water

Review

Separating the Impacts of Climate Change and Human Activities on Runoff: A Review of Method and Application

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Abstract: Separating the impact of climate change and human activities on runoff is an important topic in hydrology, and a large number of methods and theories have been widely used. In this paper, we review the current papers on separating the impacts of climate and human activities on runoff, summarize the progress of relevant research methods and applications in recent years, and discuss future research needs and directions.

Keywords: climate change; human activities; runoff; water management

1. Introduction

Water is the substance on which all the organisms on the earth depend for their survival, and the operation of nature and the development of human society are inseparable from it [1]. About 75% of the Earth's surface is covered with water, while freshwater resources account for only 2.5% of the Earth's water, less of which can be easily utilized by human beings [2]. However, the problems of population expansion, resource shortage, and environmental deterioration in the world make the scarcity of water resources more and more serious [3,4]. Therefore, how to evaluate water resources scientifically is the precondition for efficient management and rational utilization of water resources. Runoff, as an important indicator of water resources, is the result of interaction between climate and underlying surface [5,6]. It is not only disturbed by human activities, but also very sensitive to climate changes [7]. Therefore, separating the effects of climate change and human activities on runoff is helpful to understand the formation process and evolution law of water resources.

The effects of human activities and climate change on runoff appear in all aspects of the water cycle. Human activities mainly affect the hydrological process by changing the underlying surface conditions of the basin, including the impacts of land use [8], water conservation measures [9], and water conservancy projects [10] on the processes of runoff yield and concentration. In addition, human beings also influence hydrological processes through agricultural irrigation [11], groundwater exploitation [12], and urban water supply and drainage [13]. Human activities have changed natural hydrological processes [14,15]. Human-induced land-use change leads to a decrease in global scale terrestrial evapotranspiration at a rate of 3500 km^3/year, which may directly lead to a 7.6% increase in runoff [16]. Dam construction and unsustainable groundwater consumption lead to changes in surface water and aquifer storage, which contribute to global sea level rise [17–19]. Reservoirs operation and irrigation have reduced the global discharge from 1981 to 2000 by 2.1% [20]. Climate change mainly affects runoff by changing precipitation and evapotranspiration. On a long-term scale, runoff is equal to the difference between precipitation and evapotranspiration, that is to say, precipitation is the supplement of runoff and evapotranspiration is the consumption of runoff. According to the fourth report of IPCC, the global temperature has increased by 0.85 °C and continues to increase [21]. The increase of temperature will not only promote the melting of glaciers and snow into precipitation [22–24], but also affect the evapotranspiration.

Separating the impacts of climate change and human activities on runoff is the basis of water resources research and one of the hot topics in hydrological research [25]. Methods including the hydrological model, scenario combination, Budyko framework, paired catchment, and empirical statistics have been used in such studies. In addition, machine learning has recently been used to separate the impacts of climate change and human activities on water resources [26,27]. Therefore, in this paper, we first review the key to separating the impacts of climate change and human activities on runoff, and then summarize each method and its application.

2. Key to Separating the Impacts of Climate Change and Human Activities on Runoff

2.1. Determination of Reference Period and Human Activities Interference Period

In the study of separating the impacts of climate change and human activities on runoff, the first problem to be solved is to determine the reference period and human activities interference period. Generally, the method of abrupt change test is used to identify the change point of runoff series. The period before the change point is regarded as the reference period, when the impact of human activities on runoff is too insignificant to be ignored. Therefore, runoff is considered to be only affected by climate change in the reference period. The period after the change point is regarded as the human activities interference period, when the impact of human activities on runoff becomes significant and runoff is affected by both climate change and human activities. The commonly abrupt change test of hydrological variables include accumulative anomaly, Mann–Kendall test, Pettitt's test, order cluster analysis, and double-mass curves [28–33].

Due to the different hypothesis and precondition of different abrupt change tests, the positions of the change point of the same hydrological series may be different. We use order cluster analysis, Pettitt's test, and the Mann–Kendall test to identify the change point of annual runoff in Minjiang watershed from 1956 to 2017 (Figure 1). The results show that the change points identified by ordered cluster analysis were in 1993 (Figure 1a), and the change points identified by the Pettitt's test were also in 1993 (Figure 1b), while the Mann–Kendall test determined three change points in 1996–1999 (Figure 1c). Therefore, in practical application, at least two methods should be used and then determine the change point location according to the actual situation of the specific study area.

However, although we can determine the location of the change point, we cannot directly determine whether this abrupt change in runoff is due to human activity or to a significant change in climate. However, we can answer this question by simultaneously detecting whether climate factors change significantly before and after the change point. If the climate change is significant, it can be considered that the abrupt change of runoff is caused by significant climate change, otherwise human activities will be responsible for the abrupt change of runoff.

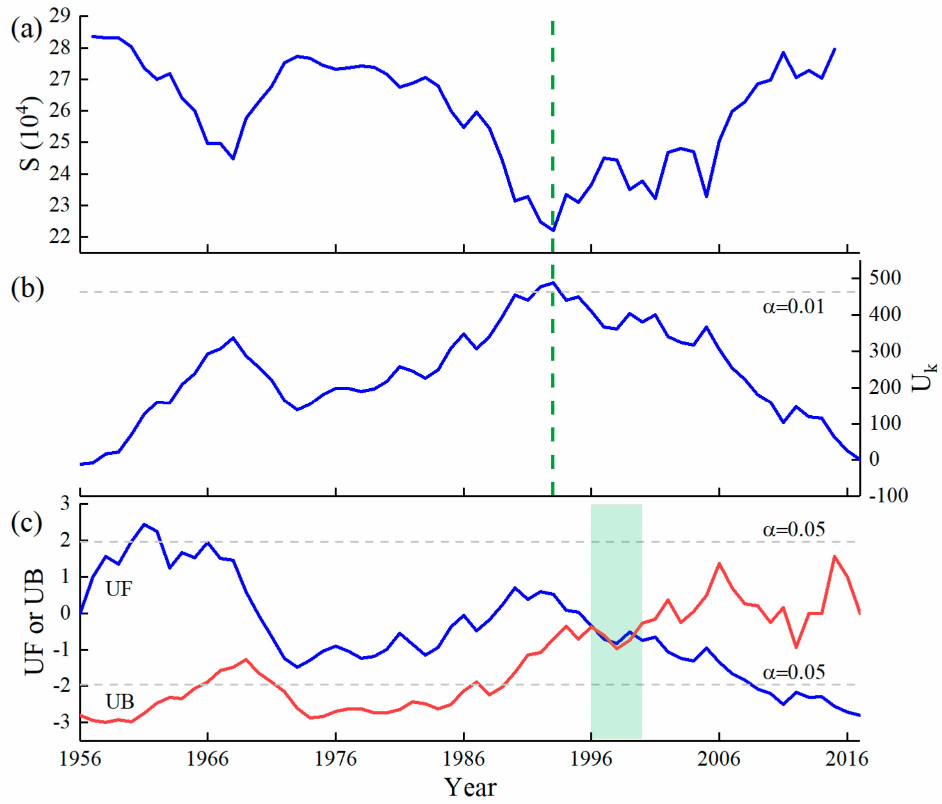

Figure 1. Three different abrupt change test methods were used to identify the change point of annual runoff in Minjiang watershed from 1956 to 2017: (**a**) is the result of order cluster analysis and the identified change point was in 1993; (**b**) is the result of Pettitt's test and the identified change point also appeared in 1993 ($\alpha = 0.01$); (**c**) is the result of the Mann–Kendall test and the change point location is between 1996 and 1999 ($\alpha = 0.05$). S is the statistic of order cluster analysis, U_k is the statistic of Pettitt's test, UF and UB are the statistics of Mann-Kendall test.

2.2. Research Framework

In the past, researchers have developed many methods, including the hydrological model, scenario combination, paired catchment, Budyko framework, and empirical statistics, to separate the impacts of climate change and human activities on runoff [34–36]. When using all the above methods, the research always assumes that climate change and human activities are relatively independent, and, based on this assumption, the research framework is developed:

$$\Delta Q_{total} = Q_{post} - Q_{pre} \tag{1}$$

$$\Delta Q_{total} = \Delta Q_c + \Delta Q_h \tag{2}$$

$$\eta_c = \frac{\Delta Q_c}{\Delta Q_{total}} \times 100\% \tag{3}$$

$$\eta_h = \frac{\Delta Q_h}{\Delta Q_{total}} \times 100\% \tag{4}$$

where ΔQ_{total} is the total amount of runoff change, Q_{post} is the runoff in the human activities interference period, Q_{pre} is the runoff in the reference period, ΔQ_c is the runoff change caused by climate change, ΔQ_h is the runoff change caused by human activities, η_c is the contribution rate of climate change to runoff, and η_h is the contribution rate of human activities to runoff.

3. Methods and Applications

3.1. Hydrological Model

The hydrological model is a series of equations that use many parameters to describe basin characteristics to estimate runoff [37]. The model is driven by hydrological, meteorological, and underlying surface data, in which precipitation and runoff data must be input. When the hydrologic model is used to separate the impacts of climate change and human activities on runoff, the general procedure is to first use the hydrological, meteorological, and underlying surface data in the reference period to calibrate the model parameters, and it is assumed that these parameters can reflect the natural runoff yield of the basin. Then, one only needs input the meteorological data of the human activities interference period into the calibrated model to simulate the natural runoff of this period. The difference between the actual runoff and the simulated runoff in the human activities interference period is the impact of human activities on runoff, and the difference between the simulated value and the actual runoff of the reference period is the impact of climate change on runoff, which can be expressed as:

$$\Delta Q_h = Q_{post} - Q_{sim} \tag{5}$$

$$\Delta Q_c = Q_{sim} - Q_{pre} \tag{6}$$

where Q_{sim} is the runoff only effected by climate change simulated by the model in the human activities interference period.

After a long-term development, researchers have used many hydrological models to separate the impact of climate change and human activities on runoff (Table 1). Generally speaking, hydrological models refer to the models that consider the physical process of runoff formation process, using some physical and empirical parameters to summarize runoff formation [38], which can be divided into lumped model and distributed model. Lumped models such as SIMHYD (a simplified version of the HYDROLOG model), the Xinanjiang model, etc., do not consider the spatial differences of underlying surface characteristics, the hydrological process or the input variables of the model, and the input variables are in the form of watershed averages [39]. For distributed models, such as SWAT (Soil and Water Assessment Tool), VIC (the Variable Infiltration Capacity), HBV (the Hydrologiska Byrans Vattenavdelning), GBHM (Geomorphology Based Hydrological Model), TOPMODEL (topography-based hydrological model), etc., the watershed is divided into small units and taken as the calculation object, so that the spatial differences of hydrological process, input variables, boundary conditions and watershed geometric characteristics are fully considered [40]. These hydrological models have been tested for a long time, so the analysis results are believable. However, there are still some shortcomings. On the one hand, the existing studies are based on point data to calibrate and validate the model and then apply the same set of parameters to the region, which makes the hydrological model have high uncertainty. On the other hand, a large number of observed data or hydrological process parameters are needed to train model parameters, and a high accuracy of data is required.

Table 1. Hydrological models and scenario combinations for research on the impact of climate change and human activities on runoff.

Study Area	Model	Time	Trend	Contribution (%) [1]	Dominant Factor	Reference
Luan River Basin	SWAT SIMHYD	1958–2009	Decrease	42.1% for SWAT46.8% for SIMHYD	Human activity	Zeng et al. [41]
Guanzhong River	SIMHYD	1958–2008	Decrease	34.2%	Human activity	Zhan et al. [42]
Miyun Reservoir catchment	GBHM	1956–2005	Decrease	55%	Climate change	Ma et al. [43]
Harvey River Catchment	HBV	1971–2015	Decrease	56%	Climate change	Kazemi et al. [44]
Northwest China	SWAT	1957–2008	Decrease	14.3%	Human activity	Dong et al. [45]
Kuyehe River basin	VIC	1955–2008	Decrease	25.1–41.4%	Human activity	Wang et al. [46]
Northern China	VIC-3L	1964–2008	Decrease	11%	Human activity	Jiang et al. [47]

[1] Contribution only refers to the contribution of climate change to runoff.

3.2. Scenario Combination

Scenario combinations are usually coupled with hydrological models when used to separate the impact of climate change and human activities on runoff [48]. Researchers combine different periods of climate and land-use/cover change (LUCC) to obtain different scenarios, and then analyzed the differences of simulated runoff under different scenarios. Generally, there are four scenarios:

1. S1: Climate in the reference period and LUCC in the reference period.
2. S2: Climate in the human activities interference period and LUCC in the reference period.
3. S3: Climate in the reference period and LUCC in the human activities interference period.
4. S4: Climate in the human activities interference period and LUCC in the human activities interference period.

Therefore, the impacts of climate change and human activities on runoff can be expressed as:

$$\Delta Q_c = Q_{sim2} - Q_{sim1} \tag{7}$$

$$\Delta Q_h = Q_{\mathrm{sim}3} - Q_{sim1} \tag{8}$$

Among them, Q_{sim2} is the simulated runoff under scenario S2, and Q_{sim3} is the simulated runoff under scenario S3.

Scenario combination coupled with the hydrological model is also used to predict the runoff change under future scenarios. The simulation of future scenarios includes the simulation of future climate and the simulation of future LUCC. General Circulation Models (GCMs) are often used to predict future climate, and the estimated concentration of greenhouse gases under future emission scenarios is used as input to simulate the response of the atmosphere to changes in greenhouse gas concentrations [49]. However, due to the limitation of GCMs' resolution for regional applications, researchers propose to nest Regional Climate Models (RCMs) based on GCMs or to improve the resolution of GCMs' output by statistical methods [50]. Nijssen et al. [51] used VIC to couple four GCMs to study the hydrological responses of nine large continental river basins to climate change in the future and concluded that the annual runoff in tropical and mid latitudes would decrease, while that in high latitudes would increase. Zhang et al. [52] used VIC coupled with Providing Regional Climates for Impacts Studies (PRECIS) to study the potential impacts of climate change on runoff in the Huaihe River Basin under A2, B2 and A1B scenarios and found that global warming will aggravate regional floods and water shortage. Land-use prediction in the future is implemented by

LUCC models, which mainly address the location (where the change occurs) or the quantity (what rate of change) in the process of land-use change [53]. The existing LUCC models can be divided into three types: (1) Pattern-based models, which focus on describing and extrapolating the past, such as the Conversion of Land Use and its Effects at Small regional extent (CLUE-S), a Cellular Automaton Model (CA) [54,55]. (2) Process-based models, which represent the environment and decision-making process that causes pattern change, such as Agent-Based Models (ABM) [56]. (3) Hybrid models, such as the CA-Markov model [57]. Numerous studies have used GCMs/RCMs and LUCC models to assess the hydrological effects of climate and LUCC in future scenarios [58–62].

The scenario combination method can simulate runoff process in multiple scenario modes by coupling hydrological models, which has a more realistic physical basis, but also makes this method require a variety of high-precision data to drive. In addition, due to the gap between the combined scenario and the ideal state assumed by the researchers, the analysis results will be affected.

3.3. Budyko Framework

In recent years, the Budyko framework has been widely used to study the impact of climate change and human activities on runoff because of its clear physical concept and concise mechanism. Budyko believes that in a closed basin, the long-term evapotranspiration (E) of the land surface is mainly determined by the water supply of the atmosphere and the evapotranspiration capacity of the land surface, and there is a boundary condition (Figure 2): in extremely arid areas, the evapotranspiration capacity is far greater than the water supply, then the evapotranspiration is equal to the water supply; in extremely humid areas, the water supply is far greater than the evapotranspiration capacity, then the evapotranspiration is equal to the evapotranspiration capacity [63,64]. On the year or multi-year scale, precipitation (P) represents the water supply, and potential evapotranspiration (ET_0) represents the evapotranspiration capacity. Later, the ratio of ET_0 to P is defined as "Aridity index", and the ratio of E to P is defined as "evapotranspiration index" [65].

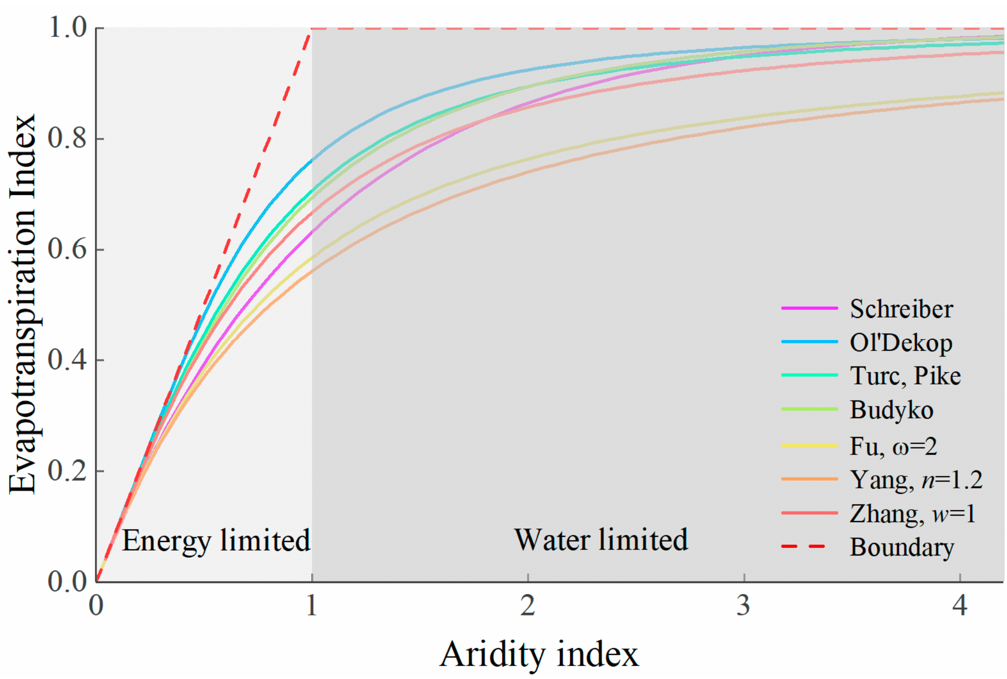

Figure 2. Boundary conditions of the Budyko framework and different Budyko-type functions. The red dotted lines represent the boundary conditions of the Budyko framework, and the colored lines are different Budyko-type functions.

With the development of the Budyko framework, a large number of functions describing the relationship between drought index and evapotranspiration index appear (Table 2). The original

Budyko framework only considered the influence of P and ET_0 on E, and ignored the influence of other unknown reasons. There are two interpretations of the unknown reasons: (1) the underlying surface characteristics of the basin, such as soil [66], vegetation [67], and topography [68]; (2) the seasonality of climate variables [69], precipitation depth [70], and precipitation frequency [66]. In order to explain the influence of unknown parameters, researchers introduce parameters such as ω, n, and w into the Budyko function. At present, most researchers think that the parameters represent the characteristics of underlying surface [71]. Although each Budyko function has different forms, it follows the boundary of the Budyko framework (Figure 2). So, Zhou [72] expresses the Budyko function as:

$$\frac{E}{P} = F\left(\frac{ET_0}{P}, c\right) \tag{9}$$

where c represents the underlying surface characteristics of the basin, and different c represents different forms of Budyko functions.

Table 2. Relationship between the aridity index and evapotranspiration index based on the Budyko framework.

Reference	Function	Supplement
Schreiber [73]	$\frac{E}{P} = 1 - e^{\left(-\frac{a_{sch}}{P}\right)}$	a_{sch} is the adjustment coefficient, and this function has no clear physical mechanism.
Ol'Dekop [74]	$\frac{E}{P} = \frac{ET_0}{P} tanh\left(\frac{ET_0}{P}\right)^{-1}$	Revised from Schreibe's research, and the function has no physical mechanism to support.
Pike [75]	$\frac{E}{P} = \frac{ET_0}{P} / \sqrt{\left(\frac{ET_0}{P}\right)^2 + 1}$	Revised from Turc [76].
Budyko and Miller [64]	$\frac{E}{P} = \sqrt{\frac{ET_0}{P} tanh\left(\frac{ET_0}{P}\right)^{-1}\left[1 - e^{\left(-\frac{ET_0}{P}\right)}\right]}$	Based on the research of Schreiber and Ol'dekop, their functions are geometrically averaged.
Fu [77]	$\frac{E}{P} = 1 + \frac{ET_0}{P} - \left[\left(\frac{ET_0}{P}\right)^{\omega} + 1\right]^{\frac{1}{\omega}}$	It is derived from dimensional analysis and mathematical derivation and has clear physical meaning. $\omega \in [1, +\infty]$, which is the control parameter of hydrothermal coupling [1].
Zhang et al. [78]	$\frac{E}{P} = \left(1 + \omega \frac{ET_0}{P}\right) / \left(1 + \omega \frac{ET_0}{P} + \left(\frac{ET_0}{P}\right)^{-1}\right)$	Modified from the function of Fu's function.
Yang et al. [79]	$\frac{E}{P} = \left[\left(\frac{ET_0}{P}\right)^{-n} + 1\right]^{-\frac{1}{n}}$	n is a dimensionless parameter without physical meaning. This function is revised based on the research of Turc [76], Mezentsev [80], and Choudhury [81].
Zhang et al. [82]	$\frac{E}{P} = \left(1 + w \frac{ET_0}{P}\right) / \left(1 + w \frac{ET_0}{P} + \left(\frac{ET_0}{P}\right)^{-1}\right)$	$w \in (0, 2]$, indicating the water use coefficient of vegetation, reflecting the difference of evapotranspiration of soil water absorbed by vegetation. For forest, $w = 2$; for Gramineae, $w = 0.5$.

[1] $\omega = n + 0.72$ [79].

When using Budyko framework to study the impact of climate change and human activities on runoff, the elasticity method [83] and decomposition method [84] are the most representative.

The elasticity method is to introduce climate elasticity coefficient to express the sensitivity of runoff to climate variables. The elastic coefficient is defined as the ratio of runoff change to climate variable change:

$$\varepsilon_x = \lim_{\Delta x / x \to 0} \frac{\Delta Q / Q}{\Delta x / x} = \frac{\partial Q}{\partial x} \times \frac{x}{Q} \tag{10}$$

ε_x is the elasticity coefficient of runoff to climate variable x. If ε_x is 0.1, it means that a 10% increase in x will cause a 1% increase in Q. On a long-term scale, the water balance of a watershed can be expressed as:

$$P = E + Q \tag{11}$$

Then, according to Equations (9)–(11), there are:

$$\frac{dQ_c}{Q} = \varepsilon_P \frac{dP}{P} + \varepsilon_{ET_o} \frac{dET_0}{ET_0} \tag{12}$$

It can also be expressed as:

$$\frac{\Delta Q_c}{Q} = \varepsilon_P \frac{\Delta P}{P} + \varepsilon_{ET_o} \frac{\Delta ET_0}{ET_0} \quad (13)$$

Wang and Hejazi [84] put forward a decomposition method based on the Budyko framework, which considers that climate change causes the basin state to change along the Budyko curve, while human activities will make the basin state change in the vertical direction. As shown in Figure 3, the watershed state A_1 in the reference period moves to A_1' along the Budyko curve under the influence of climate change, and, due to the interference of human activities, the watershed state changes to A_2 along the vertical direction. Therefore, the runoff change caused by human activities can be expressed as:

$$\Delta Q_h = \left(\frac{E_2}{P_2} - \frac{E_2'}{P_2} \right) P_2 \quad (14)$$

where $\frac{E_2'}{P_2}$ is calculated with Budyko curve in the reference period, $\frac{E_2}{P_2}$ is calculated by Budyko curve in the period of the human activities interference period, and P_2 is the precipitation in the period of human activity disturbance.

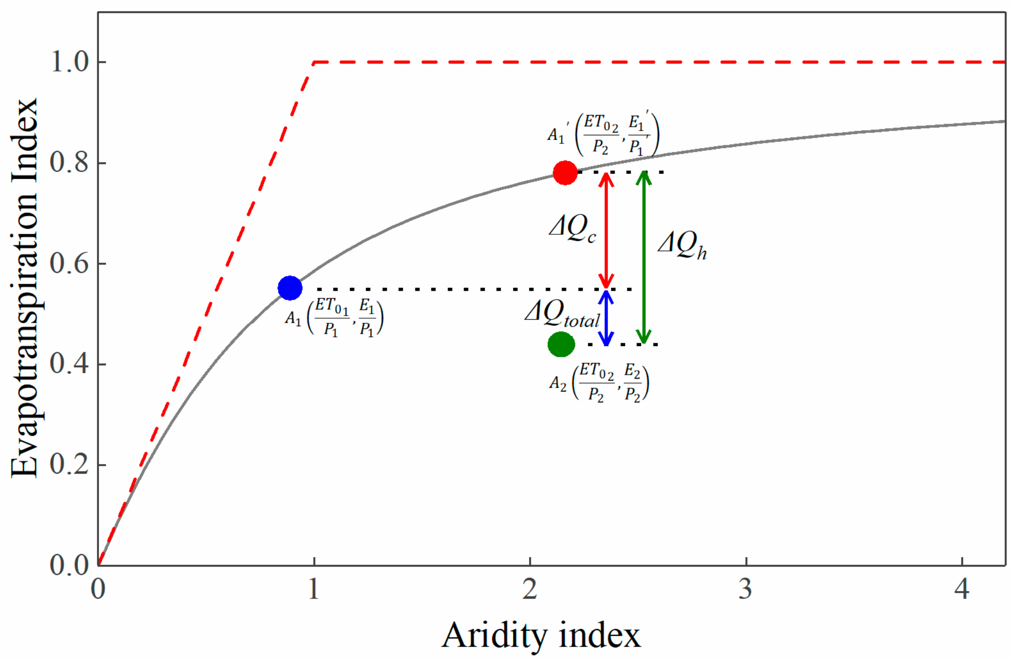

Figure 3. Decomposition method based on the Budyko framework (modified from Berghuijs and Greve [71]). A_1 represents the basin state in the reference period, A_2 represents the basin state in the human activities interference period, and $A_{1'}$ represents the basin state only under the influence of climate change.

Because the Budyko framework has a certain physical basis and can reflect the relationship between water and energy in the basin, many studies use it to study the impact of climate change and human activities on runoff (Table 3). Studies have shown that the Budyko framework is better than the hydrological model method at analyzing the impact of climate change on annual runoff in large areas and limited data areas, but it is not suitable for the analysis of runoff variation in the given scenario [85]. In addition, ET_0 must be calculated when using the Budyko framework, although researchers have developed many ET_0 algorithms [86–90], there is no system to verify the ET_0 calculation results.

Table 3. Studies on the impact of climate change and human activities on runoff based on the Budyko framework.

Study Area	Time	Trend	Contribution (%) [1]	Dominant Factor	Reference
Soan River basin	1983–2012	Decrease	65.92%	Climate change	Shahid et al. [91]
Haihe basin	1956–2005	Decrease	22.4%	Human activity	Xu et al. [92]
Agula watershed	1992–2012	Decrease	22%	Human activity	Fenta et al. [93]
Wei River basin	1958–2008	Decrease	22–29%	Human activity	Zhan et al. [94]
Shiyang river basin	1950–2005	Decrease	64.5–87.9%	Climate change	Ma et al. [95]
Guanzhong River	1958–2008	Decrease	39.31–47.25%	Human activity	Zhan et al. [42]
Luan River Basin	1958–2009	Decrease	28.3–37.5%	Human activity	Zeng et al. [41]
Miyun Reservoir catchment	1956–2005	Decrease	51%	Climate change	Ma et al. [43]
Harvey River Catchment	1971–2015	Decrease	55%	Climate change	Kazemi et al. [44]
Hun-Tai River basin	1961–2006	Decrease	43%	Human activity	Zhang et al. [96]

[1] Contribution only refers to the contribution of climate change to runoff.

3.4. Paired Catchment

The paired catchment method is a classic method to separate the impacts of climate change and human activities on runoff. After Bosch and Hewlett [97] reviewed the impact of vegetation change on water production through catchment experiments, the paired catchment method developed rapidly and was mostly used for the impact of vegetation change on runoff. The paired catchment method requires locate adjacent catchments, which have similar physical geographical characteristics, including slope, slope direction, soil, area, climate, and vegetation, and so on. After catchments go through a correction period, some catchments will be kept in a natural state as controls, and human activities will be conducted in other catchments as treatments. The control and treatment catchments will be observed in parallel. In the calibration period, linear regression is usually made between the control and treatment catchments to predict the runoff without human activities in the control catchments, and then the difference between the predicted runoff and the real runoff is considered to be caused by human activities [98,99]. Stoof et al. [100] used the paired catchment to investigate the hydrological response before and after the fire on the eastern slope of Serra da Lousã in central and northern Portugal and found that vegetation removal played an important role in the increase in runoff after the fire. Cheng et al. [101] studied the effect of vegetation change on the dynamic of catchment storage-discharge using streamflow data from six paired catchment experiments, and found that one of the important mechanisms of runoff variation caused by groundwater storage–discharge relationship variation caused by vegetation change was found. The interaction of surface water–groundwater has a great correlation with the non-stationary change of rainfall–runoff, which may lead to incorrect runoff estimates at a given rainfall than predicted at both seasonal and annual scales [102–104]. Meteorological drought also affects the non-stationary change of rainfall–runoff, but it is less than the interaction of surface water–groundwater. Therefore, the interaction of surface water–groundwater should be considered when conducting rainfall–runoff modeling.

Since the method of paired catchment excludes climate change, it can better represent the runoff change caused by the change of underlying surface [99], but the result is very fuzzy, and it is difficult to extrapolate to other regions. Moreover, the study area can only be selected in a small-scale catchment (usually < 1 km^2), where the distribution of climate, soil, topography, vegetation and other characteristics between the treatment catchment and the control catchment is more likely to be similar [105]. In addition, due to the long research period, the accumulation of test data is insufficient, and the underlying surface condition of the catchment area cannot guarantee the stability all the time, so the repeatability of the experiment is low.

3.5. Empirical Statistics

Empirical statistics is a common method to study the impact of climate change and human activities on runoff. Because it establishes the relationship between runoff and climate variables, the long-term observation of hydrological and meteorological data is needed [106]. Firstly, the relationship model is established by using the climate variable data and runoff data in the reference period:

$$Q_{pre} = f(c_{pre}) \tag{15}$$

where c_{pre} represents the climatic variables in the reference period. Then, the meteorological data in the human activities disturbance period are input into the model to simulate the natural runoff during that period:

$$Q_{sim} = f(c_{post}) \tag{16}$$

where c_{post} represents the climatic variables in the human activities interference period. Finally, the influence of human activities on runoff is analyzed by comparing the simulated runoff with the observed runoff in human activities interference period.

The relationship between runoff and climate variables can be linear or non-linear [107,108]. Zhang et al. [109] used linear regression to establish the relationship between precipitation and runoff, and estimated that human activities caused a 41.74% reduction in runoff in the Yi River Basin of China. Du and Shi [110] used multiple stepwise regression to establish the relationship between climate variables and runoff and finally determined that only precipitation and temperature are related to runoff. Additionally, they estimated that precipitation, temperature and human activities are, respectively, responsible for 33.0%, 15.9% and 51.1% of the runoff reduction in the Weihe River Basin. Zhang et al. [111] established a non-linear runoff model driven by precipitation and potential evapotranspiration in the Xitiaoxi River Basin of China and analyzed that the contribution rate of human activities to runoff reduction in the basin was 57.2%.

Empirical statistical methods are very easy to implement because only runoff observation data and meteorological data are needed to simulate the runoff process. The accuracy of model simulation and the reliability of meteorological data are the key to the calculation of this method, so it requires high-quality observation data, but the application of data is relatively simple. In addition, due to the lack of physical mechanism, this method can only analyze the hydrological effects of climate change.

3.6. Machine Learning

Due to the development of big data, the application of machine learning based on big data in hydrological research is increasing [112]. As we all know, in the process of the hydrological cycle, each variable interacts with each other, but the interaction mechanism among many variables is not clear, let alone able to establish their mathematical relationship. However, machine learning can mine useful information from massive data and help to find response patterns among variables. Therefore, using machine learning for hydrological simulation is efficient and intelligent, which can solve the shortcomings of physical models and statistical models in hydrological research, such as accuracy and uncertainty, high computational cost, and large data demand [113–115]. Bai et al. [116] trained hybrid models of Depth Belief Networks (DBN) and Neural Network (NN) to predict the Three Gorges reservoir inflow, and the results were highly matched. Tongal and Booij [117] coupled Support Vector Regression (SVR), Artificial Neural Networks (ANNs) and Random Forest (RF) with the base flow separation method to simulate the runoff of four rivers in the United States and found that the separation of base flow can improve the simulation performance of machine learning models. Hu et al. [118] used the framework of integrating long short-term memory (LSTM) and the reduced order model (ROM) in flood forecasting research. After testing with Okushiri tsunam, he found that LSTM-ROM can not only ensure the accuracy of prediction, but also reduce the cost of prediction.

Kratzert et al. [119] trained LSTM with daily meteorological and runoff data from 241 catchments for 15 years to establish rainfall–runoff models, with better performance as the SACSMA + Snow-17 model. The work of Kratzert et al. makes it possible to use machine learning to separate the impacts of climate change and human activity on runoff. Firstly, the machine learning model is trained with the meteorological data and runoff data of the reference period to simulate the natural runoff response to climate, and then the trained model is used to estimate the natural runoff during the human activities disturbance period. The difference between the observed value and the simulated value during the human activities disturbance period is the runoff change caused by human activities, and the impact of climate change on runoff is calculated by comparing the difference between the simulated value and the observed value in the reference period.

Although machine learning has obvious advantages in hydrological simulation, it is limited by the sample sizes [114]. If there is a lack of samples, the trained machine learning model will be difficult to be constrained. Kratzert et al. [119] think that the sample size of 15-year daily data may be the lower bound of machine learning's demand for data. Therefore, machine learning cannot be applied indiscriminately.

4. Interaction between Human Activities and Climate Change

The relationship between climate change and human activities has always been assumed to be independent of each other in studies that separate their effects on runoff, when in fact they affect each other [120,121]. Haddeland et al. [122] found that the demand for irrigation water will increase with the increase in global average temperature. On the scale of catchment area, climate change is the main cause of land-use and land-cover change, which may change the runoff process [109]. Greenhouse gas emissions lead to global warming and changes in aerosol thickness, which have an impact on precipitation [123,124].

Moreover, even if the assumption that climate change and human activity are independent of each other is accepted, some shortcomings in the separation approaches have been proposed. Yang et al. [125] found that when the first-order Taylor expansion of Budyko functions is used to calculate the contribution of climate to runoff, the increased P or reduced ET_0 will lead to the underestimation of climate contribution, while the decreased P or increased ET_0 overestimates the contribution of climate. Xu et al. [126] pointed out that the empirical statistical method only distinguishes the impacts of precipitation and non-precipitation factors on runoff, thus underestimating the contribution of climate change to runoff.

Therefore, it is impractical to completely separate climate change from human activities. If it is expected to accurately quantify the impact of specific human activities and each climatic element on runoff, more efforts are needed.

5. Conclusions

The separation of the impacts of climate change and human activities on hydrological variables is the basic work of water resources assessment. It is not only conducive to the rational development and scientific management of regional water resources, but also of great significance for decision makers to cope with global climate change. After reviewing the relevant studies on separating the impacts of climate change and human activities on runoff, this paper finds that, although the hydrological model, scenario combination, paired catchment, Budyko framework, and empirical statistics have been developed and great progress has been made, there are still some problems to be further explored in the future:

1. At present, an abrupt change test is often used to determine the reference period and the human activities interference period, but it can only explain the variation of hydrological series statistically. However, some change points in the time series of hydrological variables may only be change in a series period, not a real variation point. How to find and verify the real mutation point and demonstrate the objectivity and reliability of mutation need further research.
2. The contribution rates calculated by using different methods to separate the impacts of climate change and human activities on runoff may be different. Most researchers use various methods to verify each other at the same time, but the results still have great uncertainty.

3. The existing studies on separating the impacts of climate change and human activities on runoff are based on the fact that human activities and climate change are relatively independent. However, it is a fact that human activities have an impact on climate change, and there is no feasible method to distinguish the changes caused by human activities and natural climate fluctuations in climate change.
4. In the application of the hydrological model, there are few studies considering the uncertainty of model calibration and model scale. How to quantify these uncertainties and explain the differences between them in order to improve the accuracy of the research results also needs to be further studied.

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