Abstract: The Hanjiang River, as a water donor basin, plays a fundamental role in supporting water supply security in northern China while maintaining the health and stability of ecosystems within the basin. However, the combined influence of climate change and anthropogenic interference has resulted in a significant change in the flow regime of the basin, challenging the sustainability of the river system. In order to understand the impact of the above factors on the river runoff, we analyzed the temporal and spatial pattern of runoff and climate factors in the basin and quantitatively assessed the contribution of climate change and human activities to the change in runoff using the elasticity coefficient method. Our results indicate that annual runoff has experienced a significant downward trend over the past 60 years, which is projected to continue into the future. It is also found that the temporal pattern of the runoff regime differed upstream and downstream of the Danjiangkou Reservoir due to the joint operation of the reservoir and China’s Middle Route Project of South-to-North Water Diversion (MRP-SNWD). A significant decrease in runoff was primarily attributed to human activities, followed by precipitation. In contrast, evapotranspiration had the least effect. In particular, the MRP-SNWD was a significant anthropogenic factor, contributing to about 20.3% of the total change in runoff. Our results highlighted the unfavorable effects of human activity on the hydrological system in the Hanjiang River and provided some constructive suggestions to turn vulnerability into resilience.

Keywords: runoff; climate change; human activity; attribution analysis; Hanjiang River basin

1. Introduction

The Earth’s ecosystem, on which everything depends, is becoming increasingly fragile as a result of human activities and climate change. As an important factor in maintaining the health of the river ecosystem, under the influence of human activities and climate change, the hydrological processes of catchments have been altered to some extent [1,2]. These processes are mainly influenced by climatic factors, such as precipitation, potential evapotranspiration ($E_T$), and temperature, as well as by anthropogenic activities such as dam and reservoir construction, agricultural irrigation, urban expansion, and ecological restoration [3,4]. In particular, precipitation is often considered to be the dominant factor in humid regions [5], directly influencing the hydrological inputs to rivers. At high latitudes and elevations, rivers are primarily recharged by snowmelt and glacier melt; therefore, temperature plays a dominant role in altering runoff in alpine areas [6]. In addition, $E_T$...
is likely to be a major contributor in either tropical or cold regions [7]. For example, water resources throughout the Arctic have shown a declining trend, and Suzuki et al. [8] attributed it to the increasing ET₀. Thus, the combination of different climatic factors drives the variation in runoff, although their mechanisms are different and affect regions in different ways. Climate change is not the only variable affecting runoff [9]. Artificial water withdrawals for various purposes can directly reduce runoff, while land cover change can first modify water generation and concentration by affecting interception, infiltration, and evapotranspiration, and then alter runoff processes. Agricultural intensification has been identified as a dominant factor in runoff reduction [10]. In addition, the operation of water diversion projects, as one of the most influential human activities, can tremendously reshape the spatial pattern of water resources in watersheds [11]. Therefore, in this context, the available water resources are facing unprecedentedly uncertain characteristics, which poses immense challenges to agriculture, industry, and municipal water supply along rivers [12,13].

Water scarcity is now a common global problem [14,15], resulting from a combination of climatic and human influences. Here, climatic factors refer to land parameters, as runoff is much more strongly associated with regional environmental factors than with oceanic ones [16]. In short, different predictors interact to influence hydrological processes. However, analyses of hydrologic changes often fail to distinguish between these factors [17]. In view of this, disentangling the separate impacts of climate change and human activities on river runoff is an important prerequisite for ensuring the health and stability of river ecosystems and the sustainable development of human society and has attracted increasing attention from scholars around the world [18], which can provide a reference for proposing targeted countermeasures to mitigate adverse impacts [19]. The attribution analysis methods for runoff change mainly include statistical methods, hydrological simulation methods, and coupled water–energy balance methods. The statistical method is easy to use but lacks sufficient physical mechanisms [20]. The hydrological simulation method can investigate the influence of various predictors on the runoff generation process by applying a distributed hydrological model. For example, Yonaba et al. [21] used the SWAT model with dynamic land use/land cover inputs to assess the variability and attribution of changes in surface runoff in a Sahelian watershed. The model, in combination with the Coupled Model Intercomparison Project Phase 6, can also be used to predict future changes in runoff [22]. However, a large amount of high-quality geographical information is required to construct the hydrological model, and the model parameters are also highly elusive due to the different characteristics of different catchments [23], which inevitably limits the widespread application of hydrological simulation methods. In contrast, the Budyko framework considers the interaction among various factors in the basin [20], and the Budyko method [24], as a representative of coupled water–energy balance methods, has been used by many researchers [25–27] to determine the relative contribution of climate change and human activities to changes in runoff over time. This method has physical significance, and its parameters used are easy to obtain [28]. Therefore, this method has been widely used in different catchments, and satisfactory results can be obtained [29].

The Hanjiang River basin is a region rich in water resources, and the water quality of the upper reaches is excellent, ranking above the second class on China’s five-tier surface water quality scale throughout the year. For this reason, it was selected as the water source for China’s Middle Route Project of South-to-North Water Diversion (MRP-SNWD), which brings abundant water resources to Beijing and Tianjin municipalities and Hebei and Henan provinces in the north, including more than 20 large and medium-sized cities. To date, more than 50 billion m³ of water have been transferred, positioning the Hanjiang River as an essential water resource supply in northern China. However, due to climate variability and human activities such as the operation of a series of cascading reservoirs and diversion projects, the ecohydrological flow regimes of the river have changed drastically in recent years, affecting the function and structure of the mid-downstream ecosystem of the Hanjiang River [30] and exacerbating the contradiction between the supply and demand.
for water resources within the basin. It is noteworthy that runoff reduction in the upper Hanjiang River basin is on the increase [31,32]. While climate change plays a vital role in causing the changes in basin-wide runoff, the influence of human activities on runoff reduction should not be ignored. For example, the volume of water diverted from the MRP-SNWD accounts for 30% of the average annual runoff into the Danjiangkou Reservoir. Although there is ample evidence that the MRP-SNWD has brought great benefits in terms of water supply and ecosystem restoration in the water-receiving region [33,34], it has resulted in negative groundwater budgets in the Jianghan Plain [34]. The increasing water transfer has made the hydrological and ecological impacts in the Hanjiang River a pressing issue. However, the impact of the MRP-SNWD on runoff reduction in the Hanjiang River has rarely been discussed. Therefore, the present study aims to separately investigate the effects of climate change and anthropogenic disturbance, including the MRP-SNWD, on runoff change in the Hanjiang River basin. The water balance method, based on the Budyko hypothesis, was used to quantify the contribution of climate change and human activities in this study. The contribution rate of runoff change caused by the MRP-SNWD was determined, which can provide a reference for government decision-makers to make full use of the water resources in the Hanjiang River, eliminate the unfavorable effects of the MRP-SNWD on the middle and lower reaches, and ultimately achieve the goal of sharing the benefits of the MRP-SNWD between north and south China.

2. Materials and Methods

2.1. Materials

2.1.1. Study Area

The Hanjiang River is the longest tributary of the Yangtze River, flowing from the southern foothills of the Qinling Mountains in Shaanxi Province and joining the Yangtze River at the city of Wuhan. The basin lies between 106°15'–114°20' E and 30°10’–34°20’ N (Figure 1). The main stem flows through Shaanxi and Hubei provinces, with a total length of 1577 km, while its tributaries extend to the four provinces of Sichuan, Gansu, Chongqing, and Henan, spanning over a basin area of about 1.59 × 10^5 km^2. It is characterized by plentiful water resources, with an average annual discharge of 5.39 × 10^{10} m^3, close to that of the Yellow River, the second longest river in China [35].

![Figure 1. Distribution of hydrological and meteorological stations in the Hanjiang River basin.](image)

The Hanjiang River basin receives most of its precipitation from water vapor carried by two warm and humid air currents from the southeast and southwest directions. The
annual precipitation, averaging 881 mm, varies from year to year, and its distribution within the year is uneven, with 55–65% of the yearly precipitation occurring in the four wettest consecutive months (from May to August). Precipitation reduces gradually from south to north and from west to east. Surface evaporation ranges from 700 mm to 1100 mm throughout the basin, increasing from southwest to northeast. The basin’s annual temperature averages 12–16 °C, with the monthly temperature reaching the highest point in July (24–29 °C) and the lowest point in January (0–3 °C).

Located in the middle reach of the Hanjiang River, Danjiangkou Reservoir is a key water conservancy project, with a total storage capacity of 17.4 billion m³. It serves as the water source for the MRP-SNWD. The MRP-SNWD went into operation in December 2014 and was designed to reallocate water resources from Danjiangkou Reservoir, which provides water to the North China Plain. This project has benefited over 85 million individuals and plays a crucial role in the national water resource allocation strategy. However, diverting water out of the reservoir has negatively impacted the environment and navigation downstream of the Danjiangkou Reservoir. This alteration of the environmental flows has caused frequent algal blooms in the Hanjiang River, posing potential risks to the drinking water safety of residents living along the river [36]. Acknowledging the potential consequences of the MRP-SNWD, the Chinese government has tried to commence the design and construction of the Yangtze-Hanjiang Water Diversion (YHWD) to mitigate the adverse impact of the MRP-SNWD.

2.1.2. Data Sources

Based on the topographical and geomorphological features and the distribution of hydrological stations in the Hanjiang River basin, we selected five major hydrological stations: Ankang, Huangjiagang, Xiangyang, Shayang, and Xiantao. Ankang station lies upstream, Huangjiagang and Xiangyang stations midstream, and Shayang and Xiantao stations downstream. We obtained daily runoff data for the five hydrological stations from the Hydrologic Yearbook (1960–2019). In addition, we extracted basin topographic data (DEM) from the Geospatial Data Cloud website, Computer Network Information Center, Chinese Academy of Sciences, and 1960–2019 meteorological data of 18 meteorological stations from the National Meteorological Information Center. In addition, the Normalized Difference Vegetation Index (NDVI) data were obtained from the GIMMS NDVI dataset, provided by the National Aeronautics and Space Administration (NASA). The dataset has a spatial resolution of 8 km × 8 km and a temporal resolution of 15 days. The map of the Hanjiang River watershed and the locations of the hydrological stations and meteorological stations are shown in Figure 1.

2.2. Methods

2.2.1. Calculation of Climate Factors

The Penman–Monteith formula [37] modified by FAO is adopted to estimate the potential evapotranspiration, and the formula is:

$$ET_0 = \frac{0.408 \Delta (R_n - G) + \frac{900}{7.275} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 U_2)}$$

where $ET_0$ is reference evapotranspiration (mm/d); $\Delta$ is the slope of the vapor pressure curve (kPa/°C); $R_n$ is the net radiation at surface (MJm⁻²d⁻¹); $G$ is the soil heat flux density (MJm⁻²d⁻¹); $\gamma$ is the psychrometric constant (kPa/°C); $U_2$ is the wind speed at a height of 2 m (m/s); $T$ is the mean daily air temperature (°C); $e_s$ is saturation vapor pressure (kPa), $e_a$ is actual vapor pressure (kPa), and $(e_s - e_a)$ is the saturation vapor pressure deficit (kPa).
Basin-averaged annual precipitation or ET\(_0\) is calculated based on the Thiessen polygon [38], and the calculation formula is as follows:

\[
P_{\text{avg}} = \frac{\sum (P_i \cdot f_i)}{F} \tag{2}
\]

\[
\text{ET}_{\text{avg}} = \frac{\sum (\text{ET}_i \cdot f_i)}{F} \tag{3}
\]

where \(P_i\) and \(\text{ET}_i\) are the annual precipitation and potential evapotranspiration of station \(i\), mm; \(f_i\) is the area occupied by station \(i\), km\(^2\); \(F\) is the total area of the basin, km\(^2\); \(P_{\text{avg}}\) and \(\text{ET}_{\text{avg}}\) are the annual precipitation and potential evapotranspiration of the Hanjiang River basin, mm.

2.2.2. Calculation of Annual Runoff Depth

The runoff depth of the basin is calculated from the basin outlet, and the formula is:

\[
R = \frac{Q \Delta t}{1000A} \tag{4}
\]

where \(Q\) is the average flow rate (m\(^3\)/s), \(\Delta t\) is the period (s), and \(A\) is the basin area (km\(^2\)). In this paper, Xiantao station is chosen as the outlet station of the whole Hanjiang River basin.

2.2.3. Mann–Kendall Test

The Mann–Kendall test [39] is a non-parametric statistical test suitable for climate and environmental studies because it does not require samples to follow a particular distribution and can handle outliers. The test is useful for detecting trends in temperature, precipitation, river flow, and other environmental variables over time.

(1) Mann–Kendall trend test

The Mann–Kendall test is used to analyze the temporal trend of the time sequence, and its output yields the statistical value \(Z\). A positive or negative value of \(Z\) signifies whether the corresponding series exhibits an increasing or decreasing trend, respectively. If the absolute value of \(Z\) is greater than or equal to 1.96, the statistical significance of the 95% confidence interval is reached.

(2) Mann–Kendall abrupt change test

The Mann–Kendall abrupt change test can detect abrupt changes when the UF and UB curves exceed the critical line and intersect. The point of intersection corresponds to the point of abrupt change. However, if the intersection point lies outside the critical line, or there are multiple intersection points, additional tests must be performed to confirm that this is indeed the abrupt change point.

2.2.4. Pettitt Test

The Pettitt test [40] is a convenient detection method that can specify the mutation time series and can well identify the mutation points in the distribution of trending hydrological series [41]. For 2 samples \(x_1, \ldots, x_t\) and \(x_{t+1}, \ldots, x_N\) from the same sequence, the calculation formula is:

\[
U_{t,N} = U_{t-1,N} + \sum_{j=1}^{N} \text{sgn}(x_t - x_j), \lambda(t = 2, \ldots, N). \tag{5}
\]

\(k(t)\) represents the maximum value of \(|U_{t,N}|\) at the most significant variable point \(t\), calculated as:

\[
k(t) = \max_{\xi \leq \eta \leq N} |U_{\xi,\eta}| \tag{6}
\]
If the correlation probability $P \leq 0.05$, the $t$ point is a significant variation point. The significance test formula is:

$$P \approx 2 \exp \left\{ -6(K_N)^2 / \left( N^3 + N^3 \right) \right\}$$

(7)

2.2.5. Sustainability Test

R/S analysis [42] is a statistical technique designed to assess the nature and magnitude of variability in data over time, which has been widely used in the analysis of hydrological time series. Closely associated with R/S analysis is the Hurst index, indicated by H. The Hurst index can be used to determine if there is a hidden long-term trend, statistically known as a long-memory process. A Hurst index ranges between 0 and 1 and measures three types of trends in a time series: persistence, randomness, or mean reversion. Three forms are as follows [43]:

If $0.5 < H < 1$, it shows that the time series is a persistent sequence, and that is to say, future changes are consistent with past trends, and the closer $H$ is to 1, the stronger the persistence.

If $H = 0.5$, then the time series is random and there is no long-term correlation.

If $0 < H < 0.5$, then the time series has inverse persistence, i.e., the future trend is opposite to the past trend, and the closer $H$ is to 0, the stronger the inverse persistence.

2.2.6. Attribution Analysis Method

The attribution analysis is based on the Budyko hypothesis of the water and energy balance investigations, and Budyko’s theory is based on the hydrothermal equilibrium equation, whose expression is:

$$R = P - E - \Delta S$$

(8)

where $R$ is the mean runoff depth, mm; $P$ is the mean precipitation, mm; $E$ is the mean actual evapotranspiration, mm; and $\Delta S$ is the change in water storage, mm, which is generally considered to be 0 when analyzing hydrological changes on long time scales.

The Budyko coupled hydrothermal balance equation assumes that the long-term hydroclimatic characteristics of the basin follow the water and energy balance and that the actual evaporation ($E$) of the basin is controlled mainly by precipitation ($P$) and potential evaporation ($E_0$) under certain underlying surface characteristics, which can be combined with the water balance equation to derive the actual runoff [44]. Choudhury [45] and Yang et al. [46] proposed a coupled hydrothermal equilibrium equation for the watershed based on the Budyko hypothesis:

$$E = \frac{P \times E_0}{\left( P^n + E_0^n \right)^{1/n}}$$

(9)

where, $E_0$ is the potential evaporation, mm, and $n$ is the lower bedding surface parameter that provides a comprehensive view of the influence of subsurface characteristics on the water balance of the basin [47].

Considering that humans interact with the world around us every day in almost every aspect, it is challenging to quantify the intensity of human activities with a single indicator. Changes in land use are relatively the most direct manifestation of human disturbances of ecosystems and concentrated human activities, so $n$ here, to an extent, can reflect the intensity of human activities.

Combining Equations (8) and (9), the water balance equation can be expressed as:

$$R = P - \frac{P \times E_0}{\left( P^n + E_0^n \right)^{\frac{1}{n}}}$$

(10)

Substituting $R, P,$ and $E_0$, $n$ can be obtained.
Assuming that \( P, \ ET_0, \) and \( n \) do not affect each other, the partial derivative gives the expression for the sensitivity coefficient for runoff. The water balance equation obtained from Equation (9) combined with the definition of the elasticity factor \( \varepsilon \):

\[
\varepsilon = \frac{\partial Q}{\partial X}
\]  

(11)

\( \varepsilon \) represents the elastic coefficient of runoff \( Q \) to independent variable \( X \), and \( X \) represent \( P, \ ET_0, \) and \( n \).

The elasticity coefficients of each impact factor are as follows:

\[
\varepsilon_p = \frac{(1 + \phi^n)^{1+1} - \phi^{n+1}}{(1 + \phi^n)\left[(1 + \phi^n)^{x} - \phi\right]}
\]  

(12)

\[
\varepsilon_{ET_0} = \frac{1}{(1 + \phi^n)\left[1 - (1 + \phi^{-n})^{\frac{1}{n}}\right]}
\]  

(13)

\[
\varepsilon_n = \frac{\ln(1 + \phi^n) + \phi^n\ln(1 + \phi^{-n})}{n\left[(1 + \phi^n) - (1 + \phi^n)^{\frac{1}{n}}\right]}
\]  

(14)

Combining the effects of the variables on runoff, the calculated change in runoff can be expressed as:

\[
\Delta R' = \varepsilon_p \Delta p + \varepsilon_{ET_0} \Delta ET_0 + \varepsilon_n \Delta n
\]  

(15)

According to the runoff abrupt change point, the runoff series is divided into two periods: the base period and the change period. The runoff depth of the base period is \( R_1 \), and the runoff of the change period is \( R_2 \). The actual change of runoff \( \Delta R \) can be expressed as:

\[
\Delta R = R_2 - R_1
\]  

(16)

The contribution of \( P \), \( ET_0 \), and \( n \) to runoff, \( C \), can be expressed as:

\[
C_p = \frac{\Delta R}{\Delta R'} \times 100\% \\
C_{ET_0} = \frac{\Delta R_{ET_0}}{\Delta R'} \times 100\% \\
C_n = \frac{\Delta R_n}{\Delta R'} \times 100\%
\]  

(17)

Furthermore, to address the impact of the MRP-SNWD, modifications are made to the Budyko framework. Water transfer by the MRP-SNWD is incorporated to assess the impact of the MRP-SNWD on the observed total runoff.

3. Results

3.1. Trends in Precipitation, \( ET_0 \)

Figure 2 shows the interannual variation of precipitation and \( ET_0 \) in the Hanjiang River basin, while Figure 3 shows their spatial distribution. From the results, we found that the multi-year average annual precipitation during the study period was 881 mm, with an extreme value ratio of 1.96, and a coefficient of variation (CV) of 0.14. The interannual variability of precipitation was not significant, but its distribution within a year was significantly uneven, with 47% of the annual precipitation falling in summer. Our spatial analysis shows a decreasing trend from south to north in spring, summer, and winter and from west to east in spring, summer, and autumn. We also found that the multi-year mean \( ET_0 \) was 974 mm, with an extreme value ratio of 1.22 and CV of 0.04. The spatial distribution of \( ET_0 \) indicated a trend of increasing from west to east. The spatial heterogeneity of precipitation and \( ET_0 \) was evident and varied between seasons. However, \( ET_0 \) exhibited much less interannual and spatial variation than precipitation. This is explained by the
fact that precipitation is influenced by a wide range of complex atmospheric processes that vary significantly over both short and long timescales. And, precipitation often exhibits significant spatial variability, with some areas experiencing high rainfall and others experiencing drought conditions. In contrast, ET\textsubscript{0} is mainly influenced by surface conditions such as temperature, humidity, and soil moisture availability, which are less influenced by large-scale atmospheric processes than precipitation.

Figure 2. Trends in multi-year precipitation and potential evapotranspiration in the Hanjiang River basin.

Figure 3. Multi-year average precipitation and ET\textsubscript{0} distribution by season.

To further illustrate the trends, linear fits of multi-year precipitation and ET\textsubscript{0} were performed. It was found that the overall trends of both precipitation and ET\textsubscript{0} were decreasing with time, with decrease rates of $-0.17$ mm/a and $-0.28$ mm/a, respectively. The annual and seasonal precipitation and ET\textsubscript{0} variations in the Hanjiang River basin were analyzed using the Mann–Kendall test, and the obtained test statistics’ Z-values are presented in Table 1. The results showed that the Z-values of precipitation and ET\textsubscript{0} were $-0.13$ and $-0.86$, respectively, both of which were less than $1.96$ in absolute value and did not pass the 95% significance test of confidence, indicating a slightly decreasing trend for both, but the decreasing trend was not significant. In terms of seasons, precipitation increased in summer and winter and decreased in spring and autumn, albeit inconspicuously, while ET\textsubscript{0} showed a significant increasing trend in spring but a dropping trend in the remaining three seasons, with a notable decline in summer. It is clear that the temporal pattern of precipitation and ET\textsubscript{0} varied across seasons. In the future, the projected precipitation and ET\textsubscript{0} were expected to represent an upward trend, but with increased spatial heterogeneity [48]. This could
inevitably further alter the hydrological regime in the middle and lower reaches of the Hanjiang River.

Table 1. Temporal characteristics of precipitation, ET₀ from 1960 to 2019.

<table>
<thead>
<tr>
<th>Average Precipitation (mm)</th>
<th>Z</th>
<th>Average ET₀ (mm)</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>year</td>
<td>881</td>
<td>−0.13</td>
<td>974</td>
</tr>
<tr>
<td>spring</td>
<td>239</td>
<td>−0.98</td>
<td>277</td>
</tr>
<tr>
<td>summer</td>
<td>478</td>
<td>0.41</td>
<td>394</td>
</tr>
<tr>
<td>autumn</td>
<td>263</td>
<td>−1.37</td>
<td>188</td>
</tr>
<tr>
<td>winter</td>
<td>47</td>
<td>0.11</td>
<td>106</td>
</tr>
</tbody>
</table>

Note: Z stands for the statistical value of the Mann–Kendall test.

3.2. Trends in Runoff

3.2.1. Interannual Temporal Variation

The runoff of the five selected hydrological stations was analyzed separately, and the evolution trend of annual runoff is shown in Figure 4. Table 2 presents the temporal characteristics of the annual runoff. On average, the annual runoff exceeded 1000 m³/s at all hydrological stations except Ankang station. Compared to the other four stations, the interannual variability in runoff at Ankang station was more prominent, with an extreme value ratio of 6.10 and a CV value of 0.39. Our CV results reveal that the variability of the interannual streamflow gradually decreased downstream due to the operation of the multi-year regulation of Danjiangkou Reservoir. Specifically, the release is reduced for the purposes of flood control and power generation from June to September, while increased to replenish downstream river channels for municipal water supply and agricultural irrigation from November to March and to empty the flood control storage capacity in April and May. As a result, Danjiangkou Reservoir’s storage and release significantly reduce the interannual variability of downstream river flows. In addition, the Ankang station’s runoff increased after 2014 compared to previous years, while the remaining four hydrological stations did not experience a significant increase in runoff during this period. This finding suggests a recent increase in water resources in the upper reaches of the Hanjiang River basin, while the streamflow in the middle and lower reaches was reduced by the MRP-SNWD, inconsistent with that in the upper reach. Evidently, the MRP-SNWD played an important role in the development of the discharge in the middle and lower Hanjiang River.

Figure 4. Temporal variation of annual runoff at hydrological stations in the Hanjiang River basin.
Table 2. Temporal characteristics of annual runoff at hydrological stations.

<table>
<thead>
<tr>
<th>Hydrological Stations</th>
<th>Multi-Year Average (m³/s)</th>
<th>Extreme Value Ratio</th>
<th>CV</th>
<th>Z</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankang</td>
<td>558</td>
<td>6.10</td>
<td>0.39</td>
<td>−2.65</td>
<td>0.81</td>
</tr>
<tr>
<td>Huangjiagang</td>
<td>1035</td>
<td>4.24</td>
<td>0.37</td>
<td>−3.85</td>
<td>0.77</td>
</tr>
<tr>
<td>Xiangyang</td>
<td>1187</td>
<td>5.12</td>
<td>0.35</td>
<td>−3.09</td>
<td>0.73</td>
</tr>
<tr>
<td>Shayang</td>
<td>1394</td>
<td>3.83</td>
<td>0.35</td>
<td>−1.94</td>
<td>0.64</td>
</tr>
<tr>
<td>Xiantao</td>
<td>1271</td>
<td>4.14</td>
<td>0.31</td>
<td>−1.60</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Note: CV stands for coefficient of variation, Z for the statistical value of the Mann–Kendall test, and H for the Hurst index.

On the whole, the five hydrological stations in the Hanjiang River basin exhibited similar trends in annual runoff, consistently showing a declining trend, although the rate of decrease varied across stations. In particular, Huangjiagang Station had the most pronounced rate of decrease, with a linear decrease of −8.84 mm/a. Ankang station, however, had the slowest rate of decline, with a linear decline of −4.07 mm/a. The linear decrease rates for Xiangyang, Shayang, and Xiantao stations were −8.60 mm/a, −6.28 mm/a, and −4.73 mm/a, respectively. The Z-values for Huangjiagang, Xiangyang, and Ankang stations indicated a substantial decrease in annual runoff at these three hydrological stations.

3.2.2. Intra-Annual Distribution

Figure 5 shows the intra-annual distribution of runoff in the Hanjiang River basin. The runoff at the five hydrological stations in the basin was unevenly distributed within the year, mainly concentrating in summer and autumn. The highest runoff, comprising 35.40% of the year’s overall runoff, was observed during the summer season, followed by the autumn with 32.14%. Conversely, lower runoff occurred during spring and winter, which are characterized as dry seasons, contributing 19.17% and 13.29% of the annual runoff, respectively.

Decreasing trends in spring, summer, and autumn runoff were observed at all five stations, with declines that were significant in autumn, but not significant in spring and summer (Table 3). Furthermore, during the winter season, all four hydrological stations
in the middle and lower reaches showed an increasing trend, except for Ankang station where a significant decrease in runoff was observed over time (Table 3). Typically, the runoff regime is significantly impacted by the catchment inflow, with the upstream inflow holding a dominant influence over changes in the middle and lower reaches. Nevertheless, our study found a lack of correlation between wintertime runoff in the upstream and middle–lower reaches, which may be attributable to the joint operation of the Danjiangkou Reservoir, resulting in the disruption of the natural connection between upstream and downstream.

Table 3. Statistical test value (Z) of seasonal runoff at hydrological stations in Hanjiang River basin.

<table>
<thead>
<tr>
<th>Season</th>
<th>Ankang</th>
<th>Huangjiagang</th>
<th>Xiangyang</th>
<th>Shayang</th>
<th>Xiantao</th>
</tr>
</thead>
<tbody>
<tr>
<td>spring</td>
<td>-4.28</td>
<td>-1.74</td>
<td>-2.35</td>
<td>-1.42</td>
<td>-2.22</td>
</tr>
<tr>
<td>summer</td>
<td>-0.64</td>
<td>-2.31</td>
<td>-2.55</td>
<td>-1.69</td>
<td>-2.35</td>
</tr>
<tr>
<td>autumn</td>
<td>-3.24</td>
<td>-3.74</td>
<td>-3.51</td>
<td>-3.25</td>
<td>-2.83</td>
</tr>
<tr>
<td>winter</td>
<td>-5.12</td>
<td>1.52</td>
<td>0.82</td>
<td>1.37</td>
<td>0.39</td>
</tr>
</tbody>
</table>

3.2.3. Persistent Characteristics

The annual runoff persistence characteristics were assessed using R/S, and the Hurst index (H value) was obtained (Table 2). Ankang station recorded the highest H value of 0.81, while Huangjiagang, Xiangyang, Xiantao and Shayang stations had H values of 0.77, 0.73, 0.64, and 0.63, respectively. This implies that there will be a consistent downward trend in annual runoff in the future, comparable to the trend observed over the past 60 years, with the persistence strength descending from upstream to downstream.

3.3. Detection of Runoff Abrupt Change Points

Mann–Kendall and Pettitt tests were employed to identify the abrupt changes in annual runoff depth within the Hanjiang River basin (Figures 6 and 7). UF and UB curves obtained from the Mann–Kendall test intersected in 1992, 2009, and 2012, and the intersection points were all located within the critical line. Meanwhile, the year of runoff abrupt change obtained from the Pettitt test was 1992. Combining the results of both tests, it was found that abrupt changes in annual runoff occurred in 1992 and 2012 within the Hanjiang River basin. Thus, the time series of runoff observed between 1960 and 2019 was divided into three distinct periods. Specifically, 1960–1992 was regarded as the base period, while 1993–2012 and 2013–2019 were viewed as the change periods.

Figure 6. Mann–Kendall test curve.
Given that the MRP-SNWD began transferring water northward from the Danjiangkou Reservoir in 2014, with a total of 22.5 billion cubic meters of water being transferred from the Hanjiang River by June 2019, a significant impact on the spatial and temporal runoff of the basin can be expected. Therefore, this paper included a change period of 2013–2019 *. It was hypothesized that this portion of water would not be diverted from Danjiangkou Reservoir during this change period; this was adopted to determine the contribution of the MRP-SNWD to the decline in Hanjiang River’s runoff during that period.

3.4. Sensitivity Analysis

Table 4 provides the values of the hydroclimatic characteristics and elasticity coefficients of runoff for ET0, precipitation and n for each period observed within the basin. The results show that, in comparison to the base period, the mean annual runoff depth and precipitation were lower during the change periods in the Hanjiang River basin. In the two change periods, the runoff depth decreased by 16.79% and 20.76%, and the precipitation declined by 2.45% and 4.39%, respectively. Additionally, the runoff coefficient (R/P) decreased significantly in the change period as well compared to the base period, and the n values for the change periods were greater than those for the base period. The variation in n values showed that the intensity of human activities had changed dramatically during the change period, which would have a profound effect on runoff.

<table>
<thead>
<tr>
<th>Period</th>
<th>ET0/mm</th>
<th>R/mm</th>
<th>P/mm</th>
<th>n</th>
<th>R/P</th>
<th>ET0/P</th>
<th>Elasticity Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ε&lt;sub&gt;ET0&lt;/sub&gt; ε&lt;sub&gt;P&lt;/sub&gt; ε&lt;sub&gt;n&lt;/sub&gt;</td>
</tr>
<tr>
<td>1960–1992</td>
<td>978</td>
<td>308</td>
<td>893</td>
<td>1.48</td>
<td>0.35</td>
<td>1.10</td>
<td>−0.89  1.89  −0.88</td>
</tr>
<tr>
<td>1993–2012</td>
<td>975</td>
<td>257</td>
<td>871</td>
<td>1.72</td>
<td>0.29</td>
<td>1.12</td>
<td>−1.08  2.08  −0.96</td>
</tr>
<tr>
<td>2013–2019</td>
<td>995</td>
<td>244</td>
<td>854</td>
<td>1.70</td>
<td>0.28</td>
<td>1.17</td>
<td>−1.09  2.09  −1.01</td>
</tr>
<tr>
<td>2013–2019 *</td>
<td>995</td>
<td>264</td>
<td>854</td>
<td>1.57</td>
<td>0.31</td>
<td>1.17</td>
<td>−0.98  1.98  −0.98</td>
</tr>
</tbody>
</table>

Note: * denotes the assumption that the MRP-SNWD was not operational during the period between 2013 and 2019.

In general, there is a positive correlation between runoff and precipitation, and a negative correlation between runoff and ET0, n. Based on the magnitude of the sensitivity coefficients, it was evident that runoff was most sensitive to changes in precipitation. The elasticity coefficients of ET0, n, and precipitation ranged from −0.89 to −1.09, −0.88 to −1.01, and 1.89 to 2.09, respectively (Table 4). The absolute values of the elasticity coefficients tended to increase over time. The 2013–2019 period showed the most significant
changes compared to the base period, with ET₀ elasticity coefficient (ε_ET₀), precipitation elasticity coefficient (ε_p), and subsurface change elasticity coefficients (ε_n) of −1.09, 2.09, and −1.01, respectively (Table 4). This means that when ET₀ increased by 1%, runoff decreased by 1.09%, when precipitation increased by 1%, runoff increased by 2.09%, and when n increased by 1%, runoff decreased by 1.01%.

Compared to the period 2013–2019, for the period 2013–2019 * (not considering the impact of the MRP-SNWD), the annual runoff depth increased by 20 mm, the n value decreased by 0.13, the runoff index increased by 0.03, and the drought index remained almost unchanged. This indicates that the water transfer project led to a reduction of 20 mm in basin runoff.

3.5. Attribution Analysis

Our attribution analysis based on the Budyko hypothesis was shown to be reliable, with errors between calculated and measured values of 9.8%, 8.0%, and 3.9% for each variation period. Table 5 shows the impact of each variable on runoff. In the first two change periods, the most significant driver of runoff variation was human activities, followed by precipitation and ET₀. However, when disregarding MRP-SNWD, the primary driver of runoff variation was precipitation, then human activities, followed by ET₀. During the period 1993–2012, human activities, precipitation, and ET₀ induced runoff changes of 34.14 mm, 13.41 mm, and 0.84 mm, respectively, with contribution rates of 73.09%, 28.70%, and −1.80%, respectively (Table 5). During the second change period from 2013 to 2019, runoff changes amounting to 30.94 mm, 23.42 mm, and 4.5 mm were caused by human activities, precipitation, and ET₀. Their contribution rates were 52.56%, 39.79%, and 7.65%, respectively (Table 5). The contribution of human activities decreased by 21.34 percentage points and that of precipitation increased by 11.09 percentage points from the first to second change period. In the change period from 2013 to 2019 *, the contribution rate of human activities to runoff reduction was 32.26%, 20.3% lower than that during the change period from 2013 to 2019. Thus, it can be concluded that the contribution rate of the MRP-SNWD to the runoff change was 20.3% (Table 5).

Table 5. Attribution results of runoff change in the Hanjiang River basin.

<table>
<thead>
<tr>
<th>Base Period</th>
<th>Change Period</th>
<th>ΔR_p (mm)</th>
<th>ΔR_ET₀ (mm)</th>
<th>ΔR_n (mm)</th>
<th>ΔR'</th>
<th>ΔR</th>
<th>C_p (%)</th>
<th>C_ET₀ (%)</th>
<th>C_n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960–1992</td>
<td>1993–2012</td>
<td>−13.41</td>
<td>0.84</td>
<td>−34.14</td>
<td>−46.70</td>
<td>−51.75</td>
<td>28.70</td>
<td>−1.80</td>
<td>73.09</td>
</tr>
<tr>
<td></td>
<td>2013–2019</td>
<td>−23.42</td>
<td>−4.50</td>
<td>−30.94</td>
<td>−58.87</td>
<td>−63.98</td>
<td>39.79</td>
<td>7.65</td>
<td>52.56</td>
</tr>
<tr>
<td>2013–2019 *</td>
<td></td>
<td>−24.05</td>
<td>−4.40</td>
<td>−13.56</td>
<td>−42.05</td>
<td>−43.77</td>
<td>57.27</td>
<td>10.47</td>
<td>32.26</td>
</tr>
</tbody>
</table>

Note: * denotes the assumption that the MRP-SNWD was not operational during the period between 2013 and 2019.

4. Discussion

Significant changes have occurred in the runoff processes within the Hanjiang River basin, while the variations in precipitation and evapotranspiration show no significant trends. Consequently, the impact of climate factors on the basin’s runoff is considered secondary. Our research findings also indicate that the contributions of precipitation to the runoff changes during the periods 1993–2012 and 2013–2019 are 28.7% and 39.8%, respectively, while the contributions of evapotranspiration are −1.8% and 7.7%, respectively. Peng et al. [49] also detected climate change as a secondary driver of the hydrological regime change in the Hanjiang River, which is similar to many rivers in China. For example, precipitation was not the dominant factor causing the decrease in runoff in the Yellow River [50]. In contrast, in sparsely populated watersheds, climate change generally poses a predominant influence on the hydrological processes [5]. However, in the context of a changing environment, in any case, the influence of climate factors is increasingly becoming more pronounced.
The Hanjiang River serves as an important agricultural area and national commercial grain base in China, contributing 5–12% of the country’s total agricultural production, so it is subject to intense human activities [51]. According to our research findings, human activities exert a dominant influence on the runoff in the Hanjiang River basin, but their impact in the period of 2013–2019 shows a decreased trend compared to the 1993–2012 period, which could be explained by the temporal variation in NDVI [52]. During the first change period, the NDVI increased remarkably compared to the base period, indicating an improvement in vegetation cover within the Hanjiang River basin. However, starting from the second period of change, the NDVI growth no longer exhibited significant increments but rather shows a gradual and slow trend, gradually stabilizing over time (Figure 8). Evidently, the runoff and NDVI had a relatively consistent trend, indicating their close positive relationship. Vegetation plays a critical and multifaceted role in mitigating surface runoff, prolonging infiltration time and enhancing soil conditions [49]. Its presence significantly improves soil permeability, allowing water to penetrate more effectively, while concurrently decreasing the volume of runoff [52]. By acting as a natural barrier, vegetation intercepts rainfall. Moreover, the intricate root systems of plants contribute to soil stabilization, creating channels and pores that further facilitate water absorption and reduce surface runoff velocity. Various studies indicate that a series of ecological restoration policies in China has contributed to the increase in vegetation cover, becoming one of the significant factors behind the reduction in runoff in various river basins [9,50]. It is worth noting that even within the same watershed, different regions may exhibit varying responses of hydrological processes to human activities [53]. A detailed study on this aspect will be conducted in the future.

**Figure 8.** Temporal variation in NDVI from 1982 to 2020 (a) and spatial distribution of NDVI difference between the change period (1993–2012) and the base period (1982–1992) (b) [49] in the Hanjiang River basin.

Due to the direct impact of inflow from the upper reaches of the Hanjiang River on the operation and efficiency of the MRP-SNWD, previous hydrologists have predominantly focused on the hydrological processes in the upper reaches of the Hanjiang River [54,55], but research on water resources in the middle and lower reaches is noticeably lacking. Moreover, with the ongoing operation of the MRP-SNWD, water resources in the middle and lower reaches of the Hanjiang River face even greater challenges [56], making it imperative to investigate the effects of the project. According to our study results, the MRP-SNWD poses a huge influence on the runoff reduction of the Hanjiang River, and its contribution is as high as 20.3%, which is a major social concern. Although climate change was the important driver of hydrological changes, as observed in other large basins [52,57], ignoring the effect of MRP-SNWD would be unwise in the Hanjiang River. For example, previous studies have modeled that after the operation of the MRP-SNWD, the water level would decline by 0.38–0.65 m [56]. In addition, the MRP-SNWD reduced groundwater discharge by 69.3% compared to natural conditions [34], which could negatively impact
the evolution of wetlands in the Jianghan Plain, which are dependent on groundwater discharge. This indicates that the MRP-SNWD implementation may cause a decline in in-stream runoff and increase the risk of wetlands shrinking.

Moreover, the MRP-SNWD has led to environmental deterioration downstream of the Danjiangkou Reservoir, with increasing pollutant concentration and reduced water quality [36, 58]. An integrated river algal bloom model revealed that the implementation of the MRP-SNWD could result in twice as many river algal bloom events in the middle–lower reach of the Hanjiang River under the 9.5 billion cubic meters per year water transfer scenario and a 2.5-fold increase under the 13 billion cubic meters per year water transfer scenario [36]. The eco-environmental degradation has led to a serious decline in the fish population and habitat in the mid-downstream of the Hanjiang River [58]. It can be predicted, with the accelerated warming, that these environmental problems will become more serious if water resource management is neglected and sustainable measures to mitigate the impacts of climate change and human interventions are not implemented.

Therefore, it is crucial for authorities in China to promote the implementation of the YHWD. As a compensation project, the operation of YHWD could mitigate the negative impact of MRP-SNWD on the quantity and quality of surface water and groundwater bodies. Additionally, according to Yin et al. [35], the YHWD could increase the runoff of the middle–lower Hanjiang River when operated together with MRP-SNWD.

5. Conclusions, Limitations, and Future Directions

5.1. Conclusions

In this paper, the temporal variation of runoff and climate predictor time series from 1960 to 2019 in the Hanjiang River basin was analyzed by using the Mann–Kendall test, the Pettitt test, and the R/S analytical method, and water and energy balance investigations based on the Budyko hypothesis were used to quantify the separate contribution of climate change and human activities to changes in runoff. The following conclusions were drawn:

1. Precipitation and \( \text{ET}_0 \) had a decreasing trend over the period of 1960–2019, albeit statistically insignificantly, and meanwhile, they had great spatial heterogeneity. In terms of seasons, the temporal patterns and spatial distribution were different. The interannual and spatial variation of \( \text{ET}_0 \) was much slighter compared to that of precipitation.

2. The annual runoff at the five hydrological stations decreased significantly with time, but their declining patterns were different. Different from Ankang station upstream, the other four stations in the Jianghan Plain had slighter variability, a more significant downward trend, and weaker persistence in annual runoff and increasing wintertime runoff, which was attributed to the joint operation of the Danjiangkou Reservoir and MRP-SNWD.

3. The elasticity coefficients of \( \text{ET}_0 \), \( n \), and precipitation tended to increase with time, and runoff was the most sensitive to changes in precipitation. The most significant impact on runoff reduction during the change period was human activities, with their contribution rate reaching 73.09% during the first change period (1993–2012) and 52.56% during the second change period (2013–2019), followed by precipitation, and \( \text{ET}_0 \) had little influence on runoff during two change periods.

4. The contribution of the influence of the MRP-SNWD on runoff change was 20.3%.

5.2. Limitations and Future Directions

1. It is noteworthy that our study still has some limitations. For example, there are uncertainties in the Budyko method, especially when considering the complex interactions between human activities and climate change in the Hanjiang River. Nevertheless, the results can still be valuable, reflecting the impacts of climate change, the MRP-SNWD, and other human activities on the changes in the Hanjiang River runoff.

2. Our study only focuses on changes in water quantity in the Hanjiang River basin, with inadequate studies of environmental flows that may have implications for water
quality, aquatic organisms, and other water-related ecosystems. In light of the recent occurrence of cyanobacterial outbreaks and other water-related ecological events throughout the middle and lower reaches, further research on ecological flows must be needed to address the water quality issue. In addition, ecological security evaluation and early warning systems should be carried out to identify ecological security risks. In addition, long-term monitoring, extensive research, improved legislation, policies, and management practices, including ecological compensation, are needed to alleviate negative environmental impacts.

3. The MRP-SNWD has had a significant effect and will continue to have a significant impact on the water balance of the Hanjiang River. So we urgently need to seek moves that make a difference and flip the script in the Hanjiang River, turning vulnerability into resilience. Non-engineering approaches are needed to move towards sustainable water management. For example, in the receiving-water area of the MRP-SNWD, there should be strict rules on water resource conservation, reducing water withdrawals and increasing ecological flows to the rivers. It is also crucial to integrate the YHWD into the national water network, linking two of China’s major water projects. This will remarkably enhance the resilience of the MRP-SNWD, benefiting the local population living along the Hanjiang River, while meeting the water needs of the country’s parched north. At the same time, joint optimal scheduling of the MRP-SNWD, YHWD, and cascading reservoirs is urgently needed to ensure sustainable water management in the Hanjiang River basin.

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References
1. Langhammer, J.; Su, Y.; Bernsteinová, J. Runoff Response to Climate Warming and Forest Disturbance in a Mid-Mountain Basin. Water 2015, 7, 3320–3342. [CrossRef]


15. Li, H.; Shi, C.; Sun, F.; Zhang, Y.; Collins, A.L. Attribution of Runoff Changes in the Main Tributaries of the Middle Yellow River, China, Based on the Budyko Model with a Time-Varying Parameter. CATENA 2021, 206, 105557. [CrossRef]


27. Shi, G.; Gao, B. Attribution Analysis of Runoff Change in the Upper Reaches of the Kaidu River Basin Based on a Modified Budyko Framework. Atmosphere 2022, 13, 1385. [CrossRef]


32. Yang, Q.; Liu, D.F.; Liu, H.; Meng, X.M.; Huang, Q.; Lin, M. Distributed Hydrological Modelling at Multiple Hydrological Stations in the Upper Reaches of Han River Based on SWAT Model. IOP Conf. Ser. Earth Environ. Sci. 2019, 344, 012081. [CrossRef]


34. Jiang, X.; Ma, R.; Ma, T.; Sun, Z. Modeling the Effects of Water Diversion Projects on Surface Water and Groundwater Interactions in the Central Yangtze River Basin. Sci. Total Environ. 2022, 830, 154606. [CrossRef] [PubMed]

35. Yin, X.; Zhang, J.; Chen, J. The Impact of Multi-Projects on the Alteration of the Flow Regime in the Middle and Lower Course of the Hanjiang River, China. Water 2020, 12, 2301. [CrossRef]


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