

Modeling and analyzing supply-demand relationships of water resources in Xinjiang from a perspective of ecosystem services (Postprint)

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Abstract

Water shortage is one bottleneck that limits economic and social developments in arid and semi-arid areas. As the impacts of climate change and human disturbance intensify across time, uncertainties in both water resource supplies and demands increase in arid and semi-arid areas. Taking a typical arid region in China, Xinjiang Uygur Autonomous Region, as an example, water yield depth (WYD) and water utilization depth (WUD) from 2002 to 2018 were simulated using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model and socioeconomic data. The supply-demand relationships of water resources were analyzed using the ecosystem service indices including water supply-demand difference (WSDD) and water supply rate (WSR). The internal factors in changes of WYD and WUD were explored using the controlled variable method. The results show that the supply-demand relationships of water resources in Xinjiang were in a slight deficit, but the deficit was alleviated due to increased precipitation and decreased WUD of irrigation. WYD generally experienced an increasing trend, and significant increase mainly occurred in the oasis areas surrounding both the Junggar Basin and Tarim Basin. WUD had a downward trend with a decline of 20.70%, especially in oasis areas. Water resources in most areas of Xinjiang were fully utilized and the utilization efficiency of water resources increased. The water yield module in the InVEST model was calibrated and validated using gauging station data in Xinjiang, and the result shows that the use of satellite-based water storage data helped to decrease the bias error of the InVEST model by 0.69×10^8 m³. This study analyzed water resource supplies and demands from a perspective of ecosystem services, which expanded the scope of the application of ecosystem services and increased the research perspective of water resource evaluation. The results could provide guidance for water resource management such as spatial allocation and structural optimization of water resources in arid and semi-arid areas.

Full Text

Preamble

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Abstract

Water shortage represents a critical bottleneck limiting economic and social development in arid and semi-arid regions. As climate change impacts and human disturbances intensify over time, uncertainties in both water resource supplies and demands increase in these areas. Taking Xinjiang Uygur Autonomous Region—a typical arid region in China—as an example, this study simulated water yield depth (WYD) and water utilization depth (WUD) from 2002 to 2018 using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model and socioeconomic data. Supply-demand relationships of water resources were analyzed using ecosystem service indices including water supply-demand difference (WSDD) and water supply rate (WSR). Internal factors driving changes in WYD and WUD were explored using the controlled variable method. The results show that water resources in Xinjiang experienced a slight deficit, though this deficit was alleviated due to increased precipitation and decreased irrigation WUD. WYD generally exhibited an increasing trend, with significant increases occurring mainly in oasis areas surrounding both the Junggar Basin and Tarim Basin. WUD showed a downward trend with a decline of 20.70%, particularly in oasis areas. Water resources in most areas of Xinjiang were fully utilized, and the utilization efficiency of water resources increased. The water yield module in the InVEST model was calibrated and validated using gauging station data in Xinjiang, and the results demonstrate that incorporating satellite-based water storage data helped reduce the model's bias error by $0.69 \times 10^8 \text{ m}^3$. This study analyzed water resource supplies and demands from an ecosystem services perspective, thereby expanding the scope of ecosystem services applications and enriching the research perspective on water resource evaluation. The findings could provide guidance for water resource management, including spatial allocation and structural optimization of water resources in arid and semi-arid areas.

Keywords: ecosystem services; water resources; climate change; human activities; arid and semi-arid areas; InVEST model; Xinjiang

1 Introduction

Ecosystem services refer to the various benefits that humans obtain from natural ecosystems, either directly or indirectly (Millennium Ecosystem Assessment, 2005). According to the Millennium Ecosystem Assessment report, ecosystem services encompass a broad range of categories including provisioning, regulating, cultural, and supporting services. Water resource supplies fall under provisioning services and play a crucial role in ecosystem service evaluation frameworks (Costanza et al., 1998; Wang et al., 2019; Ouyang et al., 2020). Studies on water resource supplies rank among the top topics in global watershed ecosystem services research (Kaval, 2019), and water yield studies constitute the most frequent category among 130 articles on ecosystem services reviewed by Ochoa and Urbina-Cardona (2017).

Water supplies are particularly critical for arid and semi-arid regions, where they constrain economic and social development. These regions cover approximately 46.00% of global land area and are home to nearly one-third of the world's population (Lal, 2019). Water shortage creates ecological and social problems in arid and semi-arid areas, including reduced drinking water availability, food scarcity, frequent sandstorms, expanding desertification, land salinization, and biodiversity loss (Yu et al., 2019). Both climate change and human activities can intensify uncertainties in water resource supplies and demands in these regions. The unique land surface environment and radiative transfer processes in arid and semi-arid areas cause temperatures to rise more rapidly than in other regions, leading to frequent heat waves, increased evaporation, and glacier melting, as documented by climate model studies (Huang et al., 2019; Yu et al., 2019). Additionally, unsustainable development practices such as excessive cultivation, population overload, and rapid industrialization and urbanization contribute further uncertainties to water resource demands.

Assessing the sustainable use of water resources in arid and semi-arid areas has become a prominent research topic in the context of climate change and human activities. The ecological footprint model, fuzzy evaluation method, and system dynamics model have been widely applied in water resource sustainability assessments. The ecological footprint model, originally proposed by William and Wackernagel (William, 1992; Wackernagel and Rees, 1997; Seidl and Tisdell, 1999), was later adapted into a water resources ecological footprint model for evaluating sustainable water use (Li et al., 2012). Novoa et al. (2019) applied this model to assess the water footprint of agricultural production in a Chilean watershed and simulated the impact of inter-annual climate change on the water footprint. Jia et al. (2018) employed the fuzzy evaluation method to assess water resource carrying capacity in the Heihe River Basin of northwestern China's arid region. Dawadi and Ahmad (2013) used a system dynamics approach to simulate water resource changes in the Las Vegas Valley of southern Nevada's semi-arid region and evaluated the impacts of climate change, population growth, and conservation policies on water resource balances.

Supply-demand relationships in ecosystem services, which reflect the coupling correlations between natural ecosystems and human society, represent a research

frontier in the ecosystem services field (Yahdjian et al., 2015). Introducing ecosystem service supply-demand relationships into water resource sustainability assessments offers several advantages over traditional approaches. First, it enriches assessment methodologies and potentially circumvents problems inherent in previous methods. For instance, some concepts in the water resources ecological footprint model, such as water ecological footprint and water carrying capacity, are artificially constructed, making model accuracy evaluation difficult. In contrast, water yield depth (WYD) results from the InVEST model can be directly validated using gauging station data. Second, this approach expands the research direction of ecosystem services. While scholars have studied ecosystem services in arid lands, focusing primarily on ecosystem service trade-offs (Kang et al., 2020), human well-being (Wei et al., 2018), and ecosystem service flow (Chen et al., 2020), there remains a need to assess and understand sustainable water resource use in arid and semi-arid areas through an ecosystem services lens.

Xinjiang Uygur Autonomous Region, China's largest administrative region, encompasses vast arid and semi-arid areas in inland Asia. Intensified climate change and human activities have introduced uncertainties in both water supplies and demands, affecting water use in Xinjiang and potentially exerting considerable impacts on sustainable community and societal development. In recent years, Xinjiang's climate has become warmer and wetter, with temperature increasing at a rate of 0.34°C per decade—significantly higher than the global average (Shi et al., 2007; Chen et al., 2015; Huang et al., 2019). These climatic changes have altered land surface processes, including increased glacier melting (Piao et al., 2010) and evapotranspiration (Chen et al., 2015), thereby creating uncertainties in water supplies. Additionally, Xinjiang has experienced rapid socioeconomic development since 2000. In this context, scholars have conducted research on water resource supplies or demands in Xinjiang. Increased water yield has been modeled and observed in the Altay Mountains (Fu et al., 2017), Bosten Lake Basin (Yang et al., 2020), and nine high-alpine catchments (Luo et al., 2019), with studies revealing that both increased precipitation and glacial meltwater contributed to this trend. Conversely, decreased water yield has been modeled and observed in the Manas River Basin (Xu et al., 2020) and Tarim River Basin (Wang et al., 2020), with these studies suggesting that human activities may have caused the reduction. Regarding water utilization, some studies indicated an increasing trend in Xinjiang due to urbanization and industrialization (Lei et al., 2012; Zhang et al., 2020), while others revealed that water-saving agriculture and industrial water recycling may have led to decreased water utilization (Chen and Shi, 2016; Zhou et al., 2020). Given these conflicting trends under climate change and human activities, how have the supply-demand relationships of water resources in Xinjiang changed? This question requires urgent attention.

The goals of our study are to: (1) account for glacial meltwater to improve InVEST model performance in arid and semi-arid areas; (2) analyze the spatiotemporal variation of water supplies and demands in Xinjiang and their driving fac-

tors; and (3) assess the sustainable use of water resources in Xinjiang based on ecosystem services. Specifically, we used the InVEST model to calculate WYD and employed socioeconomic data to calculate water utilization depth (WUD) during 2002–2018. The water supply rate (WSR) and water supply-demand difference (WSDD) were used to quantify water utilization efficiency and water resource budgets, respectively. Internal factors driving changes in WYD and WUD were explored using the controlled variable method.

2.1 Study Area

Xinjiang Uygur Autonomous Region, located in northwest China, covers approximately $1.66 \times 10^6 \text{ km}^2$, representing nearly one-sixth of China's land area. Xinjiang features a distinctive geographic original paper]. As an inland region surrounded by high mountains, most areas of Xinjiang experienced dry climate. Altitude mountains contain abundant freshwater that supplies most rivers (Chen et al., 2015; Zhan et al., 2021). m^3 (Ministry of Water Resources of the People's Republic of China, 2018).

Xinjiang's economy and technology have witnessed rapid development in recent years. The annual GDP growth rate remained above 10.00% for most years in the past two decades, higher than China's national average (Bao and Zou, 2017). The population increased from 18.5×10^6 in 2000 to 24.9×10^6 in 2018 (Statistical Bureau of Xinjiang Uygur Autonomous Region, 2019), the development and promotion of water-saving irrigation technology increased irrigation water use efficiency from 0.38 in 1990 (Shen et al., 2013) to 0.52 in 2015 (Wang et al., 2019).

2.2 Data Acquisition

Details of all data used in this study are shown in Table 1. To address differences in spatial resolution and projection systems among datasets, we resampled all data to a spatial resolution of 500 m under the GCS_{{Krasovsky}}_{{1940}} Albers projection. We prepared model input data from 2000 to 2019 based on the official InVEST documentation and optimized model parameters to ensure performance.

Tropical Rainfall Measuring Mission (TRMM) data served as precipitation input. Due to their high accuracy and temporal resolution, TRMM satellites are particularly useful in regions with sparse meteorological stations (Luo et al., 2017; Wang et al., 2018). This study used the TRMM 3B43 v7 data product with a spatial resolution of $0.25^\circ \times 0.25^\circ$. The Climatic Research Unit gridded Time Series (CRUTS) v4 dataset provided potential evapotranspiration (Monteith formula recommended by the Food and Agricultural Organization (FAO), with a spatial resolution of $0.25^\circ \times 0.25^\circ$ (Dong et al., 2020; Zhou et al., 2020).

The Gravity Recovery and Climate Experiment (GRACE) satellite, jointly developed by the German Space Agency (DLR) and NASA, provides valuable observations reflecting changes in glaciers and groundwater storage due to its low orbit and high sensitivity to Earth's gravity field (Jin et al., 2016; Rodell et al., 2018; Beveridge et al., 2018; Meng et al., 2019). Decreases in GRACE satellite data equivalent water column height correspond to reduced terrestrial

water storage, particularly from glacier melting and groundwater extraction.

For soil data, Chinese soil texture data (including sand, clay, and silt composition) were obtained from the Resources and Environmental Science Data Center, while soil organic carbon data (Fischer et al., 2000) from the Harmonized World Soil Database (HWSD) Chinese soil dataset (v1.1) were downloaded from the National Tibetan Plateau Data Center (Table 1). We calculated plant available water capacity (PAWC) using soil texture data according to the formula proposed by Gupta and Larson (1979).

The European Space Agency (ESA) CCI v2.0.7 and v2.1 land cover datasets served as crop (irrigation) distribution data. The distribution map of irrigated cultivated land in Xinjiang was obtained by extracting land cover type 20 at 300 m spatial resolution.

GDP spatial distribution data were downloaded from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences at 1 km resolution (Table 1), incorporating multiple factors closely related to human economic activities such as land use type, nighttime light brightness, and residential density. Landsat data provided population distribution density at 1 km resolution, using spatial data and multivariate asymmetric modeling methods to disaggregate census data within administrative areas. Land use types related to ecological water were extracted from ESA land use data. Data on agricultural comprehensive water consumption, industrial water consumption per 10,000 CNY GDP, domestic water per capita, and ecological water utilization volume were obtained from the Xinjiang Water Resources Bulletin (Water Resources Department of Xinjiang Uygur Autonomous Region, 2002–2018).

3.1 Water Yield Depth (WYD)

The InVEST model, jointly developed by Stanford University, World Wide Fund for Nature, and The Nature Conservancy, is widely used in ecosystem services research (Ochoa and Urbina-Cardon, 2017; Agudelo et al., 2020) as it contains modules that quantify diverse ecosystem service functions across terrestrial, freshwater, and marine ecosystems (Polasky et al., 2011). The InVEST model requires relatively few parameters and data inputs, exhibits high data availability, is less prone to parameter estimation errors and error propagation, and is easier to interpret and understand (Tallis and Polasky, 2009). The model employs the Budyko curve in its water yield module, which is widely applied in studies in the UK (Redhead et al., 2016), Australia (Donohue et al., 2012), and globally (Luo et al., 2020). We briefly describe the WYD modeling approach using the InVEST model below.

The water yield module in InVEST follows the water-heat coupling balance principle described by the Budyko curve. The model simplifies the confluence process and does not distinguish between surface runoff and subsurface flow at the raster scale (Lang et al., 2017). The formula for modeling WYD is shown in Equation 1 (Sharp et al., 2015):

$$WYD = P - ET_a$$

where WYD denotes annual water yield depth (mm), ET_a denotes actual annual evapotranspiration (mm), and P denotes annual precipitation (mm).

The ET_a/P term in Equation 1 is calculated using the Budyko curve (Zhang et al., 2001) as follows:

$$\frac{ET_a}{P} = \frac{1 + R_b - \sqrt{1 + R_b^2 + 2\omega R_b}}{2\omega}$$

where R_b denotes the Budyko drying index and ω denotes the ratio of plant available water depth to annual precipitation.

Both parameters R_b and ω in the Budyko curve can be calculated using Equations 3 and 4, respectively (Tallis et al., 2011):

$$R_b = \frac{ET_0 \times K}{P}$$

$$\omega = Z \times \frac{AWC}{P}$$

where ET_0 denotes potential evapotranspiration (mm), K denotes the plant evapotranspiration coefficient, Z denotes the seasonal distribution of precipitation (ranging from 1 to 30), and AWC denotes available water capacity reflecting the amount of water plants need from soil to grow (%). AWC can be determined based on parameters such as soil properties and root depth.

Modeled results were averaged over four-year periods (i.e., 2000–2003, 2004–2007, 2008–2011, 2012–2015, and 2016–2019) to investigate long-term changes, given high year-to-year fluctuations.

To evaluate InVEST model performance, we used runoff data from 14 outfall gauging stations in Xinjiang (seven in northern Xinjiang and seven in southern Xinjiang) as validation data. The upstream catchment area of each gauging station was derived using the Soil and Water Assessment Tool (SWAT) model. We then calculated runoff for each catchment by multiplying simulated WYD by the corresponding catchment area and validated modeled runoff against measured runoff from the corresponding gauging station for 2006–2011. Observed values from 2007 were used as the calibration dataset to optimize the Z parameter.

Glacial meltwater is an important recharge source for inland rivers in north-west China, accounting for 9.00%–43.00% of total runoff in inland river basins (Guo et al., 2016). It is essential to account for both precipitation and glacial

meltwater as water supply sources in Xinjiang water resources studies, yet previous applications of the InVEST model have often neglected glacial meltwater (Wang et al., 2019; Li et al., 2020; Yang et al., 2020). In this paper, we combined glacial meltwater data from GRACE with precipitation data from TRMM as total water yield sources to improve InVEST model performance according to water balance principles (Eq. 5). Specifically, annual changes in terrestrial water storage (TWSC) were obtained by subtracting GRACE data at the beginning of the year from data at the end of the year (Eq. 6) (Yang et al., 2015; Meng et al., 2019), after which positive values were removed. The reduction in water storage within glacier distribution areas extracted from China's second glacier inventory data was considered equivalent to glacial meltwater (Wei et al., 2014; Guo et al., 2015).

$$R = P - ET - TWSC$$

where R denotes runoff (mm), ET denotes evapotranspiration (mm), and TWSC denotes changes in terrestrial water storage (mm).

$$TWSC_i = TWS_{i_end} - TWS_{i_begin}$$

where TWSC_i denotes changes in terrestrial water storage in the *i*th year (mm), and TWS_{{i}_{end}} and TWS_{{i}_{begin}} denote terrestrial water storage at the end and beginning of the year (mm), respectively.

3.2 Water Utilization Depth (WUD)

In this study, WUD (mm) was used to characterize potential water resource demand and was modeled as the sum of irrigated water utilization depth (WUD_{irr}, mm), industrial water utilization depth (WUD_{ind}, mm), domestic water utilization depth (WUD_{dom}, mm), and ecological water utilization depth (WUD_{eco}, mm):

$$WUD = WUD_{irr} + WUD_{ind} + WUD_{dom} + WUD_{eco}$$

To calculate WUD_{irr}, we extracted the distribution map of irrigated land in Xinjiang from land cover data and then assigned agricultural comprehensive water utilization depths for different cities and regions to the irrigated cropland distribution map.

WUD_{ind} was calculated as follows:

$$WUD_{ind} = \alpha \times GDP \times w_{ind}$$

where α denotes the proportion of industrial GDP to total GDP (%), GDP denotes total GDP per square kilometer of land (10,000 CNY/km²), and w_{ind} denotes industrial water utilization per 10,000 CNY GDP (m³/10,000 CNY).

$WUD_{\{dom\}}$ was calculated as follows:

$$WUD_{dom} = POP \times w_{dom}$$

where POP denotes population per square kilometer of land (person/km²) and $w_{\{dom\}}$ denotes domestic water utilization per capita (m³/capita).

Ecological water utilization refers to the amount of water needed and used for ecosystem maintenance. In this study, ecological water utilization was accounted for different ecosystem types, including forests, grassland, water bodies (including wetlands), and urban land (Li et al., 2009; Shang et al., 2013). $WUD_{\{eco\}}$ was calculated as follows:

$$WUD_{eco} = \frac{EW}{A}$$

where EW denotes ecological water utilization for each administrative region (m³) and A denotes the area of land use type (km²).

3.3 Water Supply-Demand Relationships

Compared with previous methods such as the ecological footprint model, the ecosystem services perspective improves verifiability in water sustainability assessments and avoids reliance on empirical parameters. For example, WYD simulated by the InVEST model is more easily validated using gauging station data than water footprint and water carrying capacity metrics. The ecosystem services perspective also avoids empirical parameters such as global average yield capacity, yield factors, and equilibrium factors. While existing studies have applied ecosystem services to explore tradeoffs (Kang et al., 2020), human well-being (Wei et al., 2018), and service flows (Chen et al., 2020), few have used ecosystem services to assess sustainable water resource use in arid regions. Supply-demand relationship indices have been applied in many regions including Spain (Boithias et al., 2014), Taihu Lake in China (Li et al., 2016), and China's coastal regions (Zhai et al., 2020). These indices provide clear pictures of local ecosystem service supplies and demands, but have rarely been applied to assess water resource sustainability. In this study, we referenced and refined these indices based on Xinjiang's unique circumstances to more accurately assess water resource sustainability. We chose the difference index over the ratio index used in previous studies because Xinjiang's arid environment produces many zero values for WYD and WUD.

WSR and WSDD were used to characterize water supply-demand relationships. WSR reflects water resource utilization efficiency and was calculated as follows:

$$WSR = \frac{S_p}{S_a}$$

where WSR denotes water resource supply rate, S_p denotes potential water supply depth (mm), and S_a denotes actual water supply depth (mm). In this study, S_p refers to WYD modeled by the InVEST model, while S_a refers to actual water supply depth in each region as published in the Xinjiang Water Resources Bulletin (Water Resources Department of Xinjiang Uygur Autonomous Region, 2002–2018). A WSR greater than 1 indicates that water resources are not fully utilized, while values less than or equal to 1 indicate full utilization.

WSDD reflects the balance between water resource supplies and demands and was calculated as follows:

$$WSDD = WYD - WUD$$

WSDD values indicate water resource surplus when much greater than zero, balance when close to zero, and deficit when much less than zero.

3.4 Spatial-Temporal Analysis and Variable Analysis

Cold and hot spot analysis was used to understand spatial patterns and distributions of water supplies and demands. The G_i^* statistical method can reflect the spatial aggregation of points or patches with high or low values (Ord and Getis, 1992):

$$G_i^* = \frac{\sum_{j=1}^n w_{ij}x_j - \bar{x} \sum_{j=1}^n w_{ij}}{S \sqrt{\frac{n \sum_{j=1}^n w_{ij}^2 - (\sum_{j=1}^n w_{ij})^2}{n-1}}}$$

where G_i^* denotes the cold and hot spot analysis statistic, x_j is the attribute value of patch j , w_{ij} is the spatial weight matrix between patches i and j , n is the total number of patches, S is the variance of x_j , and \bar{x} denotes the arithmetic mean of patch attribute values.

G_i^* can be statistically tested based on Z-score and P-value. The Z-score measures the aggregation degree as the standard deviation of G_i^* , while the P-value determines the significance level of spatial aggregation. A positive Z-score indicates a hot spot area clustering high values, while a negative Z-score indicates a cold spot area clustering low values. The P-value indicates the significance level of cold or hot spots (Guerra et al., 2021). Cold and hot spot analysis was applied to examine aggregations of high and low values for WYD, WUD, WSR, and WSDD.

Both Sen trend analysis and Mann-Kendall (MK) test were employed for time series analysis. Sen trend analysis is a robust non-parametric statistical method widely used to derive trends in time series data. It is insensitive to outliers and errors but does not reflect trend significance levels. The Sen trend analysis is derived as follows:

$$\beta = \text{median} \left(\frac{x_q - x_p}{q - p} \right), \forall p < q$$

where β denotes the Sen slope value and x_q and x_p are time series data. If β is greater than zero, the time series shows an upward trend; if β is less than zero, it exhibits a downward trend.

The MK test is a non-parametric statistical test method that can assess trend significance and is not sensitive to outliers:

$$Z_m = \begin{cases} \frac{S_m - 1}{\sqrt{\text{var}(S_m)}} & \text{if } S_m > 0 \\ 0 & \text{if } S_m = 0 \\ \frac{S_m + 1}{\sqrt{\text{var}(S_m)}} & \text{if } S_m < 0 \end{cases}$$

where Z_m is the standardized test statistic following a standard normal distribution, S_m is the test statistic, sign is the sign function, and l is the number of data points. If $|Z_m| > 1.96$, the data series shows significant trends at the 0.05 significance level; otherwise, trends are insignificant at the 0.01 level (Schröter and Remme, 2016). Sen trend analysis and MK test were applied to analyze temporal trends in WYD, WUD, WSR, and WSDD.

Different input variables play varied roles in model outcomes. The controlled variable method was used to investigate each input variable's contribution to modeled results. Using the InVEST water yield module as an example, variables such as precipitation, potential evapotranspiration, and land cover data are key inputs for predicting WYD. To obtain precipitation's contribution rate to WYD, we treated 2002 precipitation data as the baseline and used them to simulate land surface processes in 2006, 2010, 2014, and 2018 while holding other variables constant. The contribution rate of a variable to output results can be calculated as follows:

$$P_{ij} = \frac{V_{act} - V_{ij}}{V_{act}}$$

where P_{ij} denotes the contribution rate of variable j to results in the i th year, V_{act} denotes results obtained by inputting all variables in the i th year according to actual conditions, and V_{ij} denotes results obtained by inputting variable j from the baseline year and other variables from the i th year. To further understand internal factors driving changes in water resource supplies and demands, we investigated the relative contributions of precipitation, potential evapotranspiration, and land cover to modeled WYD, as well as the relative contributions of WUD_{irr}, WUD_{ind}, WUD_{dom}, and WUD_{eco} to total WUD.

4.1 Model Calibration and Validation

Calibration experiments showed root mean square error (RMSE), mean absolute error (MAE), and Pearson's correlation coefficient values of $5.22 \times 10^8 (\pm 1.29 \times 10^8) m^3$, $4.08 \times 10^8 m^3$, and 0.65, respectively. Validation experiments using the remaining four year data showed RMSE, MAE, and Pearson's correlation coefficient values of $9.67 \times 10^8 (\pm 2.82 \times 10^8) m^3$, $6.87 \times 10^8 m^3$, and 0.72, respectively, when comparing modeled and observed runoff values.

Mean relative bias error between observed runoff data and modeled results without considering glacial meltwater was $1.96 \times 10^8 m^3$. By comparison, mean relative bias error between observed runoff data and modeled results considering glacial meltwater was $1.96 \times 10^8 m^3$ (Fig. 2 [Figure 2: see original paper]).

4.2 WYD and WUD

WYD in Xinjiang exhibited a spatial distribution pattern similar to precipitation, generally decreasing from north to south and from west to east, with values ranging from 0.00 to 800.00 mm (Fig. 3a [Figure 3: see original paper]1–a5). Areas with WYD above 50.00 mm were mainly distributed in northwestern Xinjiang and sparsely distributed at high altitudes in the Tianshan and Kunlun mountains. These areas, accounting for 5.26% of Xinjiang's total area, were often rich in water supplies and identified as hot spots above the 95.00% confidence level (Fig. 3b1–b5). Areas with WYD ranging from 0.10 to 50.00 mm were mainly distributed in northern and southern regions of the Junggar Basin and in oasis areas surrounding the Tarim Basin. Although these basin areas had runoff, WYD was relatively small compared to wetter areas. Areas with WYD from 0.10 to 50.00 mm were mostly identified as cold spots above the 95.00% confidence level, comprising about 0.13% of Xinjiang's total area. Areas with WYD below 0.10 mm were mainly distributed in deserts with virtually no runoff, including the Taklimakan, Gurbantungut, and Kumtag deserts. Their combined area accounted for more than 89.00% of Xinjiang's land area. These areas were considered insignificant in cold and hot spot analysis due to non-aggregated effects.

Temporally, WYD showed a continuous upward trend (Fig. 4a [Figure 4: see original paper]), increasing from 8.51 mm in 2002 to 10.86 mm in 2018—a 27.61% rise. The increasing trend was significant ($P < 0.05$) with a Pearson's correlation coefficient of 0.91. Sen trend analysis showed that 70.88% of the study area passing the trend analysis exhibited increasing WYD trends. The Sen slope was high in some northwestern Xinjiang areas. The MK test showed significance on the north and south sides of the Junggar Basin (Fig. 4b), indicating significant WYD increases in these areas. Some areas experienced decreased WYD, mainly concentrated in the eastern Tianshan and Kunlun mountains and the Ili River Valley.

WUD was high in oasis areas and cities but low in desert regions (Fig. 5a [Figure 5: see original paper]1–a5). WUD in Xinjiang primarily ranged from 0.00 to 4000.00 mm. Areas with WUD above 500.00 mm were mainly distributed in urban and irrigated croplands, such as agricultural areas near the Irtysh River, Ili River, and Tarim River, and oases near the northern Tianshan Mountains

slopes. These areas were often identified as hot spots above the 95.00% confidence level, accounting for 6.35% of Xinjiang's total area (Fig. 5b1–b5). Areas with WUD below 1.00 mm were widely distributed in deserts without clustering. Many areas with WUD from 1.00 to 100.00 mm were identified as cold spots above the 95.00% confidence level, mainly distributed in mountainous areas of the Altay, Tianshan, and Kunlun mountains, comprising 13.94% of Xinjiang's total area.

Temporally, average WUD showed a downward trend with a Pearson's correlation coefficient of -0.85 . Average WUD decreased from 67.50 mm to 53.53 mm during the study period—a 20.70% reduction (Fig. 6a [Figure 6: see original paper]). Sen trend analysis showed that WUD in hot spots mostly declined (Fig. 6b), and the MK test revealed significantly decreased WUD above the 95.00% confidence level in northern Urumqi City (Xinjiang's provincial capital) and central Changji Hui Autonomous Prefecture. Areas experiencing WUD decline accounted for 43.21% of Xinjiang's total area, with significantly declining areas being 1.80 times larger than significantly increasing areas. Areas with increased WUD were mainly located in the Altay, Tianshan, and Kunlun mountains, where the MK test showed significant increasing trends. WUD also increased in downtown Urumqi City.

4.3 WSR and WSDD

In Xinjiang, 93.39% of areas had WSR less than 1.00, while only a few areas had WSR greater than 1.00. Most areas with $WSR > 1.00$ were identified as hot spots (Fig. 7 [Figure 7: see original paper]), such as areas in Altay Prefecture, northern Tacheng Prefecture, around the Tianshan Mountains, and in western Kunlun Mountains. These areas highly overlapped with WYD hot spots. Areas with WSR less than 1.00 were widely distributed without obvious spatial aggregation, resulting in few WSR cold spots.

During the study period, average WSR in Xinjiang decreased from 0.30 to 0.22—a 26.67% decline (Fig. 8a [Figure 8: see original paper])—with a Pearson's correlation coefficient of -0.79 . Areas with increased WSR were mainly distributed in oases surrounding the Junggar and Tarim basins (Fig. 8b). Areas with decreased WSR included regions in the eastern Tianshan Mountains and northern Bayangol Mongolian Autonomous Prefecture, Ili Kazak Autonomous Prefecture, and northern Altay Prefecture.

In the study area, WSDD mostly ranged from -4000.00 to 800.00 mm (Fig. 9a [Figure 9: see original paper]1–a5), with averages generally ranging from -59.00 to -42.00 mm. Areas with negative WSDD values accounted for 82.40% of Xinjiang's total area. Spatially, WSDD was often in surplus in mountainous areas and in deficit in irrigation areas. Large areas with WSDD greater than 30.00 mm were identified as hot spots located in high-altitude areas. Additional hot spots appeared in Altay Prefecture, Tacheng Prefecture, and Bortala Mongolian Autonomous Prefecture (Fig. 9b1–b5). Hot spot areas above the 90.00% confidence level accounted for 27.81% of Xinjiang's total area. Areas

with WSDD less than -500.00 mm were often identified as cold spots, with spatial distributions highly coincident with WUD hot spots. Cold spot areas above the 90.00% confidence level accounted for 7.73% of Xinjiang's total area. Areas where WSDD was close to 0.00 mm were considered non-significant in cold and hot spot analysis.

Average WSDD in Xinjiang increased from -59.10 mm in 2002 to -42.72 mm in 2018 ($P < 0.05$; Fig. 10a [Figure 10: see original paper]). Sen trend analysis showed that WSDD increased in 64.65% of the study area passing the trend analysis, particularly in northern Tacheng Prefecture, Bortala Mongolian Autonomous Prefecture, and western Tianshan and Kunlun mountains. The MK test showed significant WSDD increases with high confidence levels on the rim of the Junggar Basin (Fig. 10b). Some areas experienced decreased WSDD, with water supply-demand tensions occurring in the eastern Tianshan and Kunlun mountains. Areas on the southern Tianshan Mountains slope and in the Ili River Valley also showed water supply-demand tensions.

4.4 Controlled Variable Analysis

The controlled variable method was used to analyze the relative contributions of precipitation, potential evapotranspiration, and land cover to WYD, as well as the contributions of $WUD_{\{irr\}}$, $WUD_{\{ind\}}$, $WUD_{\{dom\}}$, and $WUD_{\{eco\}}$ to total WUD (Fig. 11 [Figure 11: see original paper]). Contribution rates reflect the importance of factors in driving WYD changes. Figure 11a shows that precipitation had large impacts on WYD, with its contribution rate reaching 19.52% in 2018. The contribution rate of precipitation to WYD increased over time as precipitation rose in Xinjiang (Fig. 11a and c). The contributions of potential evapotranspiration and land cover to WYD remained below 6.00%. Potential evapotranspiration had negative impacts on WYD, with WYD decreasing as potential evapotranspiration increased (Fig. 11a and d). Land cover changes in Xinjiang showed positive contributions to WYD, with a slight upward trend in contribution rates. In 2018, the contribution rate of land cover changes to WYD reached 5.52%. The land cover transfer matrix in Table 2 indicates that large areas of bare land were transformed into grassland, ice and snow, cropland, shrubland, and water bodies. The area of bare land converted to grassland reached $40,470 \text{ km}^2$, accounting for nearly 3.40% of total bare land in 2002. These land cover changes led to increased water yields.

Results in Figure 11b indicate that $WUD_{\{irr\}}$ contributions accounted for the majority of total WUD changes at nearly -30.00% . The relative contribution of $WUD_{\{irr\}}$ was negative, contrasting with $WUD_{\{ind\}}$ and $WUD_{\{dom\}}$. The reduction in $WUD_{\{irr\}}$ became increasingly important to total WUD changes over time. The relative contributions of $WUD_{\{ind\}}$ and $WUD_{\{dom\}}$ to total WUD changes were relatively low but positive, with both showing increasing trends. The contribution rate of $WUD_{\{eco\}}$ remained at a relatively unimportant level across all years.

5 Discussion

The mean relative bias error of the InVEST model decreased by 34.00% when we accounted for glacial meltwater using GRACE data. Our study demonstrates that incorporating glacial meltwater into the InVEST model using satellite-based water storage data can help reduce bias errors in arid and semi-arid areas such as Xinjiang. Previous studies indicated that including glacial meltwater in water supply calculations could improve InVEST model performance in high-altitude and glacier-covered areas (Scordo et al., 2018; Benra et al., 2021). Although the Budyko curve does not account for detailed hydrological processes, this simple hydrological model provides sufficient accuracy in areas lacking precise input data. According to validation results, the InVEST model's accuracy meets the requirements for ecosystem services studies at annual scales (Pan et al., 2015; Scordo et al., 2018).

High WYD was mainly distributed in two major areas: northwestern Xinjiang and mountainous regions. Precipitation was the primary WYD source in northwestern Xinjiang, while glacial meltwater dominated in mountainous areas. Notably, decreased WYD occurred mainly in the eastern Tianshan and Kunlun mountains, which have fewer glaciers, possibly due to the arrival of the “bonus period.” Global warming has caused considerable glacier melting in the Tianshan and Kunlun mountains, leading to increased runoff. However, this represents an unsustainable way to increase water resources. After the glacial melting “bonus period” ends, runoff will decrease significantly, causing substantial water resource reductions. This poses a major future challenge for water resources in the region (Hartmann et al., 2016; Bolch et al., 2021).

Decreased WUD occurred principally in oases containing vast irrigated croplands. Agricultural irrigation represents the largest water consumption sector in Xinjiang (Chen et al., 2016). As technology advances, water-saving irrigation technology has become increasingly sophisticated and widely adopted in agriculture. By the end of 2016, water-saving agricultural area accounted for 74.59% of total cultivated area in Xinjiang—the highest proportion in China (Cao et al., 2020). Water-saving agriculture has contributed greatly to WUD reduction.

Increased WUD was mainly distributed in mountainous areas. Since 2000, ecological engineering projects have greatly improved vegetation cover in Xinjiang (Niu et al., 2019), and the warmer, wetter climate has also increased Normalized Difference Vegetation Index (NDVI) values (Xu et al., 2016; Luo et al., 2020). Overall, vegetation status has improved slightly, especially in mountains where vegetation is concentrated, which can increase ecological water consumption. Notably, WYD and WUD hot spots mismatched spatially according to spatial analysis. Mountainous areas were generally hot spots for water yield but cold spots for water utilization, whereas oases were hot spots for water utilization but cold spots for water yield.

Water resources in most of Xinjiang (with WSR < 1.00) were fully utilized, requiring new facilities for local water supplies. Water yields in northwestern

Xinjiang were not fully used for water supply. Hot spots and increased areas of WSR aligned with WYD patterns, indicating that WSR spatial and temporal patterns were greatly influenced by WYD. During the study period, water resources in 82.40% of Xinjiang were in deficit, consistent with previous research findings. Specifically, current water resources cannot meet Xinjiang's leap-forward development needs (Dai et al., 2017), and water resources in Alar, a city in southern Xinjiang, also cannot satisfy economic development demands (Liu et al., 2019). Fortunately, WSDD exhibited increasing trends in 64.65% of the region passing trend analysis, with increased WSDD areas mainly distributed in northern Xinjiang, indicating that water deficits have been alleviated in some areas. Existing research shows that improvements in water-saving technology and ecological management have alleviated water shortages in Xinjiang (Ling et al., 2019; Zhou et al., 2020).

According to controlled variable analysis, precipitation dominated WYD changes, and its contribution rates increased as precipitation rose. Previous studies also indicated that water yield predictions were more sensitive to precipitation than to potential evapotranspiration in Ethiopia (Sahle et al., 2019), with similar conclusions confirmed in the UK (Redhead et al., 2016). The Budyko curve used in the InVEST model partitions precipitation into evapotranspiration and runoff according to the aridity index. Increased potential evapotranspiration often leads to decreased runoff if precipitation remains unchanged. While local climate and environmental changes have increased WYD in Xinjiang in recent years, attention must still be paid to water resource uncertainties due to global climate change. When climate becomes warmer and wetter, increased precipitation positively impacts water yield, but increased potential evapotranspiration negatively affects water yield. Further research and continuous observations may be required to determine which factor dominates.

Regarding WUD, controlled variable analysis illustrated that $WUD_{\{irr\}}$ dominated total WUD changes, and its contribution rates decreased as $WUD_{\{irr\}}$ declined. Previous studies also indicated that irrigation accounted for the largest proportion of total water consumption in Xinjiang, reaching up to 97.00% (Chen et al., 2016), with similar conclusions in Guo et al. (2015). In addition to water-saving agriculture improvements, increased precipitation also mitigated water use pressures on agricultural irrigation. The contribution rates of $WUD_{\{ind\}}$ and $WUD_{\{dom\}}$ were relatively low but positive, with upward trends. Local population, economy, and urbanization rates have all increased in recent years, positively contributing to WUD (Tang et al., 2012; Gong et al., 2020). Notably, industrial structure upgrades and increased proportions of secondary and tertiary industries in Xinjiang led to higher $WUD_{\{ind\}}$ and $WUD_{\{dom\}}$. Xinjiang must control total WUD through measures such as developing water-saving industries and advocating water conservation lifestyles. Since $WUD_{\{irr\}}$ dominated total WUD changes in recent years, it is important to continue promoting water-saving irrigation technologies and controlling cropland expansion. Reasonable cropland layout and expansion planning are also needed (Lei et al., 2012;

Dai et al., 2017).

This research focused on inter-annual spatial distributions and temporal changes of water resource supplies, demands, and their relationships. Due to Xinjiang's climatic and topographical conditions, intra-annual water resource variation is also considerable. On the supply side, northern Xinjiang, western Xinjiang, and high-altitude areas often experience heavy winter snowfall. Although snowfall accumulates as solid water, it does not generate runoff in the same year but gradually transforms into runoff as temperatures rise in the following year. This snowmelt-to-runoff transformation has a lag effect, meaning most snowfall benefits water supply services in subsequent years. Future studies should refine the temporal scale to monthly rather than annual to account for this lag effect. On the demand side, $WUD_{\{irr\}}$ peaks generally occur from July to August (Shen et al., 2013), coinciding with high temperature and evapotranspiration periods, resulting in seasonal agricultural irrigation water shortages and reduced water utilization efficiency. Research is needed on storing water resources during surplus months for use during deficit months.

This study assessed sustainable water resource use from an ecosystem services perspective. As ecosystem services constitute a broad topic, trade-offs and synergies among service functions could be further discussed to better reflect ecosystem integrity (Hong et al., 2020). With improved understanding of ecosystem services, emerging research hotspots include ecosystem service evaluations, ecosystem service flows, and ecological compensation (Yu and Bi, 2011). Methods for studying ecosystem services could extend from single functions to multiple functions, helping deepen and broaden sustainable water resource assessments within the ecosystem services framework.

6 Conclusions

This study evaluated water resource supply-demand relationships in Xinjiang during 2002–2018 from an ecosystem services perspective. The InVEST model simulated WYD, while socioeconomic data modeled WUD. WSR and WSDD served as indices to characterize water resource supply-demand relationships, and the controlled variable method analyzed internal factors driving supply and demand changes. The results showed that WYD experienced a significant increasing trend, especially in oasis areas. WUD showed a downward trend, decreasing from 67.50 mm to 53.53 mm, with declines also concentrated in oasis areas. During the study period, Xinjiang's water resources were in slight deficit but this deficit mitigated over time with climate change and human activities. Increased precipitation dominated WYD increases, while decreased $WUD_{\{irr\}}$ dominated WUD decreases. Water resources in nearly 93.39% of Xinjiang were fully utilized, and water resource utilization rates increased during the study period. Incorporating satellite-based water storage data helped reduce InVEST model bias error. Xinjiang's water resource contradictions are easing, but vigilance is still needed regarding worsening supply-demand contradictions during later glacier melting stages.

From an ecosystem services perspective, this study assessed water supply-demand relationships and evaluated water resource sustainability in arid and semi-arid areas, diversifying water resource sustainability evaluation methods by addressing issues in previous approaches and extending application scenarios for ecosystem services supply-demand relationship research. Compared with previous methods like the ecological footprint model, incorporating ecosystem services in the InVEST model can improve assessment verifiability and avoid empirical parameters. This research may provide a reference for evaluating sustainable water resource use in other global regions.

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

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