Postprint of Ecological Management Zoning in the Ili River Valley Based on the Supply-Demand Relationship of Water Provisioning Services

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Abstract

Water supply services sustain the survival and development of human society and constitute a critical factor in advancing ecological civilization construction and high-quality watershed development in China. Taking the Ili River Valley in Xinjiang as the study area, and based on statistical yearbook data and remote sensing data, this study employs methods including the water supply service supply-demand model, Water Resource Security Index (FSI), and supply-demand matching to analyze the balance characteristics and matching status of water supply service supply and demand in the study area from 2005 to 2020. The results indicate: (1) The Water Resource Security Index in the Ili River Valley exhibits a "rise-decline" fluctuation, while the supply-demand balance demonstrates a three-stage evolution of "general deficit-general surplus-persistent deficit." Spatial differentiation is significant: five county-level administrative units—Yining City, Yining County, Huocheng County, Qapqal Xibe Autonomous County, and Xinyuan County—maintain persistent deficits; while Nileke County, Tekes County, Zhaosu County, and Khorgos City (in 2020) maintain surpluses, with a phased surplus inflection point occurring in 2010. (2) The supply-demand matching of water supply services exhibits three dominant types: "low supply-high demand," "low supply-low demand," and "high supply-low demand." The spatial distribution of supply-demand matching types demonstrates an east-central-west gradient differentiation, with counties and cities of the same pattern exhibiting spatial agglomeration and industrial convergence characteristics, and being significantly driven by regional economic structure. Specifically: pastoral areas with superior ecological endowments maintain high supply capacity, while cultivated land-intensive agricultural areas continuously face high demand pressure. Based on these research findings, ecological management zones including ecological conservation areas, ecological regulation areas, and ecological improvement areas are delineated to promote sustainable watershed ecosystem management and efficient water resource utilization.

Full Text

Ecological Management Zoning in the Ili River Valley Based on the Supply and Demand of Water Supply Services

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Abstract

Water supply services sustain the survival and development of human society and are key to promoting the construction of China' s ecological civilization and the high-quality development of river basins. As a significant component of ecosystem services, water supply services are central to ensuring the stability of watershed ecosystems and advancing ecological civilization construction in China' s arid and semi-arid regions. This study focuses on the Ili River Valley in Xinjiang, analyzing the equilibrium characteristics of water supply and demand from 2005 to 2020. Using statistical yearbook and remote-sensing data, we apply models of water supply services, the water resources security index (FSI), and supply-demand matching analysis. The results indicate: (1) The FSI of the Ili River Valley fluctuates from "rising to falling," and the supply-demand balance exhibits a three-stage evolution from "general deficit to general surplus to persistent deficit." Spatial differentiation is significant: five counties and cities (Yining City, Yining County, Huocheng County, Qapqal Xibe Autonomous County, and Xinyuan County) remain in persistent deficit; three counties (Nilek County, Tekes County, Zhaosu County) and Horgos City maintain surplus, with a surplus inflection point appearing in 2010. (2) The match between water supply and demand presents three dominant types: "low supply-high demand," "low supply-low demand," and "high supply-low demand." The spatial distribution of matching types is differentiated by gradients in the east, middle, and west. Counties and cities with the same matching pattern exhibit spatial agglomeration and industrial convergence, significantly driven by the regional economic structure. Specifically, livestock areas with superior ecological fundamentals maintain high supply capacity, while arable land-intensive agricultural areas continuously face high demand pressure. To support regional sustainable development, this study analyzes county-scale water supply-demand matching in the Ili River Valley, considering socioeconomic and natural geographic factors. Based on the analysis, ecological management zones—conservation, regulation, and improvement—are delineated to promote integrated development, ecosystem sustainability, and efficient water resource use.

Keywords: Water supply services; Supply-demand relationship; Ecological zoning; Ili River Valley

In the 21st century, water has become a global focus. Clean drinking water has been included in the United Nations Sustainable Development Goals for 2030. As a primary component of ecosystem services, water supply services play a pivotal role in ensuring watershed ecosystem stability and advancing ecological civilization construction in China' s arid and semi-arid regions. Meanwhile, climate change and human activities have intensified watershed ecological risks, causing environmental problems such as declining groundwater levels, soil erosion, and biodiversity loss, which subsequently weaken the water supply capacity of watershed ecosystems and severely hinder coordinated development of social, economic, and ecological interests. The Ili River Valley region, as a transboundary inland river basin between China and Kazakhstan and a key ecological protection area in the Silk Road Economic Belt, holds important strategic value for socioeconomic development and the ecological environment construction of the "Belt and Road" initiative. It also plays a critical role in flood control, runoff regulation, and water storage and drought prevention. As an important water collection area for northern and southern Xinjiang, its water source conservation and water purification functions are the resource and environmental foundation for the survival and development of all ethnic groups in Xinjiang, making the security of production, living, and ecological water use a primary task. However, with the expansion of agricultural cultivated land in the region, the substantial increase in irrigation water consumption has encroached upon ecological and domestic water spaces, while inefficient water resource development and utilization have caused structural water shortages, leading to severe imbalances between supply and demand of ecosystem water supply services.

Quantitative assessment and spatial mapping of ecosystem service supply and demand represent the frontier and hotspot of ecosystem service research. Foreign scholars primarily rely on methods such as land use estimation, ecological process simulation, spatial overlay, and expert judgment to assess supply and demand levels of different ecosystem services at global or regional scales. In recent years, domestic research on ecosystem service supply and demand has often discussed water supply services together with other ecosystem services, lacking specificity and making it difficult to accurately identify supply-demand contradictions. Therefore, this study takes the Ili River Valley as the research area, employs multi-source data and multiple models, and constructs a system for actual supply and demand of water supply services to comprehensively evaluate their relationship. Focusing on the spatiotemporal matching characteristics of water supply services, differences in supply-demand matching at different spatial scales, and optimization measures, this study aims to provide theoretical support for ensuring water resource security and promoting high-quality watershed development.

1 Study Area and Methods

1.1 Study Area Overview

The Ili River Valley (located in the western section of the Tianshan Mountains (Fig. 1), 80°09 ~84°56 E, 42°14 ~44°50 N) has a watershed area of 5.64$×10^{4}$ km^2. Influenced by its trumpet-shaped topography surrounded by mountains on three sides and opening to the west, westerly moisture is uplifted here to form regional precipitation, with annual precipitation of 215~800 mm and annual sunshine hours of 2870 h, creating Xinjiang' s unique humid microclimate known as the "Western Isle of Humidity." Geomorphological vertical differentiation is significant: low mountain zones serve as spring and autumn pastures, mid-mountain zones are covered with spruce forests, and high mountain zones are summer pastures. The Ili River Basin preserves Quaternary glacial relict plants, with existing wild fruit forests concentrated in Gongliu County and Xinyuan County. The basin contains over 2000$×10^{4}$ hm^2 of natural grassland and more than 3000 species of seed plants. The hydrological system is dominated by the Ili River, whose runoff originates from permanent glacier replenishment, with three major tributaries—the Tekes River, Kunes River, and Kashi River—all originating from high-altitude mountainous areas. Administratively, it encompasses two cities (Yining and Horgos) and eight counties including Yining County. Water supply services in this basin are dominated by surface water, exhibiting watershed coupling characteristics. Its complete ecosystem structure maintains the stability of the agro-forestry-pastoral production system. The region cultivates corn, wheat, rice, and other crops, serving as an important grain production base in Xinjiang.

1.2 Data Sources

1.2.1 Remote Sensing Data The meteorological data used in this paper includes daily atmospheric pressure, relative humidity, solar radiation, wind speed, sunshine hours, maximum temperature, and minimum temperature for the study area, obtained from the China Meteorological Data Sharing Network (http://data.cma.cn/). Professional meteorological interpolation software ANUSPLIN was used for batch interpolation to obtain daily-scale climate grid data with a resolution of 1 km, primarily used to calculate potential evapotranspiration and annual precipitation data. Land use data, soil data, water system data, and Digital Elevation Model (DEM) were downloaded from the Resource and Environmental Science and Data Center (http://www.resdc.cn/), with land use data having a spatial resolution of 30 m. NDVI data were downloaded from the Geospatial Data Cloud (www.gscloud.cn), and the maximum value composite method was used to extract annual maximum values, thereby synthesizing annual NDVI data. The InVEST model' s water yield module was used for quantification, based on the water balance principle, using precipitation minus actual evapotranspiration to calculate runoff for each grid cell. Parameters such as vegetation evapotranspiration coefficient, NDVI coefficient, plant available water content, root depth, and maximum soil thickness were referenced from relevant studies. The formula is as follows:

$$Y_{xj} = AET_{xj}$$

where Y_{xj} is the annual water yield of grid cell x under vegetation cover type j (mm); P_x is the annual precipitation of grid cell x (mm); and AET_{xj} is the annual actual evapotranspiration of grid cell x under land cover type j (mm).

1.2.2 Statistical Yearbook Data Population, industrial water use, and other relevant data used in this study were obtained from the Xinjiang Statistical Yearbook, Ili Kazakh Autonomous Prefecture Statistical Yearbook, Xinjiang Uygur Autonomous Region Statistical Bulletin, and Xinjiang Water Resources Bulletin. Statistical data for Horgos City began in 2016, so water supply service demand data for Horgos City were only calculated for 2020.

1.3 Methods

1.3.1 Water Supply Service Supply and Demand Quantification The calculation of water supply service demand refers to the method used by Ou Weixin et al. to quantify water supply service demand in the Taihu Basin. It mainly includes water consumption for human production and living activities, excluding water consumed by other processes such as vegetation absorption and river infiltration. Since ecological water consumption accounts for the smallest proportion, it is ignored here. The water supply service demand model primarily includes four categories: primary industry water use, secondary industry water use, tertiary industry water use, and residential domestic water use.

1.3.2 Water Resources Security Index Model The water resources security index (FSI) is used to characterize the "supply-demand" balance relationship of water supply services in the Ili River Valley. It applies a common logarithm to the supply-demand ratio to enhance the visibility and comparability of supply-demand contradictions in space, revealing surplus or deficit conditions. Referencing previous studies, the calculation formula is as follows:

$$FSI_i = \lg\left(\frac{S_i}{D_i}\right)$$

where i represents counties/cities in the valley; S_i represents the water supply service supply of county/city i; and D_i represents the water supply service demand of county/city i. When $FSI > 0$, water supply services are in surplus; when $FSI < 0$, water supply services are in shortage; when $FSI = 0$, water supply services are in balance. Building on Chen Dengshuai et al.'s classification of water resources security index into 5 categories, this study divides the supply-demand ratio threshold into 7 levels to more clearly quantify the balance status, as shown in Table 1.

Table 1 Classification criteria for the "supply-demand" balance of water supply services

1.3.3 Ecosystem Services Supply-Demand Matching Model The z-score standardization method is applied to explore the spatial differentiation characteristics of water supply services' "supply-demand" relationship. Based on climate, terrain, and land use data, the InVEST model' s water yield module is used for quantification. According to the water balance principle, runoff for each grid cell is calculated using precipitation minus actual evapotranspiration. Based on the standardization results, quadrants are divided for supply-demand matching. The x-axis represents standardized supply, and the y-axis represents standardized demand, dividing into four quadrants: Quadrant I—high supply-high demand; Quadrant II—low supply-high demand; Quadrant III—low supply-low demand; Quadrant IV—high supply-low demand. The formulas are as follows:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

$$s = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

where x is the standardized supply and demand of water supply services; x_i is the value for county/city i; $\bar{x}$ is the watershed average; s is the watershed standard deviation; and n is the number of evaluated counties/cities.

2 Results

2.1.1 Temporal Characteristics of Water Supply Service Supply-Demand Balance in the Ili River Valley

From 2005 to 2020, the water resources security index (FSI) of the Ili River Valley showed a "rise then fall" trend, reaching its lowest value in 2020. When $FSI < 0$, water resources are in short supply, indicating a deficit state. From a stage perspective, the supply-demand balance of the Ili River Valley from 2005 to 2020 showed an overall deficit state, transitioning to higher deficit levels. The evolution path was: general deficit → general surplus → persistent deficit. This indicates that under the dual effects of insufficient supply and increasing demand, water supply services in the Ili River Valley are in an overall shortage state.

2.1.2 Spatial Characteristics of Water Supply Service Supply-Demand Balance in the Ili River Valley

As shown in Figure 2, spatially, the water supply service supply-demand balance relationships from 2005 to 2020 exhibit distinct patterns. Five counties and cities—Yining City, Yining County, Huocheng County, Qapqal Xibe Autonomous County, and Xinyuan County—remained in persistent deficit. Huocheng County is located in the middle reaches of the Ili River, far from the sources of the three main tributaries, resulting in relatively low water supply. Xinyuan County showed the most stable supply-demand balance, being in surplus only in 2010 and in deficit in other years. Yining City experienced changes from "high deficit → general deficit → high deficit," with an overall shortage state that intensified in 2020. Due to high population density (over 1000 people/km^2), large living water demand, and improved urban facilities and road hardening that reduce urban ecosystem water supply capacity, Yining City faces severe challenges. Nilek County, Tekes County, and Zhaosu County maintained general surplus states, with $FSI > 1$ indicating high surplus, as these three counties are located upstream of the Ili River with abundant water resources. Gongliu County' s supply-demand balance changed from "general deficit → general surplus → general deficit," shifting from supply shortage to supply surplus in 2010, joining Nilek, Tekes, and Zhaosu counties in general surplus. Yining County' s balance changed from "higher deficit → general deficit → higher deficit," while Huocheng County' s changed from "higher deficit → general deficit → higher deficit."

Figure 2 [**Figure 2: see original paper**] Evolution trend of the supply-demand balance relationship of water supply services in the Ili River Valley from 2005 to 2020

Figure 3 [**Figure 3: see original paper**] Supply-demand balance of water supply services in counties and cities in the Ili River Valley from 2005 to 2020

2.2 Supply-Demand Matching Types of Water Supply Services in the Ili River Valley

The supply-demand matching analysis reveals three dominant types: "low supply-high demand," "low supply-low demand," and "high supply-low demand." As shown in Figure 4, counties and cities are mainly distributed in three quadrants, with few in the "high supply-high demand" quadrant. Nilek County (2005, 2010, 2015), Zhaosu County, and Tekes County belong to the "high supply-low demand" type. Yining County, Qapqal Xibe Autonomous County, Huocheng County, and Xinyuan County (2015, 2020) belong to the "low supply-high demand" type. Yining City and Gongliu County belong to the "low supply-low demand" type. Yining City (2005) belongs to the "low supply-high demand" type, while Nilek County (2020) belongs to the "high supply-high demand" type.

Figure 4 [**Figure 4: see original paper**] Matching characteristics of water supply services in the Ili River Valley from 2005 to 2020

2.3 Ecological Management Zoning

The supply-demand status of water supply services in the Ili River Valley exhibits spatial heterogeneity, with distinct distributions of supply and demand zones. To achieve regional sustainable development goals, based on county-scale analysis of supply-demand matching types and combined with the "Ili Prefecture Direct Ecological Environment Protection Master Plan (2018-2035)" and the socioeconomic and natural geographic conditions of the Ili River Valley, this study conducts ecological management zoning from the perspective of integrated regional development and ecological management. The area is divided into three major zones: ecological conservation zone, ecological regulation zone, and ecological improvement zone.

2.3.1 Delineation of Ecological Conservation Zone Nilek County, Zhaosu County, and Tekes County are located in the southwestern and eastern mountainous forest and grassland areas upstream of the Ili River Basin. As "high supply-low demand" ecological conservation zones situated along the three major tributaries (Kashi River, Kunes River, and Tekes River), they exhibit general water supply surplus. According to the Xinjiang Uygur Autonomous Region Ecological Environment Status Bulletin, these three counties are rich in animal and plant resources, hosting national protected species such as snow leopards and ibexes, with well-preserved grassland and forest ecosystems. The regional industrial structure is dominated by grassland animal husbandry and tourism. During summer snowmelt periods, river runoff is substantial, fully meeting water demands for agriculture, animal husbandry, and tourism. Influenced by industrial characteristics, water resource utilization efficiency is relatively high while demand remains comparatively low.

2.3.2 Delineation of Ecological Regulation Zone The central and western agricultural irrigation areas of the Ili River Valley, namely Yining County, Qapqal Xibe Autonomous County, Huocheng County, Xinyuan County, and Yining City, are "low supply-high demand" ecological regulation zones. As the largest consumption areas of water supply services, these counties should focus on achieving efficient utilization. Through bioengineering measures such as land leveling, reducing ground slope, soil fertilization, and soil and water conservation, land slope can be improved and soil fertility and texture enhanced. Efficient water-saving irrigation technologies such as sprinkler and pipe irrigation should be promoted, and integrated water-fertilization systems should be advanced to reduce agricultural water consumption. Agricultural planting structure and scale should be appropriately adjusted and optimized to improve the matching degree between water resources and crop planting structures.

2.3.3 Delineation of Ecological Improvement Zone Gongliu County in central Ili River Valley is an ecological improvement zone dominated by "low supply-low demand," focusing on improving ecosystem functions. It is necessary to fully utilize the ecosystem' s self-repair capacity. Under the premise of ensuring existing vegetation is not damaged, measures such as artificial grass planting, afforestation, and construction of farmland shelterbelts should be implemented to rapidly increase county vegetation coverage. In terms of water use structure, irrigation areas should be strictly controlled, water use proportions adjusted, and ecological water use guaranteed to improve vegetation survival rates.

3 Discussion

Water supply services, as the most fundamental ecosystem services for maintaining human well-being, have coordinated supply-demand relationships that are crucial for promoting positive interactions between natural ecosystems and socioeconomic systems and achieving water ecological security and high-quality watershed development. However, research results confirm that water supply services in the Ili River Valley suffer from supply-demand imbalances and mismatches. The flow resulting from supply-demand mismatches demonstrates that the generation and consumption processes of water supply services are not static but directional flow processes. Counties and cities at different geographic locations in the watershed exhibit significant differences in supply-demand balance and matching types. Nilek County, Zhaosu County, and Tekes County in the southwestern and eastern mountainous forest and grassland areas upstream of the Ili River Basin are "high supply-low demand" ecological conservation zones that function as "water towers" at the river' s source. Measures should be taken to reduce ecological pressure and enhance ecosystem water conservation capacity. These counties should continue implementing the Grain for Green policy, increase artificial forest planting, and raise forest coverage. Strict grassland-livestock balance systems should be enforced, with rotational grazing, seasonal grazing bans, and rest periods to restore grassland water conservation functions. Grassland fire prevention and pest control should be strengthened to maintain ecological balance.

Yining County, Qapqal Xibe Autonomous County, Huocheng County, and Xinyuan County experienced persistent water supply deficits, belonging to the "low supply-high demand" type. According to the Xinjiang Water Resources Bulletin, these four counties in the middle reaches receive only 30%~50% of the precipitation in upstream mountainous areas, with surface water resources merely 20%~30% of upstream counties. Cultivated land accounts for 40%~60% of the area, and high water-consumption agricultural patterns intensify demand pressure, leading to significant water resource supply-demand contradictions. In 2020, Yining City belonged to the "low supply-high demand" type, with annual water consumption reaching 2.8×10^{8} m^{3}. Driven by economic scale and population size, industrial water use proportion rose to 30%~50%, while domestic water use increased to 20%~30%. The transformation of water demand structure and insufficient supply capacity have exacerbated supply-demand imbalances. Overall, water supply services in the Ili River Valley exhibit spatial heterogeneity. Upstream "high supply-low demand" counties continuously transport water to downstream "low supply-high demand" areas through watershed hydrological cycles, forming a spatial distribution pattern of cross-regional water supply service provision and benefit zones. Future research should focus on the spatial flow characteristics of water supply services, establishing spatiotemporal connections between generation and consumption, and mapping flow pathways. Quantifying flow rates and velocities can precisely identify supply and benefit zones. Furthermore, the spatial heterogeneity of water supply service supply and demand causes water resource allocation inequity issues that warrant deeper investigation. Using the total ecological value of water supply services as a reference standard for ecological compensation may lead to unrealistic compensation zones and amounts. Discussing watershed ecological compensation mechanisms from the perspective of water supply service flows could help objectively delineate compensation zones and scientifically calculate compensation standards.

4 Conclusions

Using methods such as the water resources security index model and supply-demand matching model, this study characterized the supply-demand relationship of water supply services in the Ili River Valley from both balance and matching perspectives, and conducted ecological management zoning accordingly. The main conclusions are:

(1) From 2005 to 2020, the water resources security index of the Ili River Valley showed an overall "rise then fall" trend. The supply-demand balance was in deficit during 2005-2015 and in surplus during 2010. The balance relationship exhibited a stage change characteristic of "general deficit → general surplus → general deficit." The supply-demand balance relationships of Yining City, Yining County, Huocheng County, Qapqal Xibe Autonomous County, and Xinyuan County remained in persistent deficit, while those of Nilek County, Tekes County, Zhaosu County, and Horgos City (2020) remained in persistent surplus.

(2) The supply-demand matching of water supply services in the Ili River Valley is dominated by three types: "low supply-high demand," "low supply-low demand," and "high supply-low demand." Different counties and cities exhibit spatial heterogeneity and temporal variability in supply-demand matching types, showing east-west-middle spatial differences. Counties/cities with the same matching type exhibit a "neighboring effect" in space and similar production structures. Grassland pastoral areas are dominated by the "high supply-low demand" matching type, while agricultural irrigation areas are dominated by the "low supply-high demand" matching type.

(3) Based on the relationships among water supply service supply-demand quantity, balance, and matching, three ecological management zones are delineated: ecological conservation zone, ecological regulation zone, and ecological improvement zone, with differentiated ecological protection strategies proposed.

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