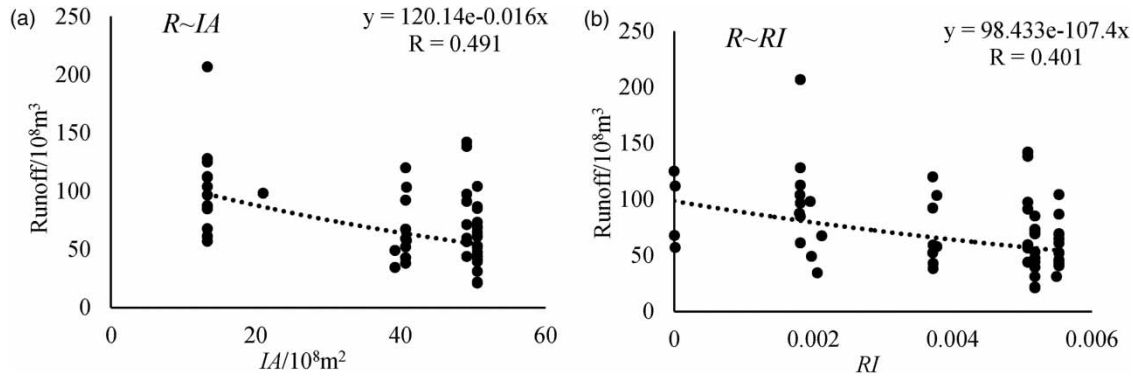


Figure 7 | The estimated influence law of (a) IA and (b) RI on the annual runoff.

4.2. Attribution

4.2.1. The influence of single factor

After removing the influence of the T , the stationarity of the reconstructed series RS_T was significantly improved; both the first and second moments reached a stationary state at a significance level of 0.05. Therefore, the influence of the temperature rise on the nonstationary change in the annual runoff is significant. The second moment of the T does not exhibit a significant nonstationary change; however, after the reconstruction by removing the effects of the T , the second moment of the reconstructed series achieved stationarity. From this observation, we conclude that the impact of the T on the runoff is nonlinear.

Because the P does not exhibit a significant nonstationary change, removing the influence of P results in a new reconstructed series RS_P that still has significant nonstationarity in the first moment. However, the second moment of that new reconstructed series is stationary. In fact, although the P is statistically stationary, the M-K test statistic is close to the critical value. Therefore, the P exerts some influence on the second moment of the annual runoff. Compared to the impact of the T , the P has a less influence on the nonstationarity of the river runoff.

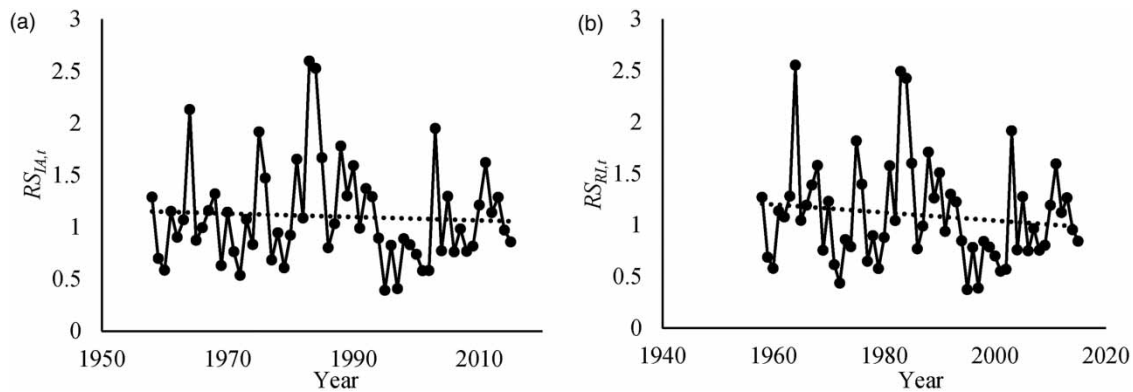


Figure 8 | The reconstructed series of the annual runoff after removing the influence of (a) IA and (b) RI.

Table 3 | Trend analysis of the de-nonstationarity series reconstructed by human activity factors

Object	M-K test for mean	B-P test for variance	Result
Annual runoff	-3.52*	6.15*	Significant in the first and second moments
$RS_{IA,t}$	-0.50	0.68	Nonsignificant
$RS_{RI,t}$	-0.90	1.67	Nonsignificant

* $p < 0.05$.

After removing the influence of the human activity factors from the original annual runoff series, the reconstructed series is stationary both in the first and second moments. Table 3 indicates that the removal of IA results in a reconstructed series RS_{IA} with better stationarity in both the first and second moments. Therefore, IA exerts more influence than RI on the nonstationary change in the first and second moments of the annual runoff in the Weihe River. The influence of RI is relatively small because only the capacity and the control area of the reservoir are included in the RI calculation, while its water dispatching rules are ignored.

4.2.2. The combined influence of climate change and human activity

Both climate change and human activities cause nonstationary changes in the annual runoff in the WRB. Tables 2 and 3 indicate that the T -reconstructed series RS_T has better stationarity than the IA-reconstructed series RS_{IA} , but the difference is small. For IA and RI, their impacts overlap to some extent because most irrigation projects are built with the reservoir projects. Because of this overlap, we identified IA as the most important human activity factor. To determine the sum of the effects of climate change and human activity on the annual runoff, we applied the de-nonstationarity method with two influence factors: T and IA. Following the logic described in Section 3.2, we use T as the first reconstruction factor and IA as the second factor.

The influence law of the T is still defined by Equation (4). After removing the influence of T , there was no significant correlation between obtained reconstructed series RS_T and IA. For comparison, we still fitted the statistical relationship between them, as shown in Figure 9 and Equation (8).

$$RS_T(t) = 1.2171e^{-0.0061A} \quad (8)$$

By removing the influence of the T and IA from the annual runoff series according to Equation (2), we obtained the reconstructed series RS_{double} (Figure 10). The nonstationary analysis of the reconstructed series RS_{double} is shown in Table 4.

Both the first and second moments of the reconstructed series RS_{double} achieve stationarity, which further indicates that both the climate change and human activity factors contribute to the nonstationary change in the annual runoff of the Weihe River. Comparing the results in Tables 2–4, while all the reconstructed series were stationary, the stationarity has not been improved after removing the influence of IA from the RS_T series. The reason of this phenomenon is: first, after the reconstruction by T , the correlation between T -constructed series RS_T and IA is nonsignificant, the fitted influence law according to this nonsignificant relationship has a great uncertainty. Second, both T and IA exhibit a significant increase trend, and this synchronous trend leads to a certain correlation between the two series, which means that these two factors may have some overlapped influence on annual runoff. In fact, the increase of T may also lead to the adjustment of irrigation planning and management.

According to Tables 2 and 3, the influence of IA on the annual runoff of the Weihe River is slightly smaller than that of the T ; therefore, the influence of human activities on the WRB annual runoff is slightly smaller than that of climate change.

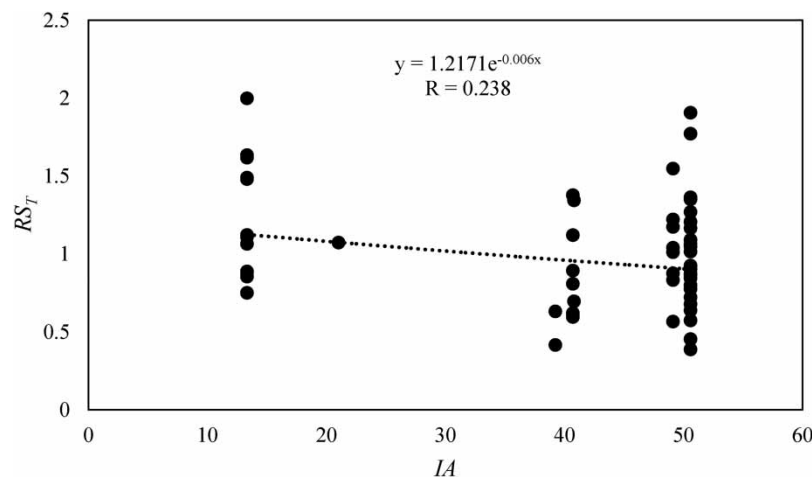


Figure 9 | The relationship between RS_T and IA in the WRB.

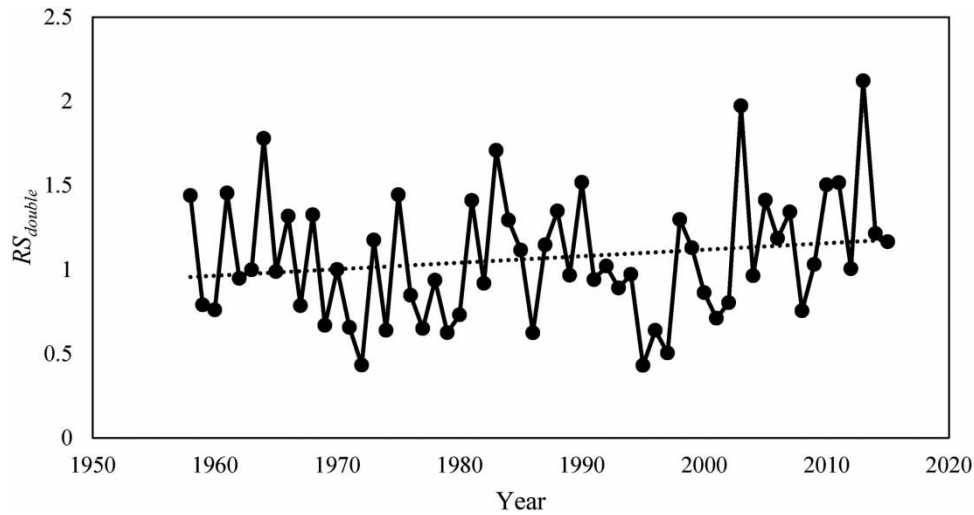


Figure 10 | The reconstructed annual runoff series RS_{double} of the WRB after removing the influence of T and IA.

Table 4 | Trend analysis of the double-factor reconstructed series

Object	M-K test for mean	B-P test for variance	Result
Annual runoff	-3.52*	6.15*	Significant in the first and second moments
RS_{double}	1.31	0.35	Nonsignificant

* $p < 0.05$.

4.3. Uncertainties of the de-nonstationarity method

For complex hydrological problems caused by the nonstationarity, [Montanari & Koutsoyiannis \(2014\)](#) believed that the combination of physical mechanism and statistical theory should be an important research direction in future. On the basis of statistical approaches, the de-nonstationarity method introduces the estimated influence law of the driving factors on research variable. Therefore, when the influence law is accurate enough, the de-nonstationarity method can realize the combination of the nonstationary physical process with the data-driven statistical principle. However, the de-nonstationarity method still has some limitations. Because the understanding of the physical mechanisms of the hydrological process is far from sufficient, the existence of uncertainty is inevitable. Due to this uncertainty, different reconstruction order, such as T followed by IA or IA followed by T , may lead to different de-nonstationarity series. This uncertainty is due to the fact that people cannot absolutely accurately describe the influence law of the factors on the research variable. Strictly speaking, this influence law should be determined by theoretical derivation or experimental analysis. However, due to the complexity of hydrological behaviors and our limited understandings, it is difficult to obtain the absolutely accurate mathematical expressions that represent the physical mechanism of hydrological behaviors. At present, the uncertainty of the approximate estimation of influence law $f(x)$ is indeed the source of the uncertainty of this method. The exploration of the mechanism of influence factors on the research variables is not only the guarantee of the reliability of this method, but also an inevitable research direction to understanding the hydrological system. It should be pointed out that the de-nonstationarity series calculated by the accurate physical mechanism expressions will not be disturbed by the reconstruction order.

Although it is difficult to obtain the absolutely accurate influence law, there are still ways to estimate the uncertainty of its approximate estimation. From the perspective of causality, the stationarity test of the reconstructed de-nonstationarity series obtained by the de-nonstationarity method can reflect the uncertainty of the estimated expression of the influence law $f(x)$. The better the stationarity, the less the uncertainty. In addition, [Li et al. \(2021\)](#) and [Li & Qin \(2022\)](#) used this method to conduct the frequency analysis on the annual runoff series of WRB and the Jialu River Basin in northern Shaanxi, China. The design values were also consistent with the measured data, such as the 50%-frequency design annual runoff is close to the average annual runoff, which also proves that the de-nonstationarity method has a certain reliability.

The de-nonstationarity attribution method is different from the data-based attribution and the simulation-based attribution methods. Due to the lack of physical consideration, it is difficult to measure the reliability of the data-based attribution unless the influencing factors and their influence laws are very clear. While it is also difficult to obtain a reliable attribution results just through the simulation-based approaches without any statistical analysis due to the complexity of hydrological system and the limitation of cognitive and technical ability. The biggest advantage of the de-nonstationarity method is that we can judge the accuracy of the estimation of the influence law by the stationarity test of the de-nonstationarity series, so as to ensure the reliability of attribution. As mentioned in Section 4.1.1, if the precipitation series is used to reconstruct the annual runoff series, the reconstructed series is still nonstationary. According to the stationarity test, it can be concluded that precipitation is not the main influencing factor of the nonstationary changes of annual runoff. Similarly, if the estimation of influence law function $f(x)$ of T , RI , or IA has a large deviation, we also cannot obtain the reconstructed series with good stationarity.

It should be noted that the human activity factors selected in this paper have an indirect effect on runoff compared with the climate factors. It is difficult to investigate the actual water consumption, and the reliability of the survey also cannot be guaranteed. Although RI or IA cannot fully represent the changes of water consumption, the overall trend can be reflected, and the attribution results only reflect the influence degree of reservoir or irrigation engineering, rather than that of actual water consumption. In the following research, we will continue to introduce more reliable influence factors and influence law functions to obtain more reliable attribution.

5. CONCLUSION

Due to climate change and human activity, reports of nonstationarity in hydrological series are increasing rapidly. A number of studies have attempted to identify the cause of the nonstationary change observed in the annual runoff of the Weihe River, but no consensus has been reached. In this paper, we use the de-nonstationarity method to attribute the nonstationary change in the annual runoff of the Weihe River to climate change and human activity factors. The de-nonstationarity method transforms a nonstationary hydrological series into a new stationary reconstructed series. The improvement in the stationarity of the reconstructed series reconstructed by different driving factors indicates the relative contribution of those factors to the nonstationary change observed in the annual runoff. The de-nonstationarity method can achieve the simultaneous attribution of the nonstationary change in both the first and second moments of the hydrological runoff series.

We chose climatic factors and human activity factors as the potential driving factors. P and T reflect climate change, while IA and RI reflect human activity. The removal of the T , IA , and RI all resulted in new reconstructed series with statistically stationary first and second moments. The T is the most significant contributor to the nonstationary change in the annual runoff of the Weihe River, which has a nonlinear impact on the first and second moments, while IA and RI exert lesser influence on the nonstationary change. As the P is statistically stationary, it has a small influence on the nonstationary changes of annual runoff, but it still exerts some impacts on the second moment of the annual runoff.

Because the correlation between T -constructed series RS_T and IA is nonsignificant, the fitted influence law according to this nonsignificant relationship has a great uncertainty. And the synchronous increase trend in T and IA leads to a certain correlation between the two series. For the two-factor reconstruction, the stationarity of the reconstructed series RS_{double} has not been improved significantly after removing the influence of IA from the RS_T series. However, the stationarity of the reconstructed series RS_{double} still proves that both temperature rises and human activities have a significant impact on the nonstationary change in the annual runoff.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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