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Nonstationary Ecological Instream Flow and Relevant Causes in the Huai River Basin, China

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Abstract: Based on the daily precipitation data during 1960–2016 at 72 stations and the daily streamflow data during 1956–2016 at 7 hydrological stations in the Huai River Basin (HRB), China, eco-surplus and eco-deficit under influences of abrupt streamflow behaviors were analyzed using Flow Duration Curve (FDC). The relations between indicators of hydrological alteration (IHA) and ecological indicators (Shannon Index, SI) were quantified, investigating impacts of altered hydrological processes on the evaluations of the ecological instream flow. Besides, we also quantified fractional contributions of climatic indices to nonstationary ecological instream flow using the Generalized Additive Models for Location Scale and Shape (GAMLSS) framework. While the possible impact of human activities on ecological instream flow will be revealed based on land use changes data. The results indicated that: (1) FDC is subject to general decrease due to hydrological alterations, and most streamflow components are lower than 25% FDC. We found increased eco-deficit and decreased eco-surplus due to altered hydrological processes. The FDC of the streamflow in the main stream of the HRB is lower than that along the tributaries of the HRB. Eco-surplus (eco-deficit) changes are in good line with precipitation anomaly changes during the Spring, Autumn and Winter periods. However, the hydrological alterations due to hydrological regulations by the reservoirs are the primary cause behind the mismatch between ecological instream flow and precipitation anomalies during summer; (2) Annual and seasonal eco-surplus (eco-deficit) is decreasing (increasing) and that during winter season is an exception. Although higher eco-surplus in winter than in other seasons, the eco-surplus is decreasing persistently and the 21st century witnessed the lowest eco-surplus along the main stream of the HRB. Meanwhile, the Shannon index indicated decreased ecological diversity across the HRB; (3) The ecological instream flow is highly sensitive to The Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO) and Niño 3.4 Sea Surface Temperature Index (Nino3.4). Meanwhile, the ecological instream flow along the mainstream of the HRB is highly sensitive to climate indices. While the ecological instream flow by GAMLSS model has better fitting performance in describing the extreme values and local trends.

Keywords: ecological instream flow; nonstationary; GAMLSS; climatic factors; Huai River basin

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1. Introduction

Variations of ecological instream flow are closely related to variability and availability of water resources and are also related to the diversity of the river ecological system and river health [1]. Human activities e.g., building water conservancy projects, industrial and irrigation demand water have caused the river hydrological variation and environmental degradation, which have affected natural hydrological variation. Therefore, the quantity and quality of water required for protection of water resources and ecosystems are required [2–4]. Alterations of river discharge have normally occurred in a great number of rivers caused by climate change and human activities, usually through the construction of DAMS. Moreover, river discharge is a vital component of the ecological integrity of river systems [5,6]. The Intergovernmental Panel on Climate Change (IPCC) report showed that climate change would accelerate the global water cycle, thereby resulting in increased extreme events [7]. Meanwhile, intensified human activities, such as changing land use and the building of water reservoirs, have significantly altered natural streamflow regimes for the past six decades [8].

In recent years, a series of water resources and water environment problems such as water shortages and river outages have occurred. To evaluate the HRB change of ecological instream flow and provide suggestions for river management, it is essential to use ecological indicators to evaluate ecological health of the river and hydrological [3,9]. The Tharme et al. [2] research shows that a global review of the present status of environmental flow methodologies revealed the existence of some 207 individual methodologies, recorded for 44 countries within six world regions. A common hypothesis states that the ecological regime becomes well-adjusted to the hydrological regime, and the ecological requirements of river-living organisms have been satisfied from a hydrological standpoint [10,11]. In general, ecological instream flow index can be classified into 4 categories [12], such as the Tennant method [13,14], the 7Q10 (seven-day low flow with a 10-year recurrence interval) method [15], Instream Flow Incremental Methodology (IFIM) [16], minimum monthly mean flow method [17], flow duration curve method [18] and so on. These multiple ecological instream flow indicators enable researchers and policy makers to quantitatively evaluate the multiple impacts of changes in ecological instream flow on the river ecosystems. Nevertheless, great numbers of complex ecological instream flow indicators are sometimes unavailable, and many interconnected ecological indicators cause statistical redundancy [4,12]. The Richter proposed a most widely used method, named "Indicators of Hydrologic Alteration" (IHA), for assessing the degree of hydrological alteration attributable to human influence within an ecosystem [19–21]. The IHA indicators, including 33 hydrologic parameters, statistically characterized variation in ecological instream flow, including five groups and these have been widely used in the analysis of hydrological alterations [22,23]. The inter-correlation and complexity of the IHA indicators motivated a number of researchers to develop generalized ecological instream flow indicators that could be widely used for evaluating ecological instream flow changes in environmental change. The study area of arable land and agricultural population in HRB accounted for 10% and 20.4% respectively, and providing 20% of China's agricultural products [24,25]. Therefore, irrigated agricultural production is vital to China's food security [26–29]. However, uneven distribution of precipitation in time and space in the HRB leads to frequent droughts and floods. Since the beginning of the 21st century, the annual average drought-affected crop area reached 2.698 $hm^2 \times 10^6$ hm^2 and the drought-destroyed cropland area has reached 1.408 $hm^2 \times 10^6$ hm^2, accounting for 21% and 11% of the total cropland of the basin, respectively [25]. Many studies have analyzed the of the altered ecological instream flow caused by climate change and human activity such as damming by reservoirs has been done [22,23]. However, only a few research have studied the ecological instream flow of the HRB. Such as Liu et al. [30] used Adapted Ecological Hydraulic Radius Approach (AEHRA) to discussed the influence of dam regulation on ecological instream flow [30], Liu et al. [31] were Estimating the minimum in-stream flow requirements via wetted perimeter method based on curvature and slope techniques, Pan et al. [32] used patio-temporal analysis of satisfactory degree of ecological water demand in HRB, Liu et al. [33] and Zuo et al. [34] used Ecological hydraulic radius approach to Impact factors and health assessment of aquatic ecosystem in HRB.

While the ecological instream flow of the HRB has been calculated considering hydrological alterations [32–34], However, inter-correlations in 33 hydrological indicators has not been comprehensively analyzed. Milly et al. [35] ascribed the demise of stationarity to anthropogenic changes of Earth's climate, changes in land use/land cover, and regulation of rivers by dams and reservoirs. The warming climate have cause more intense precipitation regimes [36–38]. Besides, human activities also have increasing affected streamflow processes and extreme hydrological processes [23]. Therefore, the nonstationary assumption has been widely accepted in the quantification of region flow frequency analysis [39–41]. However, studies on ecological instream flow with consideration of nonstationary in the HRB have been scarce. Furthermore, the existence of inter-correlations amongst the various indicators cannot meet the requirement of ecological instream flow with consideration of nonstationary changes. Therefore, ecological instream flow (eco-surplus and eco-deficit) under influences of abrupt streamflow behaviors were analyzed use Flow Duration Curve (FDC) based on daily streamflow data at 7 stations during 1956–2016 and daily precipitation data at 72 stations during 1960–2016 in the Hua River basin (HRB).

The objectives of this study are: (1) to quantify the relations between ecological instream flow (eco-surplus and eco-deficit), ecological indicators (Shannon index) and IHA; and (2) to evaluate ecological instream flow of HRB. (3) Besides, we also quantified fractional contributions of nonstationary climatic factor to ecological instream flow using GAMLSS framework and the impact of Spatial transformation of land-use type. Potential causes such as climate change and land-use change behind hydrological variations and ecological impacts are also discussed.

2. Study Area and Data

The Hua River basin (HRB), is one of the seven major rivers in China, is located exactly in a climate transition zone between the Yangtze River and the Yellow River. (Figure 1 in this study). To the north of the huia River is a warm temperate zone with a semi-humid monsoon climate, and to the south is a north subtropical humid monsoon climate. The HRB is also a commodity grain base and an important energy source in China. The population density of 662 persons per km^2 in the HRB is the highest among the seven major rivers in China [25]. What is more, the rainy season, affected by the East Asian monsoon, is mainly from May to September in the HRB. The changing climate and human activities have caused natural disasters such as waterlogging, drought, and floods [42,43].

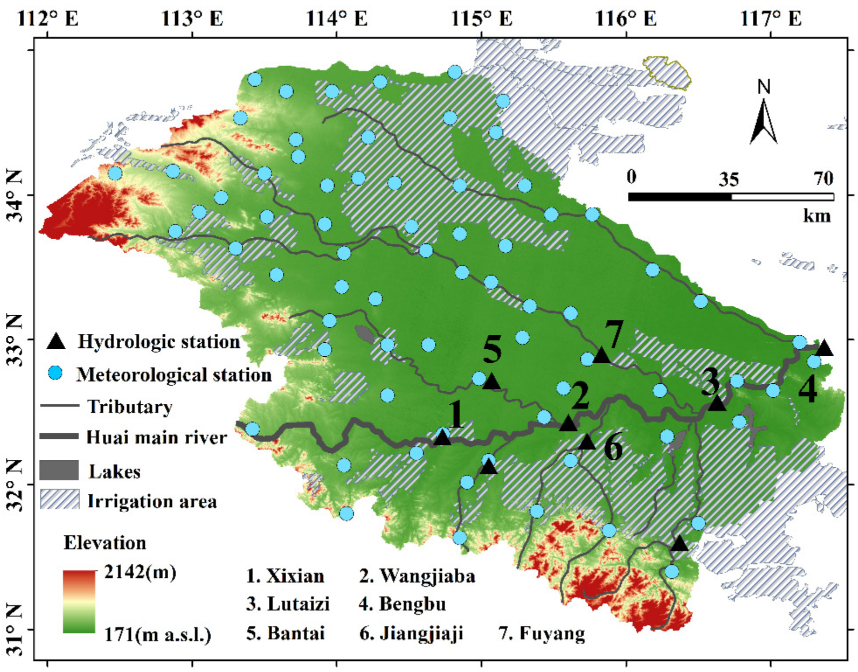

Figure 1. Locations of the hydrological and meteorological stations in the HRB.

The daily streamflow series from 1956 to 2016 at 7 hydrological stations were selected to calculate ecological instream flow in the HRB (Table 1). These data were obtained from the Water Resources Research Institute of Anhui Province and Hua River China [44]. The daily precipitation of 72 meteorological stations from 1960 to 2016 were provided by China Meteorological Administration. The land use data from the HRB in 2000, 2005, 2010 and 2015 were derived from the Chinese land use status monitoring database provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The data were extracted from Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) remote sensing images and generated through artificial visual interpretation with a spatial resolution of 1 km. Land use types included six primary types (cultivated land, forest, grassland, water bodies, artificial surfaces, and unused land) and 25 secondary types. Monthly climate factors such as Sea Surface Temperature (SST) data, North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO) were obtained from NOAA Physical Sciences Laboratory (PSL) dataset (https://psl.noaa.gov/data/).

Table 1. Locations of the hydrological stations considered in this study and related geographical features.

	River	Hydrological Station	Basin Area/km^2	Length of River/km	Slope of River Bed/%	Annual Runoff/10^8 m^3	Mean Annual Runoff Depth/mm
Main river	Upstream	Xixian	10,190	250	4.9	62.2	60.8
	Midstream	Wangjiaba	30,630	364	0.35	99.8	32.5
	Midstream	Lutaizi	88,630	529	0.3	250	28.2
	Midstream	Bengbu	121,330	651	0.3	299	24.6
Branch	Hong Ru River	Bantai	11,663	240	1	28.1	24.0
	Shi Guan River	Jiangjiaji	5930	172	9.2	31.5	53.1
	Sha Ying River	Fuyang	35,250	490	0.03	55.6	15.7

The working procedure in this study is shown in Figure 2. Firstly, different time periods of the daily streamflow data during 1956–2016 were divided using the Pettitt test [45] at 7 hydrological stations in the Huai River Basin (HRB). Secondly, on annual and seasonal scales, the area enclosed by more than 75% of FDC is defined as eco-surplus and the area enclosed by more than 25% of FDC is defined as the eco-deficit [4]. The eco-surplus and eco-deficit were defined as ecological instream flow indicators [3]. Thirdly, ecological instream, calculated by FDC, were used to verify the applicability by the IHA32 indicators and Shannon index. Finally, the relationship between climatic factors and ecological instream flow was constructed by GAMLSS framework and in order to reveal the impact of climatic factors and land use change on ecological instream flow.

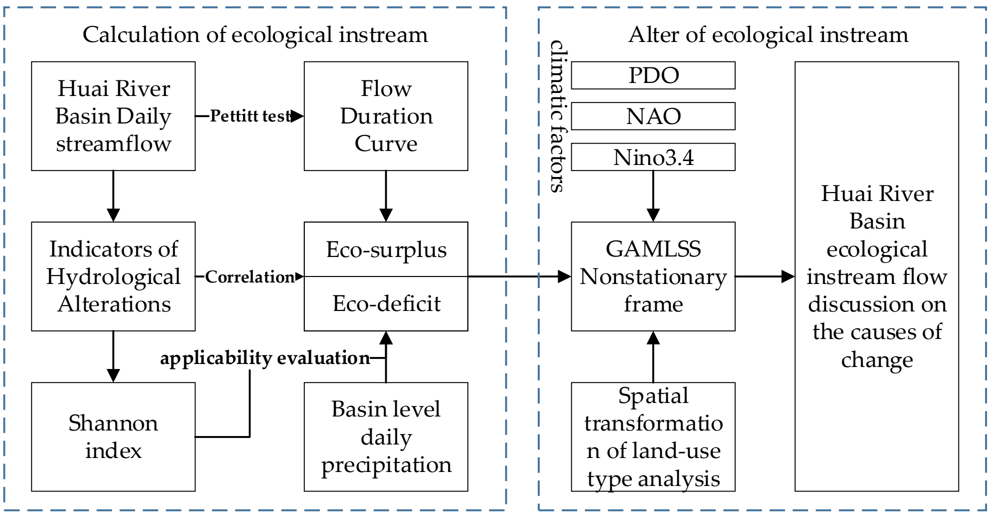

Figure 2. Working procedure for the calculation and change of ecological instream flow.

3. Methods

3.1. Eco-Surplus and Eco-Deficit

Vogel et al. [46] developed eco-surplus and eco-deficit to evaluate the ecological instream flow regimes of a river basin. Eco-surplus and eco-deficit was computed based on the Flow Duration Curve (FDC), which was constructed using daily streamflow, showing the percentage of time for daily streamflow exceeding or equaling the pre-defined streamflow threshold. Daily streamflow, Q_i was sorted in descending order and the exceeding probability was computed [1]:

$$p_i = i/(n+1) \tag{1}$$

where i is the rank and n is the sample size of observed daily streamflow, Q_i. FDC can be taken as a function with Q_i as the dependent variable and pi as the independent variable. Before analysis, daily streamflow data during 1956–2016 at 7 hydrological stations in the Huai River Basin (HRB) covering a period of 1956–2016 were subdivided into two subseries by taking the alter point using the Pettitt test [45]. The area enclosed by more than 75% of FDC is defined as eco-surplus and the area enclosed by more than 25% of FDC is defined as the eco-deficit. The eco-surplus and eco-deficit were defined as ecological instream flow indicators [1].

3.2. Hydrological Alterations

The Indicator of Hydrological Alterations (IHA) were used to evaluate the degree of hydrological alterations. The zero-flow have not been monitored in the HRB, and the indicator of “the number of zero-flow days” was removed in this study. Every indicator is ecologically relevant (Table 2) [1,24,47,48]. The daily streamflow data during 1956–2016 at 7 hydrological stations in the HRB were used in this study.

3.3. Indicators for Evaluation of Ecological Diversity

Shannon Index (SI) is widely used in the evaluation of ecological diversity [1,49]:

$$SI = -\sum_i p_i \times \log p_i \tag{2}$$

where p_i is the percentage of a kind of biota to the ith species. The larger the SI, the higher the ecological diversity. Yang et al. [50] built the optimal relations between 33 indicators of IHA33 and SI, i.e.,

$$SI = \frac{D_{\min}/Min7 + D_{\min}}{Q_3 + Q_5 + Min3 + 2 \times Max3} + R_{rate} \tag{3}$$

where $D_{\min}$ denotes the Julian date of the smallest one-day streamflow; $Min3$ and $Min7$ denote, respectively, the smallest three- and seven-day stream flows; $Max3$ denotes the largest three-day streamflow; Q_3 and Q_5 denote the stream flows during March and May, respectively; and Rrate denotes the mean positive difference between stream flows of consecutive days [6].

Table 2. IHA33-based indicators and related ecologically relevant implications.

IHA Parameter Group	Hydrological Parameters	Ecosystem Influences
Group 1: Magnitude of monthly water conditions	Meadin value for each calendar month	Habitat availability for aquatic organisms Soil moisture availability for plants Availability of water for terrestrial animals
Group 2: Magnitude and duration of annual extreme water conditions	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means Base flow index: 7-day minimum flow/mean flow for year	Balance of competitive, ruderal and stress tolerant organisms Creation of sites for plant colonization Structuring of aquatic ecosystems by abiotic vs. biotic factors Structuring of river channel morphology and physical habitat conditions
Group 3: Timing of annual extreme water conditions	Julian date of each annual 1 day maximum Julian date of each annual 1 day minimum	Compatibility with life cycles of organisms Predictability/avoidability of stress for organisms Access to special habitats during reproduction or to avoid predation Frequency and magnitude of soil moisture stress for plants
Group 4: Frequency and duration of high and low pulses	Number of high pulse esch year Number of low pulse each year Mean duration of high pulses within each year Mean duration of low pulses within each year	Frequency and magnitude of soil moisture stress for plants Frequency and duration of anaerobic stress for plants Availability of floodplain habitats for aquatic organisms Nutrient and organic matter exchanges between river and floodplain
Group 5: Rate and frequency of water condition changes	Rise rates: mean of all positive differences between consecutive daily values Fall rates: mean of all negative differences magnitude between consecutive daily values Number of hydrologic reversals	Drought stress on plants Entrapment of organisms on islands, floodplains Desiccation stress on low-mobility stream edge (varial zone) organisms

3.4. GAMLSS Model

The GAMLSS (Generalized Additive Model for Location Scale and Shape) model was proposed by Vogel et al. [46] to evaluate stationary and nonstationary of a time series [51]. In the GAMLSS model, the ecological instream flow time series of $y_1, y_2, \ldots, y_n$ is assumed to be independent and follows the distribution function of $FY(y_i \mid \theta_i)$, and $\theta_i = (\theta_1, \theta_2, \ldots, \theta_p)$ denotes the vector with p parameter, such as location, scale and shape. Here $g_k(.)$ is defined as a monotonic functional relation between the explanatory variable, θ_k, and the random component, X_k, as [23]:

$$g_k(\theta_k) = \eta_k = X_k\beta_k + \sum_{j=1}^{J_k} Z_{jk}\gamma_{jk} \quad (4)$$

where η_k and θ_k are vectors with sample size of n; $\beta_k^T = \{\beta_{1k}, \beta_{2k}, \ldots, \beta_{J_k k}\}$ is the parameter vector with sample size of J_k; X_k is the matrix of the explanatory variable with length of $n \times J_k$; Z_{jk} is the fixed design matrix of $n \times q_{jk}$; γ_{jk} is the variable following the standard normal distribution. Without considering the impact of random effects on the distribution parameters, let J_k = 0, and Equation (4) is deduced as [28]:

$$g_k(\theta_k) = \eta_k = X_k\beta_k \quad (5)$$

When t is the explanatory variable, the explanatory variable matrix can be [28]:

$$X_k = \begin{bmatrix} 1 & t & \ldots & t^{I_k-1} \\ 1 & t & \ldots & t^{I_k-1} \\ 1 & t & \ldots & t^{I_k-1} \\ 1 & t & \ldots & t^{I_k-1} \end{bmatrix}_{n\times I_k} \quad (6)$$

Putting Equation (5) into Equation (6), one can obtain the functional relations between distribution parameters and explanatory variable of t as [28]:

$$\begin{aligned} g_1(\mu_t) = g_1[\mu(t)] = \beta_{11} + \beta_{12}t + \ldots + \beta_{I_11}t^{I_1-1} \\ g_1(\sigma_t) = g_1[\sigma(t)] = \beta_{11} + \beta_{12}t + \ldots + \beta_{I_11}t^{I_1-1} \\ g_1(\nu_t) = g_1[\nu(t)] = \beta_{11} + \beta_{12}t + \ldots + \beta_{I_11}t^{I_1-1} \end{aligned} \quad (7)$$

In this study, functional relations were built between the distribution matrix of the ecological instream flow time series and climatic factors. Many studies have shown that NAO, PDO and ENSO have a strong correlation with precipitation and instream flow in eastern China, Exponential Gaussian distribution (exGAUS), Power exponential distribution (PE), Normal family distribution (NOF) and t family distribution (TF) were used investigate the climate factors (NAO, PDO and ENSO) effect on ecological instream flow. The parameters of location, scale and shape in GAMLSS was NAO, PDO and ENSO.

4. Results

4.1. Changes in the Ecological Instream Flow

Streamflow variations are driven mainly by precipitation changes in the HRB. Hence, Seasonal changes in streamflow is caused by variation of seasonal precipitation [27]. Abrupt behaviors of ecological instream flow in the seven hydrological stations are shown in the Figure 3. It can be seen from Figure 3 that the change point can be observed in 1970 in Fuyang and Jiangjiaji stations. While the change point can be found in 1991 in the Xixian station. The other stations of ecological instream flow can be detected around 2000. Therefore, based on the change points in Figure 3 It can be seen that, from annual time scale viewpoint, the variation range of FDC before and after change point is similar. The high flow and low flow after change point were greater than that before change point in Figure 4. However, there is a large difference in the variation range of high and low flow on a seasonal scale. Especially in the spring and winter, the magnitude and frequency of high flow showed a significantly decreasing trend after change point, while the magnitude and frequency of low flow showed a significantly increasing trend. Hence, increased ecological deficit and decreased ecological surplus can be caused by low flows in spring and winter. FDC has a higher variation range of high and low flow in the mainstream of HRB than that in the tributary on the annual and seasonal.

Although the change of the FDC curve can be used to illustrate the change of ecological instream flow (Figure 4). Streamflow variations are driven mainly by precipitation changes in the HRB [3,4,46]. The influence of precipitation on ecological instream flow should be further analyzed. The variation of ecological instream flow (e.g., eco-surplus and eco-deficit) and the average precipitation anomalies in the corresponding watershed of hydrological stations on the annual and seasonal scale as shown in Figure 5. The annual ecological instream flow is consistent with the annual precipitation change, and the correlation coefficient between ecological instream flow and average precipitation anomalies is more than 0.24 (p < 0.1). Moreover, the correlation between ecological instream flow and average precipitation anomalies in the mainstream of HRB (R^2 = 0.40) is higher than that in the tributary of HRB ($R^2 = 0.30$). The correlation of ecological instream flow is highest ($R^2 = 0.45$) in the Lutaizi station, and JiangJiaji station had the lowest correlation ($R^2 = 0.24$) at the annual scale. It can be seen that, from season scale viewpoint, the correlation coefficient between ecological instream flow and precipitation anomalies in spring is the highest ($r > 0.47$, $p < 0.01$), and the lowest in the summer. The correlations of Jiangjiaji and Fuyang stations, located in the tributaries of HRB, is only 0.08 and 0.09 ($p < 0.01$) in the summer. The irrigation area, located in the Jiangjiaji station of Shiguanhe and Fuyang station of Shayinghe, are respectively 1013 km^2 and 1340 km^2. Hence, the Human irrigation area has a greater impact on ecological instream flow. Moreover, summer is the flood season of the HRB, and a large number of reservoirs and flood storage areas, established around the mainstream of HRB, regulated and stored runoff formed by precipitation in the basin.

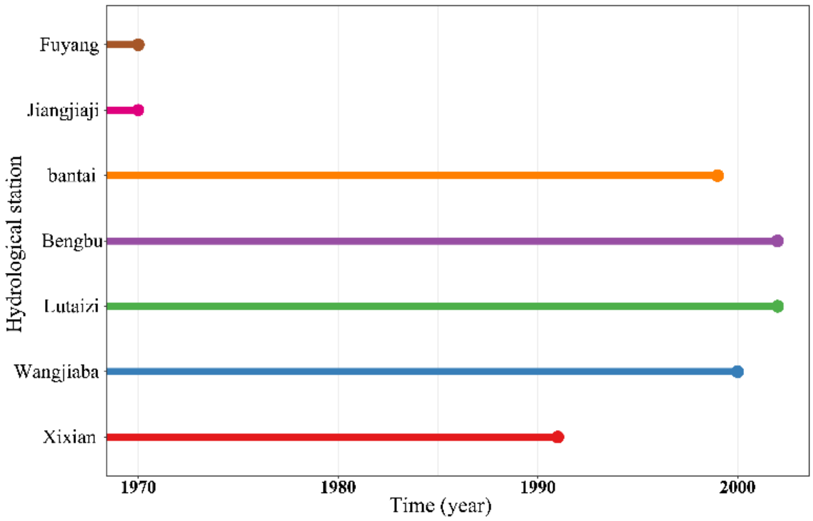

Figure 3. Results of Pettitt test in seven hydrological stations in HRB.

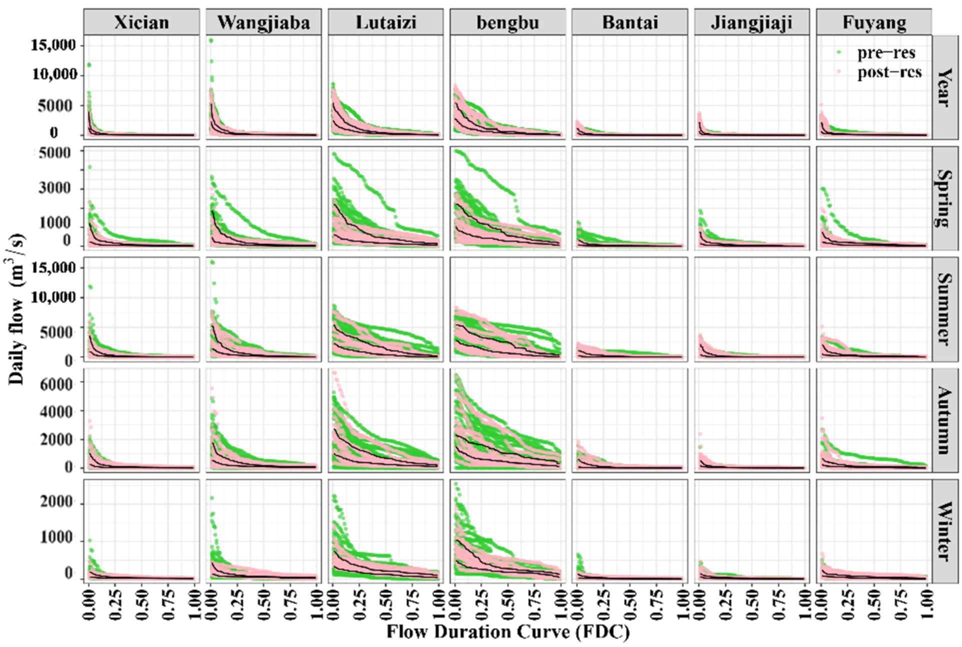

Figure 4. Seasonal and annual FDC before and after change points.

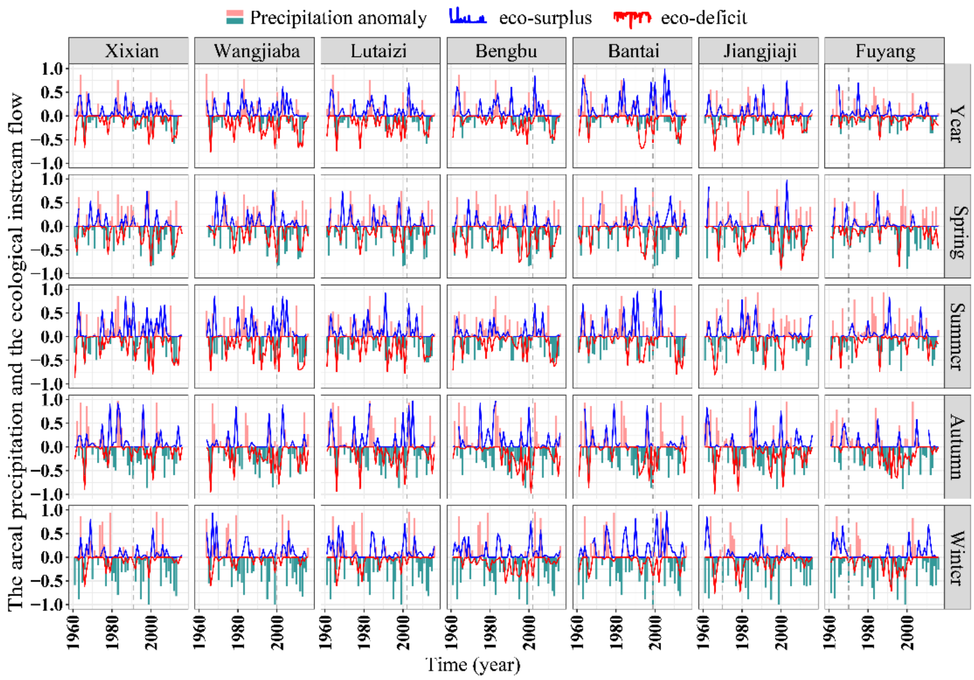

Figure 5. Temporal variations of the difference of the area precipitation and the ecological instream flow across the HRB.

In order to further analyze the relationship between eco-deficit, eco-surplus and precipitation, the coefficients of variation (Cv) of eco-deficit, eco-surplus and precipitation at different time scales were calculated. The coefficient of variation of winter precipitation is the largest (0.73), while the coefficient of variation of annual precipitation (0.27) is the smallest. The variation in eco-deficit is much smaller than the variation in eco-surplus. Moreover, the changing pattern of eco-deficit is consistent with that of precipitation. The largest variation of precipitation causes a large change in eco-deficit in winter. However, the eco-surplus is mainly related to the water demand for industrial and agricultural production. Spring is the water demand period of winter wheat in the HRB, and winter is low agricultural water consumption. Therefore, a large amount of agricultural water demand causes the eco-surplus Cv highest in spring, and the eco-surplus is the smallest in winter.

The FDC scatter plots of the ecological instream flow before and after change point on the years and seasonal scales are shown in Figures 6 and 7. The annual eco-deficit showed an increasing trend on the annual scale (Figure 6). Except for the Fuyang Station, the eco-deficits of other stations in the HRB were the largest in the 1990s and 2010s. From a seasonal viewpoint, the variation of the eco-deficit in spring, summer and autumn is consistent with that on the annual scale, showing an increasing trend. while the eco-surplus shows a decreasing trend. The agricultural drought in the HRB increased in April and May [25]. Therefore, the ecological instream flow in spring was dominated by eco-deficit. when Agricultural water demand is large in the Spring season, and the magnitude of eco-deficit flow is much larger than that of eco-surplus (Figure 7), showing the positive impact of hydraulic engineering regulation and agricultural water demand on eco-deficit. As a result of the more precipitation, the ecological deficit has an increasing trend in the summer, and the eco-surplus shows a “low-high-low” change. However, the ecological instream flow in winter is opposite to the annual and other seasonal scale changes. The mainstream is decreasing and the Bantai station of the tributaries is showing an increasing trend. The eco-deficit showed a “low-high-low” change trend, which reached a maximum in the 1990s. What is more, Bengbu and Fuyang stations having the highest eco-deficits, reaching 0.65 and 0.66, respectively. In summary, except for winter, the eco-deficits in the HRB are increasing on the annual and seasonal scale, especially in spring. The eco-surplus is decreasing on the annual and seasonal scale and is the lowest since the 2000s in the mainstream of the HRB.

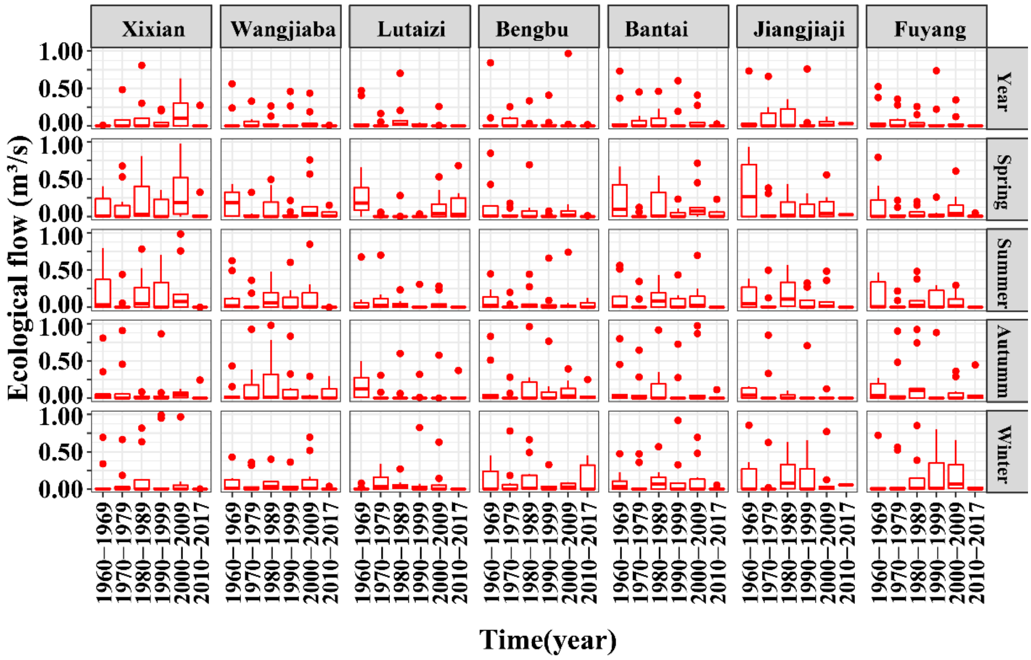

Figure 6. Change of the eco-deficit on the annual and seasonal scale.

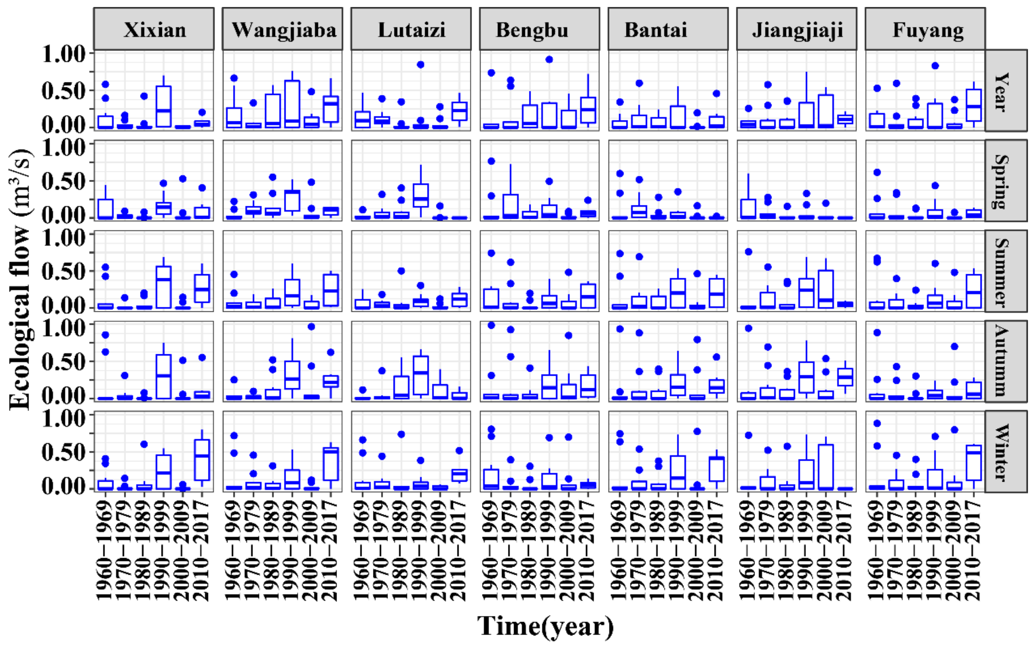

Figure 7. Change of the eco-surplus on the annual and seasonal scale.

4.2. *Impacts of Ecological Instream Flow Changes on Biodiversity*

The regression fitting curve of the seasonal ecological instream flow using locally weighted polynomials as shown in Figures 8 and 9. The eco-surplus is greater than the eco-deficit. Except for Fuyang Station, the eco-surplus of other stations shows a downward trend. Eco-surplus began to decline rapidly after 2000 and was lower than the ecological deficit after 2016. However, eco-deficit has an increasing trend and increased significantly after 1980. After 2000, the eco-surplus was nearly zero. Except for Jiangjiaji Station, the eco-deficits exceeded the eco-surplus in 2016, which shows that the ecological water demand is becoming increasingly serious in the HRB. Eco-surplus has always been higher than the eco-deficit in the Jiangjiaji station. The main reason is that JiangJiaji station of Pihe river is located in one of the three super-large irrigation districts in China, designed irrigation area is 7987 km^2. The Pihe River runoff is significantly regulated by water conservancy projects. Therefore, eco-surplus has a little change since 1980.

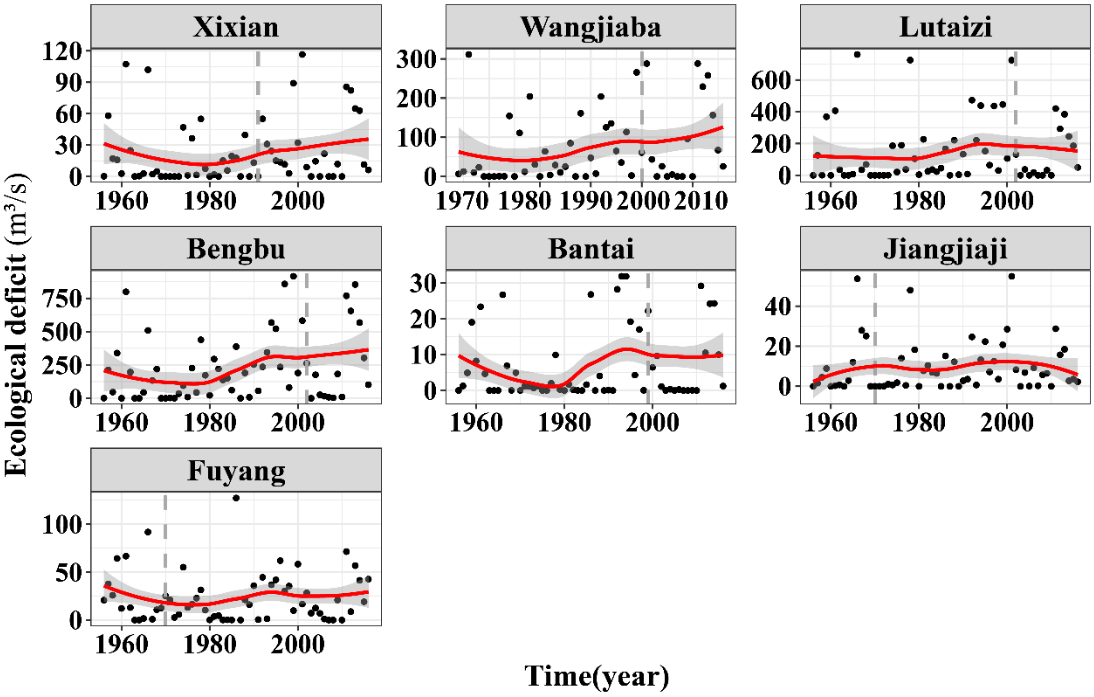

Figure 8. The trend change of the eco-deficit in the HRB.

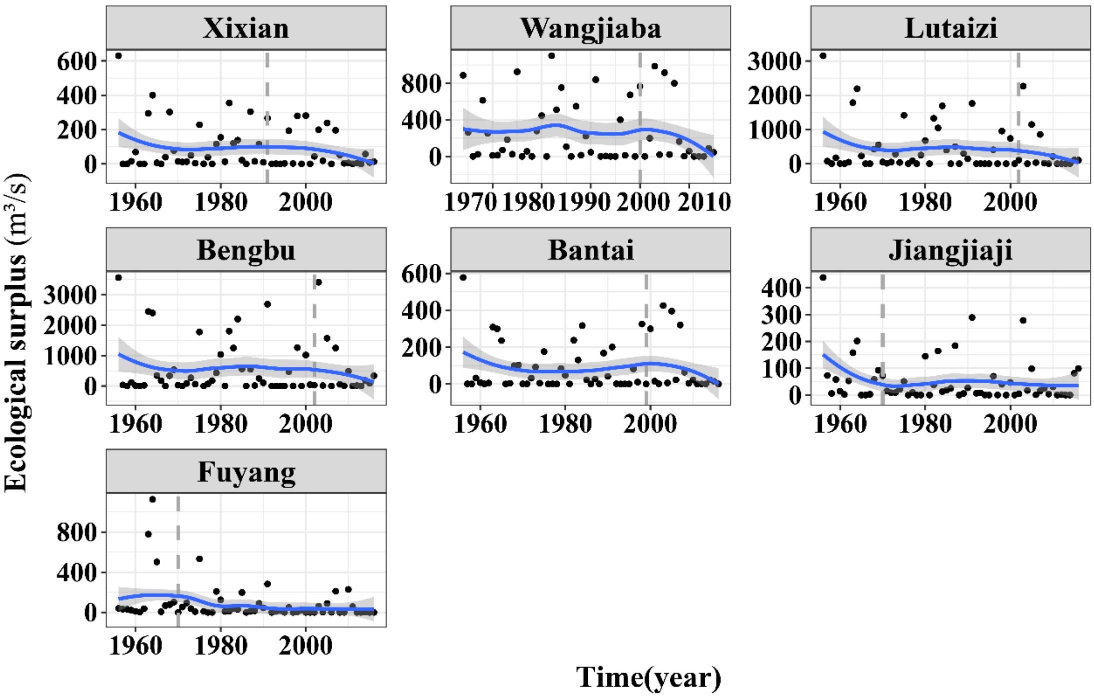

Figure 9. The trend change of the eco-surplus in the HRB.

The Shannon Index, a biodiversity indicator calculated using IHA runoff change indicators, as shown in Figure 10. The seasonal eco-deficit in the mainstream of HRB was a significantly negative correlation with the Shannon index ($r < -0.17$) but was no significant negative correlation with the Shannon in the tributary of HRB. While eco-surplus and Shannon index showed a negative correlation in Fuyang station, other stations showed a significant positive correlation in the HRB. The streamflow in Fuyang station, located in the Shaying River basin, is affected by industrial sewage, agriculture water consumption and abuse of pesticides and fertilizers [52,53]. The human activities make the biodiversity lowest, and the relationship with the ecological instream flow is not significant in the Shaying River Basin (Figure 10). The seasonal eco-surplus showed a significant downward trend before 1970 in the HRB. However, biodiversity began to decline significantly after the expansion of the Bengbu gate in 2000.

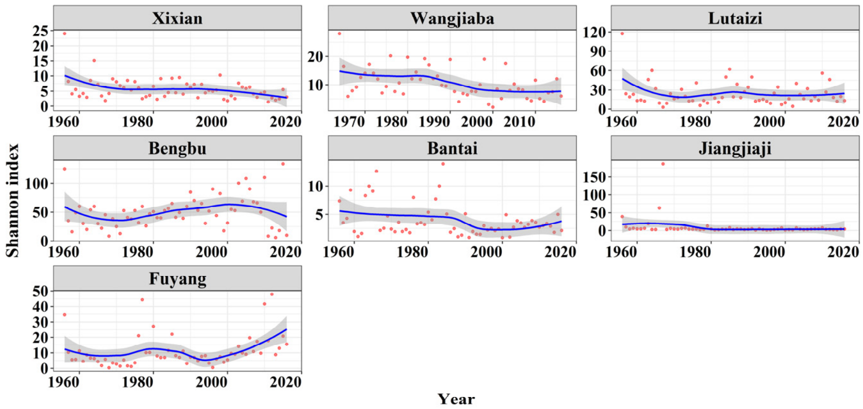

Figure 10. The trend change of Shannon index in the HRB.

Chen et al. [54] have carried out experiments to measure river microorganisms at the hydrological station of the HRB and calculated the index of biodiversity. Therefore, three stations in Bengbu, Lutaizi and Fuyang were selected to verify the SI index (Figure 11). The characteristic change of the Shannon index is consistent with the season eco-surplus, the correlation coefficient is more than 0.31 except for Fuyang station (Figure 12). The correlation analysis between the measured and calculated biodiversity indicators and the Shannon index, eco-surplus, eco-deficit and IHA-SI. The results showed that there was a significant correlation between the measured biodiversity indices and IHA-SI, the correlation coefficient was 0.74 ($p < 0.1$) (Figure 11a). The correlation coefficient between biodiversity and eco-deficit was -0.67 ($p < 0.1$) (Figure 11b), and that between biodiversity and eco-surplus was 0.64 ($p < 0.1$) (Figure 11c). The results showed that the biodiversity indices were significantly correlated with the ecological instream flow, IHA-SI. Hence, the IHA-SI and ecological instream flow can well indicate the change of ecological in the HRB.

4.3. Comparison Between Ecologically-Relevant Hydrological Indicators and IHA33

The correlations between all ecological instream flow indicators and IHA33 indicators are shown in the Figure 13. It is can be seen that the ecological instream flow indicator showed significant positive or negative correlations with IHA32 indicators. Since the selected hydrological station in the HRB was not surfaced, the number of zero flow days of IHA33 indicators was ignored. Specifically, the monthly streamflow during June and July are in significant correlation ($r > 0.54$, $p < 0.01$) with values of summer eco-surplus, all seasonal eco-surplus, all seasonal eco-deficit, annual eco-surplus and annual eco-deficit and also total seasonal eco-surplus. Besides, positive correlations can also be detected between all seasonal annual eco-deficit, eco-deficit and maximum 1-day, 3-day, 7-day, 30-day and 90-day streamflows and also with minimum 1-day, 3-day, 7-day, 30-day and 90-day streamflows ($r > 0.61$, $p < 0.01$). However, the total seasonal eco-surplus has a negative correlation with most IHA indicators. The Shannon indicator showed a significant positive correlation with HPL (r = 0.78, $p < 0.01$), and a significant negative correlation with Rise (r = 0.71, $p < 0.01$). The correlation between Low Peak Number (LPN), Low Peak Long (LPL), Reversal (RL), Date of Maximum Flow (Dmax), Date of Minimum Flow (Dmin) and the ecological instream flow indicator is not significant. This shows that the ecological instream flow indicator can only reflect the change information of flow on a larger scale, but for some extreme events, it cannot accurately reflect. Besides, the ecological instream flow indicator can accurately reflect the information of the IHA indicator. Therefore, the ecological instream flow indicator can be used in the HRB.

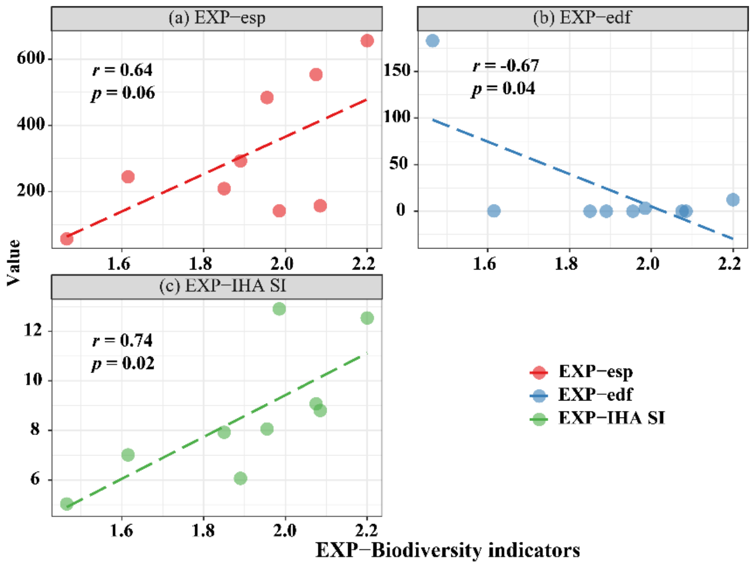

Figure 11. The correlation between measured and calculated biodiversity index, IHA-SI and ecological instream flow.

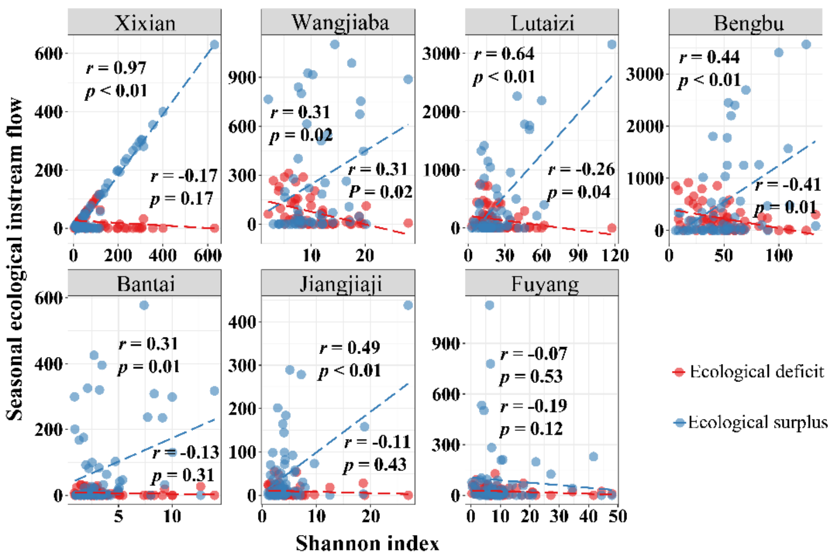

Figure 12. The correlation between seasonal ecological instream flow and Shannon index.

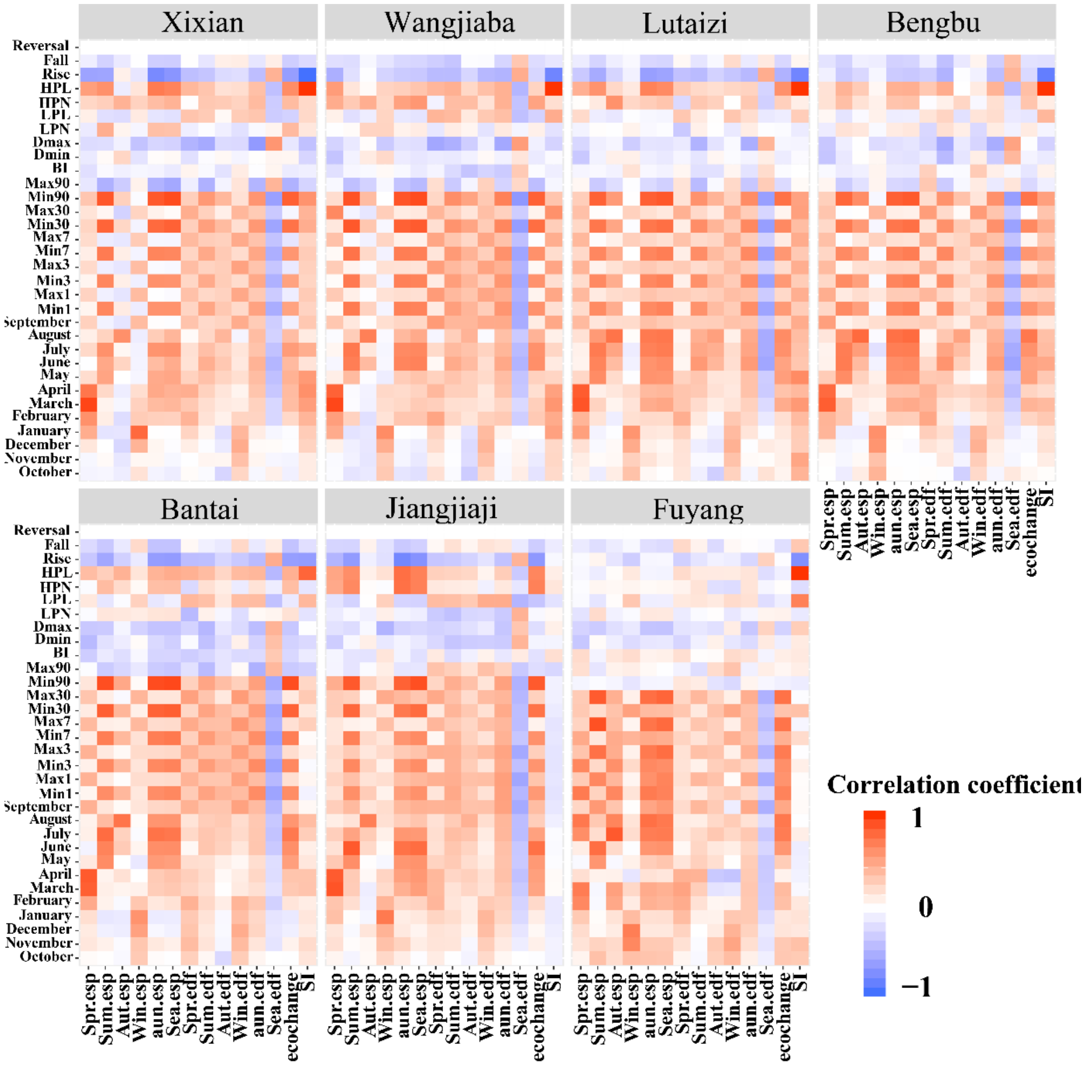

Figure 13. Correlations between ecological instream flow and IHA (Indicators of Hydrologic Alteration) in the HRB.

4.4. Potential Impacts of Climate Factors on Ecological Instream Flow

From the above section we can see that changes of ecological instream flow might be caused by the change of climate change (e.g., climate factors) and human activities (e.g., land use change, reservoir operation). The HRB is located in the humid and semi-humid monsoon climate region of eastern China, therefore, ecological instream flow is vulnerable to affect by climate factors. Based on nonstationarity theory, ecological instream flow indicators, consider with time and climate factors as location, scale and shape parameters, were constructed by the GAMLSS model. Table 3 shows that the best performance distribution function was selected by the Akaike information criterion (AIC) [55] model and nonstationary ecological instream flow was calculated for each station in the HRB. According to the AIC values, Model 2, considering only PDO, is the best performance in the Jiangjiji station and Model 8 is the second-best performance. However, Model 8, considering PDO, NAO and Nino3.4, is the best performance in other stations except for Fuyang station. The position parameters, scale parameters and shape parameters of the probability distribution function are affected by PDO, NAO and Nino3.4, respectively. Besides, the appropriate ecological instream flow model is Model 1 and ecological instream flow was not significantly affected by climatic factors. Although the optimal model of ecological instream flow in the HRB is not consistent. According to the mean AIC values, Model 8 is the best fitting with the lowest AIC value in the HRB.

Table 3. GAMLS results and AIC values.

Hydrologicalstation	Xixian	Wangjiaba	Lutaizi	Bengbu	Bantai	Jiangjiaji	Fuyang	Mean of AIC
Model	PE	exGAUS	exGAUS	exGAUS	NOF	TF	TF	
Model 1 (Stationary)	24.0	44.4	36.3	19.2	**51.0**	21.6	25.2	31.7
Model 2 (μ = PDO)	25.7	46.0	38.2	19.3	53.0	**19.5**	25.2	32.4
Model 3 (σ = NAO)	24.9	44.1	38.2	20.2	52.8	23.5	25.0	32.7
Model 4 (v = Nino3.4)	25.8	45.4	39.0	17.9	52.9	20.3	24.0	32.2
Model 5 (μ = PDO, σ = NAO)	28.2	46.8	37.0	17.7	54.3	20.9	24.7	32.8
Model 6 (μ = PDO, v = Nino3.4)	23.5	47.0	37.2	17.1	54.0	22.0	**23.9**	32.1
Model 7 (σ = NAO, v = Nino3.4)	**22.5**	48.9	37.3	18.7	54.3	22.3	24.4	32.6
Model 8 (μ = PDO, σ = NAO, v = Nino3.4)	23.1	**44.0**	**35.3**	**17.0**	52.3	19.6	24.7	**30.9**
Difference between the optimal and Model1	1.6	0.4	1.0	2.2	0.0	2.1	1.3	

AIC: Akaike information criterion; PE: Power Exponent; exGUAS: Exponential Gaussian; NOF: Normal Family; TF: *t* Family.

Figures 14 and 15 is shown centile curves of ecological instream flow considering the time (Figure 14a–g are Xixian, Wangjiaba, Lutaizi, Bengbu, Bantai, Jiangjiaji and Fuyang station) and climate factors (Figure 15a–g are Xixian, Wangjiaba, Lutaizi, Bengbu, Bantai, Jiangjiaji and Fuyang station) respectively. It can be detected that centile curves of ecological instream flow considering the time can describe the fluctuations and changes of ecological instream flow, but it does not fit well for some extreme values. What is more, the actual centile curve is significantly different from the centile curve constructed by the Gamlss model (Figure 14). Especially, the simulation centile curve of ecological instream flow is extremely unreasonable to the extreme flow series in Bengbu and Fuyang stations. However, based on the ecological instream flow simulated by the GAMLSS model with consideration of climate factors, the non-stationary change can well describe the change of extreme flow (Figure 15). For example, the extreme ecological instream flow in the Fuyang Station (Figure 15g) in 1965 can be well simulated after considering climate factors, while the changes of ecological instream flow (Figure 14g) without climate factors do not simulate the actual ecological instream flow. Therefore, it is reasonable to use the GAMLSS model framework to analyze ecological instream flow in the HRB.

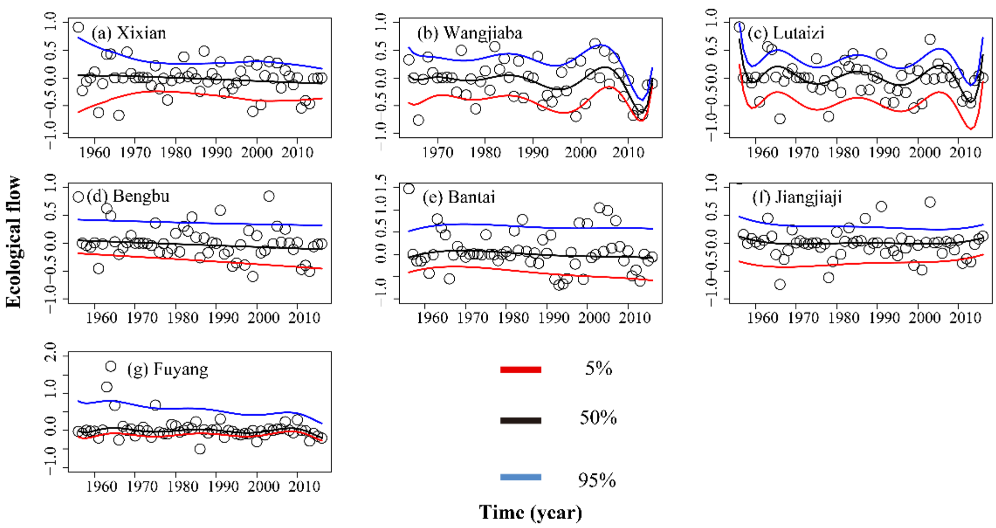

Figure 14. Centile curves of stationary ecological instream flow.

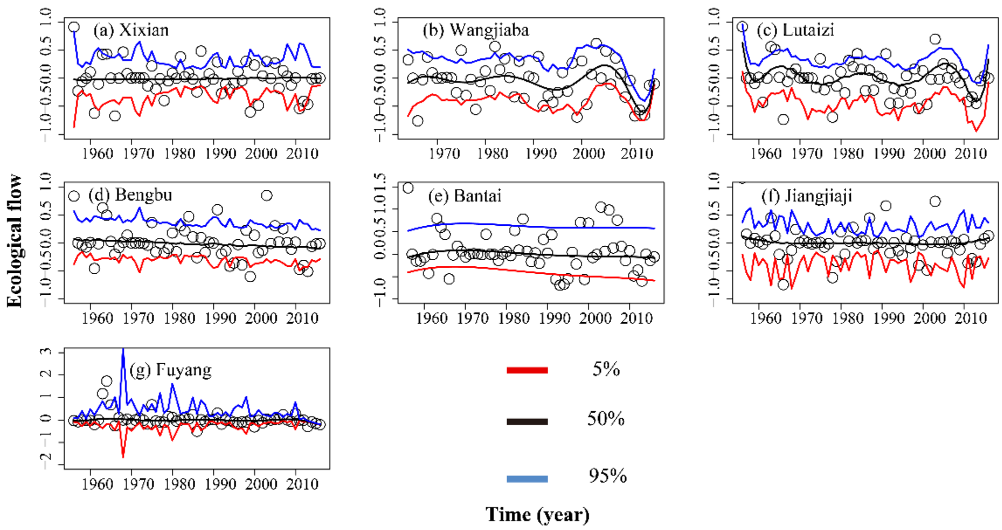

Figure 15. Centile curves of nonstationary ecological instream flow with climate factors.

5. Discussion

Many people use this method to discuss runoff and biodiversity [1,3,56]. Zhang et al. [1,3] discussed the evaluation of ecological discharge change in the Yellow River Basin and the Pearl River Delta based on hydrological changes. The ecological instream flow commonly showed a decreasing trend. The ecological instream flow indicators showed a decreasing trend in the mainstream of the Huai River except for Xixian station (Figure 10), illustrating that the contradictions between socio-economic, agricultural water consumption and ecological water demand are becoming increasingly prominent (Figure 16e). The total irrigated area of Henan and Anhui provinces has increased from 3.6×10^4 km^2 in 1991 to 3.79×10^4 km^2 in 2016 in the HRB, and the total agricultural population has increased from 83.421 million to 97.518 million [57]. Meanwhile, Figure 16 shows that land cover changed between the periods of 2000 and 2015 has shown that grassland from 3.20% to 3.24%, water bodies from 2.71% to 2.89%, and the artificial surfaces area has increased from 11.73% to 12.91%, but forest area has decreased from 10.86% to 10.83% (Figure 16a–d). The riverbed ratios of the two stations of Pantai and Fuyang are 1 and 1/3000 respectively, the annual runoff depth is 24.6 mm and 15.7 mm, and the water resources are relatively small. has The maximum farmland transforming to artificial surfaces occurred in the Fuyang station [40]. Therefore, Industrial and agriculture water consumption have caused a continuous downward trend in ecological instream flow in the Fuyang station.

Moreover, Sun et al. [28] found that the flow in the upper and middle reaches of the HRB varies drastically from year to year, the overall flow is in a downward trend, and the low flow in the upper reaches is increasing, and the middle reaches are decreasing [58]. Pan et al. [32] used the intra-year deployment method and found that the upstream area of the HRB has a higher degree of ecological security than the downstream area, and the ecological instream flow demand of the tributaries on the north bank of the HRB is showing a downward trend. Liu et al. [33] and Yu et al. [17] used the ecological hydraulic radius and wet cycle method to evaluate the minimum ecological instream flow demand of the Jialu River, and both are decreasing year by year Studies by Zuo et al. [53] and others indicate that the flow ecology in the upper and middle reaches of the HRB is seriously degraded. These researches only illustrate the decline in the ecological instream flow demand of the HRB from the perspective of water demand, without considering the impact of non-stationary and land-use changes. However, this study used the GAMlSS framework combined with the non-stationary impact of climate factors on ecological instream flow and the impact of land use changes on changes in ecological water demand, to explain the reasons for changes in ecological instream flow from these two aspects, which were not available in previous studies.

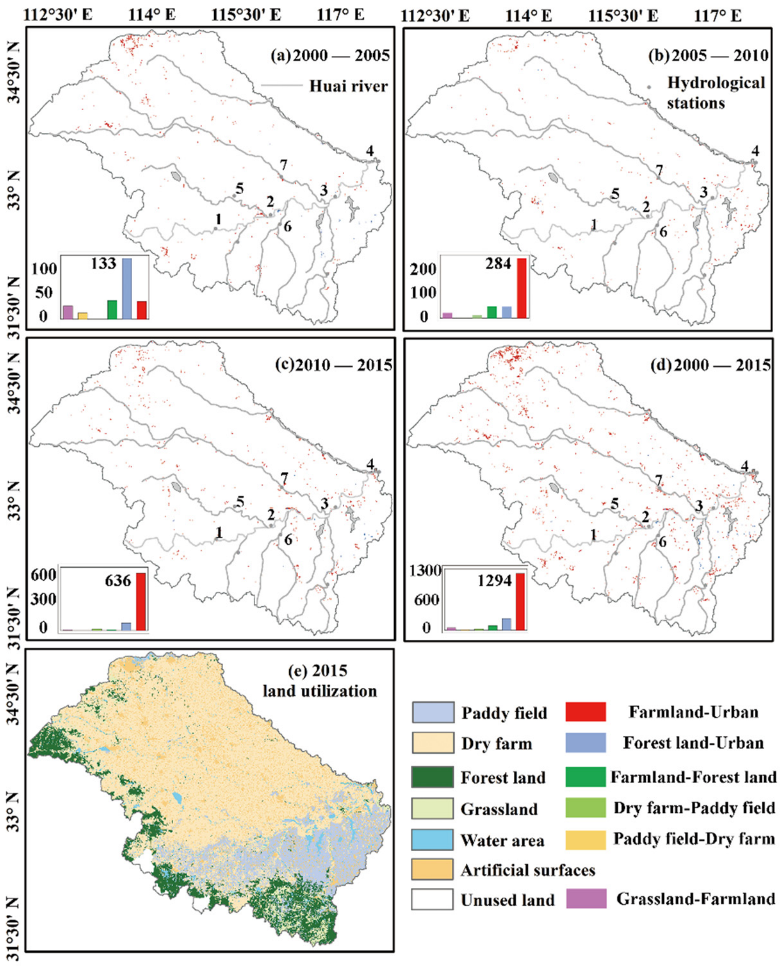

Figure 16. Spatial transformation variation map of land-use type of the HRB.

6. Conclusions

Using long-term daily streamflow series from 1956 to 2016, the eco-surplus and eco-deficit at seven hydrological stations were calculated and compared with the flow duration curve (FDC) and Indicator of Hydrological Alterations (IHA). The characteristics and attribution for the ecological instream flow changes were analyzed based on ecological instream flow indicates, annual and seasonal precipitation anomalies, land use change and the possible impacts behind the changes were discussed. The major findings can be drawn from this study:

(1) Using Pettitt non-parametric test method to detect the daily runoff change point time, the trend has a Significantly hydrological alterations in the HRB. The eco-surplus has a decreased trend when compared to those before hydrological alteration occurred and the eco-deficit was also found to decrease after the change point, and the eco-deficit in the mainstream has a significantly increasing trend than that in the tributary. Meanwhile, regional precipitation is the primary factor for the variation of eco-surplus and eco-deficit on the annual scale. Moreover, eco-surplus and eco-deficit are significantly correlated with precipitation in spring, autumn and winter. However, summer precipitation anomalies are not inconsistent with the variations of ecological instream flow indices in the Jiangjiaji and Fuyang stations, which resulted from the reservoir regulation and vegetation interception.

(2) The most noticeable change in the Shannon Index calculated by IHA was the decrease, indicating that the biodiversity of the HRB was decreasing. Besides, the Shannon index was significantly positively correlated with the eco-surplus except Fuyang station ($r > 0.31$, $p < 0.01$) and negatively correlated with eco-deficit ($r > 0.31$, $p < 0.01$).

There is a good correlation between IHA32 hydrological indicators and ecological instream flow indices, such as eco-surplus and eco-deficit, showing that eco-surplus and eco-deficit can be regarded as suitable ecological instream flow indicators to illustrate seasonal and annual ecological flow change.

(3) Exponential Gaussian distribution is the appropriate distribution function with the lowest of AIC in the study of ecological instream flow in the Wangjiaba, Lutaizi, Bengbu stations of the mainstream, followed by the t Family distribution in the tributary of HRB. Meanwhile, Ecological instream flow is primarily affected by PDO, NAO and Nino3.4, and the GAMLSS model 8, considering climate factors, was regarded as appropriate distribution in hydrological variation analysis. Moreover, the ecological instream flow by GAMLSS model has better performance in the fitting of local trend and extreme value. The changes of ecological instream flow have been significantly impacted by the land-use type change. Moreover, agricultural and industrial water use are the mainly cause ecological instream flow decline.

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References

1. Zhang, Q.; Gu, X.H.; Singh, V.P.; Chen, X.H. Evaluation of ecological instream flow using multiple ecological indicators with consideration of hydrological alterations. *J. Hydrol.* **2015**, *529*, 711–722. [CrossRef]
2. Tharme, R.E. A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. *River Res. Appl.* **2003**, *19*, 397–441. [CrossRef]
3. Zhang, Q.; Zhang, Z.J.; Shi, P.J.; Singh, V.P.; Gu, X.H. Evaluation of ecological instream flow considering hydrological alterations in the Yellow River basin, China. *Glob. Planet. Chang.* **2018**, *160*, 61–74. [CrossRef]
4. Gao, B.; Yang, D.W.; Zhao, T.T.G.; Yang, H.B. Changes in the eco-flow metrics of the Upper Yangtze River from 1961 to 2008. *J. Hydrol.* **2012**, *448*, 30–38. [CrossRef]
5. Poff, N.L.; Allan, J.D.; Bain, M.B.; Karr, J.R.; Prestegaard, K.L.; Richter, B.D.; Sparks, R.E.; Stromberg, J.C. The natural flow regime: A paradigm for river conservation and restoration. *Bioscience* **1997**, *47*, 769–784. [CrossRef]
6. Hart, D.D.; Finelli, C.M. Physical–biological coupling in streams: The pervasive effects of flow on benthic organisms. *Annu. Rev. Ecol. Syst.* **1999**, *30*, 363–395. [CrossRef]
7. Seneviratne, S.I.; Nicholls, N.; Easterling, D.; Goodess, C.M.; Kanae, S.; Kossin, J.; Luo, Y.; Marengo, J.; McInnes, K.; Rahimi, M.; et al. Changes in Climate Extremes and Their Impacts on the Natural Physical Environment. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*; A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC); Cambridge University Press: Cambridge, UK; New York, NY, USA, 2012; pp. 109–230.
8. Wang, Y.; Zhao, W.; Wang, S.; Feng, X.M.; Liu, Y.X. Yellow River water rebalanced by human regulation. *Sci. Rep.* **2019**, *9*, 9707. [CrossRef] [PubMed]
9. Park, K.; Lee, K.S.; Kim, Y.-O. Use of Instream Structure Technique for Aquatic Habitat Formation in Ecological Stream Restoration. *Sustainability* **2018**, *10*, 4032. [CrossRef]

10. Wang, X.Q.; Liu, C.M.; Yang, Z.F. Method of resolving lowest environmental water demands in river course (I)—Theory. *Acta Sci. Circumstantiae* **2001**, *21*, 544–547.
11. Xing, Z.; Wang, Y.; Gong, X.; Wu, J.; Ji, Y.; Fu, Q. Calculation of Comprehensive Ecological Flow with Weighted Multiple Methods Considering Hydrological Alteration. *Water* **2018**, *10*, 1212. [CrossRef]
12. Cui, Y.; Zhang, Q.; Chen, X.H.; Jiang, T. Advances in the theories and calculation methods of ecological water requirement. *J. Lake Sci.* **2010**, *22*, 465–480.
13. Geoffrey, E.P. Instream flow science for sustainable river management. *J. Am. Water Resour. Assoc.* **2009**, *45*, 1071–1086.
14. Zhang, C.; Wan, Z.; Jing, Z.; Zhang, S.; Zhao, Y. Calculation of ecological water requirements of urban rivers using a hydrological model: A case study of Beiyun River. *J. Clean Prod.* **2020**, *262*, 121368. [CrossRef]
15. Danial, C.; Nassir, E.J. Comparison and regionalization of hydrologically based instream flow. *Can. J. Civ. Eng.* **1995**, *5*, 235–246.
16. Barrett, M.P.J. An Evaluation of the Instream Flow Incremental Methodology (IFIM). *J. Clean Prod.* **1992**, *24*, 75–77.
17. Yu, L.J.; Xia, Z.Q.; Du, X.S. Connotation of minimum ecological runoff and its calculation method. *J. Hehai Univ.* **2004**, *32*, 18–22.
18. Lee, S.; Kim, J.; Hur, J.W. Assessment of ecological flow rate by flow duration and environmental management class in the Geum River, Korea. *Environ. Earth Sci.* **2012**, *68*, 1107–1118. [CrossRef]
19. Richter, B.; Baumgartner, J.; Wigington, R.; BRAUN, D. How much water does a river need? *Freshw. Biol.* **1997**, *37*, 231–249. [CrossRef]
20. Richter, B.D.; Baumgartner, J.V.; Powell, J.; Braun, D.P. A method for assessing hydrologic alteration within ecosystems. *Conserv. Biol.* **1996**, *10*, 1163–1174. [CrossRef]
21. Ehsani, N.; Fekete, B.M.; Vörösmarty, C.J.; Tessler, J.D. A neural network based general reservoir operation scheme. *Stoch. Environ. Res. Risk Assess.* **2016**, *30*, 1151–1166. [CrossRef]
22. Chen, Y.D.; Yang, T.; Xu, C.-Y.; Zhang, Q.; Chen, X.; Hao, Z. Hydrologic alteration along the Middle and Upper East River (Dongjiang) basin, South China: A visually enhanced mining on the results of RVA method. *Stoch. Environ. Res. Risk Assess.* **2010**, *24*, 9–18. [CrossRef]
23. Zhang, Q.; Xiao, M.; Liu, C.-L.; Singh, V.P. Reservoir-induced hydrological alterations and environmental flow variation in the East River, the Pearl River basin, China. *Stoch. Environ. Res. Risk Assess.* **2014**, *28*, 2119–2132. [CrossRef]
24. The Huai River Commission of the Ministry of Water Resources, P.R.C. Introduction: Huai River Basin. 2008. Available online: http://www.hrc.gov.cn/lyjs.jhtml (accessed on 11 March 2018).
25. Sun, P.; Zhang, Q.; Wen, Q.Z.; Singh, V.P.; Shi, P.J. Multisource data based integrated agricultural drought monitoring in the Huai River basin, China. *J. Geophys. Res.* **2017**, *122*, 10751–10772. [CrossRef]
26. Sun, P.; Sun, Y.Y.; Zhang, Q.; Wen, Q.Z. Temporal and spatial variation characteristics of runoff processes and its causes in Huaihe Basin. *J. Lake Sci.* **2018**, *30*, 497–508.
27. Sun, P.; Sun, Y.Y.; Zhang, Q.; Yao, R. Hydrological processes in the Huaihe River Basin, China: Seasonal variations, causes and implications. *Chin. Geogr. Sci.* **2018**, *28*, 636–653. [CrossRef]
28. Sun, P.; Wen, Q.Z.; Zhang, Q.; Singh, V.P.; Sun, Y.Y.; Li, J.F. Nonstationarity-based evaluation of flood frequency and flood risk in the Huai River basin, China. *J. Hydrol.* **2018**, *567*, 393–404. [CrossRef]
29. Sun, P.; Zhang, Q.; Yao, R.; Singh, V.P.; Song, C.Q.; Sun, Y.Y. Spatiotemporal Patterns of Extreme Temperature across the Huai River Basin, China, during 1961–2014, and Regional Responses to Global Changes. *Sustainability* **2018**, *10*, 1236. [CrossRef]
30. Liu, C.M.; Zhao, C.S.; Xia, J.; Sun, C.l.; Wang, R.; Liu, T. An instream ecological flow method for data-scarce regulated rivers. *J. Hydrol.* **2011**, *398*, 17–25. [CrossRef]
31. Liu, S.X.; Mo, X.G.; Xia, J.; Liu, C.M.; Lin, Z.H.; Men, B.H.; Ji, L. Estimating the minimum in-stream flow requirements via wetted perimeter method based on curvature and slope techniques. *J. Geogr. Sci.* **2006**, *16*, 242–250. [CrossRef]
32. Pan, Z.R.; Ruan, X.H. Spatio-temporal analysis of satisfactory degree of ecological water demand in Huaihe River Basin. *J. Hydraul. Eng. ASCE* **2015**, *46*, 280–290.
33. Liu, D.; Xing, Q.Q.; Guo, X.X.; Ma, M.M.; Fan, P.Y. Ecological hydraulic radius approach and its applications in ecological water demand calculation in the Jialu River Basin. *J. Water Resour. Water Eng.* **2018**, *29*, 105–110.
34. Zuo, Q.; Chen, H.; Zhang, Y. Impact factors and health assessment of aquatic ecosystem in Upper and Middle Huai River Basin. *J. Hydraul. Eng. ASCE* **2015**, *46*, 1019–1027.
35. Milly, P.C.D.; Betancourt, J.; Falkenmark, M.; Hirsch, R.M.; Kundzewicz, Z.W.; Lettenmaier, D.P.; Stouffer, R.J. Stationarity is dead: Whiter water management? *Science* **2018**, *319*, 573–574. [CrossRef] [PubMed]
36. Berg, P.; Moseley, C.; Haerter, J.O. Strong increase in convective precipitation in response to higher temperatures. *Nat. Geosci.* **2013**, *6*, 181–185. [CrossRef]
37. Bolgov, M.V.; Sentsova, N.I. Bayesian assessments of design characteristics of the minimum river runoff under nonstationary conditions. *Russ. Meteorol. Hydrol.* **2010**, *35*, 769–776. [CrossRef]
38. Kunkel, K.E.; Karl, R.T.; Easterling, R.D.; Redmond, K.; Young, J.; Yin, X.; Hennon, P. Probable maximum precipitation and climate change. *Geophys. Res. Lett.* **2013**, *40*, 1402–1408. [CrossRef]
39. Zhang, Q.; Gu, X.H.; Singh, V.P.; Xiao, M.; Xu, C.-Y.; Chen, X. Evaluation of flood frequency under non-stationarity resulting from climate change and human activities in the East River basin, China. *J. Hydrol.* **2015**, *527*, 565–575. [CrossRef]
40. Gilroy, K.L.; McCuen, R.H. A nonstationary flood frequency analysis method to adjust for future climate change and urbanization. *J. Hydrol.* **2012**, *414*, 40–48. [CrossRef]

41. Prosdocimi, I.; Kjeldsen, T.R.; Miller, J.D. Detection and attribution of urbanization effect on flood extremes using nonstationary flood-frequency models. *Water Resour. Res.* **2015**, *51*, 4244–4262. [CrossRef] [PubMed]
42. Chang, J.X.; Li, Y.Y.; Wang, Y.M.; Yuan, M. Copula-based drought risk assessment combined with an integrated index in the Wei River Basin. *China J. Hydrol.* **2016**, *540*, 824–834. [CrossRef]
43. Zhang, Y.Y.; Shao, Q.X.; Xia, J.; Stuart, E.B.; Zuo, Q.T. Changes of flow regimes and precipitation in Huai River Basin in the last half century. *Hydrol. Process.* **2011**, *25*, 246–257. [CrossRef]
44. Sun, P.; Zhang, Q.; Yao, R.; Wen, Q.Z. Hydrological Drought Regimes of the Huai River Basin, China: Probabilistic Behavior, Causes and Implications. *Water* **2019**, *11*, 2390. [CrossRef]
45. Pettitt, A.N. A non-parametric approach to the change-point problem. *J. R. Stat. Soc.* **1979**, *28*, 126–135. [CrossRef]
46. Vogel, M.R.; Sieber, J.; Archfield1, A.S.; Smith, P.M.; Apse, D.C.; Huber-Lee, A. Relations among storage, yield, and instream flow. *Water Resour. Res.* **2007**, *43*, W05403. [CrossRef]
47. The Nature Conservancy, Indicators of Hydrological Alteration Version 7.1 User's Manual: 2009. Available online: http://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/IndicatorsofHydrologicAlteration/Pages/IHA-Software-Download.aspx (accessed on 22 September 2020).
48. Shiau, J.T.; Wu, F.C. Pareto-optimal solutions for environmental flow schemes incorporating the intra-annual and interannual variability of the natural flow regime. *Water Resour. Res.* **2007**, *43*, W06433. [CrossRef]
49. Kuo, S.R.; Lin, J.H.; Shao, K.T. Seasonal changes in abundance and composition of the fish assemblage in Chiku Lagoon, south-western Taiwan. *Bull. Mar. Sci.* **2001**, *68*, 85–99.
50. Yang, Y.-C.E.; Cai, X.M.; Herricks, E.E. Identification of hydrologic indicators related to fish diversity and abundance. A data mining approach for fish community analysis. *Water Resour. Res.* **2008**, *44*, W04412. [CrossRef]
51. Rigby, R.A.; Stasinopoulos, D.M. Generalized additive models for location, scale and shape. *J. R. Stat. Soc.* **2005**, *54*, 507–555. [CrossRef]
52. Wang, Y.X.; Zuo, Q.T. Analysis of water quality change and its reasons in Henan Reach of Shayinghe River. *J. Water Resour. Water Eng.* **2012**, *23*, 47–50.
53. Zuo, Q.T.; Liu, Z.H.; Dou, M.; Gao, J.S. Research Framework of Assessment of Dams' Impact on Water Quality and Quantity and Identification of Regulation Ability. *South North Water Transf. Water Sci. Technol.* **2011**, *9*, 18–21.
54. Chen, H.; Zuo, Q.T.; Zhang, Y.Y. Impact factor analysis of aquatic species diversity in the Huai River Basin, China. *Water Sci. Technol. Water Supply* **2019**, *19*, 2061–2071. [CrossRef]
55. Aho, K.; Derryberry, D.; Peterson, T. Model selection for ecologists: The worldviews of AIC and BIC. *Ecology* **2014**, *95*, 631–636. [CrossRef] [PubMed]
56. Li, M.; Liang, X.; Xiao, C.; Zhang, X.; Jang, W. Evaluation of Reservoir-Induced Hydrological Alterations and Ecological Flow Based on Multi-Indicators. *Water* **2020**, *12*, 2069. [CrossRef]
57. Harnessing the Huaihe River Proceedings Codification Committee. *Harnessing the Huaihe River Proceedings*; Harnessing the Huaihe River Proceedings Editorial Department: Bengbu, China, 2017.
58. Sun, Y.Y.; Sun, P.; Yao, R.; Zhang, Q.; Shi, P.J.; Wang, Y.Z. Characteristics of low streamflow: Possible causes and implications in Huaihe River basin. *J. Beijing Norm. Univ.* **2018**, *54*, 543–552.