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Quantifying the Relative Contribution of the Climate Change and Human Activity on Runoff in the Choshui River Alluvial Fan, Taiwan

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Abstract: Climate factors and human activities are the leading causes of changes in the hydrological cycle. In addition to being an important part of the hydrological cycle, runoff is also an important indicator for assessing the amount of available water. Therefore, it is necessary to explore the reasons that have caused changes in runoff. In this study, the causes of runoff changes in the alluvial fan of the Choshui River from 1980–2018 are explored. Two simple methods, including a decomposition method based on the Budyko structure and a method based on climate elasticity, for which the necessary data are easy to obtain, are used to quantify the impact of climate factors and human activities on runoff changes. The results show that the runoff in the long term shows a significant transition point in 2003, where climate factors have contributed more than 90% of the change, while the influence of human activities on the changes in runoff appears to be relatively small. Moreover, the Budyko method and the Normalized Difference Vegetation Index (NDVI) show that the vegetation cover has decreased. In addition to providing a simple method to assess the causes of changes in runoff, this study also analyzes the causes of changes in the runoff of the alluvial fan of the Choshui River to provide a reference for water resource policy and land use management.

Keywords: Budyko framework; runoff; climate change and anthropogenic activity; Choshui River alluvial fan

1. Introduction

Runoff is an important indicator to measure whether available water can be supplied continuously. Evaluating the changes in runoff over time is an important challenge in water resources management [1,2]. Since the hydrological process is affected by climatological and human factors, the changes in runoff are due to climate factors and human activities. Therefore, understanding the causes of changes in runoff can help decision-makers formulate policies on managing water resources more efficiently [3–5]. Climate change can alter the availability of water and threaten water security [6]. Due to climate change, it is estimated that by 2050, more than 600 million people will have their available water reduced by more than 10% compared to current levels. The reduction in available water directly impacts agriculture, industry, domestic water supply, and water conservancy applications in rivers, including hydropower, navigation, entertainment, and ecological protection [7].

In the early days of the discussion on how climate factors and human activities change runoff, the classic paired catchment method was often used to analyze the impact of climate factors and human activities on runoff. This method needs to find catchment areas with similar conditions (e.g., climate environment, vegetation status, soil properties, area), and it is only suitable for small catchment areas. Subsequently, some scholars used the concept of ecohydrology to propose a simple method to assess the impact of changes in runoff. However, the main disadvantage of this method is the need for data



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). of precipitation, actual evapotranspiration, meteorological parameters in the long term to estimate potential evapotranspiration, and historical records of changes in land use. Moreover, the method can only give qualitative results [8,9]. The more widely used methods in recent research studies can be roughly divided into the hydrological model and the Budyko framework. The hydrological model uses a series of equations and parameters to describe the characteristics of the watershed and estimate the runoff [10]. For example, Ma et al. [11] used the Geomorphology-Based Hydrological Model (GBHM) to explore the catchment area of the Miyun Reservoir in China, showing that climatic factors are the main influencing factor of changes in runoff flow. Wang et al. [12] used the Variable Infiltration Capacity (VIC) model to infer that the main reason for the changes in the flow of the Kuye River Basin in China is human activity. Dong et al. [13] used the Soil and Water Assessment Tool (SWAT) to assess the mechanism of flow rate change of the Jinghe River Basin in China from 1957 to 2008. The analysis results revealed human activity as the main influencing factor. The advantages of using hydrological models are based on the complete consideration of model parameters, boundary conditions, and the geometric characteristics of the catchment area, such that the results of the analysis are not only highly reliable but also consider spatial differences. However, many studies use data of a single point to represent the entire study area, leading to a high degree of uncertainty in hydrological models. In contrast, although the Budyko framework needs large-scale space and time for its establishment to avoid deviations, it can obtain the required information more easily and has a clear physical meaning [14–16].

Xu et al. [17] used the Budyko framework combined with climate elasticity to explore the mechanism that causes changes in runoff of the Haihe basin of China. This study divided the causes of runoff changes into climate and land use changes and found that land use changes were the main cause of changes in runoff. Wang and Hejazi [18] further proposed a decomposition method based on the Budyko framework to understand the causes of changes in runoff and used 27 catchment areas in the United States to verify the feasibility of the proposed method. Wu et al. [19] used the Budyko framework combined with climate elasticity to explore the reasons for the changes in runoff during the low-flow season and the high-flow season for the Loess Plateau. The results show that the main reason for the changes in runoff in the high-flow season is human activity, while the main reason for the changes in runoff in the low-flow season is climate factors.

The precipitation in Taiwan is significantly unevenly distributed in both time and space. The ratio of high and low rainfall periods is as high as 8:2 in the Choshui River Basin, and the precipitation decreases from mountainous areas to plains. The alluvial fan of the Choshui River, located in the plains, has an average annual precipitation lower than that of Taiwan, showing obvious uneven distribution in time and space [20]. The water use of the alluvial fan of the Choshui River was mainly for agriculture and fishery in the first half. Therefore, the development of groundwater that can provide a stable supply of water is required. However, the recent development of Yunlin and the Changhua Coastal Industrial Park has significantly increased water demand. The extraction of a large amount of groundwater has caused disasters such as stratum subsidence in many areas of the alluvial fan of the Choshui River. Therefore, to reduce the demand for groundwater and effectively allocate water resources, the government completed the Ji Ji Conjunctive Diversion Project in 2001. Currently, there is a lack of research studies on the causes of runoff changes in central Taiwan. This study takes into consideration the complex background of natural factors such as global warming, uneven distribution of precipitation in time and space, and human activities such as agricultural irrigation, industrial area development, and large-scale water diversion projects that occur to the alluvial fan of the Choshui River, and assesses the causes of changes in runoff in an attempt to obtain a better understanding of the mechanisms that affect runoff in the long term. As mentioned above, there is a lot of reference information and scientific evidence for using the Budyko framework to explore the mechanism of changes in runoff. As such, this study considers the availability of data and adopts the Budyko framework to evaluate the reasons for the changes in the runoff of the alluvial fan of the Choshui River. This study mainly uses simple and flexible methods to quantify the contribution of climate factors and human activities to changes in runoff.

2. Methodology

2.1. Runoff Analysis

This study collects annual evapotranspiration and annual precipitation data and uses the long-term annual steady-state water equilibrium equation, such as Equation (1), to evaluate runoff data. Subsequently, the Mann–Kendall test method [21,22] and Sen's slope estimator [23,24] are used to understand the significance of the trend of runoff in the long term. In addition, this study uses the Pettit test method [25] and Sequential Mann–Kendall test method [26] to find the change point of runoff.

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

Here, P is the precipitation, E is the actual evapotranspiration, Q is the flow rate of the runoff, ΔS is the change in water storage including groundwater, which in comparison to precipitation in the long term (e.g., more than 30 years) can be neglected and is hence assumed to be zero [9,27–29]. The change in water storage is not considered in steady-state Budyko framework and should be processed in non-state Budyko framework; therefore, the advantages of ignoring the change in water storage is that a simpler steady-state Budyko framework can be used rather than a complex non-steady Budyko framework. While ignoring the change in water storage may result in deviations in estimated runoff, we can reduce deviations by means of complementary characteristics of intra-annual water storage fluctuations at the annual scale.

2.2. Budyko Framework

Budyko assumed that the ratio of the actual average annual evapotranspiration to the average annual precipitation (E/P) is a function of the ratio of the annual potential evapotranspiration to the average annual precipitation (PET/P) [30]. Since PET/P is also called the aridity index (φ), the Budyko formula can be expressed as follows:

$$\frac{E}{P} = f\left(\frac{PET}{P}\right) = f(\phi)$$
(2)

where E is the actual evapotranspiration, PET is the potential evapotranspiration, and P is the precipitation. In a dry climate ($\varphi > 1$), the actual evapotranspiration is limited by the supply of precipitation. On the contrary, in a humid climate ($\varphi < 1$), the actual evapotranspiration is limited by the supply of energy. Due to the limitations of water and energy equilibrium, the boundary conditions of the Budyko formula are:

$$\begin{cases} \frac{PET}{P} \to 0, \ \frac{E}{P} \to 0\\ \frac{PET}{P} \to \infty, \ \frac{E}{P} \to 1 \end{cases}$$
(3)

In the subsequent research, many scholars have rewritten the Budyko formula from Equation (2) into different forms, divided into non-parametric and parametric forms. Since the parametric form of the Budyko formula leads to results that are closer to the observation data in southern Taiwan as compared to the non-parametric form [31], it is adopted in this study to carry out the subsequent analyses. Different forms of the Budyko formula are suitable for different environmental conditions, as shown in Table 1.

The Budyko parameters represent the watershed characteristic, such as vegetation and topography, and we treat the watershed characteristic changes as being caused by human activities. To understand the influence of human activities on runoff, the individual Budyko parameters of the first half, second half, and the whole period should be determined. The Budyko parameters of the three different periods are obtained by using the corresponding average climatic variables (i.e., the ratio of the annual evapotranspiration to the annual precipitation and aridity index), substituting Budyko equations.

Table 1. Budyko-type equations with single parameter.

Reference.	f(φ)	Parameters	
Fu [32]	$1+ arphi - (1+ arphi^{\omega})^{1/\omega}$	ω	(4)
Choudhury [33]	$\frac{1}{(1+\omega^{-\eta})^{1/\eta}}$	η	(5)
Zhang et al. [34]	$\frac{\frac{1+m\phi}{1+m\phi}}{1+m\phi+\phi^{-1}}$	m	(6)
Wang and Tang [35]	$\frac{1\!\!+\!\phi\!-\!\sqrt{(1\!\!+\!\phi)^2\!-\!4\psi(2\!\!-\!\psi)\phi}}{2\psi(2\!\!-\!\psi)}$	ψ	(7)

2.2.1. Decomposition of the Budyko Curve

Wang and Hejazi [18] proposed the Budyko curve decomposition method to determine the influence of climate factors and human activities on changes in flow. As shown in Figure 1, the points will only move on the same Budyko curve if only climate factors are at work. Similarly, the points will only move vertically if only human activities are at work. Therefore, the contribution of human activities to changes in flow is shown in Equation (8):

$$\Delta Q_{\rm H} = P_2 \left(\frac{{\rm E_1}'}{{\rm P_1}'} - \frac{{\rm E_2}}{{\rm P_2}} \right) \tag{8}$$

where P_2 , E_2 are the average precipitation and the average actual evapotranspiration in the second half, respectively; $\frac{E_2}{P_2}$ is the ratio of the average actual evapotranspiration and the average precipitation in the second half; $\frac{E_1'}{P_1'}$ is the ratio of the average actual evapotranspiration and the average precipitation obtained using the Budyko curve in the first half and the aridity index in the second half $\left(\frac{PET_2}{P_2}\right)$, which represents the ratio that is affected by climate factors only.



Figure 1. Decomposition method based on the Budyko framework. (modified from [16]).

2.2.2. Climate Elasticity

In addition to the decomposition method, this study also uses climate elasticity to separate the impact of climate factors and human activities on the changes in runoff in the Choshui River alluvial fan. Schaake [36] proposed using the elasticity coefficient to estimate the sensitivity of runoff to climate factors. The elasticity coefficient is defined by Equation (9):

$$\varepsilon_{\rm f} = \lim_{\Delta f/f \to 0} \left(\frac{\Delta Q/Q}{\Delta f/f} \right) = \frac{\partial Q}{\partial f} \frac{f}{Q}$$
(9)

where f represents the influencing factors of the runoff. In this study, the influencing factors considered include precipitation, potential evapotranspiration, and the Budyko parameters, the elasticity coefficient of the runoff to which are denoted as ε_P , ε_{PET} , and ε_n , respectively. The elasticity coefficient indicates the percentage increase or decrease in the flow rate of the runoff when the respective influencing factor is increased by 1%. The elasticity coefficients for the first, second, and the whole period are obtained by using the climatic variables and Budyko parameters corresponding to the period. The influence on runoff flow rate due to climate factors (ΔQ_C) comes from changes in precipitation and potential evapotranspiration, while the influence on runoff flow rate due to human activities (ΔQ_H) comes from changes in the parameters of the Budyko formula. The changes in runoff due to climate factors are as shown in Equation (10):

$$\Delta Q_{\rm C} = \frac{\partial Q}{\partial P} dP + \frac{\partial Q}{\partial PET} dPET$$
(10)

Combining Equation (9) with Equation (10), the influence of climate factors on the runoff flow rate is shown in Equation (11):

$$\Delta Q_{\rm C} = \left(\epsilon_{\rm P} \frac{\Delta P}{\overline{P}} + \epsilon_{\rm PET} \frac{\Delta PET}{\overline{PET}} \right) \overline{Q} \tag{11}$$

The influence of human activities on the runoff flow rate is shown in Equation (12):

$$\Delta Q_{\rm H} = \frac{\partial Q}{\partial n} dn = \left(\epsilon_n \frac{\Delta n}{\overline{n}} \right) \overline{Q} \tag{12}$$

where \overline{Q} , \overline{P} , \overline{PET} and \overline{n} are the average runoff flow rate, precipitation, potential evapotranspiration, and the average of the Budyko parameters during the entire study period; ΔP , ΔPET , and Δn are the differences in the average precipitation, potential evapotranspiration, and the Budyko parameters between the first and the second halves.

2.3. Changes in Catchment Characteristics

In this study, the Normalized Difference Vegetation Index (NDVI) is used to verify the changes in the parameters of the Budyko formula. Since the Budyko parameters can represent the characteristics of the catchment area, including vegetation cover state, soil properties, and topography, the increase in the parameters corresponds to a lusher vegetation cover [34,37]. In addition, NDVI reflects the vegetation cover state using the characteristics of green objects in reflecting the light of different wavelengths to different degrees, which is defined as:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$
(13)

where NIR represents the reflectivity of near-infrared light, RED represents the reflectivity of the red light in visible light, taking a value between –1 and 1, such that the closer it is to 1, the higher the reflectivity of the red light and the denser the green vegetation cover. This study averages several Landsat satellite images (from 1986–2016) with low cloud cover, which are obtained from USGS EarthExplorer (https://earthexplorer.usgs.gov/ accessed on 27 June 2021). There are 10 years of images out of the first half and 8 years of images out of the second half used in the vegetation coverage analysis.

3. Study Area

The alluvial fan of the Choshui River is the largest alluvial fan in Taiwan, covering an area of approximately 2100 square kilometers that reaches the Dadu River in the north, the Beigang River in the south, the Taiwan Strait in the west, and the Bagua-Douliu Hills in the east. The administrative districts across the alluvial fan include Changhua County and Yunlin County. This study uses precipitation and evapotranspiration data collected from 1980 to 2018. The precipitation data are from nine rainfall stations near the Choshui River alluvial fan (shown in Figure 2), obtained from the annual hydrological reports published by the Water Resources Agency of Ministry of Economic Affairs [38]. There is no representative station for evapotranspiration data in the study area; hence, the GLEAM database (https://www.gleam.eu/ accessed on 27 June 2021) [39,40] jointly established by the European Space Agency and other institutions is used. The data have a resolution of $0.25^\circ \times 0.25^\circ$ in the latitude and longitude (corresponding to a grid resolution of approximately 25 km \times 25 km). During the 38-year study period, the averages of annual precipitation, annual actual evapotranspiration, and annual potential evapotranspiration in the long term are 1372 mm, 930 mm, and 987 mm, respectively.



Figure 2. Study area and spatial distribution of rainfall stations.

4. Results and Discussion

This study first analyzes the aridity index for the Choshui River alluvial fan from 1980 to 2018, and the results show that during most of the time, the climate was humid ($\varphi < 1$). Analyzing the trend reveals that the value of Z_{MK} is 1.45, determined by the Mann–Kendall test, indicating that the flow rate of the runoff has increased. However, this result is not significant at the 90% confidence level. Nevertheless, Sen's slope estimator gives a value of 0.49, and a positive slope indicates that the runoff is increasing over time. According to the above verification results, it is found that the runoff of the Choshui River alluvial fan has not increased significantly. The changes in precipitation and runoff flow rate over

time are shown in Figure 3. In this study, the Pettit test and the sequential Mann–Kendall test determine the change point of runoff flow rate. The Pettit test shows that 2003 is probably the change point, with a probability of approximately 0.89 (Figure 4). Moreover, the sequential MK test indicates that the change point may have occurred in 2003 or 2006 (Figure 4). Therefore, this study has taken 2003 as the change point of the runoff flow rate of the alluvial fan of Choshui River based on the above verification results. The variation of the average annual precipitation and runoff from the first half (1980–2002) to second half (2004–2018) has increased by 226 mm and 14.8 cms, respectively. Compared to the first half, a runoff increase of 60% is greater than a precipitation increase of 17%.



Figure 3. Historical trends of runoff and precipitation record from 1980 to 2018.



Figure 4. Result of change point test for runoff: (a) Pettit test, (b) sequential Mann-Kendall test.

After the Budyko parameters are obtained using the method of Section 2.2, we can use the Budyko equations combined with the simple water balance equation to estimate runoff. We bring the corresponding average E/P, PET/P, and the Budyko parameter in the first and second period into Budyko equations to estimate runoff in the first and second period. In this study, the runoff estimated using different forms of the Budyko formula is

compared with the observed runoff, as shown in Table 1. The results of different Budyko formulas are analyzed quantitatively with statistical indicators such as the Nash–Sutcliffe efficiency (NSE), root mean square error (RMSE), mean absolute error (MAE), and percent bias (PBIAS), which are common in hydrological models, as shown in Table 2. The analysis shows that the model proposed by Zhang [34] has led to statistical indicators (RMSE = 84.44 and MAE = 64.05), which are worse than those of the other three models, and the simulated runoff is far from the observation, indicating that the performance of this model is the worst. In contrast, the three models proposed by Fu, Choudhury, and Wang and Tang [32,33,35] all show relatively good fitting results, as shown in Figure 5. The Budyko model proposed by Wang and Tang [35], which has a relatively small standard deviation, is selected as the basis for the subsequent analysis in this study.

Table 2. Statistical performance analysis indices of single-parameter Budyko-type equations.

Budyko Model	R ²	NSE	MAE	RMSE	PBIAS (%)
Fu [32]	0.976	0.966	41.94	58.18	-5.57
Choudhury [33]	0.976	0.966	41.90	58.21	-5.55
Zhang et al. [34]	0.970	0.928	64.05	84.44	-2.42
Wang and Tang [35]	0.974	0.966	42.84	58.44	-5.91



Figure 5. Comparison of performance of runoff simulated by single-parameter Budyko equations with Taylor diagram.

Combining the model proposed by Wang and Tang and Equation (1) for water equilibrium, the runoff can be expressed in terms of precipitation, potential evapotranspiration, and Budyko parameter, as in Equation (14):

$$Q = P - \frac{P + PET - \sqrt{(P + PET)^2 - 4n(2 - n) \cdot PET \cdot P}}{2n(2 - n)}$$
(14)

where Q, P, PET, and n are the runoff, precipitation, potential evapotranspiration, and the parameter in the Budyko formula, respectively.

According to the definition of the coefficient of elasticity in Equation (9), the derivatives of Equation (14) concerning three different factors are taken, respectively. The coefficients of elasticity of runoff with respect to precipitation (ϵ_P), potential evapotranspiration (ϵ_{PET}), and the Budyko parameter (ϵ_n) are shown below:

$$_{P} = \frac{-2n^{2} + 4n - 1 + \frac{2(P + PET) - 4n(2-n) \cdot PET}{2\sqrt{(P + PET)^{2} - 4n(2-n) \cdot PET \cdot P}}}{-2n^{2} + 4n} \cdot \frac{P}{Q}$$
(15)

$$\varepsilon_{\text{PET}} = \frac{\frac{2(P+PET)-4n(2-n)\cdot P}{2\sqrt{(P+PET)^2-4n(2-n)\cdot PET\cdot P}} - 1}{-2n^2 + 4n} \cdot \frac{PET}{Q}$$
(16)

$$\epsilon_{n} = \frac{ \left[\begin{array}{c} 4(1-n)[2n^{2}P - \sqrt{4n(n-2) \cdot PET \cdot P + (P+PET)^{2}} - 4nP + P + PET] + \\ 2(2-n)n \cdot P \cdot \left(\frac{4(n-1) \cdot PET}{\sqrt{4n(n-2) \cdot PET \cdot P + (P+PET)^{2}}} - 4n + 4 \right) \end{array} \right]}{4(n-2)^{2}n^{2}} \cdot \frac{n}{Q}$$
(17)

ε

Substituting the average precipitation, average potential evapotranspiration, and the Budyko parameter in each period into Equations (15)–(17), the coefficients of elasticity for the three factors to runoff in different periods (as shown in Table 3) can be obtained. The results of sensitivity analysis show that the absolute value of each coefficient of elasticity has decreased in the second half when compared to the first half, indicating that runoff has become less sensitive to its various influencing factors. In addition, both ε_{PET} and ε_n are negative, indicating that the increase in the Budyko parameter will reduce the runoff. In general, for every 1% increase in precipitation, runoff will increase by 2.72%. In contrast, for every 1% increase in potential evapotranspiration and the Budyko parameter, the decrease in runoff is 1.72% and 0.94%, respectively. Therefore, the coefficient of elasticity of runoff is the largest for precipitation, indicating that the runoff is most sensitive to precipitation, which is hence determined as the main influencing factor.

Table 3. Comparison of elasticity coefficients for pre- and post-period and variation in the Choshui

 River alluvial fan.

Period	ε _P	ε _{PET}	ε _n
The Whole Period	2.72	-1.72	-0.94
First Half (1980–2002)	3.05	-2.04	-1.30
Second Half (2004–2018)	2.39	-1.39	-0.62

After understanding the changes in runoff and the sensitivity to factors affecting runoff, this study will use the decomposition method and climate elasticity to explore the respective contributions of human activities and climate factors to runoff. Figure 6 shows the Budyko curves for the first and second halves of the study period after fitting with the model proposed by Wang and Tang [35] Based on the results from curve decomposition, the contribution of climate factors to the change in runoff is 14.27 cms, accounting for 96.4% of the total change in runoff (which is 14.8 cms). In addition, analysis with climate elasticity shows that climate factors have caused a change of 13.94 cms in the runoff, accounting for 94.2% of the total change in the runoff. Therefore, both the curve decomposition and the climate elasticity indicate that climate factors are the main influencing factors of runoff (as shown in Table 4).



Figure 6. Budyko-type curve of pre-period and post-period fitted by the Wang and Tang equation in the Choshui River alluvial fan.

Table 4. Result of the contribution of runoff variation for climate factors and human activities by decomposition of Budyko curve method and climate elasticity method.

Method		ΔQ	$\Delta Q_{\rm H}$	ΔQ_C	
Decomposition of the Budyko Curve	Runoff Change (cms) Contribution (%)	14.8 100	0.53 3.6	14.27 96.4	
Climate Elasticity	Runoff Change (cms) Contribution (%)	14.8 100	0.86 5.8	13.94 94.2	

The factors affecting runoff are precipitation, potential evapotranspiration, and the Budyko parameter. Precipitation and potential evapotranspiration are classified as climatic factors, while the Budyko parameter is classified as human activity. The analysis of the coefficient of elasticity has revealed that precipitation is not only a primary influencing factor affecting runoff, but its increase will also cause the runoff to increase. Therefore, this study uses the MK test to explore the changes in precipitation over the years. The test results show that the precipitation from 1980 to 2018 is likely to have increased ($Z_{MK} = 1.19$), which is consistent with the conclusion that climate factors (especially precipitation) are the leading cause of the increase in runoff. In addition to precipitation, the vegetation cover state also affects the runoff; this is because plants cause evapotranspiration. Hence, the reduction of green vegetation cover will reduce the evapotranspiration, which leads to an increase in runoff [41–43]. According to the changes in the Budyko curves in both the first and the second halves, as shown in Figure 6, the Budyko parameter is reduced. It is thus speculated that the vegetation cover of the alluvial fan of Choshui River has indeed decreased. Therefore, this study uses NDVI, which can reflect the true state of vegetation cover, to verify the above speculation. Figure 7a,b are the spatial distribution of NDVI in the first and second halves of the study period, respectively, where Figure 7c indicates the change in NDVI between the first and the second halves, with green indicating an increase and red indicating a decrease in vegetation cover. It can be seen that most areas of the alluvial fan of Choshui River are red, indicating that green vegetation cover has decreased,



which is consistent with the results speculated from the Budyko parameter. Therefore, the Budyko parameter can describe the environmental changes in the catchment area.

Figure 7. Result of spatial distribution of NDVI (a) pre-period; (b) post-period; (c) variation.

The Budyko parameter reflects the characteristics of a water catchment area, such as soil properties, topography, and vegetation cover. In this study, the change in the Budyko parameter is attributed to human activities, such as the impact of economic development on vegetation cover. However, in reality, changes in the characteristics of a water catchment area may also be caused by climate factors, such as changes in vegetation cover and topography caused by heavy rainfall. It is worth mentioning that the interaction between climate change and the influence of human activities on runoff change is not easy to disentangle. As a result, this study may underestimate the indirect effects of human activities against the background that the global climate is increasingly affected by human activities, leading to the deviation of the final result. Therefore, use of the Budyko parameter to explore the interaction between human activities and climate factors is worthy of follow-up research.

Since the runoff in this study is obtained through the equation of water equilibrium in the long term, it can be found that the levels of runoff in 1980, 2003, and 2011 are all less than zero, as shown in Figure 3. In addition, the fitted Budyko curve shows that there are data points that exceed the limits of water equilibrium and energy equilibrium, as shown in Figure 6. This study explores the reasons for the above doubtful results and believes that the abnormality is related to the simple water equilibrium equation used in this study, as well as the conditions for the Budyko framework. In the long-term steady state, the change in water storage is neglected in the water equilibrium equation (as shown in Equation (1)). However, the limit of the water equilibrium is increased when underground water replenishment is considered, such that the limit exceeds the original horizontal line defined by E/P = 1, causing the phenomenon of exceeding the original limit of water equilibrium to seem reasonable [44]. The causes leading to some of the unreasonable results are related to the negligence of changes in water storage, which is affected by changes in soil water content, groundwater, and surface water [27]. To sum up, the disadvantages of ignoring the change in water storage are mainly derived from the runoff with bias, and further cause the results that exceed the water and energy limit. In order to lessen the bias of estimated runoff, the temporal scale of this study is an annual scale because the intra-annual water storage may fluctuate over the wet and dry seasons and complement the whole year [27,28]. The advantages of ignoring the change in water storage include the fact that the steady state Budyko framework is simple, rather than the more complex Budyko equation for non-steady state condition. The water storage data (e.g., soil water content) is necessary for complete water balance and the Budyko framework for non-steady condition. At present, the scarcity of parameters causing changes in the water storage changes over time, which is another reason why we adopted a simple water balance concept. In addition, the simple water equilibrium equations and steady state Budyko framework can assess the impact of runoff on future climate changes [45]. After estimating possible future precipitation and evapotranspiration data based on the severity of climate change with different models, a simple water equilibrium model can be used to explore the reasons for future changes in runoff. Moreover, if the accuracy of the assessment needs to be improved by considering the changes in water storage, it is necessary to use the Budyko framework at a non-steady state, which is a major focus of future research.

5. Conclusions

In this study, hydrological data on parameters such as precipitation, evapotranspiration, and potential evapotranspiration from the Choshui River alluvial fan between 1980 and 2018 are collected, and the contribution of climate factors and human activities to changes in runoff are quantified. The runoff calculated based on water equilibrium has experienced a change point in 2003 as indicated by two statistical test methods, while the second half (2004–2018) shows an average runoff 60% higher than that of the first half (1980–2002). The curve decomposition method and climate elasticity used in this study are both based on the Budyko framework proposed by Wang and Tang [35]. The changes in catchment area characteristics reflected by the Budyko parameter are consistent with those deduced from NDVI, showing that vegetation cover has decreased, comparing the second half to the first half. In the analysis, to quantify the contribution of climate factors and human activities to the changes in runoff, the results consistently show that the main reason for the changes in runoff is climate factors, accounting for over 90%. The impact of human activities on the runoff is less than ten, but in consideration of climate change is the affected human activities; the indirect effects of human activities may not have been estimated. The above-quantified results indicate that climate factors play an important role in the changes in the runoff of the Choshui River alluvial fan.

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