sustainability

MDPI

Article

Hydrological Response to Natural and Anthropogenic Factors in Southern Taiwan

Hsin-Fu Yeh * and Jyun Tsao

Department of Resources Engineering, National Cheng Kung University, Tainan 701, Taiwan; tsaojyun@gmail.com

* Correspondence: hfyeh22@gmail.com; Tel.: +886-6-275-7575

Received: 12 December 2019; Accepted: 1 March 2020; Published: 5 March 2020



Abstract: Global climate change and rapid industrial development have led to changes in streamflow worldwide, and determining the relative contributions from climate variability and human activity is important for water management. However, studies using attribution analysis to investigate the streamflow in Taiwan are scarce. In this study, statistical methods are used to evaluate the changes in streamflow in order to assess the variation in the hydrological environment of Taiwan. Four river basins in Southern Taiwan were selected as the study area. The impact of climate variability and human activities on the changes in the streamflow from 1980 to 2017 was quantified via the hydrological sensitivity-based method and the decomposition method, which is based on the Budyko hypothesis. The results from these two methods were consistent and demonstrated that the increase in the streamflow of the four river basins was mainly attributable to climate variability. Streamflow change was more responsive to precipitation because of the relatively larger value of the sensitivity coefficients. This study provides a basic insight into the hydrological dynamics of river basins in Southern Taiwan and may serve as a reference for related research in the future.

Keywords: climate change; human activities; Budyko; southern Taiwan

1. Introduction

Climate change and human activities are the main factors that are currently influencing the global hydrological cycle, the frequency and severity of extreme natural events, and the planning of water resources [1]. The National Oceanic and Atmospheric Administration [2] found that the impact from these two factors has been exceptional over the past three decades. Climate change affects the spatial and temporal patterns of precipitation and evaporation and human activity modifies the landscape, altering the hydrological processes [3,4]. These impacts are closely related to the availability of water worldwide.

Of the different variables that affect the hydrological cycle at a watershed, streamflow is the most important for understanding river regimes [5], as it reflects both variation in the climate and patterns of water consumption. Li et al. [6] evaluated the variation that occurs in streamflow as a result of various scenarios in the different regions within a basin. The results indicated that the notable decline in upstream discharge and wet to dry periods was mainly attributable to human intervention. Shao et al. [7] developed seven scenarios according to different land use and climatic conditions in order to analyze the annual streamflow in a basin where both the climate and the land use had changed significantly. The study indicated that climate variability had more of an impact on streamflow than changes in land use. Xin et al. [8] quantified the intra-annual changes that occurred in the streamflow of a basin that was suffering from significant anthropogenic influence on a seasonal scale. The results demonstrated that the decline in streamflow that is directly attributable to human activity is more pronounced during the irrigation season. Meng et al. [9] conducted attribution analysis

on the streamflow variation in a typical landform transitional watershed and found that land surface factor accounted for approximately 80% of the change in streamflow. Marhaento et al. [10] used attribution analysis in a tropical catchment to test whether land use change is the main driver for streamflow fluctuations. The results showed that an increasing settlement area and a decreasing forested area are the main changes observed in land use and that these factors have a significant impact on streamflow. These studies used data concerning the changes in streamflow to highlight problems occurring within different hydrological systems and thus provide guidance for water resource management. However, different objectives were under investigation in these studies and various spatial and temporal scales were used, which led to different results. These discrepancies, together with the inconsistent results in studies conducted in different areas, mean that it is increasingly important to determine the contributions of climate change and human activities to changes in streamflow.

Many recent studies have used different methods with the objective of addressing the above-mentioned issues [11–16]. A common approach used for examining streamflow is splitting the period studied into a pre-period and a post-period [17]. Most of the literature produced has evaluated the difference between two periods to quantify the contributions from climate change and human activities to streamflow. The attribution methods that have been used in previous studies can be classified into the following four groups: (1) methods based on hydrological field data, (2) approaches using hydrological modeling, (3) conceptual approaches, and (4) analytical approaches [5]. These approaches are described in the following paragraph.

Field data methods such as the paired catchment method are the oldest experimental approaches used to analyze the effect of human activities on hydrological processes. However, finding similar catchments in order to facilitate an accurate comparison is difficult [18]. Hydrological modeling is calibrated and validated by using pre-period data in order to simulate the streamflow post-period. The impacts from climate change and human activities to streamflow are thus quantified by calculating the difference between actual and simulated data. Liu et al. [19] used the Variable Infiltration Capacity (VIC) model to assess the respective and combined impacts of climate and land-use changes on hydrology. Yang et al. [20] used the Soil and Water Assessment Tool (SWAT) model to identify the dominant driving factors behind changes in runoff in the Qingliu River basin on multiple (monthly, seasonal, and annual) scales. Although several hydrological models can be used to analyze changes in streamflow, the parameters chosen to represent complex hydrological processes can lead to a high level of uncertainty [21].

Based on an experiment conducted in the US Midwest, a conceptual model was developed by Tomer and Schilling [22] to distinguish the magnitude of the impact of climate change from that of human activities. This method was applied in other areas around the world [1], but lacked the capacity to quantify values accurately for many actual watersheds [23]. Another conceptual approach that is often used in this field is the Budyko hypothesis [24], which is founded on the basic notion that the ratio of actual evapotranspiration to precipitation (Evaporative Ratio) is a function of the ratio of potential evapotranspiration to precipitation (Aridity Index). Thus, the contribution of climate change and human activities on streamflow can be quantified by calculating changes on the Budyko curve [25]. This approach has been used in many studies. Bai et al. [26] used the climate elasticity method and hydrological model to distinguish the impacts of climate variability from those of human activities on a decrease in streamflow, finding that variability in the climate was the main causal factor for streamflow decline. They derived similar results from the two methods. Guo et al. [27] applied hydrologic sensitivity analysis with a hydrologic model simulation and found that the decline in annual runoff in the upper reaches of the Weihe River was mainly attributable to human activities.

The annual precipitation in Taiwan is 2.6 times greater than the global average, but because of the uneven spatial and temporal distribution of rainfall, the actual amount of water available for use is less than 20% of the total. Taiwan has therefore suffered water shortages for an extended period. According to simulations carried out for the IPCC AR4 concerning future rainfall under different scenarios, the streamflow in Taiwan is expected to decline in the near future, especially in the south [28]. Moreover,

Taiwan ranks 56th among the 60 countries in the Climate Change Performance Index (CCPI) 2019 due to a lack of determination in implementing its Intended Nationally Determined Contributions (INDCs) and its extremely poor performance in domestic climate policy [29]. Thus, the study of factors affecting streamflow is important for management and regulation of water resources in the future. Several studies have been conducted to investigate this topic. Lin et al. [30] developed an integrated approach, comprising land use and hydrological models with statistical tests to simulate the extrapolation of land use management practices and planning policies in northern Taiwan. However, very few studies have focused on the use of statistical methods for evaluating the attribution of variations in the streamflow. More studies that use attribution analysis are therefore required to gain a better understanding of the hydrological environment of Taiwan in order to complement the lack of such analysis in previous studies.

The objective of this study was therefore to quantify the hydrological response to natural and anthropogenic factors in Southern Taiwan and to gather more insight into the hydrological environment. Four river basins in southern Taiwan were selected for quantification of the effects of climate change and human activities on streamflow. The hydrological sensitivity-based method and decomposition method were used to compare the results of the quantifications. Finally, we tried to determine the relationship between the changes in streamflow and the actual conditions. The findings made in this study may serve as a reference for the regulation of water resources in the future.

2. Materials and Methods

2.1. Study Area

The study area is located in Southern Taiwan and is part of several administrative districts including Chiayi County, Chiayi City, Tainan City, Kaohsiung city, and Pingtung County. The area studied lies within a tropical monsoon climate zone with an annual mean precipitation of 2500 mm and an annual mean temperature of 24 °C. The weather is influenced by typhoons and southwestern monsoons in the rainy season (from May to October), whereas the location of the study area at the leeward side of the northeastern monsoon means that less rain falls in this region during the dry season (from November to April) [31]. The ratio of precipitation in the dry and wet season is approximately 1:9 in this area, which means that the weather is characterized by distinct wet and dry seasons. The four basins in southern Taiwan that were selected as the study area are illustrated in Figure 1.

The four basins, namely Bazhang, Zengwen, Yanshui, and Erren River Basins, were selected based on the available meteorological and hydrological datasets for the southern district. The area covered by each basin is 83.15, 121.31, 146.46, and 139.62 km^2, with an average elevation of 939.1, 98, 47.2, and 89.5 m, respectively. Each river basin lies above a particular hydrological station. The average annual streamflow in Bazhang, Zengwen, Yanshui, Erren River Basin is 2417.5, 1520.2, 1357.3, and 1723.4 mm, respectively. Several precipitation stations were also selected for use in this research. The geographic distribution and other related information concerning the precipitation stations are presented in Figure 1 and Table 1.

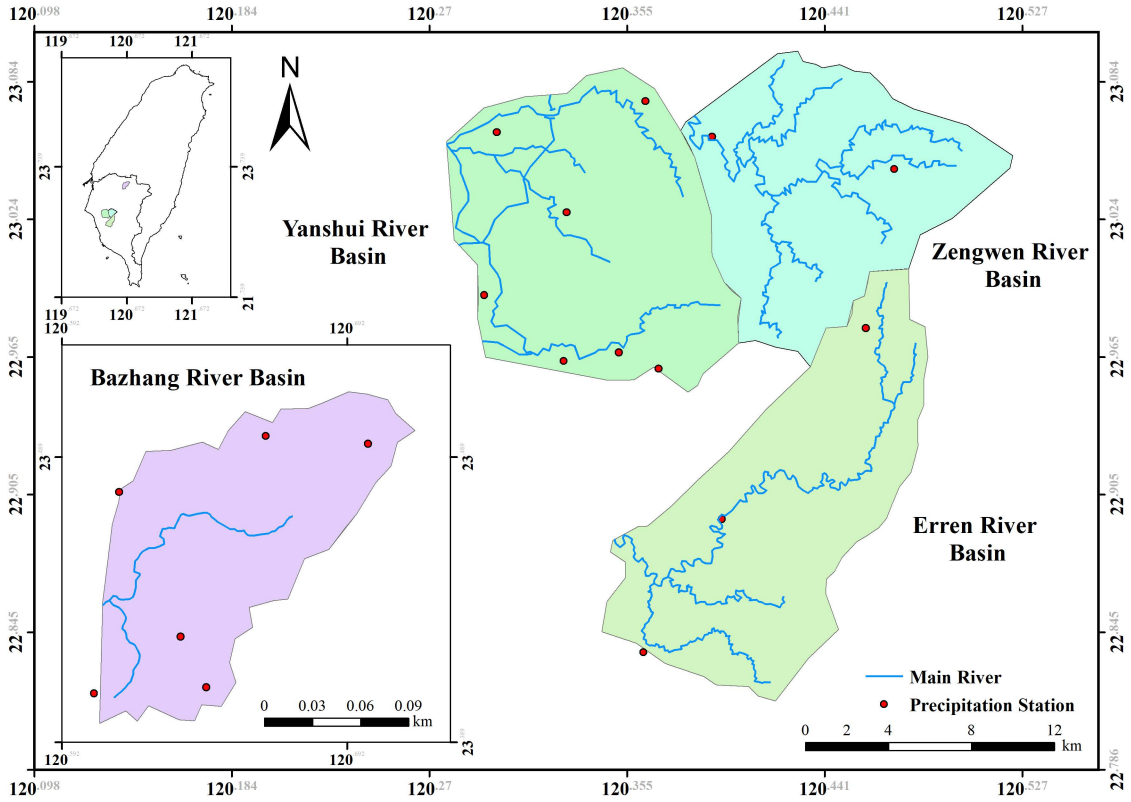


Figure 1. Location of the study area and gauging stations.

Table 1. Data concerning the gauging stations used in this study.

River Basins	Hydrological Station	Area (km^2)	Precipitation Station	Record Years
Bazhang	Chukou	83.15	Dahushan	1980–2017
			Xiaogongtian	1980–2017
			Longmei	1989–2017
			Toudong	2002–2017
			Shipanlong	2002–2017
			Fenchihu	1994–2017
Zengwen	Tsochen	121.31	Zuozhen	1989–2017
			Nanhua	1980–1992, 2000–2017
Yanshui	Hsinshih	146.46	Hutoupi	1981–2017
			Qiding (WRA)	1980–2017
			Xinshi	1993–2012
			Qiding (CWB)	2014–2017
			Mazumiao	2014–2017
			Shanshang	2014–2017
			Guanmiao	2014–2017
Erren	Chungte bridge	139.62	Gutingkeng	1980–2017
			Mucha	1980–2017
			Niuchoubu	2008–2015

WRA represents data from the Water Resources Agency; CWB represents data from the Central Weather Bureau.

2.2. Methods

2.2.1. Data Processing

The precipitation (P), evapotranspiration (E), and potential evapotranspiration (PET) were examined to identify the effects of climate change and human activities on streamflow (Q) in the basins from 1980 to 2017. The data concerning the precipitation at each station were obtained from the Central Weather Bureau (CWB) and the Water Resources Agency (WRA) in Taiwan. The evapotranspiration and potential evapotranspiration were acquired from the Global Land Evaporation Amsterdam Model (GLEAM). The underlying rationale for this method is to maximize the recovery of information contained in current satellite observations of climatic and environmental variables concerning evaporation. Through a set of algorithms, GLEAM provides datasets cataloging the evapotranspiration, bare-soil evaporation, interception loss, open-water evaporation, and sublimation on a 0.25° latitude-longitude regular grid with a daily temporal resolution [32,33]. The streamflow data considered in this study were computed via use of the water balance equation [34]. Generally, the water balance equation is expressed as follows:

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

where P, E, and Q are precipitation, evapotranspiration, and streamflow, respectively, and ΔS represents the change in water storage. ΔS can be assumed as zero in the long term (10 years or more) [35]. Before applying the data, all variables were aggregated from daily to yearly values. The annual precipitation was estimated using the Thiessen polygon method [36], which was based on the data from several of the stations in each river basin. To understand the trend of each hydrological variable, the Mann–Kendall test [37,38] was used in the preceding operation. The Pettit test [39] was used to detect abrupt points in the streamflow time series.

2.2.2. Budyko Framework

Evapotranspiration is an important variable in the evaluation of the hydrological dynamics of river basins. The annual evapotranspiration in the water balance equation (Equation (1)) is determined from the annual precipitation and the potential evapotranspiration. Budyko [24,40] assumed the evaporation ratio (the ratio of actual evapotranspiration to precipitation) to be function F of the Aridity Index (the ratio of potential evapotranspiration to precipitation). Thus, the relationship between the two variables can be expressed as follows:

$$\frac{E}{P} = F\left(\frac{PET}{P}\right) \tag{2}$$

where PET is potential evapotranspiration. If PET/P > 1, the evapotranspiration is limited by water supply (arid climate), whereas if PET/P < 1, the evapotranspiration is limited by energy supply (humid climate) [41]. Table 2 outlines the equations that were derived from this hypothesis for the purpose of this study. The value Ø in Table 2 is the ratio of potential evapotranspiration to precipitation (PET/P). The parameters used in these functions can therefore be utilized to represent the characteristics of the watershed (vegetation, soil, topography, and climate). Two boundary conditions are satisfied by each equation: when PET/P→0, E/P→0, and when PET/P→∞, E/P→1.

Table 2. The different equations used in this study based on the Budyko Hypothesis.

Model	Function	Parameter
Schreiber [42]	$1 - e^{-\varnothing}$	-
Ol'Dekop [43]	$\varnothing \tanh\left(\varnothing^{-1}\right)$	-
Budyko [44]	$\sqrt{\varnothing \tanh(\varnothing^{-1})(1 - e^{-\varnothing})}$	-
Turc [45]; Pike [46]	$1/\sqrt{1 + \varnothing^{-2}}$	-
Fu [47]	$1 + \varnothing - (1 + \varnothing^{m})^{1/m}$	m
Zhang et al. [48]	$(1 + \omega\varnothing)/\left(1 + \omega\varnothing + \varnothing^{-1}\right)$	ω
Milly [49]; Porporato et al. [50]	$\frac{\exp\left(\gamma\left(1-\varnothing^{-1}\right)\right)^{-1}}{\exp(\gamma(1-\varnothing^{-1}))-\varnothing^{-1}}$	γ
Wang and Tang [51]	$\frac{1+\varnothing-\sqrt{(1+\varnothing)^2-4\partial(2-\partial)\varnothing}}{2\partial(2-\partial)}$	∂

2.2.3. Distinguishing between the Impact of Climate Change and Human Activity on Streamflow

The Budyko model has been used in numerous studies focusing on long-term water balance and large river basins, but it is also effectively applicable for use with smaller basins [52]. The Budyko–Zhang equation [48] has been applied previously for the evaluation of the relative contribution of climate variability and human activities to streamflow change. Different curves were observed on the plot when the value of parameter ω was changed. According to previous research, the difference between the mean annual streamflow during the post-period (Q_{post}) and the mean annual streamflow during the pre-period (Q_{pre}) can be used to represent the total change in the stream discharge (ΔQ), and ΔQ is a combination of climate change (ΔQ_C) and human activity (ΔQ_H) [53]. ΔQ can be expressed as

$$\Delta Q = Q_{post} - Q_{pre} = \Delta Q_C + \Delta Q_H \quad (3)$$

The method used to quantify the impact from these two factors on streamflow is described in the following section.

2.2.4. Decomposition of the Budyko Type Curve

Wang and Hejazi [25] proposed a method that can be used to determine the proportions of streamflow changes that are caused by climate variability and human activity. The original Budyko hypothesis states that natural watersheds follow the Budyko curve. The decomposition method therefore assumes that if a watershed exhibits changes without direct human impact, the data point that is due to climate change will still move on a single curve (PET/P). A change in the horizontal direction on the Budyko curve is influenced solely by climate change, while a change in the vertical direction is caused by both human activity and climate change (see Figure 2, the change from A to B can be divided into A to C and C to B). Thus, the anthropogenic contribution can be expressed with

$$\Delta Q_H = P_{post}\left(\frac{E'_{post}}{P_{post}} - \frac{E_{post}}{P_{post}}\right) \quad (4)$$

where P_{post} is the precipitation during the post-period, E_{post}/P_{post} is the evaporative ratio during the post-period, and E'_{post}/P_{post} is the evaporative ratio calculated using the same aridity index in the pre-period. The contribution from climate change (ΔQ_C) can then be calculated using Equation (3).

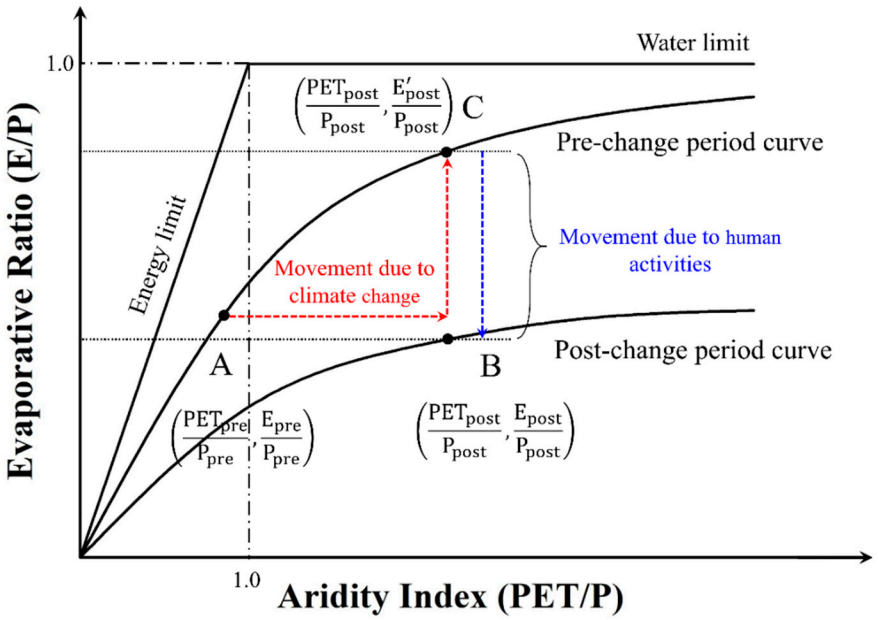


Figure 2. Decomposition of the Budyko curve to quantify the effects of climate change and human activities on streamflow (modified from reference [5]).

2.2.5. The Hydrological Sensitivity Method

The hydrological sensitivity method was used to compare the results of the quantitative analysis. The hydrological sensitivity method assumed that the change in mean annual streamflow was the summation of the change in mean annual precipitation and the potential evapotranspiration, as seen in the following expression [54,55]:

$$\Delta Q_C = \alpha \Delta P + \beta \Delta PET \quad (5)$$

where ΔQ_C, ΔP, and ΔPET describe the changes in streamflow, precipitation, and potential evapotranspiration, respectively; and α and β are the sensitivity coefficients of streamflow to precipitation and PET, which are expressed using [56]

$$\alpha = \left(1 + 2\varnothing + 3\omega\varnothing^2\right) / \left(1 + \varnothing + \omega\varnothing^2\right)^2 \quad (6)$$

$$\beta = \left(1 + 2\omega\varnothing\right) / \left(1 + \varnothing + \omega\varnothing^2\right)^2 \quad (7)$$

where ω is the parameter mentioned in Table 2 and $\varnothing$ is the ratio of potential evapotranspiration to precipitation (PET/P). The anthropogenic contribution (ΔQ_H) is thus evaluated using Equation (3).

3. Results

3.1. Time Series Analysis

3.1.1. Temporal Trends in Precipitation and Evapotranspiration

Before quantifying the variation in streamflow, the trend of each related hydrological variable needs to be understood. According to time series analysis, no significant trend was observed in the precipitation and evapotranspiration during the study period. Figure 3 shows the changes in these two variables in each river basin from 1980 to 2017. The aridity index (PET/P, the ratio of potential evapotranspiration to precipitation) was greater than 1 in each year, which indicates that the evapotranspiration in these four river basins was limited by energy supply during this period.

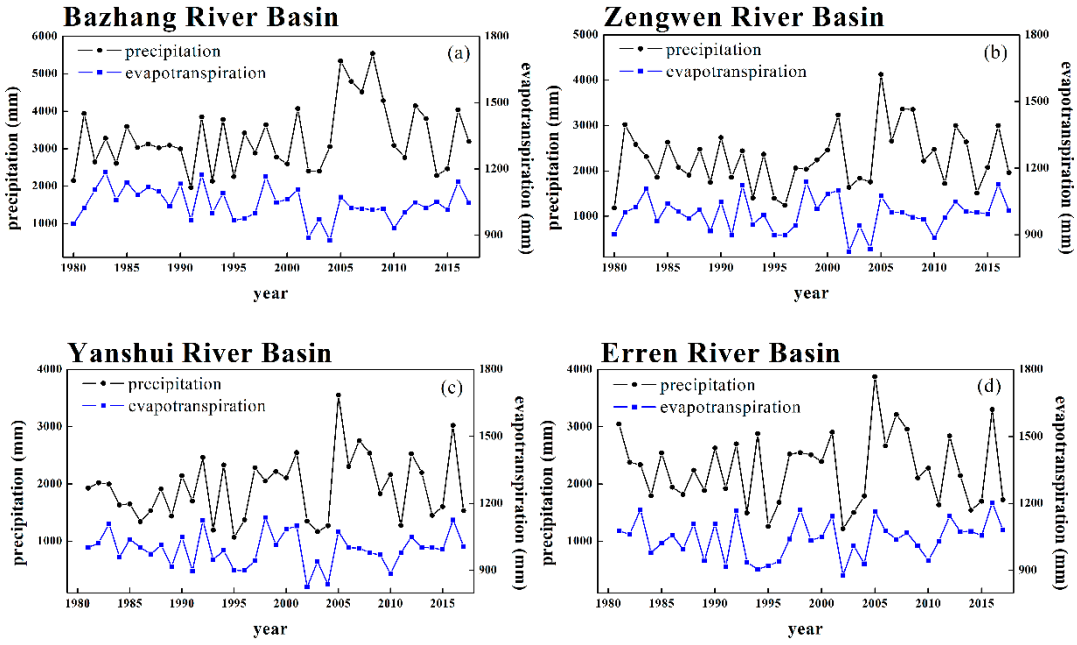


Figure 3. Time series of annual precipitation and evapotranspiration in each river basin.

3.1.2. Temporal Trend of Streamflow

Streamflow, which is the main hydrological variable analyzed in this study, can be calculated using the water balance equation (Equation (1)). Figure 4 shows the time series of the streamflow in the four basins from 1980 to 2017. The statistic Z from the Mann–Kendall test in the Bazhang, Zengwen, Yanshui, and Erren River Basins was 1.48, 0.88, 1.06, and −0.12, respectively. No significant trend was observed at a significance level of 0.05 in any of the river basins. The rate of change in the streamflow of the Bazhang, Zengwen, Yanshui, and Erren River Basins was 35.7%, 23.9%, 39.2%, and −6.8%, respectively. An abrupt point was detected in 2004 using the change-points detection method. Thus, the study period can be divided into two periods—1980 to 2003 (pre-period) and 2004 to 2017 (post-period).

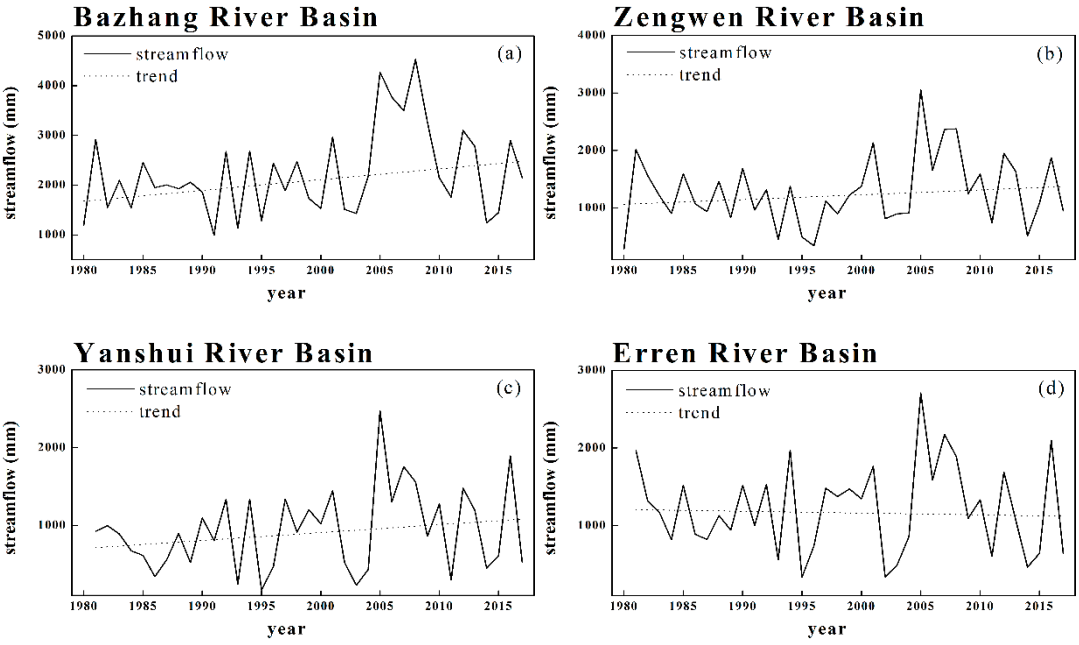


Figure 4. Time series of annual streamflow in each river basin.

3.2. The Budyko Curve

According to the basic assumption made in this study, the difference in streamflow between the post-period (Q_{post}) and the pre-period (Q_{pre}) represents the total change in stream discharge (ΔQ). ΔQ is the combination of climate change (ΔQ_C) and human activity (ΔQ_H). After determining the change point for each streamflow series, the differences between the pre-period and the post-period were evaluated. Table 3 summarizes the change in streamflow between the pre-period (1980–2003) and the post-period (2004–2017). A change of approximately 40% was observed in the streamflow of the river basins studied, except for the Erren River Basin. The Budyko–Zhang equation was selected to fit the hydrological variables, and the different values for the parameter ω in each equation represent different curves on the plot. As shown in Figure 5, the curves for the three river basins (Bazhang, Zengwen, and Yanshui) sloped upwards from the pre-period to the post-period, but the opposite was seen in the direction of the curve for the Erren River Basin. A decrease was observed in parameter ω for the Bazhang, Zengwen, and Yanshui river basins between the pre-period and the post-period. The change in ω for the Bazhang, Zengwen, Yanshui, and Erren river basins from the pre-period to the post-period was 0.87 to 0.58, 0.83 to 0.68, 1.12 to 0.9, and 0.89 to 1.02, respectively. Ning et al. [57] found that an increase in this parameter may result in increase in the vegetation, which leads to the increase in evapotranspiration and a reduction in the annual runoff from a watershed. Thus, changes in the parameter ω in each basin are critical for the quantified analysis that is conducted in the following section.

Table 3. Summary of the changes in streamflow during the study period.

River Basins	Mean Streamflow in Pre-Period (mm)	Mean Streamflow in Post-Period (mm)	Change (%)
Bazhang	1928.84	2787.62	45
Zengwen	1122.92	1566.9	40
Yanshui	807.11	1150.85	43
Erren	1151.97	1347.57	17

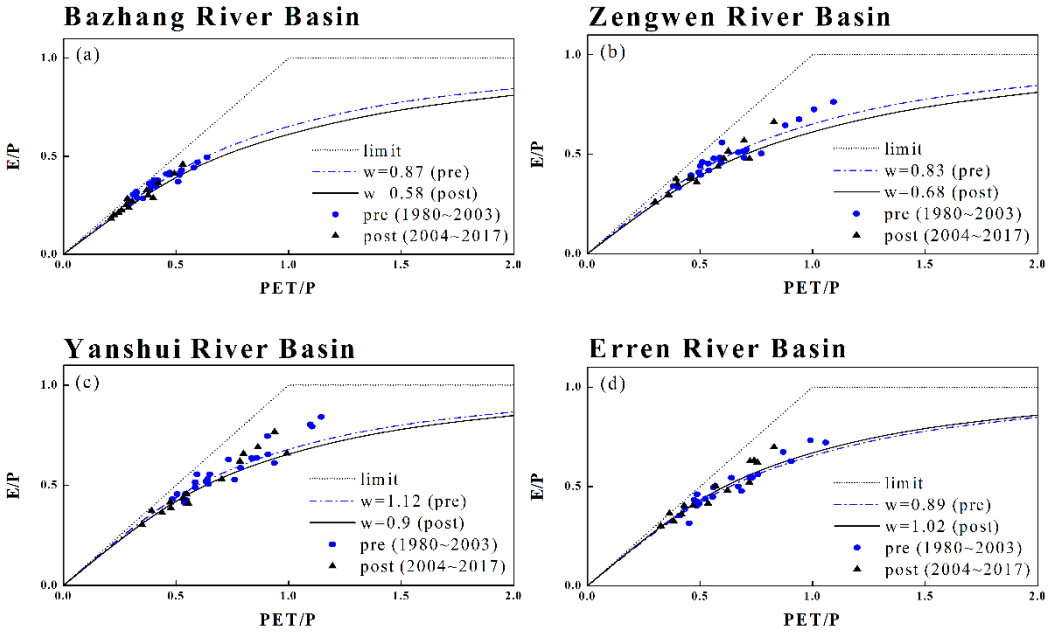
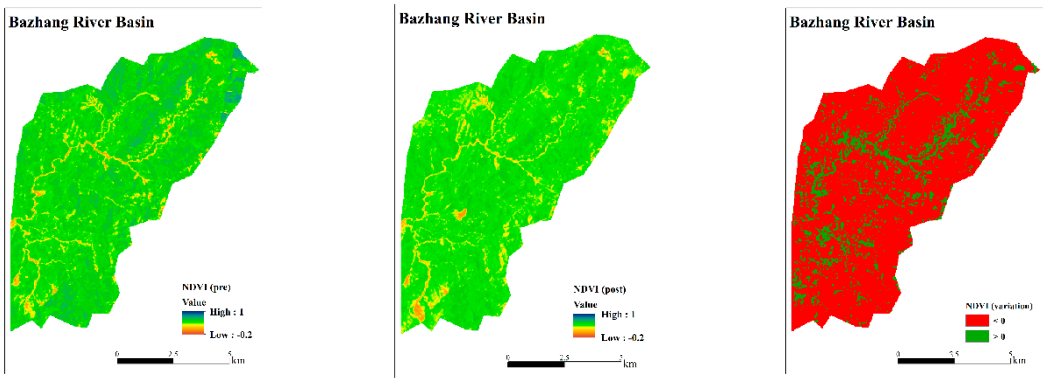


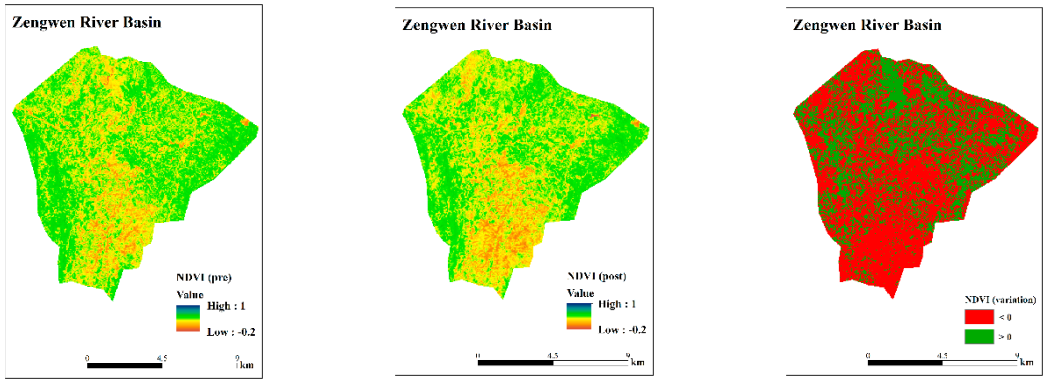
Figure 5. Changes in the Budyko curve for the pre and post period in each river basin.

Zhao et al. [41] used methods similar to those used in this study to quantify the relative contributions from climate variability and human activity to explain streamflow changes in four sub-catchments of the Wei River Basin (WRB) in China. Similar changes were seen in parameter

ω to those observed in this study, and it was found that both climate change and human activity reduced streamflow in the WRB. Identifying the change in the parameter ω for each river basin is very important to achieve the objectives of this study. Zhang et al. [48] proposed that the higher the value of parameter ω, the more abundant the vegetation cover. Therefore, changes in the actual vegetation should reflect the changes observed in the parameter ω in the Budyko–Zhang equation. To confirm the differences in ω for the Erren River Basin, the normalized difference vegetation index (NDVI) was used to represent the actual situation for further evaluation. The NDVI ranges between −1 and 1, with higher values indicating denser vegetation cover. Figure 6 presents the NDVI for the four river basins. The changes in the NDVI of the Bazhang, Zengwen, Yanshui, and Erren River Basins were −18%, −32%, −34%, and 22%, respectively. The variation in the NDVI verified the results of this study. In the Erren River Basin, the NDVI increased as parameter ω increased, but the opposite was seen in the other basins. This result proves that the parameter ω in the Budyko–Zhang equation can reflect the variation in actual vegetation cover and indicates that this method can be used to understand the vegetation conditions in the different areas in Taiwan without having to obtain data directly.



NDVI value: 0.62 NDVI value: 0.51 Variation: −18%



NDVI value: 0.48 NDVI value: 0.33 Variation: −32%

Figure 6. *Cont.*

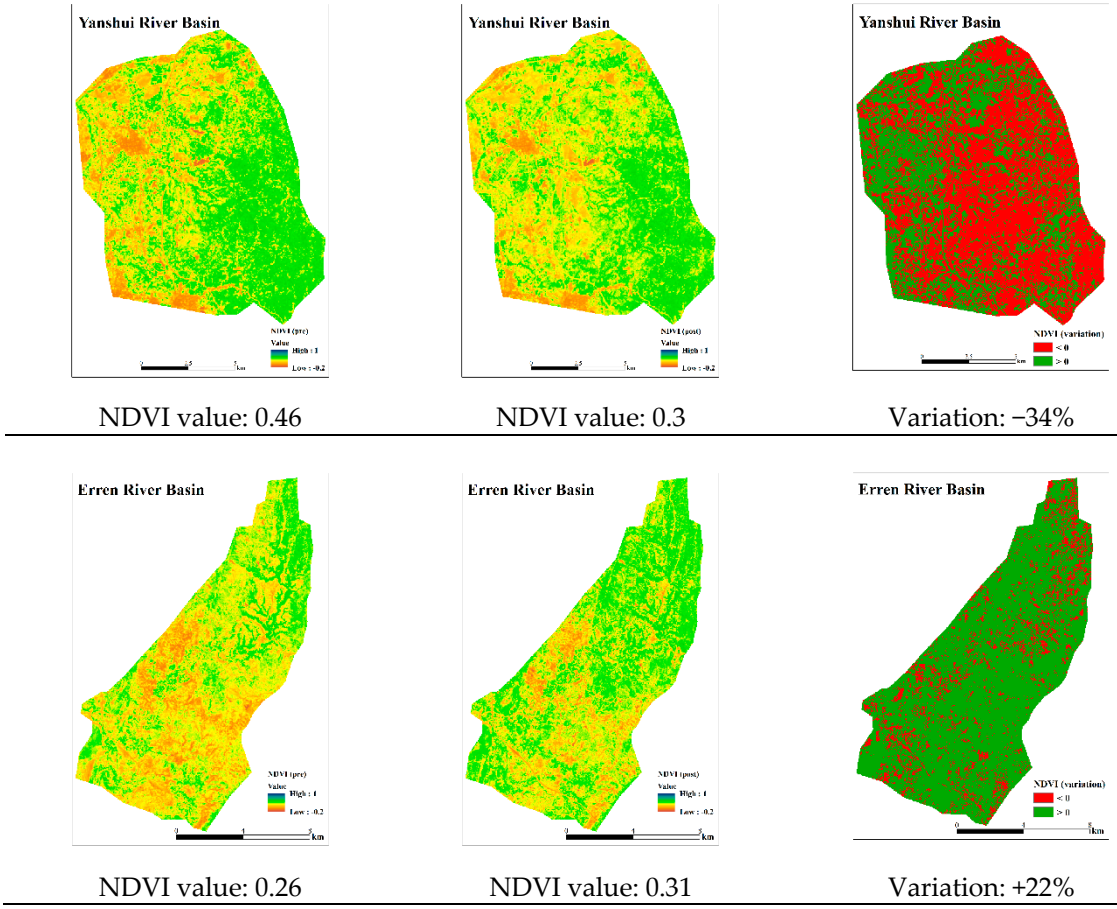


Figure 6. The variation in the normalized difference vegetation index (NDVI) for the four river basins.

3.3. The Effects of Climate Variability and Human Activity on Streamflow

The basic concept of the decomposition method is to evaluate the movement of the Budyko curves (Equation (4)) presented in Figure 5. The hydrological sensitivity method is also a method that can be used for quantification. By calculating the parameter α and β (Equations (6) and (7)), the contribution of climate change (ΔQ_C) to streamflow can be quantified. Table 4 shows all the parameters used in this method. The absolute value of the streamflow sensitivity coefficients of precipitation is greater than that of potential evapotranspiration (PET), revealing that the change in streamflow was more responsive to changes in precipitation than to changes in PET in these regions.

Table 4. Parameters used in the hydrological sensitivity method.

River Basins	ω	Ø (PET/P)	α	β
Bazhang	0.72	0.40	0.93	−0.68
Zengwen	0.75	0.59	0.86	−0.55
Yanshui	1.01	0.69	0.81	−0.50
Erren	0.96	0.59	0.86	−0.58

Finally, the quantitative results are given in Figure 7. The two methods of quantification exhibited similar results for the four river basins. Climate change accounts for more than 80% of the streamflow change observed in all river basins. Unlike that of the other river basins, human activity was found to cause a decrease in the streamflow of the Erren River Basin. This was probably a result of the opposite

directional change of parameter ω. Consequently, climate change was found to be the most influential factor affecting streamflow change in the river basins investigated in this study.

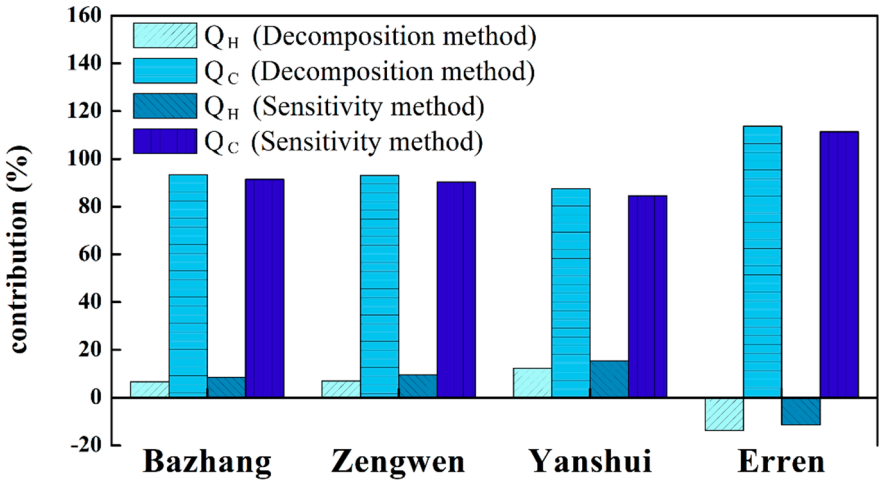


Figure 7. Comparison of the contributions from climate change (ΔQ_C) and human activity (ΔQ_H) to streamflow change using two quantitative methods.

4. Summary and Discussion

4.1. Rationale for Using the Water Balance Equation to Calculate Streamflow Data

In this study, the streamflow data is calculated using the water balance equation (Equation (1)). However, this method is seldom used in related published research. According to the Budyko equation discussed in Section 2.2.2, all the hydrological variables that were investigated in the study should satisfy the water balance equation over a sufficiently long time. Thus, using a method that is similar to this study could help ensure that the variables in the study are consistent with the water balance. Teuling et al. [34] used water balance to calculate the long-term average streamflow and simulated the distribution of green and blue water fluxes at high-resolution (1 km^2) in Europe. By combining the Budyko model, land use data, and meteorological variables, the study determined the spatial and temporal differences in each hydrological variable and the main factors affecting streamflow change. Furthermore, the results of the hydrological sensitivity method indicated that the streamflow was more responsive to changes in precipitation than to changes in potential evapotranspiration, which is consistent with the results of previous studies [58,59]. The water balance equation is therefore an appropriate method for acquiring streamflow data. Future research should examine different temporal scales and factors that affect the temporal variability in streamflow.

4.2. Confirmation of the Change of Parameter ω

The change in parameter ω for each basin shows that the hydrological environment in the four basins was influenced by a combination of climate change and human activity. In this study, NDVI was adopted to confirm the results of the Budyko framework. He et al. [60] used the Budyko–Choudhury–Yang equation to evaluate the characteristics of runoff and attribution identification as a basis for formulating climate change strategies and the rational utilization of water resources, and found that the impact of underlying surface parameters increased after abrupt changes in the runoff. If the topography and soil conditions in the underlying surface of the watershed are relatively stable, change in the vegetation is one of the main factors that influences changes at the surface. The NDVI can therefore be used as an "indicator" for vegetation growth. The same pattern of change was observed in the parameters studied and the NDVI from the pre- to post-period, which means that the parameters increase as NDVI increases. This result agrees with the definition of the parameter ω in the Budyko equation. Based on the study mentioned above, it is therefore appropriate

to use NDVI to compare changes in the parameters of a watershed. He et al. [61] also analyzed the trend in the variation of the NDVI to find areas in which the amount of vegetation present had increased, which was then used to decide the main factors reducing runoff. The increase in the amount of vegetation in the area and attribution analysis with the Budyko equation meant that the conclusion became more robust and showed consistency with many previous studies in a similar area [62]. For further study, further investigation of the trends found using NDVI is necessary in order to obtain clearer results.

5. Conclusions

Four river basins in southern Taiwan were selected and analyzed to determine the contribution from climate change (ΔQ_C) and human activity (ΔQ_H) to their streamflow from 1980 to 2017. The hydrological sensitivity-based method and decomposition method were used, based on the Budyko hypothesis, generating consistent results. The hydrological sensitivity method found that changed in streamflow are more sensitive to changes in precipitation than to changes in potential evapotranspiration. The decomposition method showed that human activity led to a decrease in the streamflow of the Erren River Basin. Moreover, climate variability in the river basins was the main factor affecting the changes in streamflow. Changes in the parameter ω can be verified using NDVI in the areas studied.

Quantification of the impact from natural causes and anthropogenic activity on streamflow in Southern Taiwan remains a challenge because of limitations in the data. Several assumptions were therefore made in this study to obtain complete results—(1) changes in water storage were neglected over the long-term period and (2) the pre-period is used to represent the natural conditions of river basins, meaning that the environment is not particularly affected by any of the factors studied. The results of this study may have been more accurate if these factors were considered, but they have little influence on the interpretation of Budyko curve analysis. Thus, investigation of the influences from water storage and adequate definition of the pre-period are recommended for further discussion in future studies. Climate change remains an important factor for the planning and management of water resources in Southern Taiwan in the future. Comparing actual basin conditions with statistical analysis is beneficial for developing environmental policies. The results of this study provide a preliminary basis for the regulation of hydrological regimes.

Author Contributions: H.-F.Y. contrived the subject of the article, performed the literature review, and contributed to the writing of the paper; J.T. participated in data processing and the elaboration of the statistical analysis and figures. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ye, X.; Zhang, Q.; Liu, J.; Li, X.; Xu, C.-y. Distinguishing the relative impacts of climate change and human activities on variation of streamflow in the Poyang Lake catchment, China. *J. Hydrol.* **2013**, *494*, 83–95. [CrossRef]
2. *State of the Climate: Global Climate Report for Annual 2017*; NOAA National Centers for Environmental Information: Asheville, NC, USA, 2018.
3. Song, S.; Xu, Y.; Zhang, J.; Li, G.; Wang, Y. The long-term water level dynamics during urbanization in plain catchment in Yangtze River Delta. *Agric. Water Manag.* **2016**, *174*, 93–102. [CrossRef]
4. Wang, Y.; Chen, X.; Chen, Y.; Liu, M.; Gao, L. Flood/drought event identification using an effective indicator based on the correlations between multiple time scales of the Standardized Precipitation Index and river discharge. *Theor. Appl. Climatol.* **2017**, *128*, 159–168. [CrossRef]
5. Dey, P.; Mishra, A. Separating the impacts of climate change and human activities on streamflow: A review of methodologies and critical assumptions. *J. Hydrol.* **2017**, *548*, 278–290. [CrossRef]

6. Li, C.; Wang, L.; Wanrui, W.; Qi, J.; Linshan, Y.; Zhang, Y.; Lei, W.; Cui, X.; Wang, P. An analytical approach to separate climate and human contributions to basin streamflow variability. *J. Hydrol.* **2018**, *559*, 30–42. [CrossRef]
7. Shao, G.; Guan, Y.; Zhang, D.; Yu, B.; Zhu, J. The impacts of climate variability and land use change on streamflow in the Hailiutu river basin. *Water* **2018**, *10*, 814. [CrossRef]
8. Xin, Z.; Li, Y.; Zhang, L.; Ding, W.; Ye, L.; Wu, J.; Zhang, C. Quantifying the relative contribution of climate and human impacts on seasonal streamflow. *J. Hydrol.* **2019**, *574*, 936–945. [CrossRef]
9. Meng, C.; Zhang, H.; Wang, Y.; Wang, Y.; Li, J.; Li, M. Contribution Analysis of the Spatial-Temporal Changes in Streamflow in a Typical Elevation Transitional Watershed of Southwest China over the Past Six Decades. *Forests* **2019**, *10*, 495. [CrossRef]
10. Marhaento, H.; Booij, M.J.; Rientjes, T.; Hoekstra, A.Y. Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model. *Hydrol. Process.* **2017**, *31*, 2029–2040. [CrossRef]
11. Chawla, I.; Mujumdar, P. Isolating the impacts of land use and climate change on streamflow. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 3633–3651. [CrossRef]
12. Liu, J.; Zhang, Q.; Singh, V.P.; Shi, P. Contribution of multiple climatic variables and human activities to streamflow changes across China. *J. Hydrol.* **2017**, *545*, 145–162. [CrossRef]
13. Liu, J.; Zhou, Z.; Yan, Z.; Gong, J.; Jia, Y.; Xu, C.-Y.; Wang, H. A new approach to separating the impacts of climate change and multiple human activities on water cycle processes based on a distributed hydrological model. *J. Hydrol.* **2019**, *578*, 124096. [CrossRef]
14. Wu, J.; Miao, C.; Wang, Y.; Duan, Q.; Zhang, X. Contribution analysis of the long-term changes in seasonal runoff on the Loess Plateau, China, using eight Budyko-based methods. *J. Hydrol.* **2017**, *545*, 263–275. [CrossRef]
15. Yang, P.; Xia, J.; Zhan, C.; Chen, X.; Qiao, Y.; Chen, J. Separating the impacts of climate change and human activities on actual evapotranspiration in Aksu River Basin ecosystems, Northwest China. *Hydrol. Res.* **2018**, *49*, 1740–1752. [CrossRef]
16. Zheng, J.; Sun, G.; Li, W.; Yu, X.; Zhang, C.; Gong, Y.; Tu, L. Impacts of land use change and climate variations on annual inflow into the Miyun Reservoir, Beijing, China. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 1561–1572. [CrossRef]
17. Wang, X. Advances in separating effects of climate variability and human activity on stream discharge: An overview. *Adv. Water Resour.* **2014**, *71*, 209–218. [CrossRef]
18. Li, Z.; Liu, W.-z.; Zhang, X.-c.; Zheng, F.-l. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *J. Hydrol.* **2009**, *377*, 35–42. [CrossRef]
19. Liu, Y.; Zhang, X.; Xia, D.; You, J.; Rong, Y.; Bakir, M. Impacts of land-use and climate changes on hydrologic processes in the Qingyi River watershed, China. *J. Hydrol. Eng.* **2011**, *18*, 1495–1512. [CrossRef]
20. Yang, Q.; Luo, S.; Wu, H.; Wang, G.; Han, D.; Lü, H.; Shao, J. Attribution Analysis for Runoff Change on Multiple Scales in a Humid Subtropical Basin Dominated by Forest, East China. *Forests* **2019**, *10*, 184. [CrossRef]
21. Wang, H.; Stephenson, S.R. Quantifying the impacts of climate change and land use/cover change on runoff in the lower Connecticut River Basin. *Hydrol. Process.* **2018**, *32*, 1301–1312. [CrossRef]
22. Tomer, M.D.; Schilling, K.E. A simple approach to distinguish land-use and climate-change effects on watershed hydrology. *J. Hydrol.* **2009**, *376*, 24–33. [CrossRef]
23. Renner, M.; Seppelt, R.; Bernhofer, C. Evaluation of water-energy balance frameworks to predict the sensitivity of streamflow to climate change. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 1419–1433. [CrossRef]
24. Budyko, M.I. *Climate and Life*; Academic Press: New York, NY, USA, 1974; Volume 508.
25. Wang, D.; Hejazi, M. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resour. Res.* **2011**, *47*, 10. [CrossRef]
26. Bai, P.; Liu, W.; Guo, M. Impacts of climate variability and human activities on decrease in streamflow in the Qinhe River, China. *Theor. Appl. Climatol.* **2014**, *117*, 293–301. [CrossRef]
27. Guo, Y.; Li, Z.; Amo-Boateng, M.; Deng, P.; Huang, P. Quantitative assessment of the impact of climate variability and human activities on runoff changes for the upper reaches of Weihe River. *Stoch. Env. Res. Risk Assess.* **2014**, *28*, 333–346. [CrossRef]
28. *Water Resources Agency, the Third Stage Management Project of Climate Change Impacts and Adaptation on Water Environment (1~5)*; Ministry of Economic Affairs: Taipei, Taiwan, 2016. (In Chinese)

29. Burck, J.; Hagen, U.; Marten, F.; Höhne, N.; Bals, C. *The Climate Change Performance Index: Results 2019*; Germanwatch: Bonn, Germany, 2018.
30. Lin, Y.; Hong, N.-M.; Wu, P.-J.; Wu, C.-F.; Verburg, P.H. Impacts of land use change scenarios on hydrology and land use patterns in the Wu-Tu watershed in Northern Taiwan. *Landsc. Urban Plan.* **2007**, *80*, 111–126. [CrossRef]
31. *Water Resources Agency, Hydrological Year Book of Taiwan*; Ministry of Economic Affairs: Taipei, Taiwan, 2018. (In Chinese)
32. Martens, B.; Miralles, D.G.; Lievens, H.; van der Schalie, R.; de Jeu, R.A.; Fernández-Prieto, D.; Beck, H.E.; Dorigo, W.; Verhoest, N. GLEAM v3: Satellite-based land evaporation and root-zone soil moisture. *Geosci. Model Dev.* **2017**, *10*, 1903–1925. [CrossRef]
33. Miralles, D.; Holmes, T.; de Jeu, R.; Gash, J.; Meesters, A.; Dolman, A. Global land-surface evaporation estimated from satellite-based observations. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 453. [CrossRef]
34. Teuling, A.J.; de Badts, E.; Jansen, F.A.; Fuchs, R.; Buitink, J.; Hoek, A.J. Climate change, re-/afforestation, and urbanisation impacts on evapotranspiration and streamflow in Europe. *Hydrol. Earth Syst. Sci.* **2019**. under review. [CrossRef]
35. Jiang, C.; Xiong, L.; Wang, D.; Liu, P.; Guo, S.; Xu, C.-Y. Separating the impacts of climate change and human activities on runoff using the Budyko-type equations with time-varying parameters. *J. Hydrol.* **2015**, *522*, 326–338. [CrossRef]
36. Thiessen, A.H. Precipitation averages for large areas. *Mon. Westher. Rev.* **1911**, *39*, 1082–1089. [CrossRef]
37. Mann, H.B. Nonparametric tests against trend. *J. Econom. Soc.* **1945**, *13*, 245–259. [CrossRef]
38. Kendall, M. *Rank Correlation Measures*; Charles Griffin: London, UK, 1975; Volume 202, p. 15.
39. Pettitt, A. A non-parametric approach to the change-point problem. *J R Stat. Soc. C Appl.* **1979**, *28*, 126–135. [CrossRef]
40. Budyko, M.I. *Evaporation under natural conditions*; Gidrometeorizdat: Leningrad, Russia, 1948.
41. Zhao, J.; Huang, S.; Huang, Q.; Wang, H.; Leng, G. Detecting the Dominant Cause of Streamflow Decline in the Loess Plateau of China Based onthe Latest Budyko Equation. *Water* **2018**, *10*, 1277. [CrossRef]
42. Schreiber, P. Über die Beziehungen zwischen dem Niederschlag und der Wasserführung der Flüsse in Mitteleuropa. *Z. Meteorol.* **1904**, *21*, 441–452.
43. Ol'Dekop, E. On evaporation from the surface of river basins. *Trans. Meteorol. Obs.* **1911**, *4*, 200.
44. Budyko, M.I. *Evaporation under Natural Conditions, Israel Program for Scientific Translations*; Available from the Office of Technical Services; US Department of Commerce: Washington, DC, USA, 1963.
45. Turc, L. The water balance of soils. Relation between precipitation, evaporation and flow. *Ann. Agron* **1954**, *5*, 491–569.
46. Pike, J. The estimation of annual run-off from meteorological data in a tropical climate. *J. Hydrol.* **1964**, *2*, 116–123. [CrossRef]
47. Fu, B. On the calculation of the evaporation from land surface. *Sci. Atmos. Sin* **1981**, *5*, 23–31.
48. Zhang, L.; Dawes, W.; Walker, G. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resour. Res.* **2001**, *37*, 701–708. [CrossRef]
49. Milly, P. An analytic solution of the stochastic storage problem applicable to soil water. *Water Resour. Res.* **1993**, *29*, 3755–3758. [CrossRef]
50. Porporato, A.; Daly, E.; Rodriguez-Iturbe, I. Soil water balance and ecosystem response to climate change. *Am. Nat.* **2004**, *164*, 625–632. [CrossRef] [PubMed]
51. Wang, D.; Tang, Y. A one-parameter Budyko model for water balance captures emergent behavior in Darwinian hydrologic models. *Geophys. Res. Lett.* **2014**, *41*, 4569–4577. [CrossRef]
52. Redhead, J.; Stratford, C.; Sharps, K.; Jones, L.; Ziv, G.; Clarke, D.; Oliver, T.; Bullock, J. Empirical validation of the InVEST water yield ecosystem service model at a national scale. *Sci. Total Environ.* **2016**, *569*, 1418–1426. [CrossRef] [PubMed]
53. Zhang, X.; Zhang, L.; Zhao, J.; Rustomji, P.; Hairsine, P. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China. *Water Resour. Res.* **2008**, *44*, 7. [CrossRef]
54. Dooge, J.; Bruen, M.; Parmentier, B. A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation. *Adv. Water Resour.* **1999**, *23*, 153–163. [CrossRef]
55. Milly, P.; Dunne, K. Macroscale water fluxes 2. Water and energy supply control of their interannual variability. *Water Resour. Res.* **2002**, *38*, 24-1–24-9. [CrossRef]

56. Li, L.J.; Zhang, L.; Wang, H.; Wang, J.; Yang, J.W.; Li, J.Y.; Jiang, D.J.; Qin, D.Y. Assessing the impact of climate variability and human activities on streamflow from the Wuding River basin in China. *Hydrol. Process. Int. J.* **2007**, *21*, 3485–3491. [CrossRef]
57. Ning, T.; Li, Z.; Liu, W. Separating the impacts of climate change and land surface alteration on runoff reduction in the Jing River catchment of China. *Catena* **2016**, *147*, 80–86. [CrossRef]
58. Peng, D.; Qiu, L.; Lin, H. Identification for the impact of climate change and human activities on streamflow in Xitiaoxi river basin, China. In Proceedings of the 6th International Conference on Flood Management, ICFM6, São Paulo, Brazil, 16–18 September 2014.
59. Wang, W.; Shao, Q.; Yang, T.; Peng, S.; Xing, W.; Sun, F.; Luo, Y. Quantitative assessment of the impact of climate variability and human activities on runoff changes: A case study in four catchments of the Haihe River basin, China. *Hydrol. Process.* **2013**, *27*, 1158–1174. [CrossRef]
60. He, Y.; Song, J.; Hu, Y.; Tu, X.; Zhao, Y. Impacts of different weather conditions and landuse change on runoff variations in the Beiluo River Watershed, China. *Sustain. Cities Soc.* **2019**, *50*, 101674. [CrossRef]
61. He, Y.; Jiang, X.; Wang, N.; Zhang, S.; Ning, T.; Zhao, Y.; Hu, Y. Changes in mountainous runoff in three inland river basins in the arid Hexi Corridor, China, and its influencing factors. *Sustain. Cities Soc.* **2019**, *50*, 101703. [CrossRef]
62. Cong, Z.; Shahid, M.; Zhang, D.; Lei, H.; Yang, D. Attribution of runoff change in the alpine basin: A case study of the Heihe Upstream Basin, China. *Hydrolog. Sci. J.* **2017**, *62*, 1013–1028. [CrossRef]



© 2020 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 (http://creativecommons.org/licenses/by/4.0/).