Evaluation of Water Conservation Function in the Ili River Delta of Central Asia Based on the InVEST Model (Postprint)

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Abstract

The Ili River Delta (IRD) is an ecological security barrier for the Lake Balkhash and an important water conservation area in Central Asia. In this study, we selected the IRD as a typical research area, and simulated the water yield and water conservation from 1975 to 2020 using the water yield module of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. We further analyzed the temporal and spatial variations in the water yield and water conservation in the IRD from 1975 to 2020, and investigated the main driving factors (precipitation, potential evapotranspiration, land use/land cover change, and inflow from the Ili River) of the water conservation variation based on the linear regression, piecewise linear regression, and Pearson's correlation coefficient analyses. The results indicated that from 1975 to 2020, the water yield and water conservation in the IRD showed a decreasing trend, and the spatial distribution pattern was "high in the east and low in the west"; overall, the water conservation of all land use types decreased slightly. The water conservation volume of grassland was the most reduced, although the area of grassland increased owing to the increased inflow from the Ili River. At the same time, the increased inflow has led to the expansion of wetland areas, the improvement of vegetation growth, and the increase of regional evapotranspiration, thus resulting in an overall reduction in the water conservation. The water conservation depth and precipitation had similar spatial distribution patterns; the change in climate factors was the main reason for the decline in the water conservation function in the delta. The reservoir in the upper reaches of the IRD regulated runoff into the Lake Balkhash, promoted vegetation restoration, and had a positive effect on the water conservation; however, this positive effect cannot offset the negative effect of enhanced evapotranspiration. These results provide a reference for the rational allocation of water resources and ecosystem protection in the IRD.

Full Text

Preamble

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Evaluation of the water conservation function in the Ili River Delta of Central Asia based on the InVEST model

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Abstract

The Ili River Delta (IRD) serves as an ecological security barrier for Lake Balkhash and represents a critical water conservation area in Central Asia. This study selected the IRD as a typical research area and simulated water yield and water conservation from 1975 to 2020 using the water yield module of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. We analyzed the temporal and spatial variations in water yield and water conservation in the IRD during this period and investigated the main driving factors—precipitation, potential evapotranspiration, land use/land cover change (LUCC), and inflow from the Ili River—using linear regression, piecewise linear regression, and Pearson's correlation coefficient analyses. The results indicated that water yield and water conservation in the IRD exhibited a decreasing trend from 1975 to 2020, with a spatial distribution pattern characterized as "high in the east and low in the west." Overall, the water conservation capacity of all land use types decreased slightly, with grassland showing the most significant reduction in water conservation volume despite an increase in grassland area due to enhanced inflow from the Ili River. Meanwhile, the increased inflow led to wetland expansion, improved vegetation growth, and elevated regional evapotranspiration, ultimately resulting in an overall reduction in water conservation. The spatial distribution patterns of water conservation depth and precipitation were similar, and changes in climatic factors represented the primary reason for the decline in water conservation function in the delta. The reservoir in the upper reaches of the IRD regulated runoff into Lake Balkhash, promoted vegetation restoration, and exerted a positive effect on water conservation; however, this positive effect could not offset the negative impact of enhanced evapotranspiration. These findings provide a valuable reference for rational water resource allocation and ecosystem protection in the IRD.

Keywords: water conservation function; water yield; Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model; climate change; land use/land cover change (LUCC); Ili River Delta; Lake Balkhash

1 Introduction

Water conservation function constitutes one of the most critical ecosystem service functions in watersheds and serves as an important indicator of regional ecosystem health [?, ?]. Research on water conservation functions originated from forest ecosystems and has primarily focused on the role of trees, shrubs, litter, and soil in redistributing precipitation [?, ?]. In the context of global water scarcity and rapidly declining groundwater reserves, the sustainability of water conservation has become a core component of regional ecological security assessments [?, ?]. The water conservation function of wetlands in delta regions of arid inland river basins has been widely studied for its effects on biodiversity maintenance, soil and water conservation, runoff regulation, climate regulation, and freshwater supplies [?, ?, ?].

Numerous studies have investigated water conservation functions and their spatial and temporal variations across different scales and regions [?, ?, ?, ?]. Several methods have been developed to assess ecosystem water conservation functions, including the water balance method [?, ?], canopy residual interception method [?, ?], and precipitation storage method [?, ?]. However, due to the pronounced spatial and temporal scale characteristics of water conservation functions, econometric models exhibit limited adaptability to regional scales and are unsuitable for long-term time series applications in large-scale regions with complex topography and diverse ecosystem types [?, ?]. The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model can integrate these analytical features [?, ?]. This model serves as a modeling tool for assessing ecosystem services and their economic values to support ecosystem management and decision-making [?, ?].

Unlike other hydrological models, the InVEST model operates on a grid scale at an average annual time step, enabling large-scale spatiotemporal modeling based on water balance principles. Consequently, it is well-suited for assessing the impacts of land use/land cover change (LUCC) on multiple ecosystem services, including water yield, carbon storage, and habitat quality [?, ?].

The earliest application of the InVEST model occurred in the Amazon Basin, where it was used to assess ecosystem services in ecologically functional areas [?, ?]. This study's results significantly influenced international ecological evaluations and greatly facilitated the application of the InVEST model in other regions. Subsequently, Erik et al. [?] applied the InVEST model to the Willamette Basin in Oregon, USA, designing three plausible LUCC scenarios to analyze spatial patterns of ecosystem services such as hydrological services, soil conservation, carbon storage, and biodiversity. Sánchez-Canales et al. [?] assessed water conservation service functions in Mediterranean watersheds. Since 2013, research on ecosystem services based on the InVEST model has increased rapidly, covering habitat quality [?, ?], soil erosion [?, ?], carbon storage [?, ?], water yield [?, ?], and water conservation [?, ?]. For example, Baral et al. [?] used the InVEST model to evaluate biodiversity in north-central Victoria, Australia, analyzing the impact of LUCC to assess its applicability in habitat quality assessment and ecological conservation planning. Li et al. [?] analyzed the effects of soil change, land use, and soil and water conservation on water conservation functions in the Danjiang watershed of the Qinling Mountains, China. From the perspective of different climate types, the spatial and temporal variability of water conservation under alpine climates, mid-latitude monsoon climates, and subtropical monsoon climates has been extensively assessed [?, ?]. For instance, Wang et al. [?] analyzed water conservation in the eastern Loess Plateau, China, and quantified the environmental drivers of water conservation change, while Xue et al. [?] studied water conservation functions and their spatiotemporal variations in the alpine region of the Tibetan Plateau, China.

The Ili River is an international river crossing the border between China and Kazakhstan and represents the largest cross-border river in Xinjiang Uygur Autonomous Region, China, in terms of water volume. The Ili River Delta (IRD), characterized by a fragile arid ecosystem, is located in the lower reaches of the Ili-Balkhash Basin (an arid endorheic basin shared by China and Kazakhstan) in Central Asia and constitutes an important water conservation area in this basin. Water resources play a crucial role in improving the regional ecological environment. Many previous studies have focused on analyzing hydrological, vegetation, and wetland changes in the IRD [?, ?, ?]. From the 1840s to the late 1950s, the IRD ecosystem remained relatively stable. However, beginning in the 1960s, regional climate change and increasing human activities upstream of the delta substantially reduced or even cut off river runoff into the delta until the 1970s, causing continuous ecosystem deterioration [?, ?]. Since the 1990s, as human activities in the middle reaches of the Ili River Basin have decreased and river inflows to the IRD have increased, the delta's ecological environment has gradually improved [?, ?]. Deng et al. [?] noted that the construction of the Kapchagay Reservoir and overexploitation of water resources in the middle and lower reaches of the Ili River have caused declining water levels in Lake Balkhash and ecological deterioration in the IRD. Wang and Lu [?] suggested that climate change is the dominant factor influencing Lake Balkhash water level dynamics, while human activities serve as reinforcing factors affecting lake water level changes. Inflow to the lake is significantly correlated with Lake Balkhash water volume, representing the leading factor affecting lake water volume changes [?, ?]. Between 1970 and 1990, the wetland area of the IRD decreased from 2607 to 1841 km^2 (a 29.38% reduction), with half of the lost area converting to grassland and one-third to saline-alkali land [?, ?]. Yao et al. [?] studied the conversion of large areas of bare land to grassland around the IRD from 2000 to 2020 and found that forests within the delta degraded into grassland. Runoff into the delta and Lake Balkhash water levels are significantly and positively correlated with wetland area, representing the primary drivers of wetland evolution [?, ?, ?]. Since the 1990s, under the influence of climate change and human activities, not only have Lake Balkhash's water level and area continued to decline, but the water overflow capacity, wetland area, and ecosystem services of the IRD have also been severely weakened [?, ?], resulting in significant changes in the IRD's water conservation function. However, the spatial and temporal variations in the water conservation function of the IRD and their driving factors remain unclear.

This study employed the InVEST model with localized parameters to simulate water yield in the IRD from 1975 to 2020 and visually and quantitatively evaluated the ecosystem's water conservation function. We also investigated the effects of local climate change, LUCC, and inflow from the Ili River on water conservation function in the IRD. The results can provide a basis for making scientific and reasonable decisions regarding water conservation function in the IRD.

2.1 Study Area

The IRD (74°00 –76°30 E, 45°20 –46°15 N) is located in southeastern Kazakhstan, Central Asia, covering an area of approximately 8.00×10^{3} km^2 in the southwestern part of Lake Balkhash [?, ?] [Figure 1: see original paper]. The delta is bordered by the Saryesik-Atyrau Desert to the northeast, the Tawkum Desert to the southwest, and Lake Balkhash to the northwest. The geomorphological unit consists of a sedimentary-alluvial plain in the lower reaches of the Ili River, with overall topography that is high in the southeast and low in the northwest [?, ?]. The delta experiences an extremely dry continental climate with minimal precipitation and high evapotranspiration. The average annual precipitation in the study area is 192 mm, the average annual temperature is 7°C, and the average annual evapotranspiration is approximately 1000 mm [?, ?, ?]. The vegetation primarily consists of *Calamagrostis pseudophragmites* and reeds (*Phragmites communis*) [?, ?]. The main land use types in the delta are water body, grassland, and unused land.

Lake Balkhash (73°21 –79°30 E, 44°45 –46°44 N) is a typical plain terminal lake [?, ?] with a surface area of approximately 1.83×10^{4} km^2, measuring about 71 km at its widest point and 600 km in length [?, ?]. As the main water artery of Lake Balkhash, the Ili River flows into the western part of the lake through the IRD, contributing 78.00% of the total runoff to the lake and representing the primary source of Lake Balkhash's water volume [**?**, **?**]. The Ili-Balkhash Basin constitutes one of the world's largest lake ecosystems, extending radially from Lake Balkhash as its center. The highest point is located at Khan Tengri Peak in the Tianshan Mountains, while the lowest point is at Lake Balkhash, forming the terminal end of the river system [**?**, **?**].

[Figure 1: see original paper]

2.2 Datasets

In this study, we collected and calculated data on precipitation, potential evapotranspiration, land use, soil depth, root depth, plant available water content (PAWC), velocity coefficient, topographic index, percentage slope, soil saturation hydraulic conductivity, runoff, Normalized Difference Vegetation Index (NDVI), digital elevation model (DEM), and water level to estimate water conservation and evaluate the water conservation function of the IRD from 1975 to 2020. The data sources and parameter processing methods for the input data are listed in Table 1 . The raster resolution of model inputs was uniformly set to 30 m$×$30 m. The biophysical parameters for each land use type are also listed in Table 2 .

Additionally, we verified the accuracy of the InVEST model's simulated results by calculating measured annual water conservation volume from surface runoff data (obtained from the Uskerma hydrological station). The results indicated that while the simulated water conservation volume from the InVEST model was smaller than the measured volume from surface runoff during the study period (1975–2020), the trends remained essentially consistent [Figure 2: see original paper].

[Figure 2: see original paper]

2.3.1 Land Use Transfer Matrix

The land use transfer matrix is a classical method for studying the direction and magnitude of transfers between land use types, reflecting the structural characteristics of regional LUCC and the evolution of spatial patterns [**?**, **?**]. Using spatial analysis tools in ArcGIS, we superimposed land use data from different periods to obtain dynamic changes in land use types between adjacent periods. The formula is as follows [**?**, **?**]:

$$\begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix}$$

where S_{ij} represents the area of land use type i converted to land use type j during the study period (km^2), and n is the number of land use types.

2.3.2 Calculation of Water Yield

The water yield model in the InVEST model is based on the principle of water balance. Regional water yield can be calculated using annual precipitation and the Budyko curve. The formulas are as follows:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{p_x}\right) \times p_x$$

$$AET_{xj} = \frac{p_x \times (1 + \omega_x \times R_{xj})}{1 + \omega_x \times R_{xj} + \frac{1}{R_{xj}}}$$

$$R_{xj} = \frac{K_{xj} \times PET_0}{p_x}$$

$$\omega_x = Z \times \frac{AWC_x}{p_x} + 1.25$$

where Y_{xj} represents the annual water yield depth at grid unit x under land use type j (mm); AET_{xj} represents the annual actual evapotranspiration at grid unit x under land use type j (mm); p_x represents the annual precipitation at grid unit x (mm); ω_x is a non-physical parameter representing natural climate-soil properties; R_{xj} is the Budyko dryness index; and Z is the seasonal factor (Zhang coefficient) representing seasonal precipitation distribution and depth, with Z-values close to 10 indicating precipitation concentrated in winter and values close to 1 indicating precipitation concentrated in summer or more uniformly distributed throughout the seasons [?, ?]. The Z-value was determined to be 1 in this study because multi-year precipitation is concentrated in summer in the study area. AWC_x represents the available soil water content (mm), determined by soil texture and effective soil depth; K_{xj} is the evapotranspiration coefficient of land use type j at grid unit x; and PET_0 represents the potential evapotranspiration (mm) [?, ?, ?, ?, ?].

2.3.3 Calculation of Water Conservation

The calculation of water conservation is based on water yield combined with soil saturation conductivity, runoff coefficient, and topographic index. The formulas are as follows:

$$Retention = \min\left(1, \frac{Velocity}{K_{sat}}\right) \times \min(1, 0.9 \times TI) \times Y_{xj}$$

$$Velocity = \min\left(1, \frac{Drainage\_Area}{Soil\_Depth \times Percent\_Slope}\right)$$

$$TI = \log\left(\frac{Drainage\_Area}{Percent\_Slope}\right)$$

where $Retention$ is the annual water conservation depth (mm); $Velocity$ is the runoff coefficient (dimensionless), representing the impact of different land use types on surface runoff; K_{sat} represents soil saturation conductivity (mm/d); TI is the topographic index; $Drainage\_Area$ indicates the number of grids in the catchment area; $Soil\_Depth$ is the soil depth (mm); and $Percent\_Slope$ is the percentage slope (%) [**?**, **?**, **?**].

2.3.4 Analysis of Driving Factors

To investigate dynamic temporal and spatial trends in water conservation function in the IRD from 1975 to 2020 at the pixel scale, we established linear regression and piecewise linear regression equations with year as the independent variable and water conservation as the dependent variable, following the approach of Hu and Sheng [**?**]. Piecewise linear regression is a regression estimation method applied when the relationship between y and x follows a certain linear relationship within one range of x and a different linear relationship with varying slopes in other ranges. This method uses indicator variables to fit a unified regression model to each data segment simultaneously. Pearson's correlation coefficients were used to test correlations between annual-scale water conservation and driving factors [**?**, **?**]. The correlation coefficient can be calculated using Equation 8 [**?**, **?**]:

$$r = \frac{\sum_{i=1}^{m}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{m}(x_i - \bar{x})^2 \sum_{i=1}^{m}(y_i - \bar{y})^2}}$$

where r is the correlation coefficient between two variables (correlations between potential evapotranspiration and water conservation, and between precipitation and water conservation), generally used to infer the overall correlation coefficient; m is the number of samples; x_i and y_i are sample values of variables x and y, respectively; and $\bar{x}$ and $\bar{y}$ are the average values of variables x and y, respectively.

3.1.1 Temporal Variation

From 1975 to 2020, the annual average water yield depth in the IRD exhibited "M"-shaped fluctuations, with an average value of 62.88 mm over the 46-year study period, a minimum of 34.76 mm in 2020, and a maximum of 98.15 mm in 1978 [Figure 3a: see original paper]. During the study period, the water conservation volume of the IRD varied considerably, with a multi-year average of 9.06$×10^{9}$ m^3; the minimum value was 2.59$×10^{9}$ m^3 in 2020, and the maximum was 19.86$×10^{9}$ m^3 in 1993 [Figure 3b: see original paper]. Using 2000 as a baseline year to compare differences in water yield depth and water conservation volume between the end of the 20th century and the beginning of the 21st century, the changes in water conservation volume over the 46-year study period can be divided into two stages. Specifically, from 1975 to 2000, annual water conservation volume showed a decreasing trend with a rate of change of -0.19$×10^{9}$ m^3/a, while from 2000 to 2020, it showed a slightly increasing trend with a rate of change of 0.01$×10^{9}$ m^3/a ($P<0.05$). Overall, water conservation volume in the IRD exhibited a decreasing trend from 1975 to 2020.

[Figure 3: see original paper]

3.1.2 Spatial Distribution

From 1975 to 2020, the spatial distribution pattern of annual average water yield depth in the IRD showed a trend of "high in the east and low in the west" [FIGURE:4a1–a6]. High-value regions with water yield depth greater than 62.88 mm were located in the central part of the IRD, while low-value regions with water yield depth less than 62.88 mm were primarily observed at the delta's terminus. The spatial distribution patterns of water conservation depth in the IRD from 1975 to 2020 did not change markedly and generally exhibited regularity consistent with changes in water yield depth, which directly influenced the spatial distribution of water conservation depth in the region. Using the natural breaks classification method, we divided water conservation depth in the IRD into five classes: I (0.00–2.00 mm), II (2.00–4.00 mm), III (4.00–6.00 mm), IV (6.00–8.00 mm), and V ($ $8.00 mm), with high-value regions mainly located in the central part of the IRD and low-value regions primarily around Lake Balkhash [FIGURE:4b1–b6]. This spatial distribution pattern resulted from the combined effects of climate and topography. The Ili-Balkhash Basin extends radially with Lake Balkhash at its center; the highest point is at Khan Tengri Peak in the Tianshan Mountains, and the lowest point is at Lake Balkhash. The IRD is a low-altitude region with high annual precipitation and low evapotranspiration. Large areas of wetland vegetation and water bodies are located in the middle of the delta, which are conducive to vegetation growth and provide higher water conservation capacity. In contrast, large areas of water bodies and unused land around Lake Balkhash experience intense evapotranspiration and have low water conservation capacity.

The spatial distribution of water conservation volume variation in the IRD from 1975 to 2020 is shown in Figure 5 [Figure 5: see original paper], divided into four categories: significantly decreased, slightly decreased, basically unchanged, and significantly increased. From 1975 to 2020, the area with decreased water conservation volume was 1756.20 km^2, accounting for 5.91% of the total IRD area, while the area with increased water conservation volume was 743.26 km^2, accounting for 2.50% of the total area. Water conservation volume remained largely stable and unchanged in most regions, representing 91.59% of the total IRD area. Regions with increased water conservation volume were concentrated at the delta front, primarily due to two factors: conversion of unused land to grassland and increased precipitation. Regions with decreased water conservation volume were mainly distributed in the middle and terminus of the delta, which constitute the main parts of the delta wetland. With increased runoff into the delta, gradual recovery of wetland vegetation, and elevated regional evapotranspiration, combined with decreased precipitation, water yield depth and water conservation volume have declined in these regions. Simultaneously, the expansion of wetland water bodies covering original grassland and other land cover conversions have also reduced water conservation volume. Water conservation volume remained largely stable and unchanged in the western part of Lake Balkhash.

[Figure 4: see original paper]

[Figure 5: see original paper]

3.2.1 Impact of Regional Climate Change on Water Conservation

Precipitation and potential evapotranspiration are important climatic factors influencing water conservation function in the IRD, and their temporal and spatial variability drives changes in water conservation function. The spatial differences in average annual precipitation in the IRD during 1975–2020 were significant. The Lake Balkhash area was dry and rainless, with precipitation gradually increasing from the lake center outward, while the spatial distribution of potential evapotranspiration was opposite to that of precipitation [FIGURE:6a and b]. Water conservation depth and precipitation showed similar spatial distribution characteristics. At the lake center, precipitation was low, potential evapotranspiration was high, and water conservation depth was low. From 1975 to 2020, annual precipitation in the IRD showed a decreasing trend [Figure 6c: see original paper], annual potential evapotranspiration showed an increasing trend [Figure 6d: see original paper], and annual water conservation volume showed a decreasing trend [Figure 3b: see original paper], indicating that relative changes in precipitation and potential evapotranspiration determined the general declining trend of water conservation function. Water conservation depth was significantly positively correlated with precipitation and negatively correlated with potential evapotranspiration [FIGURE:6e and f], with correlation coefficients of 0.72 and -0.12, respectively ($P<0.05$). The temporal and spatial variations in precipitation significantly impacted water conservation function in the study area. This is primarily because regions with abundant precipitation correspond to areas with good vegetation growth, sufficient water for plants and soil, and strong water conservation capacity. In contrast, regions with high potential evapotranspiration experience heavy depletion of water in vegetation and soil, resulting in weak water retention capacity.

[Figure 6: see original paper]

3.2.2 Impact of LUCC on Water Conservation

The dominant land use types in the IRD were grassland, water body, wetland, and unused land, which accounted for more than 95.00% of the total delta area [FIGURE:7a1–a4]. Cropland comprised a small proportion of the total IRD area, never exceeding 1.00%. Forest land area fluctuated more markedly between 1990 and 2020, showing an overall decreasing trend [Figure 7b: see original paper]. In general, the areas of grassland, wetland, water body, cropland, and construction land all showed increasing trends, while forest land and unused land areas decreased [Figure 7c: see original paper]. From 1990 to 2020, forest land exhibited the largest decrease in area at -53.38%, while construction land showed the largest increase at 41.07%. From 1990 to 2020, unused land experienced the largest absolute area decrease (2673.64 km^2), which was converted into grassland, wetland, water body, forest land, cropland, and construction land. The area of unused land converted to grassland was the largest (1959.97 km^2). The areas of lost cropland and construction land were the smallest, at 2.09 km^2 and 15.34 km^2, respectively. Cropland was mainly converted to grassland, and construction land was primarily converted to grassland and unused land [Figure 7d: see original paper].

The annual water conservation volume of grassland during 1975–2020 was the highest, with an average value of 42.93\$×10^{8}\$ m^3, followed by forest land and cropland (1.96\$×10^{8}\$ and 0.22\$×10^{8}\$ m^3, respectively) [FIGURE:8a1–a3]. The canopy and litter layers of grassland and forest land can effectively retain water [?, ?], giving these land use types stronger water conservation functions. In contrast, cropland has a shallow root system and occupies a small area in the IRD, resulting in poor water conservation function. From 1975 to 2020, the annual water conservation volume of grassland, forest land, and cropland showed an overall decreasing trend in the IRD. However, they all exhibited an increasing trend between 2000 and 2020, which is consistent with the trend of annual average NDVI in the IRD, indicating that vegetation growth in the delta has gradually improved during 2000–2020.

From 1990 to 2020, the annual potential evapotranspiration of grassland, forest land, and cropland showed an increasing trend [FIGURE:8b1–b3]. Specifically, the annual potential evapotranspiration of grassland increased at a rate of 5.23 mm/10a, while the total grassland area increased. However, the water yield depth of grassland decreased from 139.63 mm in 1990 to 74.57 mm in 2020 [FIGURE:8c1], and the corresponding water conservation volume also decreased from 46.91$×10ˆ{8}$ m^3 in 1990 to 14.82$×10ˆ{8}$ m^3 in 2020 [FIGURE:8a1]. The water yield depth of cropland decreased from 119.14 mm in 1990 to 72.27 mm in 2020 [FIGURE:8c2], and the corresponding water conservation volume decreased from 0.24$×10ˆ{8}$ m^3 in 1990 to 0.07$×10ˆ{8}$ m^3 in 2020 [FIGURE:8a2]. The water yield depth of forest land decreased from 128.22 mm in 1990 to 70.07 mm in 2020 [FIGURE:8c3], and the corresponding water conservation volume decreased from 3.28$×10ˆ{8}$ m^3 in 1990 to 0.40$×10ˆ{8}$ m^3 in 2020 [FIGURE:8a3]. The main reason for this pattern is that increased potential evapotranspiration leads to significant consumption of water in vegetation and soil and a decrease in water yield, thereby affecting soil water accumulation and water-holding function, which results in declining water conservation capacity.

Grassland was classified as low-coverage (coverage >50%), medium-coverage (coverage 20%–50%), and high-coverage (coverage 5%–20%) according to the classification system. From 1990 to 2020, although the areas of low-coverage and medium-coverage grasslands increased, the areas of high-coverage grassland and forest land showed a decreasing trend, resulting in the decline of water conservation in the IRD [Figure 9: see original paper].

[Figure 7: see original paper]

[Figure 8: see original paper]

[Figure 9: see original paper]

3.2.3 Impact of Inflow from the Ili River on Water Conservation in the IRD

From 1990 to 2015, the Ili River entered a period of abundant water, and runoff into the lake at the Uskerma hydrological station increased. After 2015, runoff into the lake at the Uskerma hydrological station decreased, Lake Balkhash water levels declined, precipitation decreased, and water conservation volume continued to decrease [FIGURE:6c and 10]. Thus, water conservation was affected by both inflow from the Ili River and precipitation.

[Figure 10: see original paper]

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4 Discussion

Generally, the evolution of ecosystem service functions is driven by various natural and human factors [?, ?]. Human activities directly or indirectly affect regional ecosystem service functions (e.g., water conservation) by altering the type and structure of the land surface [?, ?]. Regarding natural factors, vegetation spatial distribution significantly impacts water conservation, primarily because vegetated and non-vegetated lands differ in soil physical and chemical properties, vegetation coverage, and root systems, thus affecting surface evapotranspiration and soil water storage capacity [?, ?]. Different altitudes have different water and heat conditions, resulting in varying degrees of vegetation coverage. Higher vegetation coverage corresponds to stronger plant water conservation function, while low vegetation coverage indicates weak water conservation function [?, ?]. Secondly, land use type changes caused by human activities affect water conservation capacity. The water conservation volume ranking from highest to lowest is grassland, forest land, cropland, and construction land [?, ?]. This is mainly because the canopy and litter layers of grassland and forest land can effectively retain water, resulting in strong water conservation function [?, ?].

Meanwhile, water resources development in the Ili River began in the 1920s, and the region's largest reservoir, the Kapchagay Reservoir, was constructed in 1970. Reservoir construction has altered the volume and distribution of annual runoff in the lower reaches of the Ili River, significantly impacting the ecological environment of the delta and Lake Balkhash [?, ?]. From 1970 to 1985, Kapchagay Reservoir construction and water diversion for irrigation on the reservoir's left bank significantly exacerbated the decline in Lake Balkhash water levels and ecological shrinkage of the natural oasis. High-coverage grassland and forest land areas decreased, while changes in runoff and precipitation into the lake at the Uskerma hydrological station showed an initial increasing trend followed by a decreasing trend, affecting water conservation [?, ?]. As Lake Balkhash water levels rose, ecological problems caused by water shortages were alleviated, but vegetation ecological water demand increased, leading to reduced water conservation [?, ?]. The areas with the greatest reduction in water conservation coincided with areas showing the greatest increase in grassland, as shown in Figures 4 and 7a1–a4. This indicates that increased runoff to Lake Balkhash resulted in higher vegetation coverage in the IRD, while simultaneously increasing surface evapotranspiration in vegetated areas and vegetation ecological water demand, leading to reduced water conservation.

Furthermore, climate factors are key natural drivers of water conservation changes. Regions with abundant precipitation correspond to areas with good vegetation growth, adequate water in plants and soils, and strong water conservation capacity [?, ?]. In contrast, regions with high evapotranspiration experience heavy depletion of water in vegetation and soils, resulting in weak water retention capacity [**?**, **?**].

In addition, two main limitations exist when modeling water yield. First, due to the specific geographical location of the study area, biophysical parameters such as K_c and root depth in this study were derived from empirical data in the literature, which affects model simulation accuracy to some extent; however, this does not affect the basic distribution pattern of water yield. Second, this study used meteorological data from the current year for model estimation, thus failing to consider time lags of meteorological factors acting on environmental processes. Validation with actual survey and monitoring data will be further improved in the future, and attention should also be paid to modeling inter-annual and seasonal water yields along with parameter localization.

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5 Conclusions

The temporal and spatial variations in water conservation in the IRD from 1975 to 2020 were analyzed using the InVEST model, and the main driving factors were discussed. The main conclusions are as follows:

1. From 1975 to 2020, water conservation in the IRD showed a decreasing trend; spatially, it exhibited a pattern of “high in the east and low in the west.”
2. The spatial distribution of water conservation was affected by land use types. From 1975 to 2020, the water conservation and water yield of each land cover type decreased slightly. The water conservation volume of grassland was the highest among all land use types.
3. Water conservation depth and precipitation showed similar spatial distribution characteristics. During the study period, precipitation in the delta continued to decrease, and the increase in delta inflow promoted the expansion of vegetated areas, especially grassland, which had a positive effect on water conservation function. However, this effect could not offset the negative impact of enhanced evapotranspiration in the IRD.

This study used the InVEST model to evaluate the temporal and spatial variations and driving factors of water conservation function in the IRD. Changes in water conservation function in the IRD were strongly correlated with climate change and LUCC, with precipitation having a direct effect on water conservation function. These results provide a scientific basis for making informed ecological protection decisions in the IRD under the impacts of climate change and human activities.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Bai Y, Chu D, Tian L, et al. 2014. Assessing the importance of water conservation function in Wuhan City Circle. *Journal of Geo-information Science*, 16(2): 233–241. (in Chinese)

Bao Y B, Li T, Liu H, et al. 2016. Spatial and temporal changes of water conservation of Loess Plateau in northern Shaanxi Province by InVEST model. *Geographical Research*, 35(4): 664–676. (in Chinese)

Baral H, Keenan R J, Sharma S K, et al. 2014. Spatial assessment and mapping of biodiversity and conservation priorities in a heavily modified and fragmented production landscape in north-central Victoria, Australia. *Ecological Indicators*, 36: 504–514.

Canadell J, Jackson R B, Ehleringer J B, et al. 1996. Maximum rooting depth of vegetation types at the global scale. *Oecologia*, 108(4): 583–595.

Cao Y J, Ma Y G, Liu T, et al. 2022. Analysis of spatial-temporal variations and driving factors of typical tail-reach wetlands in the Ili-Balkhash Basin, Central Asia. *Remote Sensing*, 14(16): 3986, doi: 10.3390/rs14163986.

Deng K M, Shi P L, Xie G D, 2002. Water conservation of forest ecosystem in the upper reaches of Yangtze River and its benefits. *Resources Science*, 24(6): 68–73. (in Chinese)

Deng M J, Wang Z J, Wang J Y, 2011. Analysis of Balkhash Lake ecological water level evolvement and its regulation strategy. *Journal of Hydraulic Engineering*, 42(4): 403–413.

Fan L Y, Cai T Y, Wen Q, et al. 2023. Scenario simulation of land use change and carbon storage response in Henan Province, China: 1990–2050. *Ecological Indicators*, 154: 110660, doi: 10.1016/j.ecolind.2023.110660.

Gao Y H, Wang H L, Zhou X, et al. 2016. Remote sensing monitoring and analyses of the dynamic change of Balkhash Lake in the last 30 years. *Environment and Sustainable Development*, 41(1): 102–106. (in Chinese)

Guo L D, Xia Z Q, Wang Z J, 2011. Comparisons of hydrological variations and environmental effects between Aral Sea and Lake Balkhash. *Advances in Water Science*, 22(6): 764–770. (in Chinese)

Guo L D, Xia Z Q. 2014. Temperature and precipitation long-term trends and variations in the Ili-Balkhash Basin. *Theoretical and Applied Climatology*, 115(1): 219–229.

Hong Y C, Bai L, Yu S L. 2018. Study on the change of water conservation function of Mu Chuan County. *Technology Innovation and Application*, (25): 91–92. (in Chinese)

Hu Y T, Zhang F, Luo Z Z, et al. 2023. Soil and water conservation effects of different types of vegetation cover on runoff and erosion driven by climate and underlying surface conditions. *CATENA*, 231: 107347, doi: 10.1016/j.catena.2023.107347.

Hu M, Sheng Y W. 2022. Study on variation characteristics of precipitation and water resources in Qingdao. *Journal of China Hydrology*, 42(1): 103–108, 128. (in Chinese)

Hu W M, Li G, Li Z N. 2021. Spatial and temporal evolution characteristics of the water conservation function and its driving factors in regional lake wetlands—Two types of homogeneous lakes as examples. *Ecological Indicators*, 130: 108069, doi: 10.1016/j.ecolind.2021.108069.

Jia G Y, Hu W M, Zhang B, et al. 2022. Assessing impacts of the ecological retreat project on water conservation in the Yellow River Basin. *Science of the Total Environment*, 828: 154483, doi: 10.1016/j.scitotenv.2022.154483.

Jin X. 2016. Study on the red line for water containment protection in typical semi-arid areas. MSc Thesis. Xi'an: Northwest University. (in Chinese)

Lee Rodgers J, Alan Nicewander W. 1988. Thirteen ways to look at the correlation coefficient. *The American Statistician*, 42(1): 59–66.

Li M Y, Liang D, Xia J, et al. 2021. Evaluation of water conservation function of Danjiang River Basin in Qinling Mountains, China based on InVEST model. *Journal of Environmental Management*, 286: 112212, doi: 10.1016/j.jenvman.2021.112212.

Li X, Cui X, He X F, et al. 2022a. Analyses of spatial and temporal characteristics of water conservation function in Qaidam Basin. *Pratacultural Science*, 39(4): 660–671. (in Chinese)

Li X, Zou C X, Chen Y M, et al. 2022b. Spatial-temporal pattern changes and driving factors of water conservation function in Beijing-Tianjin-Hebei region from 2000 to 2019. *Bulletin of Soil and Water Conservation*, 42(5): 265–274. (in Chinese)

Li Y Y, Ma X S, Qi G H, et al. 2022c. Studies on water retention function of Anhui Province based on InVEST model of parameter localization. *Resources and Environment in the Yangtze Basin*, 31(2): 313–325. (in Chinese)

Liu S. 2019. Wetland ecosystem services evaluation based on the InVEST model. MSc Thesis. Harbin: Harbin Normal University. (in Chinese)

Long A H, Deng M J, Xie L, et al. 2011. A study of the water balance of Lake Balkhash. *Journal of Glaciology and Geocryology*, 33(6): 1341–1352. (in Chinese)

Luo G P, Wang Y G, Zhu L, et al. 2012. Influence mechanism of landscape structure in River Ili Delta. *Arid Land Geography*, 35(6): 897–908. (in Chinese)

Marquès M, Bangash R F, Kumar V, et al. 2013. The impact of climate change on water provision under a low flow regime: A case study of the ecosystem services in the Francoli River basin. *Journal of Hazardous Materials*, 263: 224–232.

Nakayama Y, Tanaka S, Sugimura T, et al. 1997. Analysis of hydrological changes in lakes of Asian arid zone by satellite data. *Earth Surface Remote Sensing*, 3222: 201–210.

Nelson E, Mendoza G, Regetz J, et al. 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment*, 7(1): 4–11.

Qiao X R, Li Z J, Lin J K, et al. 2023. Assessing current and future soil erosion under changing land use based on InVEST and FLUS models in the Yihe River Basin, North China. *International Soil and Water Conservation Research*, doi: 10.1016/j.iswcr.2023.07.001.

Sánchez-Canales M, López-Benito A, Passuello A, et al. 2012. Sensitivity analysis of ecosystem service valuation in a Mediterranean watershed. *Science of the Total Environment*, 440: 140–153.

Sharp R, Chaplin-Kramer R, Wood S, et al. 2018. *InVEST User's Guide*. The Natural Capital Project: Stanford University, University of Minnesota, the Nature Conservancy, and World Wildlife Fund. [2022-12-17]. https://www.researchgate.net/publication/323832082_{{{InVEST}}*{{User}}}'s*{Guide}.

Su C H, Fu B J. 2013. Evolution of ecosystem services in the Chinese Loess Plateau under climatic and land use changes. *Global and Planetary Change*, 101: 119–128.

Tallis H, Polasky S. 2009. Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. *Annals of the New York Academy of Sciences*, 1162: 265–283.

Wang H Y, Song J X, Wu Q. 2022a. Temporal and spatial variation characteristics of water conservation function of Qinling Mountains under the background of climate change. *Journal of Soil and Water Conservation*, 36(5): 212–219. (in Chinese)

Wang J F, Wu T L, Li Q, et al. 2021a. Quantifying the effect of environmental drivers on water conservation variation in the eastern Loess Plateau, China. *Ecological Indicators*, 125: 107493, doi: 10.1016/j.ecolind.2021.107493.

Wang J Y, Lu J Y. 2009. Hydrological and ecological impacts of water resources development in the Ili River Basin. *Journal of Natural Resources*, 24(7): 1297–1307. (in Chinese)

Wang N, Bi H X, Peng R D, et al. 2023. Disparities in soil and water conservation functions among different forest types and implications for afforestation on the Loess Plateau. *Ecological Indicators*, 155: 110935, doi: 10.1016/j.ecolind.2023.110935.

Wang X X, Shen H T, Li X Y, et al. 2013. Concepts, processes and quantification methods of the forest water conservation at the multiple scales. *Acta Ecologica Sinica*, 33(4): 1019–1030. (in Chinese)

Wang Y F, Ye A Z, Peng D Z, et al. 2022b. Spatiotemporal variations in water conservation function of the Tibetan Plateau under climate change based on InVEST model. *Journal of Hydrology: Regional Studies*, 41: 101064, doi: 10.1016/j.ejrh.2022.101064.

Wang Z, Xue Z C, Wang L, et al. 2021b. Analysis of the spatio-temporal characteristics of the water retention function of the Wulie River Basin in Chengde City. *Pratacultural Science*, 38(6): 1047–1059. (in Chinese)

Wang Z, Huang Y, Liu T, et al. 2022c. Analysis of the water demand-supply gap and scarcity index in Lower Amu Darya River Basin, Central Asia. *International Journal of Environmental Research and Public Health*, 19(2): 743, doi: 10.3390/ijerph19020743.

Wen X, Théau J. 2020. Spatiotemporal analysis of water-related ecosystem services under ecological restoration scenarios: a case study in northern Shaanxi, China. *Science of the Total Environment*, 720: 137477, doi: 10.1016/j.scitotenv.2020.137477.

Wu D, Shao Q Q, Liu J Y, et al. 2016. Spatiotemporal dynamics of water regulation service of grassland ecosystem in China. *Research of Soil and Water Conservation*, 23(5): 256–260. (in Chinese)

Wu Q, Song J X, Sun H T, et al. 2023. Spatiotemporal variations of water conservation function based on EOF analysis at multi time scales under different ecosystems of Heihe River Basin. *Journal of Environmental Management*, 325: 116532, doi: 10.1016/j.jenvman.116532.

Xiao T T, Xia Z Q, Guo L D, et al. 2011. Temperature characteristics in the Balkhash Lake Basin from 1936 to 2005. *Journal of Hohai University (Natural Sciences)*, 39(4): 391–396. (in Chinese)

Xie L, Long A H, Deng M J, et al. 2011. Study on ecological water consumption in delta of the lower reaches of Ili River. *Journal of Glaciology and Geocryology*, 33(6): 1330–1340. (in Chinese)

Xie Y C. 2015. Spatiotemporal change of ecosystem services based on InVEST Model in the Bailong River Watershed, Gansu. PhD Dissertation. Lanzhou: Lanzhou University. (in Chinese)

Xu F, Zhao L L, Jia Y W, et al. 2022. Evaluation of water conservation function of Beijiang River basin in Nanling Mountains, China, based on WEP-L model. *Ecological Indicators*, 134: 108383, doi: 10.1016/j.ecolind.2021.108383.

Xue J, Li Z S, Feng Q, et al. 2022a. Spatiotemporal variation characteristics of water conservation amount in the Qilian Mountains from 1980 to 2017. *Journal of Glaciology and Geocryology*, 44(1): 1–13. (in Chinese)

Xue J, Li Z X, Feng Q, et al. 2022b. Spatiotemporal variations of water conservation and its influencing factors in ecological barrier region, Qinghai-Tibet Plateau. *Journal of Hydrology: Regional Studies*, 42: 101164, doi: 10.1016/j.ejrh.2022.101164.

Yang C D. 1993. Changes in the water level of Lake Balkhash and its causes. *Arid Land Geography*, 16(1): 36–42. (in Chinese)

Yang D, Liu W, Tang L Y, et al. 2019. Estimation of water provision service for monsoon catchments of South China: Applicability of the InVEST model. *Landscape and Urban Planning*, 182: 133–143.

Yao J, Chen Q H, Li Q F, et al. 2022. Spatial and temporal variability of evapotranspiration and influencing factors in the Ili River-Balkhash Lake Basin. *Arid Zone Research*, 39(5): 1564–1575. (in Chinese)

Yin G D, Wang X, Zhang X, et al. 2020. InVEST Model based estimation of water yield in North China and its sensitivities to climate variables. *Water*, 12(6): 1692, doi: 10.3390/w12061692.

Yu X L, Wen J G, Yu J L, et al. 2010. Image correction algorithm of water quality remote sensing based on piecewise linear regression. *Remote Sensing Information*, 32(6): 39–43.

Zhang X N, Li X D, Ning L L, et al. 2022. A bibliometric evaluation of the status of the water conservation function of grassland ecosystems. *Acta Prataculturae Sinica*, 31(6): 35–49. (in Chinese)

Zheng Q H, Luo G P, Zhu L, et al. 2010. Prediction of landscape patterns in Ili River Delta based on CA_{Markov} model. *Chinese Journal of Applied Ecology*, 21(4): 873–882. (in Chinese)

Zhou W J, Xia Z Q, Huang F, et al. 2013. Variation characteristics of precipitation and its annual distribution in Balkhash Lake Basin. *Water Resources and Power*, 31(6): 10–13. (in Chinese)

Note: Figure translations are in progress. See original paper for figures.