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Assessing the Impact of Vegetation Variation, Climate and Human Factors on the Streamflow Variation of Yarlung Zangbo River with the Corrected Budyko Equation

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Abstract: The Yarlung Zangbo River (YZR) is the largest river on the Qinghai Tibet Plateau, and changes in its meteorology, hydrology and vegetation will have a significant impact on the ecological environment of the basin. In order to deepen our understanding of the relationship of climate–vegetation–hydrological processes in YZR, the purpose of this study is to explore how vegetation growth in the YZR affects its runoff changes. We first identified the abrupt year of discharge in the YZR using a heuristic segmentation algorithm and cumulative anomaly mutation test approach. After that, the functional equation for NDVI and the Budyko parameter (*n*) was computed. Finally, the NDVI was introduced into the Budyko equation to evaluate the impact of vegetation changes on the streamflow in the YZR. Results showed that: (1) NDVI and discharge in the YZR both presented an increasing trend, and the mutation year of annual runoff in Nuxia station occurred in 1997. (2) *n* had a significant negative correlation with NDVI in the YZR ($p < 0.01$). (3) The contributions of Pr, ET_0, $NDVI$, and n on streamflow change in the S2 period (1998–2015) were 5.26%, 1.14%, 43.04%, and 50.06%. The results of this study can provide scientific guidance and support for the evaluation of the effects of ecological restoration measures, as well as the management and planning of water resources in the YZR.

Keywords: streamflow change; NDVI; climate change; human activities; attribution analysis

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1. Introduction

Climate change characterized by global warming has significantly changed the hydrological cycle, which has had a very profound impact on natural ecosystems and the development of human society. For example, changes in the hydrological cycle process will increase the frequency of extreme hydrological events [1,2], change the spatial and temporal distribution of water resources, damage the ecological environment, and exacerbate the current situation of unbalanced and inadequate regional development [3,4]. In addition, since the Industrial Revolution, human activities have increasingly interfered with hydrological processes in basins, significantly changing hydrological cycle elements in terms of time and space, quantity, and quality [5,6]. Runoff is an important resource related to natural environmental changes and human social progress, and directly affects agricultural irrigation and production, ecological protection and restoration, and economic development and stability [7–9]. Therefore, clarifying and understanding the runoff evolution rules and its influencing factors under the context of changing environments can provide suggestions and guidance for regional ecological environment development and human production activities.

As the "water tower of Asia", the Qinghai Tibet Plateau is the birthplace of major rivers in Asia (the Yellow River, Yangtze River, Nu River, Indus River, Yarlung Zangbo River, Lancang River, etc.) [10] and is also the ecological security barrier in Asia and the world [11]. The Yarlung Zangbo River (YZR) is located in the southern part of the Qinghai–Tibet Plateau, with an average altitude of 4000 m. It is an important water vapor channel for the warm and humid Indian Ocean flow to enter the hinterland of the Qinghai–Tibet Plateau [12]. The national ecological function protection zone at the headstream provides an important ecological safety barrier for the economic center of Tibet and the Grand Canyon region in the downstream. The one river and two rivers region in the middle reaches of the basin (YZR, Nianchu River, and Lhasa River) is an important commodity grain base and population gathering place in Tibet [13]. In addition, the YZR is an important international river, and its water resources changes are related to the economic development and social stability of the Southeast Asian countries.

In recent years, many scholars have analyzed the characteristics of runoff changes and influencing factors in the YZR [14,15]. Liu et al. [16] found that both climate and land use changes can lead to runoff change trends in the YZR. Wang et al. [17] used the trend analysis and wavelet analysis methods to analyze the annual runoff change trend in Yangcun and Nuxia stations on the YZR from 1970 to 2012. The results showed that runoff presented an insignificant growth trend. Li et al. [18] used the heuristic segmentation algorithm to identify the mutation year of the runoff, and then used Mann–Kendall nonparametric test to analyze the temporal variation characteristics of runoff, and used the concentration degree and concentration period method to study the intra-annual change law of runoff based on the monthly runoff data of Nuxia station in the YZR from 1961 to 2015. Based on meteorological data, monthly scale runoff data, and land use data, Liu et al. [19] used improved hydrological models to clarify the impact of climate and underlying surface changes on runoff from 1991 to 2010. The results showed that during the period from 1991 to 2010, the contribution rates of climate and underlying surface changes to runoff change varied significantly between different periods, and climate change contributed more to runoff change than underlying surface changes. From a spatial perspective, the contribution rate of climate change to watershed runoff production was larger in the upstream and middle reaches, and smaller in the northeast of the downstream. Yang et al. quantitatively analyzed the impact of climate change on the runoff of the upper Yarlung Zangbo River. The results showed that the annual runoff and evapotranspiration of the upper reaches of the Yarlung Zangbo River showed a significant increasing trend from 1981 to 2010, and the increase of precipitation was the main factor for the increase in runoff [20].

Since 1999, the Chinese government has implemented a number of large-scale ecological restoration projects, such as the returning farmland to forest/grassland project, the Three-North Shelterbelt Program project [9], which has significantly increased the vegetation coverage across China [21]. The elevation of the YZR varies greatly. The cold and dry conditions in the upper reaches have changed into warm and humid conditions in the lower reaches, resulting in high vegetation diversity in the basin. In recent years, many scholars have analyzed the characteristics of vegetation changes and influencing factors in the YZR [22–24]. Lv et al. [25] analyzed the temporal and spatial changes in vegetation cover in the YZR, and found that there was an obvious positive correlation between NDVI and precipitation. Sun et al. [26] investigated how vegetation growth changed in the YZR, and determined the driving mechanisms. Wang et al. [27] analyzed the variation characteristics of vegetation cover from 1985 to 2018 in the YZR, and found that NDVI showed an overall growth trend. Meng et al. [28] found that the vegetation change in the YZR was greatly affected by precipitation and temperature, of which the impact of temperature was slightly stronger than precipitation, and the impact of climate change on the vegetation in the basin had a lagging effect. Cui et al. [29] assessed the sensitivity of vegetation change in the YZR to temperature and precipitation, and found that NDVI had a positive relationship with temperature and precipitation changes, and annual NDVI was more sensitive to temperature than to precipitation. Zuo et al. [30] analyzed the impact mechanism of climate change on vegetation dynamics in the YZR. There was a significant positive correlation between NDVI and precipitation and drought in the upstream and middle reaches of the basin, while there was a significant negative correlation between

NDVI and temperature in the southeast of the middle and lower reaches. The vegetation changes in the YZR could change the underlying surface characteristics and the energy balance, and then significantly affect the river runoff of the basin [31,32]. Nevertheless, few research works have computed the contribution of vegetation variation on the streamflow of the YZR.

The debate on the relationship between "vegetation and water" dates back to at least the mid-19th century [33]. Some research works displayed how vegetation growth had a negative effect on discharge increase [34]. However, some research works demonstrated that vegetation growth had few effects on discharge [35,36] and even a positive effect on discharge increase [37,38]. In order to deepen our understanding of the relationships of the climate–vegetation–hydrological process in the YZR, the purpose of this study is to explore how vegetation growth in the YZR affects runoff changes. The contents of this paper include: (1) Analyzing the temporal variation characteristics of hydro-meteorological elements in the YZR, and identifying the abrupt year of runoff at Nuxia hydrological station; (2) Analyzing the temporal variation characteristics of NDVI and the Budyko parameter (n), and quantifying the functional equation for NDVI and n. (3) Assessing the impact of vegetation variation, human activities, and climate change on runoff change. The results of this study can provide scientific guidance and support for the evaluation of the effects of ecological restoration measures, as well as the management and planning of water resources in the YZR.

2. Research Area and Data

The YZR is the largest river on the Qinghai–Tibet Plateau. It originates from the Jamayangzong Glacier, leaves China in Bashika and enters India in Assam, where it is renamed the Brahmaputra River. The total length of the river is 2057 km, covering an area of about 240,000 km^2, accounting for about 20% of the Tibet Autonomous Region, with an average altitude of 4500 m. The terrain is high in the west and low in the east. Influenced by the warm and humid air flow in the Indian Ocean, the climatic conditions in the upstream and downstream of the basin vary greatly. The temperature varies significantly with altitude, with a gradual increasing trend from upstream to downstream. The annual average temperature in the high-altitude region where the source is located is about 0 to 3 °C, and in the middle reaches it is about 5 to 9 °C, while the monthly average maximum temperature in Lhasa is about 10 to 17 °C. The precipitation tends to increase gradually from upstream to downstream, with an annual precipitation of about 420 mm in Shigatse, while the annual precipitation in Bashika can reach 5000 mm. The vertical distribution of precipitation is seasonally uneven. The precipitation in the rainy season (June to September) accounts for 65% to 80% of the annual precipitation, while the precipitation in the dry season (October to April of the next year) is sparse. The average annual runoff is 166.1 billion m^3, and the distribution of runoff is uneven within the year. The water resources in the wet season account for 70%, while the water resources in the dry season only account for less than 20%. The upstream vegetation of the basin is mainly composed of alpine grasslands, alpine meadows, and some alpine vegetation, while the middle reaches are mainly covered by shrubs and meadows. The downstream vegetation is mainly composed of coniferous forests, broad-leaved forests, and some alpine vegetation.

Nuxia hydrological station is located in the main stream of the YZR and controls more than 80% of the basin area. It is one of the important hydrological stations in the Tibetan Plateau. The runoff data (1982–2015) of Nuxia station were obtained from the Tibet autonomous region hydrology and water resources survey (http://www.xzsw.com.cn/ accessed on 1 March 2023). The multi-year meteorological station data (1982–2015) in and around the YZR were obtained from the China Meteorological Administration. First of all, we computed the daily potential evapotranspiration at meteorological stations in and around the YZR using the Penman–Monteith equation, and then computed monthly precipitation and potential evaporation. Finally, we utilized the Kriging method in the ArcGIS to interpolate the monthly precipitation and potential evaporation, and we computed annual scale precipitation and potential evapotranspiration through adding monthly scale data. NDVI for the period of 1982–2015 was obtained from the GIMMS NDVI3g V1.0 dataset, and its temporal resolution and spatial resolution were day and 0.05 degree. Monthly and annual NDVI were computed using the maximum synthesis method.

3. Research Methods

3.1. Methods for Detecting Trends and Variability

A simple linear regression method was used for analyzing the temporal variation characteristics of hydro-meteorological elements in the YZR. The linear regression method has simple algorithms, fast operation speed, and is good at obtaining linear relationships and changing trends in data, with strong explanatory power. Therefore, this method is often used to analyze the temporal variation characteristics of data [39,40].

The heuristic segmentation algorithm treats mutation detection as a segmentation problem that can divide a non-smooth sequence into smooth subsequences with different mean values. The year of mutation was determined by identifying the maximum mean difference of each subsequence, depending on whether the mutation point met different statistical significances [41]. For traditional detection methods, some of the shortcomings that arise when dealing with nonlinear and non-stationary time series data could be compensated [42]. The heuristic segmentation method uses multiple iterations in the segmentation process, which greatly improved the computational efficiency and had good practicality [43,44].

To determine the accuracy of the heuristic segmentation to detect mutation points, this study will use the cumulative abnormal mutation test method to diagnose the mutation years of the same time series data to corroborate the mutation results of the heuristic segmentation method. The advantage of these two methods is that they are not only easy to calculate, but are also clear about the time of mutation occurrence.

3.2. Corrected Budyko Equation

According to the degree of description of the rainfall runoff generation system, the attribution analysis methods for watershed runoff changes are classified into three categories: (1) Empirical relationship method. Considering the watershed as a whole, based on the causal relationship between rainfall input and runoff output, a hydrological statistical relationship was established for the base period. The simulated runoff computed the hydrological statistical relationship based on rainfall conditions during the measurement period and compared it with the measured runoff during that period to obtain the contribution of human activities to water and sediment changes. This method was based on observation and experience, is also known as the hydrological statistical method, and is intuitive, concise, and has a certain degree of accuracy. The double cumulative curve method for regression after the dependent and independent variables have been accumulated year by year belongs to this category. (2) Semi empirical formula method. Based on the relevant theories of meteorology, hydrology, probability theory, etc., we established a relationship equation that was mutually causal and continuous and had a certain physical basis. Then, different conditional variables were introduced and equations were used to estimate the impact of climate factors and human activities on runoff changes, also known as the conceptual model method and semi quantitative model method. For example, the runoff elasticity coefficient method based on Budyko's water heat balance theory belongs to this category. This type of method considers the impact of climate factors (potential evapotranspiration and rainfall) on runoff, making the rainfall and runoff processes clearer. (3) Hydrological modeling method based on physical processes. The surface was divided into units according to different geographical element types, and then we reproduced physical processes such as rainfall, interception, infiltration, and runoff by considering the input and output of each unit in the vertical and horizontal directions. Finally, by changing the input conditions, the contribution of geographical elements to runoff changes can be estimated. For example, the SWAT (Soil and Water Assessment Tool) model, the WEPP

(Water Erosion Prediction Project) model, and the Xin'anjiang model all belong to this category.

There are presuppositions for the Budyko formula, which was applied for quantitatively computing the contribution of different factors to runoff. They are: (1) human factor, climatic factor, and vegetation are independent; (2) the runoff change in the base period is only affected by climatic factor; and (3) except for runoff changes caused by precipitation, potential evapotranspiration, and vegetation changes, all other factors that affect runoff changes are unanimously considered to be human factors [45–48].

$$R = Pr - ET \tag{1}$$

R, Pr and ET, respectively, denote runoff depth, precipitation, and actual evaporation of the basin.

$$ET = \frac{Pr \times ET_0}{(Pr^n + ET_0^n)^{1/n}} \tag{2}$$

ET_0 denotes potential evapotranspiration (mm) and is computed using the Penman–Monteith equation. Budyko parameter n reflects the comprehensive impact of soil, terrain, and anthropogenic factors. The soil and terrain are not prone to changes in a short period of time, so anthropogenic factors have become the main factor affecting the Budyko parameter (n). Therefore, Budyko parameter n is utilized for characterizing anthropogenic factors. Anthropogenic factors influence streamflow in YZR through numerous means, including water conservancy project, tree planting, and afforestation, etc., Li et al. [49] proved that Budyko parameter n has a significant correlation with $NDVI$ in a basin.

$$n = a * NDVI + b \tag{3}$$

$$R = Pr - \frac{Pr \times ET_0}{\left(Pr^{a*NDVI+b} + ET_0^{a*NDVI+b}\right)^{1/(a*NDVI+b)}} \tag{4}$$

ε_P is elasticity coefficient of R for Pr, ε_{ET0} is elasticity coefficient of R for ET_0, ε_n is elasticity coefficient of R for n, and ε_{NDVI} is elasticity coefficient of R for $NDVI$, and they are computed with the following equations [50].

$$\varepsilon_P = \frac{\left(1+\left(\frac{ET_0}{Pr}\right)^n\right)^{1/n+1} - \left(\frac{ET_0}{Pr}\right)^{n+1}}{\left(1+\left(\frac{ET_0}{Pr}\right)^n\right)\left[\left(1+\left(\frac{ET_0}{Pr}\right)^n\right)^{1/n} - \left(\frac{ET_0}{Pr}\right)\right]} \tag{5}$$

$$\varepsilon_{ET0} = \frac{1}{\left(1+\left(\frac{ET_0}{Pr}\right)^n\right)\left[1 - \left(1+\left(\frac{ET_0}{Pr}\right)^{-n}\right)^{1/n}\right]} \tag{6}$$

$$\varepsilon_n = \frac{ln\left(1+\left(\frac{ET_0}{Pr}\right)^n\right) + \left(\frac{ET_0}{Pr}\right)^n ln\left(1+\left(\frac{ET_0}{Pr}\right)^{-n}\right)}{n\left(1+\left(\frac{ET_0}{Pr}\right)^n\right)\left[1 - \left(1+\left(\frac{ET_0}{Pr}\right)^{-n}\right)^{1/n}\right]} \tag{7}$$

$$\varepsilon_{NDVI} = \varepsilon_n \frac{a * NDVI}{a * NDVI + b} \tag{8}$$

According to mutation analysis result, the study period was separated into S_1 and S_2. Thus, the change values of precipitation (ΔPr), potential evapotranspiration (ΔET_0), underlying surface characteristic parameter (Δn), and $NDVI$ ($\Delta NDVI$) from S_1 to S_2 were computed. ΔR_{Pr}, ΔR_{ET0}, ΔR_n, and ΔR_{NDVI}, respectively, represent streamflow variation values caused by variation values of precipitation, potential evapotranspiration, n, and $NDVI$ from S_1 to S_2.

$$\Delta R_{Pr} = \varepsilon_P \frac{R}{Pr} \times \Delta Pr \tag{9}$$

$$\Delta R_{ET0} = \varepsilon_{ET0} \frac{R}{ET_0} \times \Delta ET_0 \tag{10}$$

$$\Delta R_n = \varepsilon_n \frac{R}{n} \times \Delta n \tag{11}$$

$$\Delta R_{NDVI} = \varepsilon_{NDVI} \frac{R}{NDVI} \times \Delta NDVI \tag{12}$$

$$\Delta R_{hum} = \Delta R_n - \Delta R_{NDVI} \tag{13}$$

ηR_{pr}, ηR_{ET0}, ηR_{NDVI} and ηR_H, respectively, denote the contribution rate of Pr, potential evapotranspiration, $NDVI$, and anthropogenic factor on streamflow, and are computed with the following equations.

$$\Delta R = \Delta R_{Pr} + \Delta R_{ET0} + \Delta R_{NVDI} + \Delta R_{hum} \tag{14}$$

$$\eta R_{Pr} = \Delta R_{Pr} / \Delta R \times 100\% \tag{15}$$

$$\eta R_{ET0} = \Delta R_{ET0} / \Delta R \times 100\% \tag{16}$$

$$\eta R_{NDVI} = \Delta R_{NDVI} / \Delta R \times 100\% \tag{17}$$

$$\eta R_H = \Delta R_{hum} / \Delta R \times 100\% \tag{18}$$

4. Results

4.1. Trends Analysis of Climate Factors

The simple linear regression method was employed for analyzing the temporal variation characteristics of precipitation and potential evapotranspiration during 1982–2015 (Figure 1). The slope of annual Pr from 1982 to 2015 was 0.2084 mm/a, indicating an increasing trend ($p > 0.05$) of annual Pr. The fluctuation range of annual Pr in the YZR was 411.00–631.30 mm, and the maximum and minimum values occurred in 1991 and 1982. Figure 1b demonstrated that the ET_0 of the YZR fluctuated and decreased, with a fluctuation range of 901.78–1023.79. The maximum and minimum values appeared in 2009 and 2000, and the slope of ET_0 from 1982 to 2015 was −0.3873/a ($p < 0.05$).

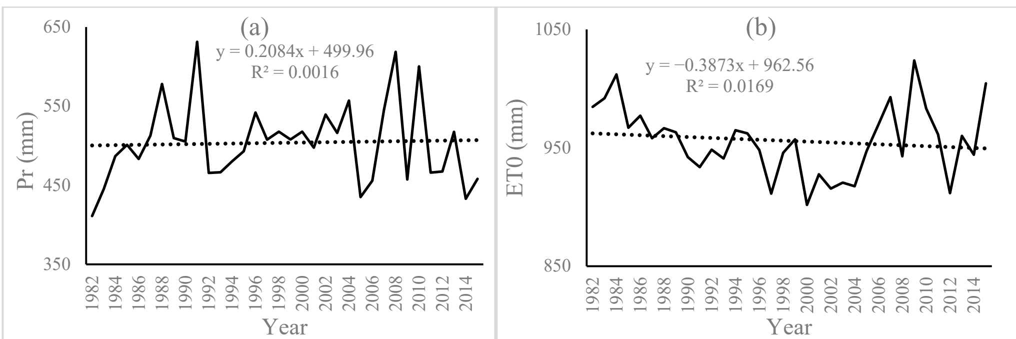

Figure 1. Temporal varying characteristics of annual average precipitation (**a**) and reference evaporation (**b**) in the YZR.

4.2. Trend Analysis and Abrupt Analysis of Runoff Depth

Figure 2 displayed the temporal varying characteristics of runoff depth in the YZR. Figure 2 demonstrates that the runoff depth of the YZR climbed up and then declined, showing an overall growth trend, with a fluctuation range of 202.30–458.78. The maximum and minimum values appeared in 2000 and 1983, and the slope of the runoff depth from 1982 to 2015 was 2.0218 mm/a ($p < 0.05$).

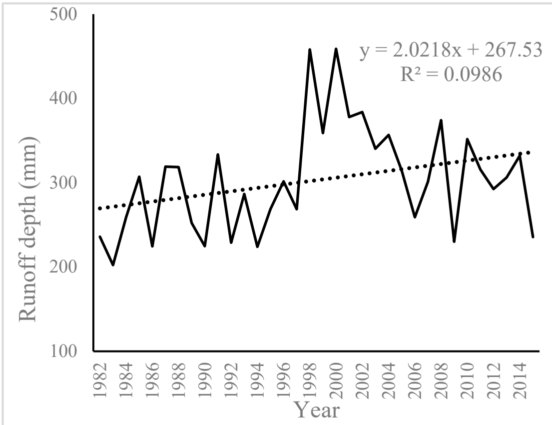

Figure 2. Temporal varying characteristics of runoff depth in the YZR.

A heuristic segmentation algorithm was applied for distinguishing the abrupt years of annual discharge data through two steps (Figure 3): (1) Calculating the T-test statistics for each year to measure the variability of the mean values of two subsequences. The year with the largest T-test statistic (T_{max}) may be the year of mutation. The largest T-test statistics were about equal to 3.6 and occurred in 1997, implying that the mutation year of annual runoff in Nuxia station may have occurred in 1997. (2) Calculating the significance probability $P(T_{max})$ corresponding to the largest T-test statistic (T_{max}). The greater the $P(T_{max})$, the better the significance. The basic parameter range was set between 0.5 and 0.95, and it is generally considered plausible to take the value between this range, and in this paper, in order to distinguish it from other points as a distinction, we took a different value according to its actual situation, i.e., P0 took the value of 0.84. Therefore, $P(T_{max})$ was 0.673 and was greater than 0.67 (P0), which proved that annual runoff of Nuxia station mutated in 1997.

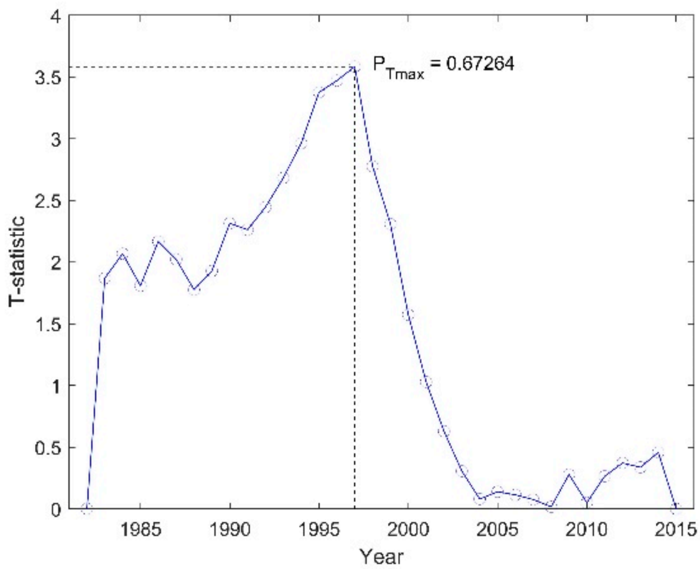

Figure 3. Heuristic segmentation algorithm abrupt test result of runoff in YZR from 1982 to 2015.

In order to verify the sudden change result of the heuristic segmentation algorithm, the cumulative anomaly mutation test approach was applied to diagnose the sudden change year of the same time series data (Figure 4). Figure 4 demonstrates that the cumulative anomaly values of runoff in the YZR showed an overall decline trend from 1982 to 1997, and showed an overall growth trend from 1997 to 2015. As a consequence, the turning point of the runoff cumulative anomaly value was 1997, which proved that the annual runoff of Nuxia station mutated in 1997. Therefore, based on the results of the two methods, we believe that the annual runoff of Nuxia station mutated in 1997, and the result of this study is consistent with the research result of Li et al. [18].

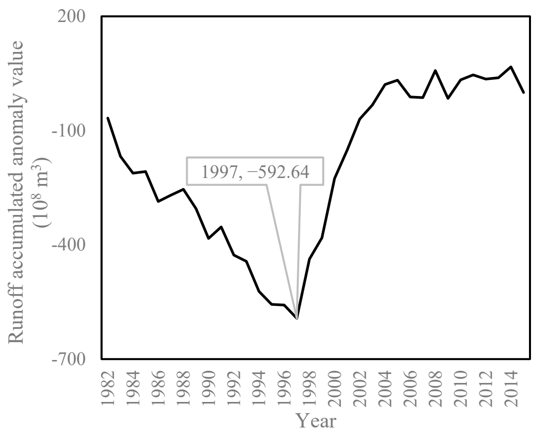

Figure 4. Runoff accumulated anomaly mutation analysis in YZR from 1982 to 2015.

4.3. Functional Equation for NDVI and n

If the elements ET_0, Pr, and R of the Budyko equation can be determined, the Budyko parameter (n) can be solved. For computing the effect of vegetation change on discharge in the YZR, we first explored the temporal varying characteristics of NDVI and n in the YZR (Figure 5). There were significant fluctuations in NDVI and Budyko parameter (n), with a fluctuation range of 0.382–0.456 and 1.069–1.527. The mean value of n decreased from 1.396 in 1982–1998 to 1.253 in 1998–2015, with a relative change rate of 10.266%.

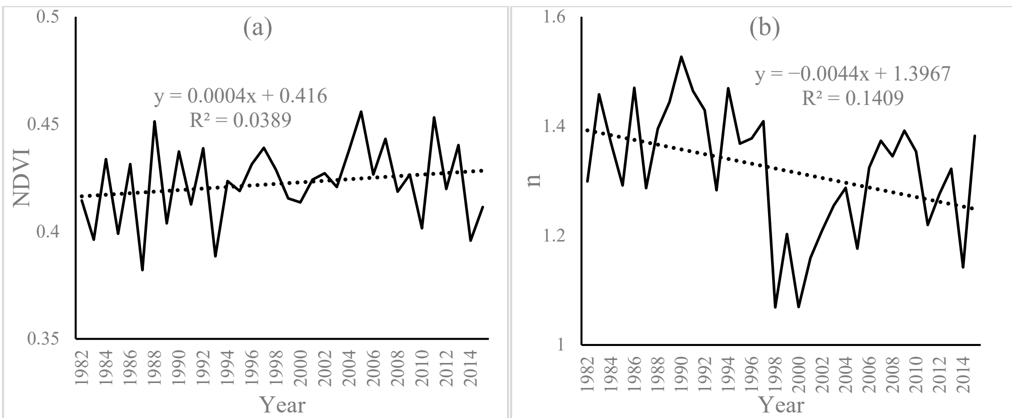

Figure 5. Temporal varying characteristics of NDVI (**a**) and n (**b**) in YZR.

Li et al. [51] found that the change rate of Budyko parameter (n) was well correlated with the vegetation index of the middle Yellow River basin; Zhang et al. [52] established a model for the lower bedding surface parameter n, which can be estimated directly using vegetation change. The 9-year sliding mean values of NDVI and Budyko parameter (n) were computed. Next, we drew a scatter diagram of the 9-year sliding mean values of NDVI and Budyko parameter (n) (Figure 6). In the end, the functional equation for NDVI and Budyko parameter (n) was computed (a = −9.9744 and b = 5.55), and its determination coefficient was 0.4604 ($p < 0.01$), implying that n had a significant negative correlation with NDVI.

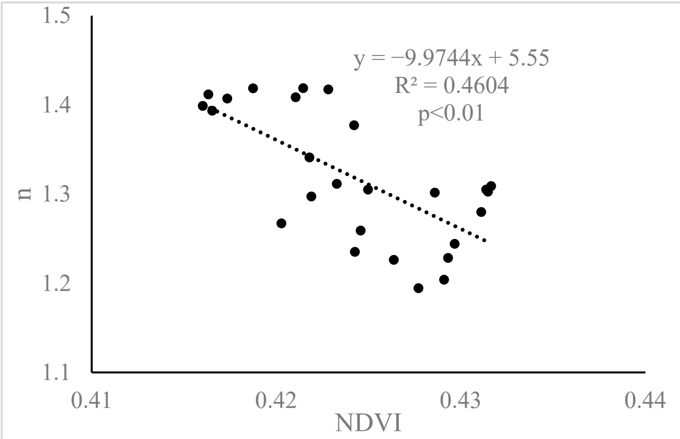

Figure 6. Functional equations for NDVI and n.

4.4. Influence Assessment of NDVI on Streamflow

According to the results of the heuristic segmentation algorithm and cumulative anomaly mutation test approach, the study period was separated into S1 (1982–1997) and S2 (1998–2015), and values of hydro-meteorological elements and NDVI of the YZR in different periods were obtained (Table 1). ET_0 in the YZR decreased by 9.22 mm from S1 (960.66 mm) to S2 (951.45 mm), and Pr and R increased by 4.74 mm and 69.96 mm from S1 to S2. NDVI increased by 0.007 from S1 (0.418) to S2 (0.425). n decreased by 0.143 from 1.396 (S1) to 1.253 (S2).

Table 1. Values of hydro-meteorological elements and NDVI in YZR.

Periods	ET_0/mm	R/mm	Pr/mm	n	$NDVI$
S1 (1982–1997)	960.66	265.87	501.10	1.396	0.418
S2 (1998–2015)	951.45	335.83	505.84	1.253	0.425

According to Table 1, the differences in Pr, ET_0, $NDVI$, and n between S1 and S2 were computed, and then the elastic coefficients of R on Pr, ET_0, $NDVI$, and n were computed using Formulas (5)–(8). Then, the amounts of runoff caused by Pr, ET_0, $NDVI$, and n were calculated with Formulas (9)–(13) (Table 2). The elasticity coefficients of R for Pr (ε_P) and $NDVI$ (ε_{NDVI}) were 1.27 and 6.18, indicating that a 1% decrease in annual Pr and $NDVI$ would lead to a decrease of 1.27% and 6.18% in runoff depth. The elasticity coefficients of R for ET_0 (ε_{ET0}) and Budyko parameter n (ε_n) were −0.27 and −1.96, indicating that a 1% decrease in annual ET_0 and Budyko parameter n would lead to an increase of 1.27% and 6.18% in runoff depth. Finally, based on Formulas (15)–(18), the contributions of Pr, ET_0, $NDVI$, and n on streamflow at the Nuxia Hydrological Station were computed (Table 2). The contributions of Pr, ET_0, $NDVI$, and n on the streamflow change in the S2 period (1998–2015) were 5.26%, 1.14%, 43.04%, and 50.06%. In summary, the increase of runoff in the YZR is mainly influenced by $NDVI$ growth and underlying surface change. Some research works demonstrated that the vegetation growth had a positive effect on discharge increase [37,38], and the areas where $NDVI$ growth led to increased runoff were mostly located in large watersheds with complex terrain [53]. The Yarlung Zangbo River is a large watershed with a complex terrain. Therefore, the conclusion of this study is similar to existing studies.

Table 2. Attribution analysis of discharge variation in YZR.

ε_P	ε_{E0}	ε_n	ε_{NDVI}	ΔR_P	ΔR_{ET0}	ΔR_{NDVI}	ΔR_{hum}	ηR_P	ηR_{ET0}	ηR_{NDVI}	ηR_{hum}
1.27	−0.27	−1.96	6.18	3.62	0.78	29.65	34.83	5.26%	1.14%	43.04%	50.06%

5. Conclusions and Discussion

5.1. Conclusions

The Yarlung Zangbo River (YZR) is the largest river on the Qinghai–Tibet Plateau. In order to deepen our understanding of the relationship of climate–vegetation–hydrological processes in the YZR, we first identified the abrupt year of discharge in the YZR using a heuristic segmentation algorithm and cumulative anomaly mutation test approach. After that, the functional equation for NDVI and n was computed. In the end, NDVI was introduced into the Budyko equation to evaluate the impact of vegetation change on streamflow in the YZR. It turned out that: (1) NDVI and discharge in the YZR both presented an increasing trend, and the mutation year of annual runoff in Nuxia station occurred in 1997. (2) n had a significant negative correlation with NDVI in the YZR ($p < 0.01$). (3) The contributions of *Pr*, *ET0*, *NDVI*, and n on streamflow change in the S2 period (1998–2015) were 5.26%, 1.14%, 43.04%, and 50.06%.

5.2. Discussion

Since 1999, the Chinese government has implemented a number of large-scale ecological restoration projects, such as the returning farmland to forest/grassland project, the Three-North Shelterbelt Program project, which has significantly increased the vegetation coverage across China. The elevation of the YZR varies greatly. The cold and dry conditions in the upper reaches change into warm and humid conditions in the lower reaches, resulting in high vegetation diversity in the basin. The implementation of a series of soil and water conservation measures in the YZR has significantly changed the rainfall–runoff relationship in the area. The underlying surface of the watershed reflects the comprehensive impact of soil, terrain, and vegetation. The soil and terrain are not prone to changes in a short period of time, so vegetation change has become the main factor affecting the changes in the underlying surface of the watershed. Liu et al. and Han et al. both found that the vegetation cover in the YZR had an overall increasing trend [54,55]. Any increase or decrease in vegetation will in turn lead to changes in runoff. The debate on the relationship between "vegetation and water" dates back to at least the mid-19th century [33]. Some research works have demonstrated that vegetation growth has a negative effect on discharge increase [34]. However, some research works have shown that the vegetation growth has few effect on discharge [35,36] and even a positive effect on discharge increase [37,38].

From Figure 6, we found that NDVI in the YZR showed a strong correlation with the Budyko parameter (n), indicating that vegetation restoration has a significant impact on the Budyko parameter (n). Subsequent attribution analysis indicated that the change in vegetation cover led to an increase in runoff in the YZR. Some research works demonstrated that vegetation growth had a positive effect on discharge increase, and the areas where NDVI growth led to increased runoff were mostly located in large watersheds with complex terrain [53]. The Yarlung Zangbo River is a large watershed with a complex terrain. Therefore, the conclusion of this study is similar to those of existing studies. The impact of vegetation reconstruction on water resources should be given significant attention. The government should plan reasonable vegetation restoration according to the actual conditions of the basin. Yang et al. [56] analyzed the impact of different vertical structures on water yield using a simulated rainfall experiment in the field, and found that the vertical structure of vegetation is an important factor influencing water yield. Therefore, in the subsequent vegetation restoration process, the vegetation structure in the YZR should be optimized.

Although this study strictly controlled data, several uncertainties existed. First of all, meteorological data of individual dates at some stations were missing. Next, precipitation and potential evapotranspiration data were obtained through interpolation, using data from national meteorological stations. Moreover, the study ignored the reciprocal effects between climatic factor, vegetation, and human factor [57–59], so we should systematically quantify the influence of climatic conditions and anthropic factor interactions on eco-hydrological systems [60–62]. In the future, we will try to build a distributed hydrological hydrothermal coupling model for computing how vegetation affects the hydrological process in the YZR [63–65]. In addition, the attribution analysis of runoff in the study area only considered four factors: precipitation, potential evapotranspiration, vegetation, and human activities. In fact, many glaciers are distributed in the YZR. With the increase in temperature, the impact of glacier melting on the runoff change of the YZR is increasing. In a follow-up study, the contribution rate of glacier melting to runoff change will be quantitatively analyzed [15,66].

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