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Human and Natural Impacts on the Water Resources in the Syr Darya River Basin, Central Asia

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Abstract: Water resources are increasingly under stress in Central Asia because downstream countries are highly dependent on upstream countries. Water is essential for irrigation and is becoming scarcer due to climate change and human activities. Based on 20 hydrological stations, this study firstly analyzed the annual and seasonal spatial–temporal changes of the river discharges, precipitation, and temperature in the Syr Darya River Basin and then the possible relationships between these factors were detected. Finally, the potential reasons for the river discharge variations have been discussed. The results show that the river discharges in the upper stream of the basin had significantly risen from 1930 to 2006, mainly due to the increase in temperature (approximately 0.3 °C per decade), which accelerated the melting of glaciers, while it decreased in the middle and lower regions due to the rising irrigation. In the middle of the basin, the expansion of the construction land (128.83 km^2/year) and agricultural land (66.68 km^2/year) from 1992 to 2015 has significantly augmented the water consumption. The operations of reservoirs and irrigation canals significantly intercepted the river discharge from the upper streams, causing a sharp decline in the river discharges in the middle and lower reaches of the Syr Darya River in 1973. The outcomes obtained from this study allowed us to understand the changes in the river discharges and provided essential information for effective water resource management in the Syr Darya River Basin.

Keywords: Syr Darya River Basin; river discharge; climate change; trend analysis; land use

1. Introduction

Due to the arid climate, water has become a priority in the socio-economic development of Central Asia. Along with the rapid economic growth and population rise in this region, the future demand for water resources will certainly continue to increase and the water shortage will likely become more and more serious [1,2]. A population growth of 20 million people in this region is expected by 2040 [3], which will require additional irrigated areas in response to a larger food production. For example, the irrigated area in Uzbekistan is expected to rise by 5–11% by 2020 [4,5], eventually causing a 5–19% increase in the water demand [6]. Also, water resource management will encounter additional

difficulties from climate change, which will increase the vulnerability of the water supplies [7]. On the one hand, the projected temperature augmentations will lead to a longer growing period and a higher actual evapotranspiration, causing a 5% rise in the irrigation water consumption by 2030 [8,9]. On the other hand, the glacier loss will augment the discharge at first and will have little effect on the annual discharge once the glaciers have disappeared. Therefore, the glacier loss in the Pamir, Tien-Shan, and Alay mountains has been accelerating because of the higher temperature, which will potentially cause the annual river discharges in Central Asia to become as low as 50% by 2050 [10,11]. Identifying the links between the water resources, human activities, and climate change in Central Asia could offer the potential to improve the water resource management for human well-being and environmental sustainability.

In addition, due to the transboundary water conflict, water resource allocation in Central Asia is a big and complicated problem [12]. After the fall of the Soviet Union in 1991, the region's major rivers (including the Syr Darya River and the Amu Darya River) became transboundary rivers, which triggered a series of water conflicts between upstream and downstream countries over the past few years [13]. The Syr Darya River is the second longest river in Central Asia, which is a typical transboundary river and shared by Kyrgyzstan, Kazakhstan, Tajikistan, and Uzbekistan. It originates from the glacial meltwater and precipitation of the Tien Shan Mountains in Kyrgyzstan and eastern Uzbekistan (the upper streams are the Naryn River and the Kara Darya) and further meanders its way for about 2212 km west and northwest through Uzbekistan and southern Kazakhstan to the North Aral Sea. The river provides an abundance of water for agricultural production, industrial, and household activities and discharges huge amounts of sediments and freshwater into the North Aral Sea, thus adjusting the sea water level and the biogeochemical cycles [14,15].

With the rapid economic development and population explosion during recent years, the amount of water flowing from the Syr Darya River into the North Aral Sea has decreased over the past sixty years, directly causing a decrease in the sea water level [16]. Typically, human activities including change in land use (especially the expansion of agricultural land) and dam construction (e.g., the Karkidon, Kasansai, and Andijan dams) have significantly affected the water supply and water demand patterns, while simultaneously being exacerbated by the increased pollutants [17,18]. Also, climate change is likely to exacerbate the water stress in the Syr Darya River Basin [19]. As the water resources of the Syr Darya River mainly come from the glaciers and snowmelting in the high mountain ranges of the Tien Shan Mountains, the rising temperatures cause melting glaciers and ice sheets and disturb the hydrological dynamics as a result (e.g., the total and seasonal streamflow) [20]. These changes eventually trigger a lower and lower runoff [21], which causes negative implications for the water availability in the Syr Darya River Basin (and for the conflicting water demands between agriculture and hydropower).

Efforts in research have led to significant improvements in the evaluation of the water environment and resources in the Syr Darya River Basin [22–24]. For example, using satellite data, Crétaux et al. [25] estimated the total water storage of reservoirs in the Syr Darya River Basin; Wegerich et al. [15] discussed the critical role of the water supply in achieving a sustainable water security and provided some measures for irrigated agriculture. Although all these studies focused on the changes in water resources in the Syr Darya River Basin, the majority of previous studies mainly discussed the water resources in a regional sub-basin and only a few researchers analyzed the water resources for the whole basin [22]. Moreover, these studies only investigated the complete basin changes based on the limited hydrological and meteorological stations and remain unclear in some fields (e.g., the seasonal changes in the river discharges) [17]. For example, Savoskul et al. [14] comprehensively investigated the water modifications and other natural resources (climate, topography, land cover, and so on) and the related socio-economic aspects, but did not show the detailed seasonal changes between the upper, middle, and lower regions of the Syr Darya River.

Therefore, the annual and seasonal changes in the river discharges, precipitation, and temperature and their correlations were investigated for the whole Syr Darya River Basin in this study. We also explored the potential for the land use impact on the water resources. Specifically, this study addresses:

(1) The manner in which climate change is affecting the high mountains and plains of the Syr Darya River Basin; (2) the differences in the upstream and middle and lower regions of the Syr Darya River Basin under global warming and human activities; and (3) the manner in which the land use changes and their impact on the water resources could be evaluated. Previous research hardly addressed these issues. In particular, our paper adds insights by analyzing the changes in water resources in the Syr Darya River Basin based on 20 hydrological stations from 1930 to 2006 (the obtained results provide essential information for effective water resource management in this basin) and exploring the annual and seasonal changes in the river discharges and their influencing factors (e.g., precipitation, temperature, and land use changes). These were explored and discussed and could offer important information for effective water resource management in the Syr Darya River Basin.

This study is structured as follows: The study area, datasets, and methodology are briefly described in the next section. The annual and seasonal trend results and possible influencing factors will be presented in Section 3, followed by the conclusions and future work (Section 4).

2. Datasets and Methods

2.1. Study Area

The Syr Darya River, the second longest river in Central Asia, originates from the Tien Shan Mountains in Kyrgyzstan and eastern Uzbekistan and flows into the North Aral Sea, with a total length of 2212 km (Figure 1). The river drains an area of about 402,760 km^2, which is shared by four countries including Kyrgyzstan, Uzbekistan, Tajikistan, and Kazakhstan (Figure 1). The Syr Darya River Basin has a hot and arid climate in the downstream plains but a cool and humid climate in the mountains [26]. Due to the snow and glacier melting in the mountains, about 80% of water resources flow between March and September [27]. The annual rainfall in the basin approximately amounts to 350 mm/year, with a huge difference between the Tien Shan (500–1000 mm/year) and the downstream plain (100–200 mm/year) [27]. About 20 million people live in the basin and 80% of the population live in rural areas and consume about 90% of the water resources for irrigation [14,26]. Due to the overall overexploitation of the water resources, the amount of water flowing into the Aral Sea has significantly decreased since the 1960s, especially during the decadal periods 1971–1980 and 1981–1990. With the collapse of the Soviet Union in 1991, more river flows have reached the Aral Sea during 1991–2000 because of the decrease in water demand (but has been constantly decreasing during the subsequent decade, contributing to the unprecedented lowering of the Aral Sea levels and an environmental disaster in the region) [14].

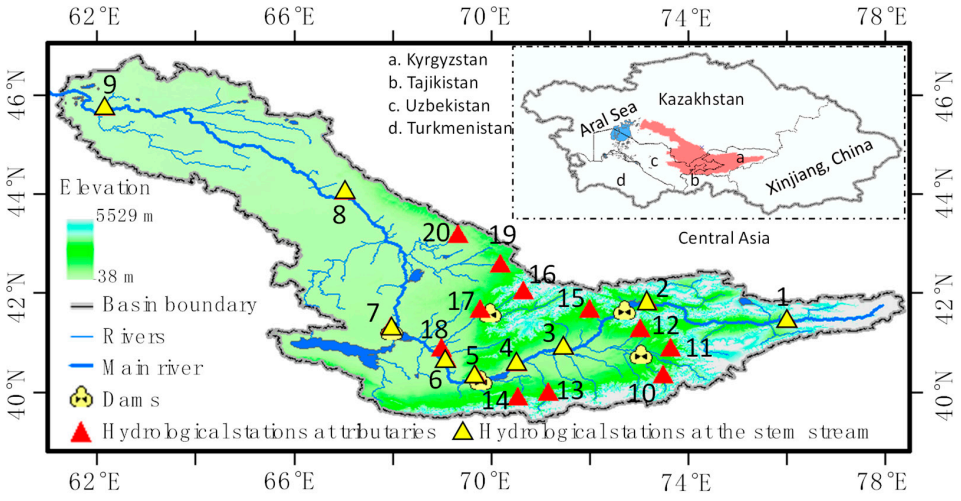

Figure 1. Map of the location, river networks, and hydrological stations of the Syr Darya River Basin, Central Asia.

2.2. Datasets

In this study, a total of 20 hydrological stations were selected so as to obtain the river flow data, in which nine stations (number 1–9) are located along the main Syr Darya River and eleven stations (number 10–20) in the major tributaries (Figure 1). The annual discharge was collected at most stations for the period 1930–2006 and the remaining sites demonstrated at least 35 years of data. Therefore, it is enough to capture the trend of the river flow in all of these stations. Due to the lack of ground observation data, the monthly, seasonal, and yearly precipitations and temperatures in the basin from 1931 to 2015 were calculated by using the Climatic Research Unit (CRU, TS v.4.01), which is a gridded dataset with a 0.5° resolution and has been confirmed to be reasonable for Central Asia [28,29].

In order to better understand the impacts of human activities on water resources, data on human population growth and land use change have also been collected. The Gridded Population of the World, Version 4 (GPWv4) was downloaded from the NASA Social Data and Application Centre (SEDAC) (http://sedac.ciesin.columbia.edu) to extract the population density for 2000, 2005, 2010, and 2015, the spatial resolution of which approximately amounts to 1 km [30]. The yearly landcover data from 1992 to 2015 have been obtained from the European Space Agency (ESA) climate change initiative (CCI), which has 37 categories with a 300 m spatial resolution and confirmed to be reliable in Central Asia [31]. Based on the categories defined by the Intergovernmental Panel on Climate Change (IPCC) [32], we merged the 37 categories into 7 types (agricultural land, forest, grassland, water body, construction land, and bare land).

2.3. Methodology

2.3.1. Trend Analysis

The Mann–Kendall (MK) test, which is a popular non-parametric statistical test [33,34], was used to detect the changes of the hydro-meteorological time series in this study. For a given time series $X_i\{X_i,\ i = 1, 2,\ \ldots,\ n\}$, the Mann–Kendall S Statistics could be calculated as follows:

$$= \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(T_j - T_i), \tag{1}$$

$$sign\left(T_j - T_i\right) = \begin{cases} 1 & if\ T_j - T_i > 0 \\ 0 & if\ T_j - T_i = 0 \\ -1 & if\ T_j - T_i < 0 \end{cases}, \tag{2}$$

where the *sign* function is an odd mathematical function that extracts the sign of a real number and T_j and T_i represent the hydro-meteorological variability on multiple time scales j and i, where $j > i$, respectively. The statistics S show the approximate normal distribution when $n \geq 10$. The mean and variance are calculated as [33]:

$$E[S] = 0, \tag{3}$$

$$\sigma^2 = \{n(n-1)(2n+5) - \sum_{j=1}^{n} t_j\left(t_j - 1\right)\left(2t_j + 5\right)\}/18. \tag{4}$$

Then, the standard test statistics Z_S are given by:

$$Z_s = \begin{cases} \frac{S-1}{\sigma},\ for\ S > 0 \\ 0,\ for\ S = 0 \\ \frac{S+1}{\sigma}, for\ S < 0 \end{cases}. \tag{5}$$

Z_S is used to measure the significance of the trend [35]. A positive value of Z_S suggests an increasing trend and a negative value of Z_S illustrates a decreasing trend. If $|Z_S|$ is greater than 1.96

on the 5% significance level, the null hypothesis of no trend is invalid, which indicates that the trend is significant.

2.3.2. Change-Point Detection

The multiple structural change detection was applied so as to detect the abrupt changes in river discharges in the Syr Darya River Basin [36]. The annual river discharge in the hydrological stations was modeled by the linear structural change model with m breaks (m + 1 segment):

$$y_i = a_j x_i + b_j + \varepsilon_i, \left(i = i_{j-1} + 1, \ldots, i_j; j = 1, \ldots, m+1\right), \quad (6)$$

where y and x represent the hydro-meteorological variability on multiple time scales j and i, j illustrates the index of the segment, $(i_1, \ldots, i_m)$ show the set of the break positions, and, by convention, $i_0 = 0$, $i_{m+1} = n$ (n is the size of the time series), a and b stand for the regression coefficients estimated by the ordinary least square approach, and ε demonstrates the residue. The minimum of the sum of the squared residues is the key factor to determine the optimal set of break positions. Detailed methodological information can be found in [36].

2.3.3. Correlation Analysis

(1) Pearson's Correlation

The Pearson's correlation coefficient was exploited to measure the relationship between the precipitation, temperature, and river discharges, which indicates the covariance of the two variables divided by the product of their standard deviations. Its correlation coefficient (r) could be computed as [37]:

$$r = \frac{\sum (x - m_z)\left(y - m_y\right)}{\sqrt{\sum (x - m_z)^2 \ \sum \left(y - m_y\right)^2}}, \quad (7)$$

where m_z and m_y illustrate the means of the x and y variables. Then, the correlation values presented for the analysis of the precipitation, temperature, and river discharge were tested on a confidence level of 95%, which is used to calculate the significance of the correlation.

(2) Multiple Linear Regression

In order to quantitatively assess the effects of the precipitation and temperature on the river discharge, a multiple linear regression analysis was performed with the river discharge as a dependent variable and the precipitation and temperature as the independent variables.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon, \quad (8)$$

where y represents the river discharge of the Syr Darya River, β_0 stands for the y-interception (constant term), x_1 shows the precipitation (mm), x_2 is the temperature (°C), ε is the model's error term, and β_1 and β_2 illustrate the slope coefficients for the precipitation and temperature, respectively.

2.3.4. Land Use Change Analysis

Land use is an important factor that affects a river's discharge. Here, the land use variance amplitude and land use transition matrix were applied so as to measure the changes in land use from 1992 to 2015 in the Syr Darya River Basin. The land use variation amplitude can be computed by the following equation:

$$\mathrm{V}_i = \frac{\mathrm{Land}_{i1} - \mathrm{Land}_{i0}}{\mathrm{Land}_{i0}} \times 100\%, \quad (9)$$

where i represents the seven land cover types including the agricultural land, forest, grassland, water body, construction land, and bare land; Land_{i0} and Land_{i1} demonstrate the area at the beginning

and end of the year (of the i_{th} land use type), respectively. The transition probability matrix can be calculated by:

$$A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{bmatrix}, \quad (10)$$

where A represents the area of different types of land use, n the number of land use types (here n is seven), and i and j in A_{ij} demonstrate the type of land use at the beginning and end of the year, respectively. The final result indicates the transferring direction of the land use types during the period 1992–2015.

3. Results and Discussion

3.1. Trend Analysis of the River Discharge

As shown in Figure 2a, the stations with a higher annual average river discharge are located mainstream, especially in the middle of the Syr Darya River. Generally, the river flow exhibited an increasing trend in the upper region, while a decreasing move in the middle and lower regions. The highest value was up to 738.5 m^3/s at the station in Kazakhstan, which decreased to 284.8 m^3/s before flowing into the Aral Sea.

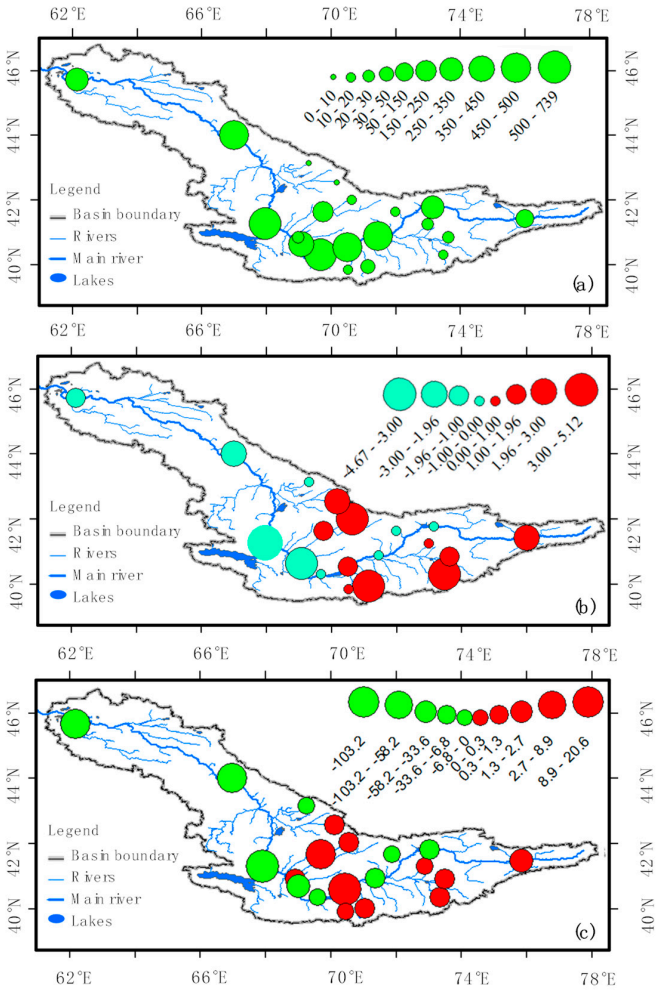

Figure 2. Map of (**a**) the mean annual river discharge (m^3/s), (**b**) the Mann–Kendall trend test (Z), and (**c**) the trend for each decade ($m^3/(s*decade)$) for 20 hydrological stations in the Syr Darya River Basin.

Figure 2b shows the results of the Mann–Kendall trend test (Z) for 20 hydrological stations in the Syr Darya River Basin, suggesting that the river discharges rose at the upper rivers, while they fell in the middle and lower regions. Concretely, there were more stations with significant positive trends (the red circle) in the Tien-Shan Mountain and the biggest Z value amounted to 5.12. By contrast, stations with important negative trends (the blue circle) were mostly scattered in the middle and lower reaches and the lowest Z value amounted to −4.67.

Figure 2c clearly illustrates the decadal trend in the annual river discharge for each station. Like the results of the Mann–Kendall trend test, most stations with positive growth rates were located at the upper rivers, whereas the stations with negative growth rates tended to be clustered in the middle and lower regions. During the study period, the largest positive growth rate was up to 20.6 m^3/(s·decade) at station 4, followed by 8.9 m^3/(s·decade) at station 17; on the other hand, the largest negative growth rate measured up to −103.2 m^3/(s·decade) at station 7, followed by −59.3 m^3/(s·decade) at station 8.

In order to further understand the detailed changes of the river discharges, six typical stations (including stations 1, 6–8, 10, and 13) were selected to detect the abrupt points and the results are shown in Figure 3. From this figure, we can conclude that the river discharges at stations 6–8 tended to fall significantly at a 95% confidence level with Z values at −3.02, −4.67, and −2.92, respectively, and increased significantly at stations 1, 10, and 13 with the Z values at 2.50, 3.90, and 4.50, respectively. The results indicate that an augmentation was noticed at the upper streams of the Syr Darya Basin, especially in the tributaries of the Tien-Shan Mountain, but a decreasing trend could be seen in the middle and lower regions during the period 1930–2006. These results are in line with the findings shown in Figure 2.

Also, Figure 3 clearly illustrates that an abrupt point (in 1973) was detected for stations 6–8, dividing the record into two time periods, including 1930–1973 and 1974–2006. The main reason is that in 1973, the largest dam (Toktogul Dam) was finished in order to control the river discharge to provide sufficient irrigation water. The annual average river discharge of these two intervals at station 8 were 565.7 and 355.3 m^3/s, respectively, a decrease of 210.5 m^3/s between these two time periods. In addition, a significant increasing trend was found from 1974 to 2006 for stations 6–8, with the Z values at 5.62, 4.85, and 4.80, respectively.

As in the case of the annual data, the river discharges tended to rise during four seasons in station 1 (see Figure 4a). Among them, a significant increase was found from 1930 to 2006 for both summer and autumn, with the Z values at 2.36 and 3.48, respectively (see Table 1 and Figure 4a), suggesting that the increases of the river discharges during the year mainly came from summer and autumn. Also, summer had the largest value of mean annual river discharges during the period 1930–2006, up to 219.4 m^3/s, followed by spring (63.9 m^3/s), autumn (57.3 m^3/s), and winter (26.5 m^3/s). Figure 4b shows the seasonal changes of the river discharges at station 8, which indicates that the river discharges tended to decrease from 1930 to 2006 for all four seasons. Winter had the largest decreasing trend (Z = −2.41), followed by summer (Z = −2.15), spring (Z= −2.12), and autumn (Z = −1.32). Also, Figure 4b shows that the river discharges at station 8 exhibited a significant rising trend for all four seasons from 1974 to 2006. During the period 1974–2006, the blue linear trend line of Figure 4b indicates that winter showed the highest increasing trend (Z = 5.16), followed by autumn (Z = 5.04), spring (Z = 3.67), and summer (Z = 2.68), eventually leading to the rise in the annual river discharges from 1974 to 2006 (Figure 3c).

3.2. Trend Analysis of the Precipitation and Temperature

Figure 5 shows the spatial distribution of the mean values and trends of the annual precipitation and temperature during the period 1930–2015. As shown in Figure 5a, the mean annual precipitation, which ranged from 100 to 700 mm across the basin, was less in the lower area of the Syr Darya Basin compared with the other regions. Also, the highest precipitation was found in the mountains in the middle of the basin, which measured up to 700 mm/year. However, an inverse distribution was detected in the precipitation trends (Figure 5c), in which the middle region illustrated the largest decrease, up to 40 mm/decade. Also, an increasing trend was found in the lower and upper regions of the basin, up to 20 mm/decade. However, the trend of the annual precipitation in each grid was not significant.

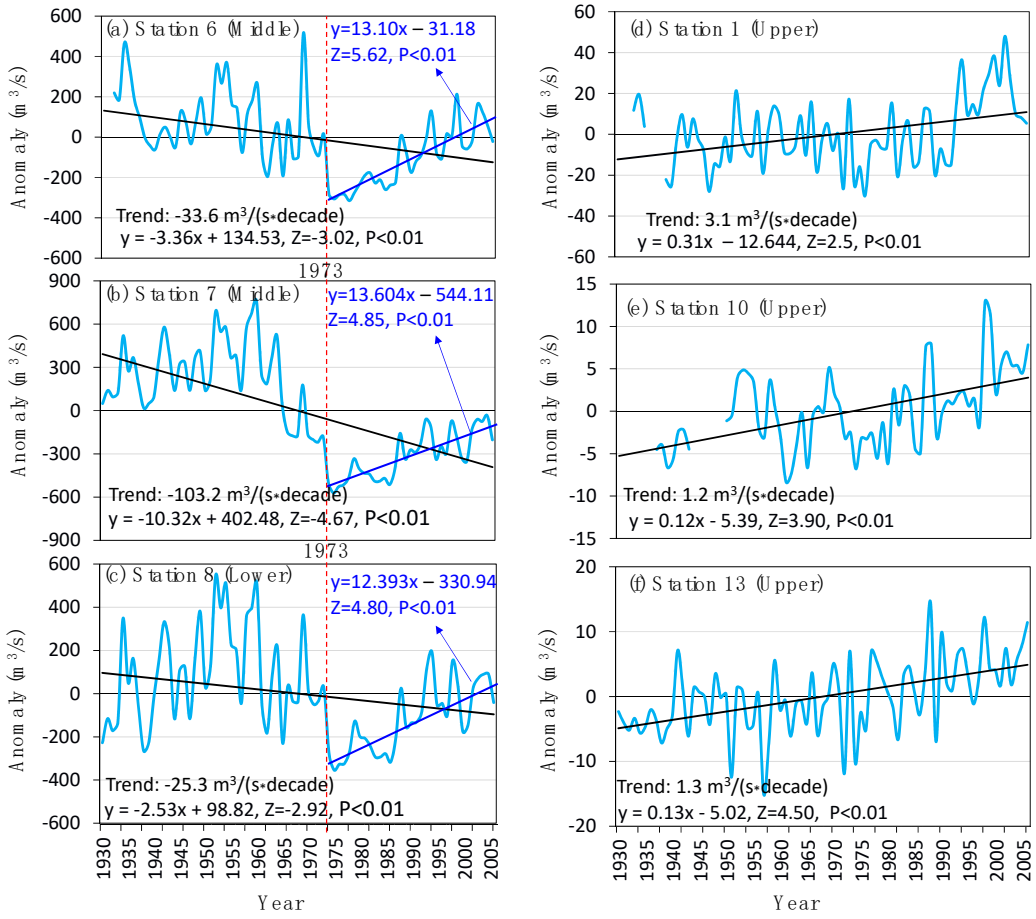

Figure 3. Time series, trends, and abrupt changes of the annual river discharge anomaly (m^3/s) at (**a**) station 6, (**b**) station 7, (**c**) station 8, (**d**) station 1, (**e**) station 10, and (**f**) station 13 from 1930 to 2006. In the trendline equation, x is the independent variable and represents the number of years relative to the base period and y is the dependent variable and represents the annual river discharge anomaly (m^3/s). Stations 6 and 7 are located at the middle stream of the Syr Darya River, station 8 at the lower stream of the Syr Darya River, and stations 1, 10, and 13 are situated at the upper stream of the Syr Darya River.

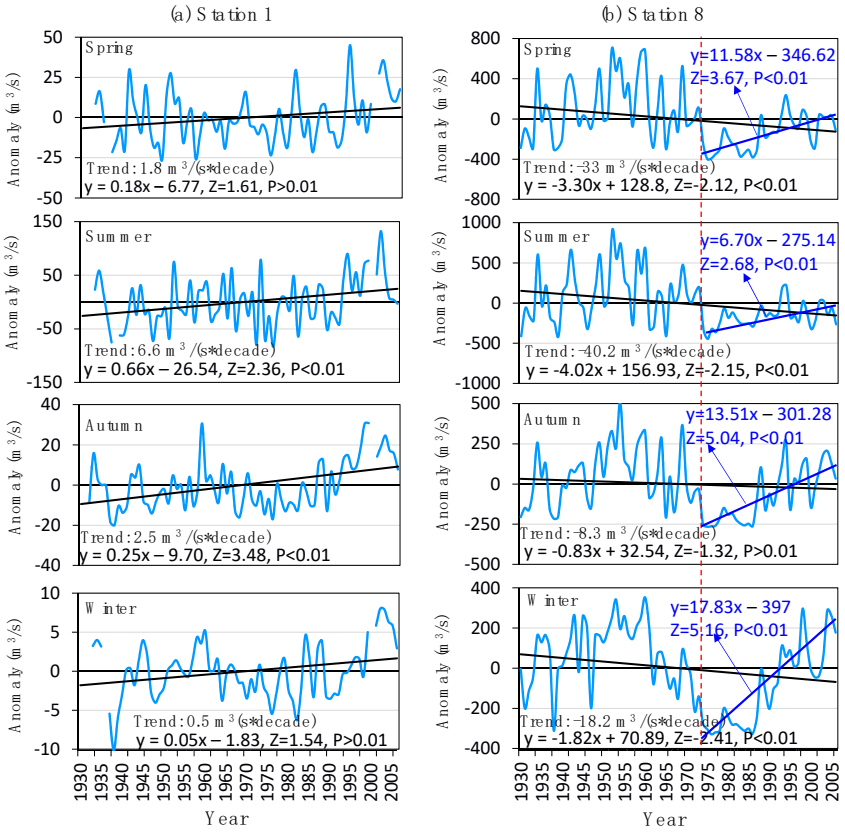

Figure 4. Time series, trends, and abrupt changes of the seasonal river discharge anomaly (m^3/s) at (**a**) station 1 and (**b**) station 8 during the study period. In the trendline equation, x is the independent variable and represents the number of years relative to the base period; y demonstrates the dependent variable and stands for the annual river discharge anomaly (m^3/s).

Table 1. Changes of the seasonal discharges (m^3/s) at station 1 and station 8 and the precipitation (mm/year) and temperature (°C) changes in the Syr Darya River Basin.

Variable	Season	Mean	Z	Decadal Trend
Station 1	Annual	92.7	2.50 *	3.1
	Spring	63.9	1.61	1.8
	Summer	219.4	2.36 *	6.6
	Autumn	57.3	3.48 *	2.5
	Winter	26.5	1.54	0.5
Station 8	Annual	475.6	−2.92 *	−33.6
	Spring	599.7	−2.12 *	−33.0
	Summer	594.3	−2.15 *	−40.2
	Autumn	319.7	−1.32 *	−8.3
	Winter	385.0	−2.41 *	−18.2
Precipitation (1930–2015)	Annual	307.2	1.60	4.3
	Spring	124.6	0.69	1.3
	Summer	32.7	0.25	0.2
	Autumn	56.8	1.07	1.4
	Winter	93.1	1.40	1.5
Temperature (1930–2015)	Annual	8.6	6.83 *	0.3
	Spring	9.5	4.29 *	0.3
	Summer	22.2	5.64 *	0.2
	Autumn	8.7	5.51 *	0.3
	Winter	−5.8	3.24 *	0.3

Note: * indicates that changes are significant on the 95% confidence level.

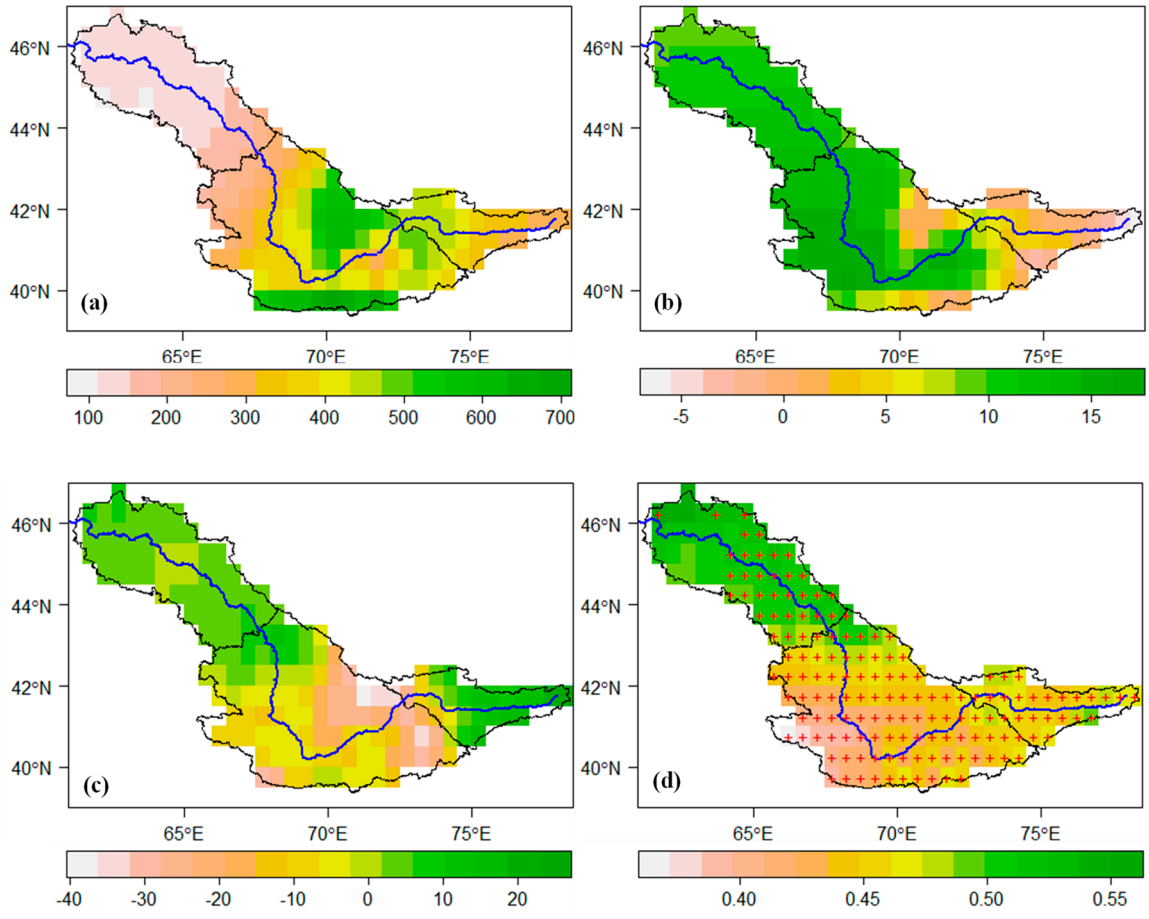

Figure 5. Maps of the mean annual values in the (**a**) precipitation (mm) and (**b**) temperature (°C) and linear decadal trends in the (**c**) precipitation (mm/decade) and (**d**) temperature (°C/decade) during 1930–2015 in the Syr Darya River Basin. Red pluses indicate the grid points with changes that are significant at a 95% significance level.

As shown in Figure 5b, the annual mean temperature was much higher in the middle and lower regions of the Syr Darya Basin compared with the high mountainous regions, ranging from around 15 °C to around −5 °C. Figure 5d clearly indicates that a rising trend was detected for all grid cells of the basin, ranging from approximately 0.4 °C/decade to 0.6 °C/decade. The lower region of the basin showed a larger increase compared with the other regions, up to 0.6 °C/decade, which reveals that the plain was more sensitive to the global warming. The augmenting temperature has accelerated the glacier melting in the Tien Shan Mountains.

Table 1 also shows the changes in precipitation and temperature on both the seasonal and annual scales, suggesting that a rising trend was found for all seasons from 1930 to 2015. The mean regional annual precipitation measured 307.2 mm with an increasing trend (Figure 6a). Spring had the largest value in mean precipitation, up to 124.6 mm/year, followed by winter (93.1 mm/year), autumn (56.8 mm/year), and summer (32.7 mm/year). Overall, the precipitation trend was not significant for all seasons. The average regional annual temperature was 8.6 °C with a rise on the 95% confidence level ($Z = 6.83$) (Figure 6b). Summer demonstrated the highest mean annual temperature, up to 22.2 °C, followed by spring (9.5 °C), autumn (8.7 °C), and winter (−5.8 °C). Also, the annual temperature in summer, autumn, spring, and winter tended to augment significantly on the 95% confidence level with the Z values at 5.64, 5.51, 4.29, and 3.24, respectively.

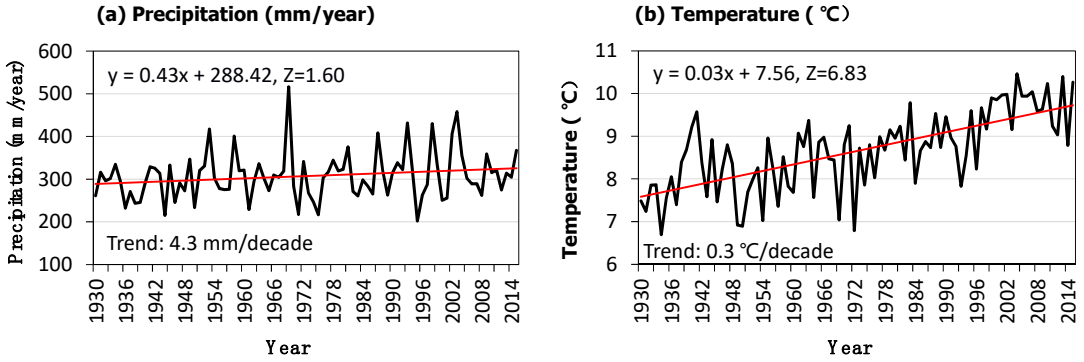

Figure 6. Time series and trends in the precipitation (mm) and temperature (°C) in the whole basin from 1930 to 2015. The red straight line in each sub-figure is the trend line. In the trendline equation, x stands for the independent variable and represents the number of years relative to the base period; y is the dependent variable and illustrates the annual river discharge anomaly (m^3/s).

3.3. Relation of the Climatic Factors and River Discharges

Table 2 shows the Pearson's correlation between the climatic factors (precipitation and temperature) and river discharges at stations 1, 6–7, 10, and 13 in the Syr Darya River Basin. Positive correlations were detected between the precipitation and river discharges for all stations from 1930 to 2015. A positive correlation on a 95% statistical significance level was found at stations 1, 6, 8, 10, and 13 with a corresponding value of 0.32, 0.31, 0.39, 0.50, and 0.23 respectively, suggesting that the increasing annual precipitation caused augmenting annual river discharges during the period 1930–2015. The correlation coefficient measured 0.14 at station 7 but was not important. Moreover, according to the interpretation of the correlation coefficients (Table 3), we found that a moderate correlation strength was only discovered at station 10 and that a weak correlation strength was detected at stations 1, 6, and 8.

Table 2. Results of the correlation analysis between the climatic factors and discharges in the Syr Darya River Basin.

Station	Station 1	Station 6	Station 7	Station 8	Station 10	Station 13
Precipitation	0.32 *	0.31 *	0.14	0.39 *	0.50 *	0.23 *
Temperature	0.29 *	−0.38 *	−0.45 *	−0.32 *	0.29 *	0.55 *

Note: * Correlation on a 95% confidence level.

Table 3. Interpretation of the correlation coefficients [38].

Correlation Coefficient (R)	Correlation Strength
0.0–0.3	Very weak
0.3–0.5	Weak
0.5–0.7	Moderate
0.7–0.9	Strong
0.9–1.0	Very strong

Note: This descriptor applies to both the positive and negative relations.

A significant correlation was noticed between the temperature and river discharges for all stations from 1930 to 2015, which could be divided into two groups. On the one hand, a positive correlation was detected at stations 1, 10, and 13, with a corresponding value of 0.29, 0.29, and 0.55, respectively, which indicates that the rising temperature caused the glaciers to melt more quickly, probably leading to increasing river discharges during the period 1930–2015. On the other hand, a negative correlation was found at stations 6–8, with corresponding values of −0.38, −0.45, and −0.32, respectively. This

difference reveals that the increasing discharges from the upper rivers (see stations 1, 10, and 13) were consumed in the middle and lower rivers of the Syr Darya River Basin, possibly offsetting the positive effects of the rising temperature. However, only station 10 demonstrated a moderate positive correlation strength between the river discharges and temperature, while other stations showed a weak negative (or positive) correlation.

In order to fully understand the combining effects of the precipitation and temperature on the river discharge of the Syr Darya River, a multiple linear regression analysis was performed with the river discharge as the dependent variable (and the precipitation and temperature as independent variables, the results of which are shown in Table 4 and Figure 7). The regression t values for the precipitation and temperature at station 1 were 3.56 ($p < 0.\ 001$) and 3.48 ($p < 0.001$), respectively, reflecting a positive correlation between the climatic factors (both the temperature and precipitation) and the river discharge. The regression t values for the precipitation and temperature at station 8 were 3.60 ($p < 0.\ 001$) and −2.93 ($p < 0.005$), respectively, revealing a positive correlation between the precipitation and river discharge (and a negative correlation between the temperature and river discharge). Additionally, the magnitude of the t values at stations 1 and 8 indicates that the effects of the interannual variability in precipitation on the river discharge are the same as those of the interannual variability in temperature.

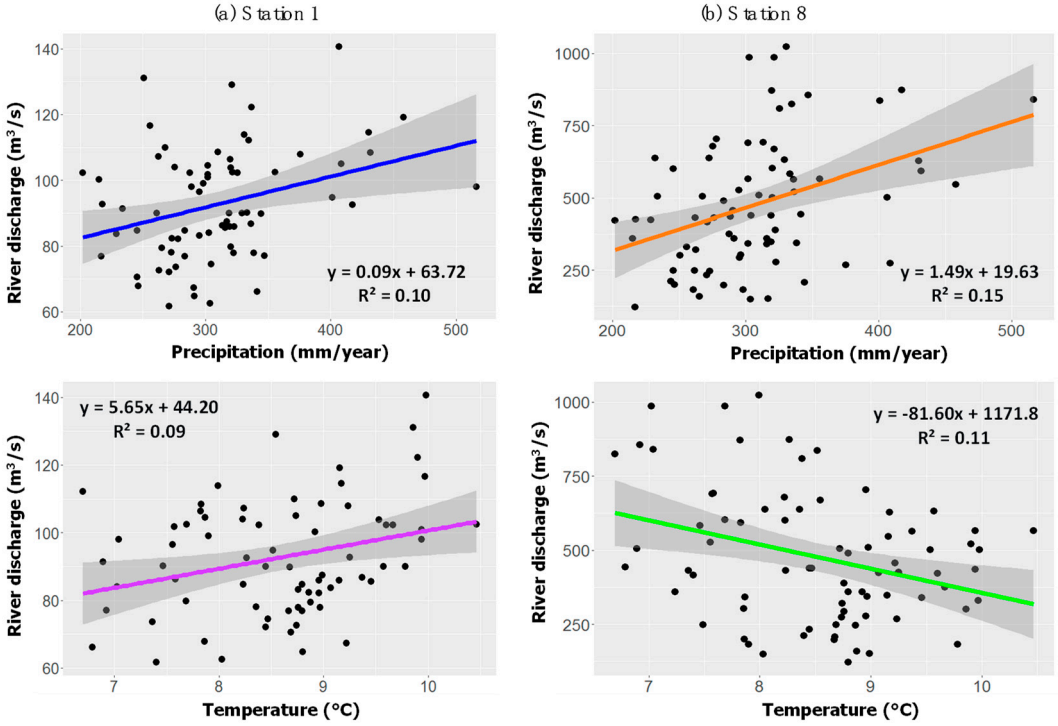

Figure 7. Correlations between the annual precipitation, temperature, and river discharges at stations 1 and 8 in the Syr Darya River Basin. The straight line represents the linear regression lines and the black shade is a 95% confidence band.

To conclude, evidence for the climate change impact (on the water resources of the Syr Darya River Basin) is plentiful. Over the past 85 years, temperatures have significantly increased in all parts of the basin, which probably caused glaciers in the high mountains to melt faster than before, shaping/creating more ice runoff [3,39]. Precipitation has increased in both the upper and lower parts of the basin and decreased in the middle of the basin (Figure 5c), which is in line with the results from Sorg et al. [21]. Also, substantial climatic changes are expected to continue occurring in the pattern of precipitation and temperatures [40], which are likely to augment the uncertainties in water supply and in water resource management.

Table 4. Linear regression of the river discharge (m^3/s) against the precipitation (mm) and temperature (°C) in the Syr Darya River Basin.

Station	Parameter	Interception	Precipitation	Temperature
Station 1	Coefficients	0.55	0.11	6.85
	Standard error	19.78	0.03	1.97
	t value	0.02	3.56	3.48
	p value	>0.05	<0.001	<0.001
Station 8	Coefficients	684.42	1.40	−74.95
	Standard error	257.13	0.39	25.57
	t value	2.66	3.60	−2.93
	p value	<0.001	<0.001	<0.005

3.4. Impact of the Land Use on the River Discharges

The discharge from a river basin depends on the precipitation, evapotranspiration, and storage factors [41,42]. The results mentioned above show the changes of the river discharges, climate factors, (precipitation and temperature) and their correlations in the Syr Darya River Basin. These results indicate that the river discharges increased in the upper streams, mainly due to the rise in melting ice, while they decreased in the middle and lower streams because of human activities. Here, we would like to further discuss the potential reasons from the two aspects of land use and reservoir construction.

Figure 8 and Table 5 show the changes in the main types of land use in the Syr Darya River Basin from 1992 to 2015. Grassland is the largest land cover, occupying about 48% of the entire basin, followed by agricultural land (29%) and bare land (19%). Three types of land cover, including the agricultural land, water body, and construction land, exhibited a noticeable increase on a 95% statistical significance level during 1992 to 2015. Among them, the change rate of construction land was the highest, up to 127.83 km^2/year, followed by the agricultural land (66.68 km^2/year) and water body (22.01 km^2/year). By contrast, the bare land decreased on a 95% statistical significance level from 1992 to 2015, up to 252.06 km^2/year, implying that most regions of bare land had been converted into agricultural land and construction land [14]. The results indicate that the rapid expansion of the construction land and agricultural land mainly came from the increases in the middle of the Syr Darya River Basin over the past 24 years (see Figure 8; Figure 9).

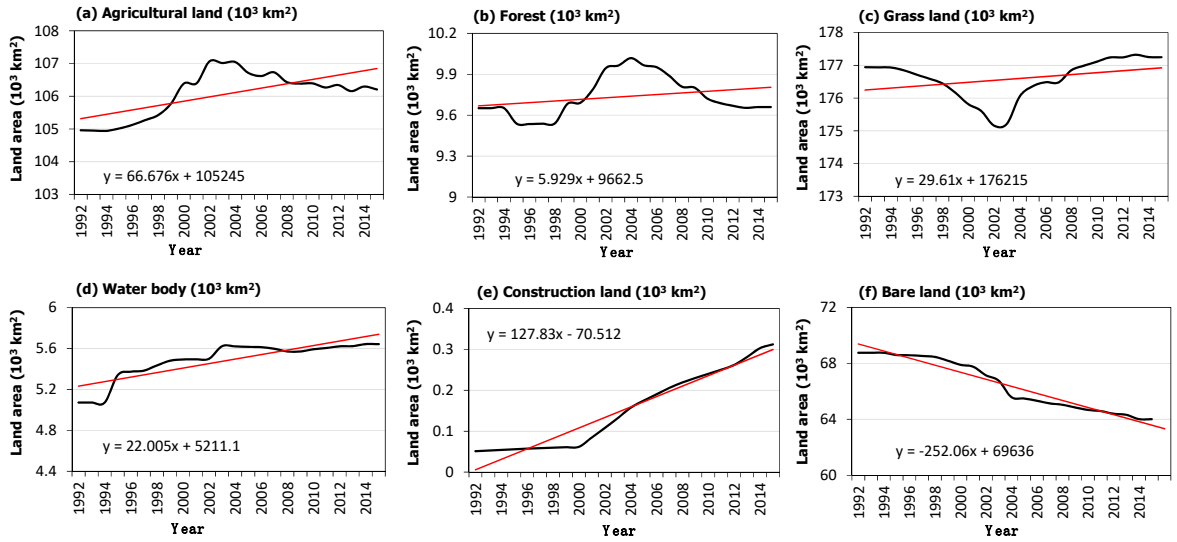

Figure 8. Change of the different land covers in the (**a**) agricultural land, (**b**) forest, (**c**) grassland, (**d**) water body, (**e**) construction land, and (**f**) bare land in the Syr Darya River Basin. In the trendline equation, x is the independent variable and represents the number of years relative to the base period; y is the dependent variable and represents the annual river discharge anomaly (m^3/s).

Table 5. Changes of the main land cover types in the Syr Darya River Basin during the period 1992–2015.

Land Use	Agricultural Land	Forest	Grassland	Water Body	Construction Land	Bare Land
Change rate (km^2/year)	66.68 *	5.93	29.61	22.01 *	127.83 *	−252.06 *
Z	1.96	1.27	1.91	5.21	6.82	−6.82

Note: * indicates the land cover with changes that are significant on the 95% significance level.

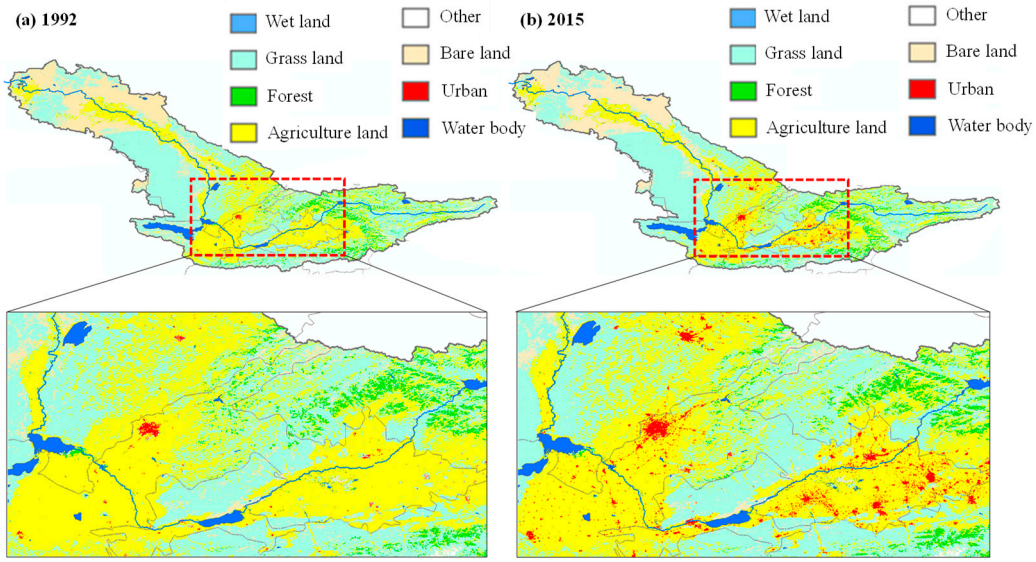

Figure 9. Maps of the land covers in the Syr Darya River Basin in 1992 and 2015.

On the one hand, the change in construction land (caused by the increasing population and the rapid economic development) had a demonstrable effect on the hydrological cycle in the Syr Darya River Basin [17]. The expansion of the urban impermeable surfaces (see Figure 9) is likely to reduce the ability of land infiltration and resulted in a significant influence on the surface-runoff dynamics [43]. Also, the rapid urbanization could drastically alter the geomorphologic complexity of the river networks [44]. All these changes have demonstrated increases in the total runoff, declines in the runoff lag time, enlargements in the peak flow, and augmentations in the urban flooding risks [45]. Therefore, the construction land's expansion generally had a positive effect on the runoff volume and a negative impact on the urban flooding in the Syr Darya River Basin.

On the other hand, with the agricultural development, a massive irrigation expansion and river-basin planning were set up for the Syr Darya River Basin from 1940 to 1983 [46,47]. During the period of 1940 to 1983, several big reservoirs (see Figure 1), including Kasansai, Karkidon, Andijan, Kasansai, and Tortogul (and small reservoirs), were constructed and the total water storage capacity measured up to 35 km^3. These reservoirs were utilized to intercept and store the water resources, which were then transported to develop the agricultural irrigation through an immense network of canals. Table 6 shows the capacity and length of several main canals. The capacity of these canals ranged from 40 to 300 m^3/s and the length ranged from 25 km to 344 km. The Fergana Valley, which is one of the most ancient world oases, generally collects about 4 km^3/year mainly through the Toktogul and Andijan reservoir operations and the Great Canal [48]. The largest reservoir (Toktogul) was finished in 1973 and was built so as to control the river discharge to provide sufficient irrigation water. All these agricultural activities probably triggered a significant decline in the river discharges in 1973.

Table 6. Main irrigation canals of the Syr Darya River Basin [48].

Canal's Name	Capacity (m^3/s)	Length (km)
Great Namangan	61	162
Northern Fergana	110	165
Great Fergana	270	344
Great Andijan	200	110
Southern Fergana	130	103
Akhunbabaeva	60	50
Upper Dalverzin	40	30
Lower Dalverzin	78	25
South Golodnaya Steppe	300	127
Kirov	260	120
Kyzylkum	200	115

Therefore, the land use changes significantly affected the water resources in the Syr Darya River Basin. On the whole, all these changes in land use would likely increase the water consumption, causing the decline of the river discharges in the middle and lower parts of the Syr Darya River [17].

3.5. Impact of the Groundwater Recharge on the River Discharges

Recently, the groundwater recharge has been an important source to feed irrigated lands in the Syr Darya River Basin. Generally, the groundwater resources were not widely used for irrigation in Central Asia during the Soviet period because of sufficient surface water, a reliable water supply, and the good maintenance of irrigation infrastructure with massive funding from the central government [49]. However, after the collapse of the Soviet Union, the groundwater was gradually extracted to feed irrigated lands in the Syr Darya River Basin, especially in the Fergana Valley [50].

Since 1990, there have been upstream/downstream impacts in the aquifer areas of the Fergana Valley due to the increased irrigated cereal production upstream. On average, about 18% of the total groundwater recharge for the aquifers having transboundary implications came from the subsurface inflow to the downstream of the Fergana Valley. The loss in water resources from canals and irrigation is the main source of groundwater in the downstream areas and up to 49% of the groundwater recharge is contributed by irrigation in the Fergana Valley. Currently, 31% of the total recharge originates from the groundwater extraction in the Fergana Valley and it is also needed to manage the groundwater recharge to prevent issues related to the groundwater depletion, degradation of the groundwater quality, and the high extraction cost [51].

4. Conclusions, Management Measures, and Future Work

The annual and seasonal changes of the water resources in the Syr Darya River Basin were evaluated based on 20 hydrological stations from 1930 to 2006. Also, the correlations between the river discharges, climate factors, land use changes, and reservoirs were characterized. Some interesting findings were gathered and summarized as follows: (1) The stations located in the upper streams of the Syr Darya Basin showed an increasing trend in the river discharges from 1930 to 2006, while a decreasing trend was visible in the middle and lower regions; (2) the increased precipitation and melting water led to a rise in the amount of water that flows from the upper to the middle and lower rivers, eventually leading to a rise of the annual river discharges from 1974 to 2006; (3) the expansion of the construction land (128.83 km^2/year) and agricultural land (66.68 km^2/year) from 1992 to 2015 increased the water consumption, exacerbating the stress of the water resources in the Syr Darya River

Basin; and (4) the establishment of dams (e.g., Kasansai, Karkidon, Andijan, Kasansai, and Tortgul) and irrigation canals has significantly cut off the river discharge, especially from the 1970s onwards.

Results could offer useful information that will help to establish effective water resource management in the Syr Darya River Basin. The future progress in the sustainable water resource development in this basin will require (1) an updated, legal, and executable framework for managing the transboundary water resources between Kyrgyzstan, Kazakhstan, Tajikistan, and the Uzbekistan countries, (2) the development of an integrated water management system in the Syr Darya River Basin for the optimal management of hydropower and irrigated agriculture, and (3) the increased investments in national water sectors including agricultural techniques, irrigation networks, and technologies so as to increase the water use efficiency and productivity. Therefore, in future work, more detailed conditions should also be considered for a sustainable water resource development for the whole basin.

This study also has a few shortcomings and suggests several areas for future work. Firstly, due to the lack of ground observation data, the CRU dataset was applied to calculate the precipitation and temperature and its course resolution (0.5°) could not perfectly capture the real precipitation and temperature, probably causing some uncertainties. If possible, more gridded climate datasets will be combined with the existed observed data in order to obtain more reliable climate data. In addition, the outcomes from the Pearson's correlation could not fully measure the effects of the river discharges because the Syr Darya River was affected by many factors, including the precipitation, temperature, evapotranspiration, and so on. Finally, more complicated hydrological cycles will be considered in order to fully assess the water resources, especially in society-relevant extreme events such as floods, droughts, and so on.

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