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Article

# Current Status and Countermeasures of Water and Soil Resources in the Syr Darya River Basin of Kazakhstan

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**Abstract:** Climate change and anthropogenic activities pose significant challenges to agricultural sustaina-bility in the Syr Darya River Basin. This study investigates the spatial distribution of land use and assesses the current state of water resource development and utilization in the basin. Furthermore, it analyzes trends in temperature and precipitation from 1950 to 2021. Our findings reveal that between 2000 and 2015, the areas of cultivated land, forest land, grassland, construction land, and bare land increased overall. During 1950–2021, the basin experienced a temperature increase of 0.323°C per decade and a precipitation increase of 1.393 mm per decade. The accurate classifi-cation and monitoring of land use and cropping systems are crucial for clarifying the spatial dis-tribution and utilization patterns of land and water resources in the Syr Darya region. Such analysis is pivotal for diagnosing the driving mechanisms behind soil salinization and ecological degradation. Consequently, this study provides a robust data foundation for formulating integrated management strategies, including the optimization of agricultural practices and the implementation of precision water allocation. Ultimately, this research establishes a scientific basis for evidence-based decision-making in regional salinization control and ecological rehabilitation.

**Keywords**: Syr Darya River Basin; Spatial distribution of land Use; Water resources

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## 1. Introduction

Since the Industrial Revolution, global warming has become an indisputable fact. The Intergovernmental Panel on Climate Change (IPCC) stated in its Sixth Assessment Report (2023) that human activities are the primary driver of this warming. The report indicates that the global surface temperature in 2020 was 1.1°C higher than the aver-age for the period 1850–1900 (Jiang et al., 2023). Climate change and human activities have also profoundly impacted agricultural development in the Syr Darya River Basin. For decades, the high-intensity exploitation of soil and water resources has disrupted the basin's ecological balance, triggering a series of environmental issues such as soil pollution, salinization, erosion, and desertification (Duan et al., 2022).

Human activities, particularly irrigation, have profoundly influenced agricultural development in the Syr Darya River Basin. Since the 1960s, the former Soviet Union initiated extensive agricultural development in the region (Zhang et al., 2019), which was accompanied by the construction of irrigation canals. However, outdated irriga-tion techniques and aging drainage infrastructure have led to widespread salinization in these irrigated areas (Liu et al., 2022). The Soviet era saw the construction of nu-merous large-scale water conservancy projects and reservoirs in the basin. Addition-ally, the intensive reclamation of land resources in the Fergana Basin and the mid-dle-lower reaches degraded the local soil ecological environment. Moreover, inefficient irrigation practices and the cultivation of water-intensive crops, such as cotton, have caused crop yields to decline or even fail, resulting in a continuous deterioration of farmland soil quality (Bissenbayeva et al., 2021).

Climate change and human activities have emerged as the primary challenges to agricultural sustainability in the region. Therefore, it is crucial to conduct a comprehensive survey on agricultural resources in the Syr Darya River Basin. Based on land use data and global climate data from the middle and lower reaches of the basin, this study investigates the land use patterns and the trends in temperature and precipita-tion. The findings are intended to provide a scientific reference for managing water and land resources within the basin.

## 2. Methodology

### 2.1 The Study Area

The Syr Darya River Basin is situated in the hinterland of the Eurasian continent, within the coordinates 61°6′–78°24′ E and 39°23′–46°6′ N. The river originates in the Middle Tien Shan Mountains north of the Pamir Plateau. It then flows through the Fergana Valley and the Golodnaya Steppe, crosses the Kyzylkum Desert, and traverses four countries from east to west—Kyrgyzstan, Uzbekistan, Tajikistan, and Kazakh-stan—before finally draining into the North Aral Sea. Topographically, the terrain of the basin slopes from the southeast to the northwest. Hydrologically, the Syr Darya is the longest river in Central Asia, stretching 2,219 kilometers from the confluence of its headstreams, the Naryn and Karadarya Rivers. Climatically, the region is strongly influenced by altitudinal variations, resulting in a wetter climate at higher elevations and a drier climate at lower elevations.

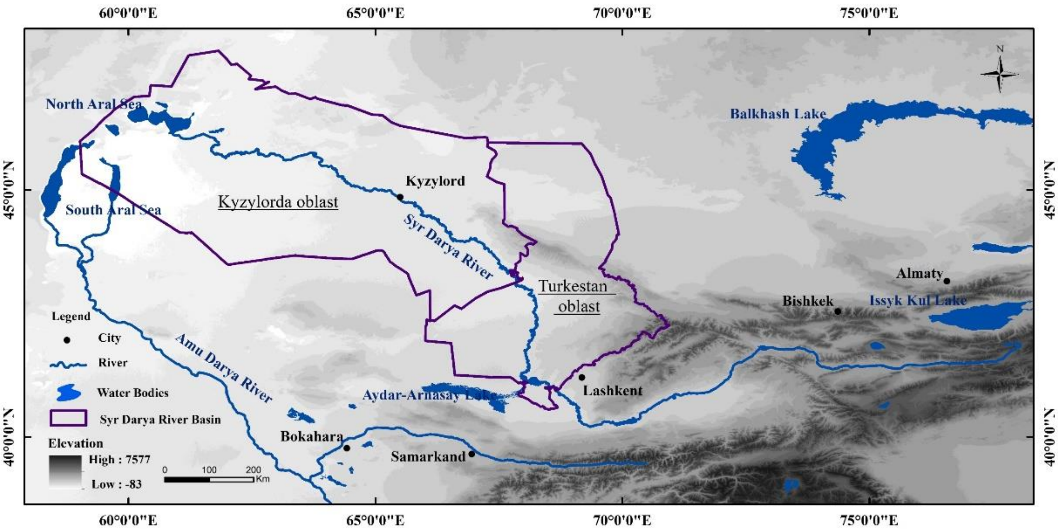


**Figure 1.** The location of the study area.

### 2.2 Data source

The Landsat 8 satellite is equipped with a multispectral imager that captures data across eight distinct spectral bands, covering the visible, near-infrared, and short-wave infrared regions. This multi-band observation capability enables the derivation of rich spectral information from the Earth's surface, significantly enhancing the potential for accurate land cover classification.

In this study, Landsat-8 imagery was acquired through the Google Earth Engine (GEE) platform. The dataset underwent preprocessing steps, including radiometric calibration and geometric correction, to mitigate atmospheric effects and normalize surface reflectance values, thereby improving data quality and usability. Subsequently, a suite of image processing functions and statistical tools available in GEE were employed to extract features relevant to land use and land cover classification. These features encompass spectral indices, textural characteristics, and morphological at-tributes. Finally, a supervised classification approach was implemented utilizing training samples defined via GEE's annotation tools, in conjunction with a feature ex-traction algorithm, to assign a specific land use category to each pixel in the imagery. This study utilized data from four years: 2000, 2005, 2010, and 2015.

Temperature and precipitation data were sourced from the Global Climate Dataset (CRU TS), produced by the U.K.'s National Centre for Atmospheric Science. This dataset has a spatial resolution of 0.5 degrees and a monthly temporal resolution. The CRU data used in this paper cover the period from 1950 to 2020 (Harris et al., 2017).

### 2.3 Research Methods

Long-term trends of temperature and precipitation in the study area were analyzed using the rank-based Mann-Kendall nonparametric statistical test, which is commonly used to test the significance of trends and has been widely used in hydro-meteorological trend tests and analyses. The methodology of the M-K statistical test is as follows (Zou et al., 2019), For a given time series $Xi\{Xi,\ i{=}1,2,\ \dots,\ n\}$, the Mann–Kendall S Statistics could be calculated.

$$S = \sum {}_{i=1}^{n-1} \sum {}_{j=i+1}^{n} sign\left(T_J - T_I\right)$$

$$sign\left(T_j - T_i\right) = \begin{cases} 1\ if\ T_j - T_I > 0 \\ 0\ if\ T_J - T_i = 0 \\ \text{-}1\ if\ T_j - T_i < 0 \end{cases}$$

This test is particularly well-suited for trend detection in non-normally distributed data, such as hydro-meteorological variables, as it does not require the data to follow a specific distribution and is robust against outliers.

For series with n≥10, the statistic S is approximately normally distributed. The standardized test statistic Z is then computed and compared against the critical values Z1−$\alpha$/2 from the standard normal distribution to determine the trend's significance. At a given significance level $\alpha$ (typically $\alpha$ = 0.05), if ∣ Z ∣ > Z1 − $\alpha$/2 (e.g., Z0.975=1.96), the null hypothesis is rejected, indicating a statistically significant trend in the series; a positive Z signifies an upward trend, while a negative Z indicates a downward trend.

In summary, the combined use of the M-K test and Sen's Slope estimator offers a robust and effective methodology. It not only detects long-term trends and rates of change in temperature and precipitation but also provides reliable evidence for assessing hydrological responses to climate change.

## 3. Results

### 3.1 Current status of land use in the Syr Darya River Basin

This study employed a Random Forest classifier to perform land cover classification based on the multi-band spectral characteristics and derived indices from Landsat 8 imagery. Areas with annual maximum NDVI values consistently below 0.15, and from which water bodies, cloud shadows, and built-up structures were excluded through visual interpretation, were defined as 'bare land'. In terms of the spatial distribution pattern of land use, arable land is mainly concentrated in the areas along the Syr Darya River and its tributaries in a belt-shaped distribution, which is due to the fact that the areas on both sides of the Syr Darya River are relatively rich in water re-sources due to the relatively fertile soils, which gives them a unique advantage in agricultural development.

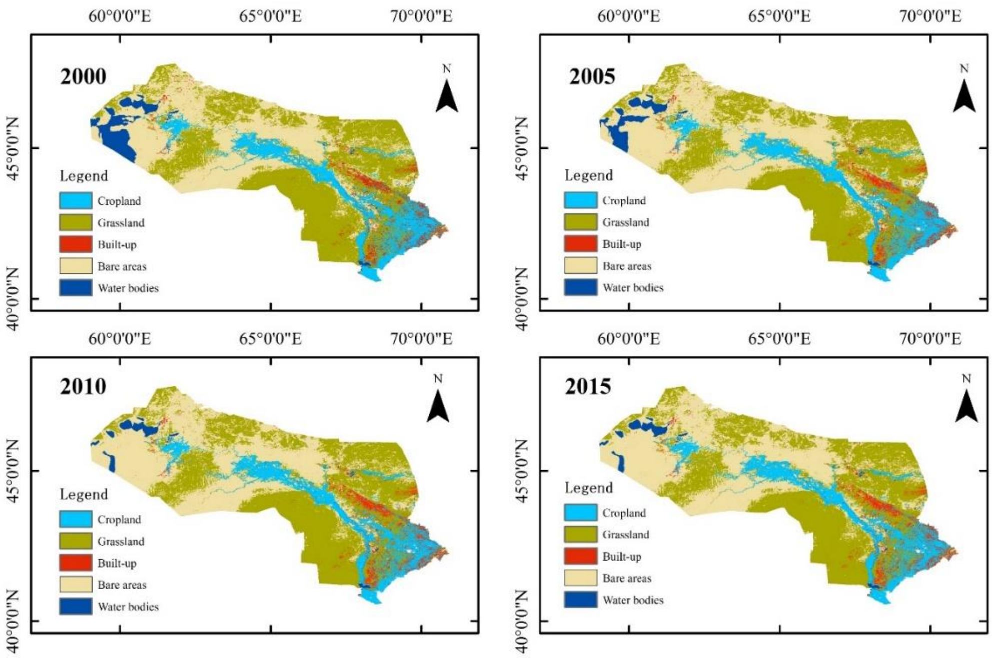


**Figure 2.** Land use types of study area

In terms of the spatial distribution pattern of land use, arable land is mainly concentrated in the areas along the Syr Darya River and its tributaries in a belt-shaped distribution, which is due to the fact that the areas on both sides of the Syr Darya River are relatively rich in water resources due to the relatively fertile soils, which gives them a unique advantage in agricultural development. The areas of arable land, forest land, grassland, construction land and bare land all show an increasing trend on the whole, with the greatest increase in the area of bare land, where deserts, the Gobi and bare soil occupy more than half of the area in Turkestan Oblast, and in Kyzylorda Ob-last, where bare land accounts for 75.7% of the total area of the Oblast, and where arable land's share of the Oblast's area has remained basically stable at between 1.5% and 1.6%. Bare land is the largest land type in Kyzylorda and Turkestan oblasts. The size of the area of the other five land-use types is: forest land > cropland > water bodies > grassland > construction land.

A stratified random sampling method was employed to select 1000 validation points across the study area. These points were visually interpreted with reference to high-resolution imagery available in Google Earth Engine. Subsequently, a confusion matrix was generated, which yielded an overall accuracy of 89%.

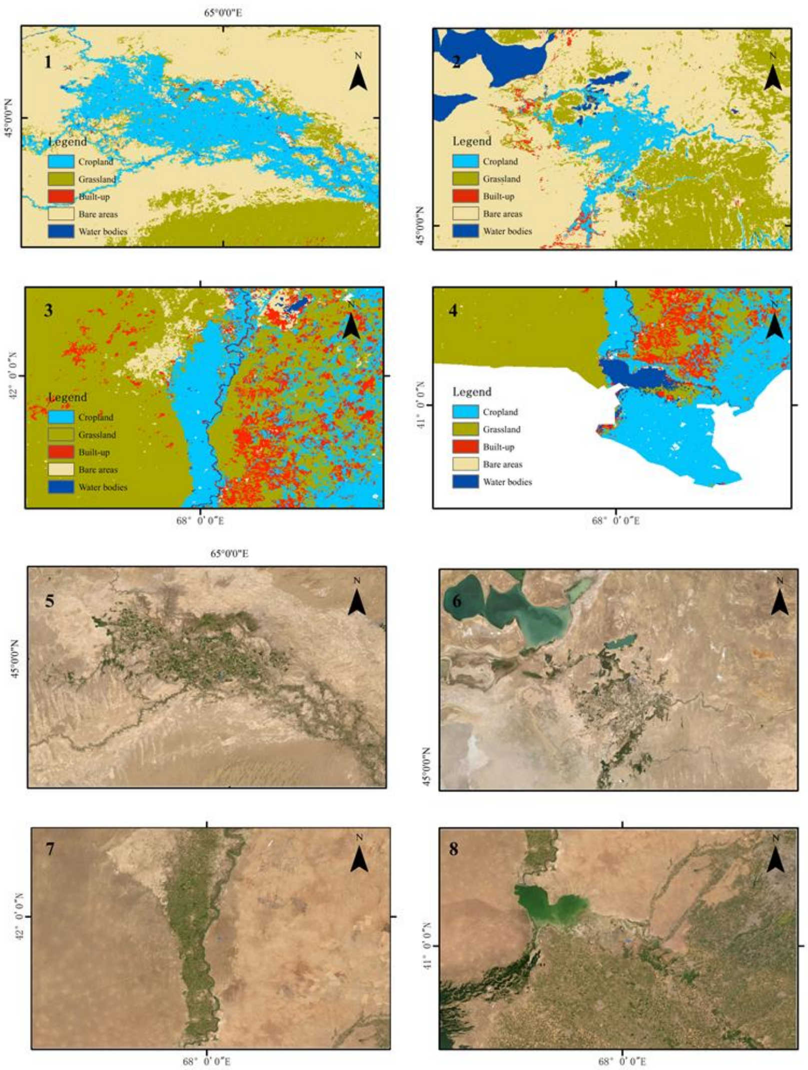


**Figure 3.** The comparative Analysis of the Land Cover Classification Results against the Land-sat 8 Remote Sensing Image

**Table 1**. The Classification Accuracy Assessment Results

| Type | Overall Accuracy | Kappa Coefficient | User's Accuracy | Producer's Accuracy |
|---|---|---|---|---|
| cropland | | | 0.89 | 0.86 |
| grassland | | | 0.80 | 0.82 |
| Built-up | 0.89 | 0.85 | 0.83 | 0.89 |
| Bare areas | | | 0.85 | 0.82 |
| Water bodies | | | 0.89 | 0.86 |

There has been a marked change in the cropping structure of crops in the riverine irrigation areas of the Syr Darya basin, with a shift from water-intensive cotton to less-demanding wheat and other cereals. This transformation is due to two main fac-tors, the shortage of irrigation water and changes in domestic politics on the supply and demand for food. Cotton is the second largest agricultural export category in Kazakhstan after grain, and Turkestan Oblast is the only cotton-producing region in Ka-zakhstan, with the planting area mainly concentrated in the Chardara and Makhtaral regions. As of 2018, the area under cotton cultivation in Turkestan Oblast has reached 227,000 hectares, with an average annual cotton planting area of 180,000-200,000 hectares. Rice is the main crop grown in Kyzylorda oblast with a long history of cultivation, and the oblast accounts for 85-88% of the country's rice production. As of 2018, the area under rice cultivation has reached 103,000 hectares, and rice production in the region has declined sharply in recent years due to degradation of irrigation and drainage facilities.

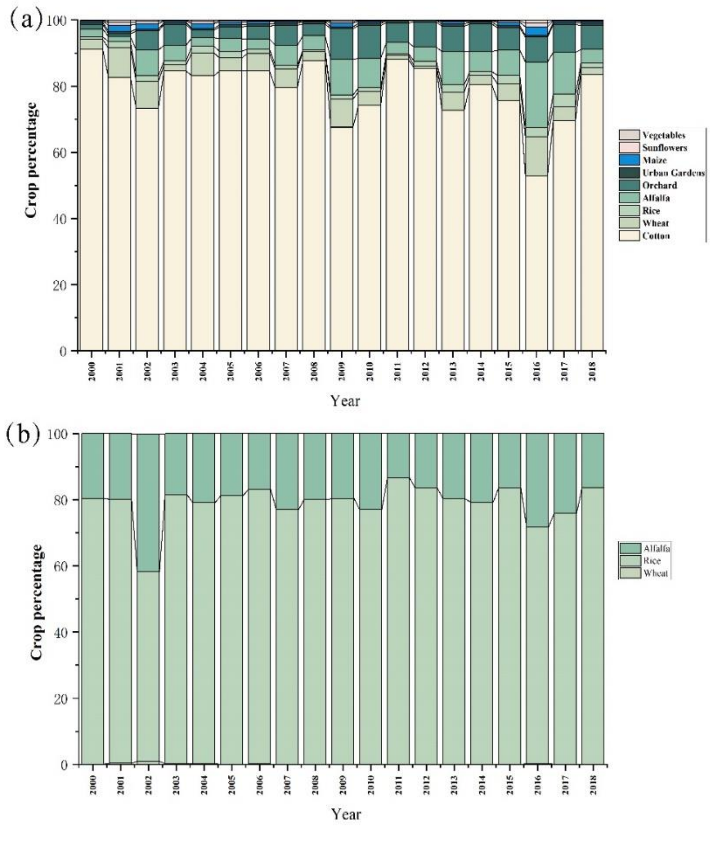


**Figure 4.** The Planting structure of the study area. (a) Kyzylord Oblast; (b) Turkestan Oblast.

### 3.2 Trend analysis of temperature and precipitation in the Syr Darya River Basin

Over the past 70 years, the Syr Darya River Basin has experienced a clear warming trend. The annual mean temperature for the basin, along with its 5-year moving aver-age, is shown in the figure. The temperature increased at a rate of 0.323°C per decade, a trend slightly more pronounced than the 0.16°C per decade observed in the broader arid zone of Central Asia. The lowest annual mean temperature of 7.05°C was record-ed in 1972, while the highest, 10.73°C, occurred in 2016.The average annual precipitation in the basin is 357.4 mm, with substantial interannual variability. The maximum precipitation of 594.9 mm was recorded in 1969, contrasting with the minimum of 231.7 mm in 1995, resulting in a difference of 363.2 mm. Figure 3 illustrates the year-to-year changes in annual precipitation and the corresponding 5-year moving average. A linear regression analysis indicates a slight upward trend in annual precipitation from 1950 to 2020, with an increase of 1.393 mm per decade. The precipitation variability in the basin exhibits a relatively regular pattern of fluctuation.

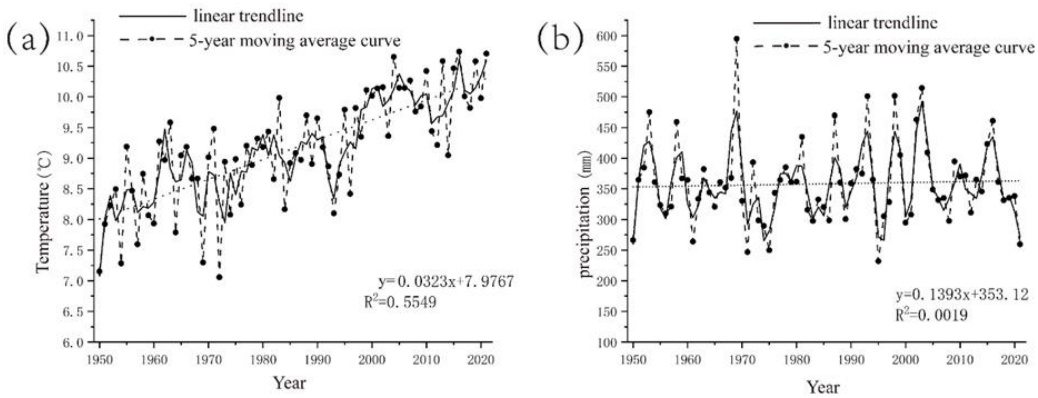


**Figure 5.** Average annual trends in the Syr Darya basin, 1950-2021 (a) Temperature (b) Precipitation

## 4. Discussion

### 4.1 Impact of climate change on agricultural development in the Syr Darya River

The Mann-Kendall trend analysis for the Syr Darya River Basin reveals a distinct upward trend in temperature since 1950, with a rate of increase of 0.323°C per decade. This warming trend became particularly pronounced and statistically significant from the 1980s onward (passing the significance test at the 95% confidence level). The analysis identified an intersection point between the forward and backward sequences in 1991. However, as this point falls outside the confidence interval, it does not indicate a statistically significant abrupt change in temperature. This significant temperature rise promotes increased evaporation from lakes and watersheds, thereby exacerbating cropland salinization (Shi et al., 2020).Regarding precipitation, the Mann-Kendall results indicate a slight increase over the past 70 years. Multiple intersections between the sequences occur within the confidence interval, suggesting that precipitation varies in a fluctuating manner without a distinct abrupt change.

The linear regression analysis indicates a slight increasing trend in annual precipitation from 1950 to 2020, at a rate of approximately 1.393 mm per decade. However, the coefficient of determination ($R^2$) for this linear model is only 0.05, suggesting that the time variable explains a very limited portion of the variation in precipitation. This result is consistent with the conclusion drawn from the Mann-Kendall test: the M-K test shows multiple crossing points within the confidence interval and detects no significant monotonic trend ($p > 0.05$). In summary, the long-term variation of annual precipitation in the study area is characterized by strong interannual fluctuations, rather than a clear and stable linear increasing trend.

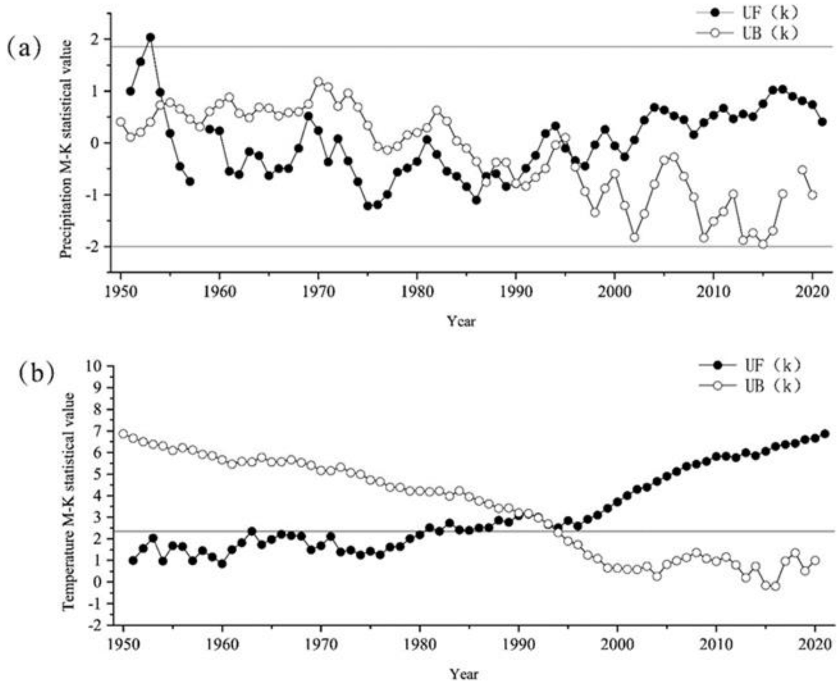


**Figure 6.** Mann-Kendall mutation test of temperature and precipitation in the Syr Darya River Basin from 1950 to 2021

### 4.2 Impact of human activities on the agricultural development of the Syr Darya River

In recent years, the cropping structure in the riverine irrigation areas of the Syr Darya Basin has undergone a marked shift. There has been a transition from water-intensive cotton cultivation to less demanding crops such as wheat and other cereals (Leng et al., 2021). This shift is primarily driven by two factors: irrigation water scarcity and changes in domestic policies affecting grain supply and demand.

Human activities have profoundly impacted the basin's ecology. The population is predominantly rural, with agriculture serving as the main economic activity. From the 1960s to the 1980s, the population grew rapidly from 1.337 million to 2.754 million, an increase of 105.9%, fueled by the expansion of agriculture and other economic sectors. The water resource development system in the Syr Darya Basin is among the most complex in the world. To meet irrigation and energy needs, a series of large and small reservoirs were constructed between 1940 and 1983, including major ones such as the Chardara, Andijan, and Tortkul reservoirs, with a total capacity of 35 $km^3$. A network of major canals, ranging in length from 25 to 344 kilometers, distributes the water. These reservoirs intercept and store water resources, which are then conveyed through an extensive canal network to support irrigated agriculture.

**Table 2.** The land use types in the Syr Darya River Basin.

| Canal 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 |

## 5. Conclusion and Recommendations

Based on the findings regarding land use and climate trends, this study proposes an integrated remediation framework to address the interconnected challenges of soil salinization and irrigation inefficiency in the Syr Darya region. The strategy centers on a systematic combination of engineering and biological interventions.

The installation of a subsurface drainage system in Yangiyer District is designed to directly combat secondary salinization by lowering the water table and leaching dissolved salts from the root zone. Concurrently, modernizing key irrigation canals near Kyzylorda City with concrete lining and automated gates is crucial for water conservation. This intervention is projected to be the primary driver for increasing irrigation efficiency from 45% to 85%, by minimizing conveyance losses and enabling precise, demand-based water allocation.

Complementing these engineering solutions, the introduction of salt-tolerant specie, *Suaeda salsa* (seepweed) and wolfberry, represents a shift toward sustainable land use. Cultivating *Suaeda salsa* on unproductive salt-alkaline wasteland facilitates the phytoremediation of degraded soils while generating economic returns through a market-oriented biomass offtake model. Similarly, promoting wolfberry agroforestry on marginal land diversifies farmers' income sources by utilizing abandoned plots (Xu et al., 2024).

The synergy of these measures—where engineering controls water and salt dynamics, and biological strategies stabilize and monetize reclaimed land—is projected to create a virtuous cycle. This integrated system is expected to reduce overall irrigation water consumption by 30% while increasing crop yields by an estimated 15%, offering a viable pathway for enhancing agricultural resilience in arid, salinity-prone regions (Chen et al., 2024).

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**Competing Interests**

The authors have no competing interests to declare that are relevant to the content of this article.

**Data, Materials, and Code Availability**

The datasets generated and/or analyzed during this study are available from the corresponding author upon reasonable request.

**Authors' Contributions**

All authors contributed equally to the conception, development, and writing of this manuscript and have approved the final version for submission.

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