

Article

Spatiotemporal Evolution Characteristics and Driving Mechanism of Water Budget in the Sanjiang Plain

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Abstract

The water supply–demand pattern directly affects the stability of ecosystems and the level of agricultural sustainable development. Based on the theoretical framework of water supply–demand ecosystem services, this study took 1990–2020 as the research period, and integrated the water yield module of the InVEST model, urban stormwater retention module, standard deviational ellipse method, and spatial interpolation to accurately calculate regional water yield, water demand, water supply–demand ratio, and gravity center shift. The aim was to reveal the spatiotemporal evolution and mechanism of water budget in the Sanjiang Plain under large-scale agricultural expansion. The results showed the following: (1) From 1990 to 2020, the annual water yield in the Sanjiang Plain fluctuated from 12.16 billion m³/yr to 23.28 billion m³/yr, with a spatial pattern of “high in the northwest and southeast, low in the central Songhua River”, and high-value areas were highly coincident with natural ecological land. (2) The multi-year average water demand was approximately 13.0 billion m³/yr, experiencing three phases, “slow growth–rapid rise–stable slowdown”, showing a distribution characteristic of “concentrated along rivers and high in urban areas”. (3) Water surplus and deficit areas maintained a rigid characteristic of “highland supply, lowland consumption” for a long time. The gravity center of deficit areas rotated counterclockwise from 132.35° E, 46.55° N to 132.58° E, 46.78° N, with an annual migration rate of 10–15 km/a. The gravity center of surplus areas rotated clockwise from 133.22° E, 47.45° N to 132.85° E, 46.92° N, with an annual migration rate of 15–20 km/a. (4) From 1990 to 2015, the regional water supply–demand pattern remained relatively stable. However, a pronounced transition occurred during 2015–2020, when surplus areas sharply decreased from 49% to 27%, while conflict zones expanded rapidly, indicating an evident deterioration of regional water security.

Keywords: Sanjiang Plain; water budget; surplus area; deficit area; water ecosystem service level



Academic Editor: Vasilis Kanakoudis

Received: 5 June 2026

Revised: 8 July 2026

Accepted: 15 July 2026

Published: 21 July 2026

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1. Introduction

Against the background of global change, the imbalance between water supply and demand has become one of the major challenges restricting regional sustainable development [1–3]. This issue is particularly pronounced in agriculture-dominated regions, where large-scale dryland-to-paddy conversion has transformed extensive areas of natural ecosystems and dry cropland into paddy fields, substantially increasing agricultural

irrigation water demand. The rapid expansion of this water-intensive agricultural system has not only altered surface evapotranspiration processes but also disrupted the natural hydrological connectivity between water and soil. Consequently, the resulting imbalance between water supply and demand has intensified regional water-resource conflicts, posing significant challenges to ecological security and the sustainable development of agriculture [4,5].

Early studies on water scarcity and water budget imbalance were pioneered by Falkenmark et al. [6], who classified water scarcity into climatic drought, intermittent drought, land degradation, and population-induced water stress based on the vulnerability of semi-arid regions. They also emphasized that large-scale water scarcity should be understood through analyses at finer spatial scales, thereby establishing a conceptual framework for subsequent studies on water supply–demand imbalance. Building upon this foundation, Vörösmarty et al. integrated climate model outputs [7], water balance data, and socio-economic information into a digital river network to conduct global-scale numerical simulations. Their findings revealed that a substantial proportion of the world’s population was already experiencing water stress and that increasing future water demand would place considerable pressure on global freshwater systems. The work shifted the focus of water-resource research from evaluating water availability alone to assessing the spatial and temporal matching between water supply and demand. At the regional scale, Pan et al. employed the InVEST model to quantify ecosystem water yield services in the Sanjiang Plain from 1980 to 2005 and further analyzed their spatiotemporal variations in relation to precipitation and runoff coefficients. Their study demonstrated that ecosystem service models provide an effective approach for characterizing basin-scale water yield capacity [8]. Subsequently, Yang et al. and Zhu et al. investigated the spatiotemporal dynamics and driving mechanisms of water yield in the Yellow River Basin and the Hanjiang River Basin, respectively, using the InVEST water yield model in combination with climate change, land-use/land-cover change, and multi-scenario simulations. These studies further advanced water-resource research from water yield assessment toward integrated analyses of water supply–demand coupling and water security evaluation [9,10]. In summary, domestic and foreign scholars have achieved systematic results in water shortage identification, supply–demand coupling analysis and spatial simulation of water production services, providing direct methodological and theoretical support for this study to explore the spatiotemporal evolution of water budget in the Sanjiang Plain using InVEST, spatial interpolation and standard deviational ellipse methods.

Despite substantial progress, three major limitations remain in current research on water supply–demand relationships. First, most studies focus on either water supply or water demand independently, with limited attention to their dynamic coupling. As noted by Deng et al., existing studies often overlook the temporal evolution and interactions of water supply–demand coupling relationships [11]. Second, conventional analyses are primarily conducted at statistical or administrative scales, providing limited spatial detail and making it difficult to capture the fine-scale heterogeneity of regional water budget patterns. Third, long-term assessments of water budget dynamics under agricultural expansion remain insufficient. Previous studies have highlighted the need for long-term investigations into the evolution of water budgets and their driving mechanisms under changing climatic and land-use conditions [12–14]. To overcome these limitations, this study incorporates three methodological advances. First, a comprehensive ecosystem service framework is developed to integrate water yield, water demand, and their coupling relationships, thereby providing a more comprehensive assessment of regional water budget conditions [15,16]. Second, spatially explicit evaluation methods are employed to characterize the spatial distribution and evolution of water budget patterns at a finer resolution [17]. Third, a

long-term analysis covering the period 1990–2020 is conducted to quantify the temporal evolution of regional water budgets under agricultural expansion.

As one of China's most important commodity grain production regions, the Sanjiang Plain plays a crucial role in ensuring national food security. Since the late twentieth century, large-scale agricultural development, particularly the conversion of dryland to paddy fields, has substantially expanded rice cultivation and significantly increased agricultural water demand. While this transformation has enhanced grain production, it has also intensified pressure on regional water resources. From a land-use perspective, cultivated land occupies a large proportion of the Sanjiang Plain, with paddy fields becoming the dominant agricultural land-use type. In contrast, the area of dry cropland has remained relatively stable, although its proportion has gradually declined. In some representative irrigation districts, rice cultivation accounts for more than 50% of the total cultivated land area. Because rice irrigation requires large amounts of water during the growing season, agricultural water demand is highly concentrated, further exacerbating the spatial and temporal mismatch between water supply and demand [18]. Agriculture is the dominant water-consuming sector in the Sanjiang Plain, accounting for more than 80% of total annual water use. However, regional water availability is strongly constrained by the uneven temporal distribution of precipitation and the limited regulation capacity of surface water resources, resulting in considerable fluctuations in water supply [19,20]. Consequently, the region has experienced a transition from traditional water-resource constraints to increasingly complex water security challenges characterized by persistent supply–demand conflicts. Owing to its intensive agricultural production and rapid expansion of paddy fields, the Sanjiang Plain provides a representative case for investigating water supply–demand relationships in agricultural regions of China [21–23].

In summary, this paper takes the Sanjiang Plain as the research area, based on the theoretical framework of ecosystem service supply and demand, comprehensively uses the InVEST 3.18.0 model water yield module and urban stormwater retention module, combined with spatial interpolation, the geographic grid assignment method, the standard deviational ellipse method, etc., to quantitatively evaluate the regional water supply and demand status. On this basis, the idea of ecosystem service flow analysis is introduced to systematically characterize the spatiotemporal evolution characteristics of water supply and demand relationship. The main research objectives of this paper are as follows: (1) reveal the spatiotemporal distribution pattern of water yield and water demand in the Sanjiang Plain; (2) analyze the evolution characteristics and driving mechanism of water supply and demand relationship; (3) identify water surplus and deficit areas, and put forward targeted suggestions for water-resource optimal allocation and engineering regulation. The present study aims to reveal long-term regional evolution characteristics rather than short-term seasonal dynamics. Therefore, annual datasets and basin-scale spatial analysis were adopted to ensure temporal consistency over the 30-year study period.

2. Materials and Methods

2.1. Overview of the Study Area

The Sanjiang Plain is located in eastern Heilongjiang Province, northeast China, at the confluence of the Songhua, Heilongjiang, and Wusuli Rivers (Figure 1). It is a typical low-lying marsh plain in the cold temperate region, extending 45–48° N and 130–135° E, with a total area of approximately 1.09×10^5 km². Elevation ranges from 50 to 100 m above sea level, and the terrain gently slopes from southwest to northeast. The region is bordered by Russia to the east, the Lesser Khingan Mountains to the west, the Changbai Mountains to the south, and the Heilongjiang River to the north. Owing to its unique geographical setting, fertile soils, and abundant wetland resources, the Sanjiang Plain plays

a critical role in both ecological conservation and agricultural production. It serves as an important ecological security barrier in northeast China and is one of the country's principal commodity grain production bases, making it strategically significant for both ecosystem protection and national food security [24].

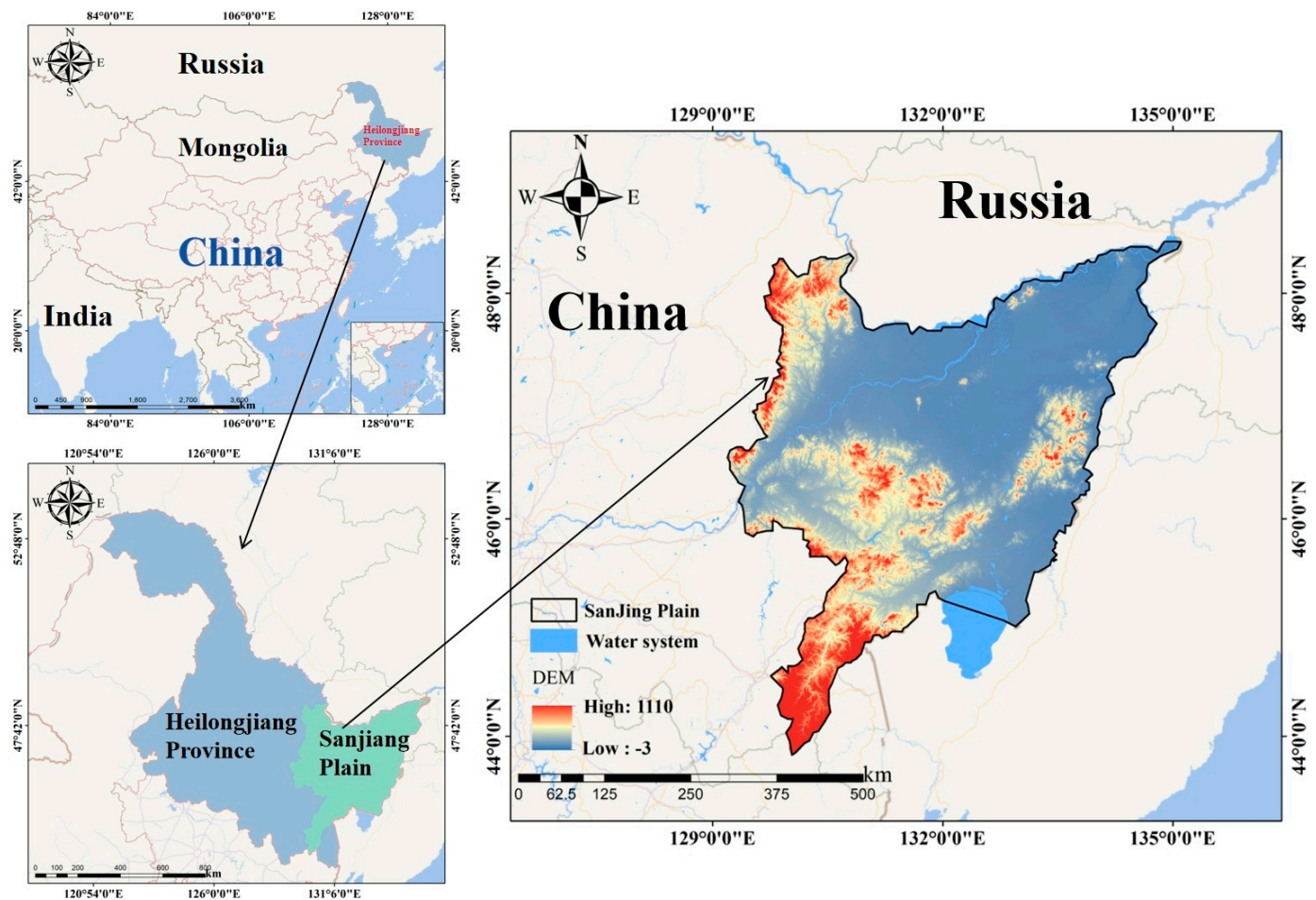


Figure 1. Overview map of the study area.

The study area has a temperate humid to sub-humid continental monsoon climate. The mean annual air temperature ranges from 2.5 to 3.6 °C, with average temperatures of −21 to −18 °C in January and 21–22 °C in July. The frost-free period lasts approximately 120–140 days, and the accumulated temperature above 10 °C is 2300–2500 °C [25,26]. Mean annual precipitation ranges from 500 to 800 mm and exhibits pronounced spatial and temporal variability, with most rainfall occurring during the summer months. Annual evaporation is also relatively high, reaching approximately 400–600 mm during summer, which, together with the seasonal concentration of precipitation, strongly influences regional hydrological processes and agricultural water availability [27,28]. At the same time, the Sanjiang Plain is rich in water resources, with total water resources amounting to approximately 18.764 billion cubic meters. The Heilongjiang River, the Songhua River, the Wusuli River and their tributaries (such as the Qihulin River, the Nongjiang River, and the Yalu River) together form a dense river system. The river channels in the region are meandering and narrow, the runoff is slow, and the flood peak is sudden, which further aggravates the formation of a surface wet environment and is also an important reason for the wide distribution of wetlands in the region [29,30]. The regional overview can be referred to Figure 1.

2.2. Data Sources

The land-use data of the Sanjiang Plain from 1990 to 2020 in this study come from the annual 30 m resolution land cover data of China from 1985 to 2023 released by Professors Yang Jie and Huang Xin of Wuhan University (<https://zenodo.org/records/12779975>) (accessed on 5 March 2026) [30]. After clipping, mosaicking and other processing, eight categories are obtained, cultivated land, forest land, shrub land, grassland, water area, barren land, impervious surface and wetland, and the geographic coordinate system is uniformly GCS_WGS_1984. Natural environment data (air temperature, precipitation, potential evapotranspiration, bedrock depth, and PAWC (Plant Available Water Capacity)) and river system data come from the Resource and Environment Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn/>), DEM data come from the Geospatial Data Cloud website (<https://www.gscloud.cn/>), and slope and aspect data are calculated using DEM data. Socio-economic data and population density come from the data shared by Professor Chen Yuehong's team [31] on the figshare platform (<https://figshare.com/s/d9dd5f9bb1a7f4fd3734>) (accessed on 5 March 2026), and GDP data come from the data published by Professor Zhao Naizhuo [32] and others in 2016 (<https://github.com/thestarlab/ChinaGDP>) (accessed on 5 March 2026). The specific data information is shown in Table 1.

Table 1. Data detail introduction table.

Data Type	Data Source	Data Details
Land use	Dataset released by Professors Yang Jie and Huang Xin, Wuhan University (https://zenodo.org/records/12779975)	Annual 30 m resolution raster dataset of China from 1990 to 2020
Natural environment data	Resource and Environment Data Cloud Platform, Chinese Academy of Sciences (RESDC) (https://www.resdc.cn/)	Including temperature, precipitation, potential evapotranspiration, bedrock depth, soil water storage capacity and river network data
Geospatial elevation data	Geospatial Data Cloud (https://www.gscloud.cn/)	Raster data with a spatial resolution of 30 m
Population density data	Dataset shared on Figshare by the research team led by Professor Chen Yuehong (https://figshare.com/s/d9dd5f9bb1a7f4fd3734 , accessed on 5 March 2026)	Raster data with a spatial resolution of 30 m
GDP	Data published in the 2016 paper by Professor Zhao Naizhuo et al. (https://github.com/thestarlab/ChinaGDP , accessed on 5 March 2026)	Raster data with a spatial resolution of 30 m

3. Calculation of Water Supply–Demand Ratio

3.1. Calculation of Water Yield

The regional water yield is estimated by the water yield module of the InVEST model. Based on the principle of water balance, the model defines water yield as the difference between precipitation and actual evapotranspiration [33].

$$Y_x = \left[1 - \left(\frac{A_x}{P_x} \right) \right] \times P_x \quad (1)$$

where Y_x is the annual water yield of grid x (mm); A_x is the actual evapotranspiration of grid x (mm); P_x is the annual precipitation of grid x (mm). Grid x represents each $1 \text{ km} \times 1 \text{ km}$ spatial raster unit in the study area, and mm refers to the unit of annual water yield per grid cell.

However, existing studies have pointed out that the InVEST model does not explicitly consider the groundwater baseflow process, which may lead to underestimation of water yield. Therefore, this study introduces a groundwater baseflow correction method to estimate groundwater recharge through runoff coefficient and baseflow ratio parameters [34,35] to improve the reliability of the model results. The calculation formula is:

$$R = P \times A \times (1 - r_c) \quad (2)$$

$$B = \frac{R}{Y_x} \quad (3)$$

where R is the groundwater recharge (mm); P represents the precipitation in the study area (mm); A is the ecosystem area (m^2); r_c is the runoff coefficient; B is the baseflow ratio; and Y_x is the initial water yield (mm).

In this paper, the baseflow ratio grid is integrated into the InVEST water yield module year by year, and the Z factor is adjusted to the optimal value (about 2.75). The Z parameter (2.75) was calibrated according to the hydrological characteristics of cold-region watersheds in northeast China by repeatedly comparing simulated water yield with observed runoff at representative hydrological stations, ensuring that the parameter better reflects regional evapotranspiration and groundwater recharge processes under seasonal frozen-soil conditions. After verification with the regional Water Resources Bulletin, the refined annual water yield data of the Sanjiang Plain from 1990 to 2020 are obtained.

3.2. Calculation of Water Demand

To construct a spatial distribution dataset of water use in the Sanjiang Plain, this study comprehensively predicts four core water demands: ecological, domestic, agricultural and industrial. Among them, ecological water replenishment is finely divided into four types of ecological water demand, forest water use, grassland water use, fishery water use and wetland ecological water replenishment, based on ecosystem type characteristics. Industrial water demand was spatially allocated using an area-weighted interpolation (areal weighting interpolation) approach. Annual industrial water consumption reported in the Heilongjiang Water Resources Bulletin was first assigned to administrative units and subsequently redistributed to 1 km raster cells according to the spatial distribution of industrial land and population density. The interpolation was implemented in ArcGIS (version 10.8) using the Polygon-to-Raster and Raster Calculator tools. Agricultural water demand was spatialized using annual irrigation quotas for paddy fields and dry farmland, whereas domestic water demand was estimated using population density and per-capita water consumption. Agricultural water use quota is interpolated annually and spatially according to the planting structure of dry land and paddy fields with a ratio of about 1:1 and significant differences in irrigation quotas; domestic water use is rasterized through the model of “per capita water use quota $\times$ population density”. After spatialization of other water demands, spatial gravity analysis is carried out by relying on the ArcGIS grid damage tool, and finally the annual total water demand grid dataset with 30-year sequence and spatial resolution of $1 \text{ km} \times 1 \text{ km}$ of the study is generated. This dataset depicts the spatiotemporal characteristics of water consumption in the Sanjiang Plain, laying a reliable data foundation for the subsequent accurate statistics of water supply–demand ratio [36,37]. Agricultural irrigation demand was estimated according to annual land-use types and irrigation quotas specified in the Code for Design of Irrigation and Drainage Engineering (GB 50288–2018) [38]. During 1990–2020, dryland and paddy fields constituted the dominant agricultural land-use types in the Sanjiang Plain, and their overall regional area remained approximately balanced. Therefore, different irrigation quotas were assigned to dryland and paddy fields to estimate agricultural water demand. This assumption is

consistent with the long-term land-use dynamics reported by [39], who demonstrated the continuous expansion of paddy fields following large-scale agricultural reclamation in northeast China.

3.3. Supply–Demand Ratio

In this study, the Morphological Spatial Pattern Analysis (MSPA) model is first used to extract the planar vector data (Shapefile format) of water surplus and deficit areas in the Sanjiang Plain from 1990 to 2020, providing a basic spatial dataset for subsequent supply–demand matching analysis and spatial pattern characterization. Morphological Spatial Pattern Analysis (MSPA) was adopted because it preserves landscape connectivity and spatial topology while identifying ecological source areas. Unlike conventional threshold-based classification methods, which simply divide raster cells according to pre-defined numerical values, MSPA considers the geometric relationships among adjacent landscape patches and identifies ecologically meaningful structural components such as core, bridge, edge, loop, and branch elements. Consequently, MSPA provides a more reliable representation of ecological networks and allows the spatial relationship between water supply areas and water demand zones to be analyzed from both structural and functional perspectives. On this basis, the water ecosystem service supply–demand ratio index is adopted to identify water surplus and deficit areas in the study area. The calculation formula refers to the standardized supply–demand ratio model proposed by scholar Sun [40], and the specific form is as follows:

$$R = \frac{S - D}{\frac{S_{\max} - D_{\max}}{2}} \quad (4)$$

where R is the water supply–demand ratio; S and D are the regional water supply and demand respectively; and $S_{\max}$ and $D_{\max}$ are the maximum regional water supply and demand during the study period respectively. The specific content of this method can be referred to research by Chen et al. [41]. With reference to the threshold setting standard of scholar Yang [42] for the water supply–demand matching characteristics of major grain-producing areas, combined with the hydrological characteristics and agricultural water use reality of the Sanjiang Plain, the supply–demand matching state is divided into three levels: ($R > 1.1$) is the water surplus area; that is, the regional water supply capacity is strong and can output water resources to the surrounding deficit areas. ($R < 0.9$) is the water deficit area; that is, the regional water demand is larger than the supply, and water resources need to be imported from the surrounding surplus areas. ($0.9 \leq R \leq 1.1$) is the water supply–demand balance area. The methodological framework integrates ecosystem structural analysis and hydrological supply–demand assessment. First, the InVEST model estimates spatial water yield, while water demand is reconstructed from land-use and socio-economic statistics. Second, the water supply–demand ratio is calculated to identify surplus and deficit areas. Third, MSPA is applied to extract ecologically connected source areas, thereby identifying the structural basis supporting regional water conservation. Finally, spatial overlay analysis combines ecological source areas with water supply–demand patterns to reveal regions where ecological conservation and water security simultaneously play critical roles.

During MSPA, a minimum patch-size threshold of 100 km² was applied to identify regional ecological source areas. This threshold was adopted for three reasons. First, patches smaller than 100 km² are generally highly fragmented and spatially isolated, providing only limited contributions to regional ecological connectivity and hydrological regulation. Second, small patches are more susceptible to classification uncertainty, edge effects, and short-term land-use changes, making them less representative of long-term ecological

processes at the regional scale. Third, the objective of this study is to identify dominant ecological source areas controlling the water supply–demand pattern across the entire Sanjiang Plain rather than local habitat fragments. Therefore, removing patches smaller than 100 km² effectively reduces landscape noise while retaining large, continuous ecological areas that play key roles in water conservation, runoff regulation, and ecological network connectivity. The selected threshold also ensures that the extracted ecological sources are consistent with the regional-scale spatial resolution and analytical objectives of this study. Preliminary sensitivity analysis showed that using a substantially smaller threshold retained numerous isolated patches with weak connectivity, whereas a much larger threshold excluded several continuous ecological areas in the western and southeastern mountainous regions. Therefore, the 100 km² threshold provided a reasonable balance between maintaining ecological connectivity and reducing landscape fragmentation, making it suitable for regional-scale ecological source identification in the Sanjiang Plain.

3.4. Standard Deviation Ellipse Method

Standard Deviation Ellipse (SDE) is a classical spatial statistical analysis method proposed by American scholar Lefever in 1926. This method can quantitatively characterize the gravity center position, dominant direction and dispersion degree of geographical elements in spatial distribution and has been widely used in the evaluation of spatial pattern evolution in ecological, economic and other fields, especially in the analysis of gravity center distribution characteristics of ecological surplus and deficit areas [43]. The core of the model is a spatial distribution with the structural distribution gravity center as the origin. The long and short semi-axes respectively represent the dispersion of features in the primary and secondary trend directions, thus investigating the spatial distribution pattern of features. The flatness of the ellipse reflects the spatial ductility: the flatter the ellipse, the stronger the distribution and agglomeration of the structure along the long semi-axis direction; on the contrary, if the ellipse tends to be a perfect circle, it indicates that the structure is scattered in space and lacks obvious directional characteristics [44]. The model mainly includes four core steps: spatial gravity center calculation, azimuth determination, and standard deviation calculation in X-axis and Y-axis directions. The model derivation and physical meaning of parameters in each step are described in detail as follows:

$$X_t = \frac{\sum_{i=1}^n S_{it} \times x_i}{\sum_{i=1}^n S_{it}} \quad Y_t = \frac{\sum_{i=1}^n S_{it} \times y_i}{\sum_{i=1}^n S_{it}} \quad (5)$$

where X_t and Y_t are the longitude and latitude coordinates of the gravity center of surplus/deficit areas in year t ; S_{it} is the area of surplus/deficit areas of grid i in year t ; and x_i and y_i are the longitude and latitude coordinates of the geometric center of grid i .

The calculation formula of gravity center migration rate is:

$$V = \frac{D}{T} \quad (6)$$

where V is the average annual migration rate of gravity center (km/a); D is the total migration distance of gravity center during the study period (km); and T is the study period (a).

3.5. Model Calibration and Validation

To evaluate the reliability of the modified InVEST water yield model, a regional-scale validation was conducted by comparing the simulated water yield with the officially reported total water resources published in the Heilongjiang Water Resources Bulletin. Because the InVEST Annual Water Yield model estimates regional water yield rather than river discharge at individual hydrological stations, the officially reported total water

resources provide a more appropriate validation dataset with a spatial scale consistent with the model output.

Three representative cities located within the Sanjiang Plain (Jiamusi, Shuangyashan, and Hegang) were selected for validation. Representative years (2010, 2015, and 2020) were chosen to characterize different stages of regional land-use and hydrological conditions, yielding a total of nine validation samples. The simulated annual water yield was compared with the reported total water resources, and model performance was evaluated using the coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), and root mean square error (RMSE), which are calculated as follows:

$$R^2 = \frac{[\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})]^2}{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (P_i - \bar{P})^2} \quad (7)$$

where O_i is the observed runoff and P_i is the simulated runoff for the i – th observation; $\bar{O}$ and $\bar{P}$ are the corresponding mean values of the observed and simulated runoff, respectively; and n denotes the total number of observations.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2} \quad (8)$$

where P_i and O_i denote the simulated and observed runoff for the i – th observation, respectively, and n is the total number of observations.

$$NSE = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (9)$$

where P_i and O_i represent the simulated and observed runoff for the i – th observation, respectively, and $\bar{O}$ is the mean observed runoff. According to commonly accepted evaluation criteria, model performance is considered satisfactory when R^2 exceeds 0.70 and NSE exceeds 0.50.

3.6. Statistical Analysis

3.6.1. Pearson Correlation Analysis

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2 \sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (10)$$

where X_i represents driving factors including precipitation and GDP, Y_i denotes water yield or water demand, and r is the Pearson correlation coefficient.

3.6.2. Partial Correlation Analysis

$$r_{xy \cdot z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1 - r_{xz}^2)(1 - r_{yz}^2)}} \quad (11)$$

where $r_{xy \cdot z}$ refers to the partial correlation coefficient between variables x and y ; r_{xy} , r_{xz} and r_{yz} represent Pearson correlation coefficients; and z indicates the controlled variable.

3.6.3. Quantitative Attribution Analysis

$$C_i = \frac{r_i^2}{\sum_{i=1}^n r_i^2} \times 100\% \quad (12)$$

where C_i represents the contribution percentage of driving factor i , r_i is the partial correlation coefficient, and n denotes the total number of driving factors.

3.6.4. Change-Point Detection

To objectively identify significant regime shifts in the temporal evolution of water yield, water demand, and water supply–demand ratio, the non-parametric Pettitt test was employed.

The Pettitt statistic is expressed as:

$$K = \max |U_t| \quad (13)$$

$$U_t = \sum_{i=1}^t \sum_{j=t+1}^n \operatorname{sgn}(x_i - x_j) \quad (14)$$

where x_i denotes the observed value in year i , n is the total number of observations, U_t represents the cumulative rank statistic at time t , and K refers to the maximum absolute value of the cumulative statistic.

A significance level of $p < 0.05$ was adopted.

4. Results and Analysis

4.1. Model Validation

To evaluate the reliability of the modified InVEST water yield model, the simulated water yield was compared with the officially reported total water resources from the Heilongjiang Water Resources Bulletin for three representative cities (Jiamusi, Shuangyashan, and Hegang) in the Sanjiang Plain. Three representative years (2010, 2015, and 2020) were selected to assess the model performance, resulting in a total of nine validation samples.

As shown in Table 2, the simulated water yield generally agreed well with the officially reported total water resources, although the simulated values were generally lower than the reported values. This discrepancy is mainly attributable to the simplified annual water balance algorithm employed by the InVEST model, which does not explicitly account for groundwater exchanges, freeze–thaw processes, river regulation, reservoir storage, and other anthropogenic water management activities.

Table 2. Comparison between simulated water yield and officially reported total water resources in representative cities of the Sanjiang Plain.

City	Year	Simulated Water Yield (InVEST) (10^8 m^3)	Official Total Water Resources (Bulletin) (10^8 m^3)	R^2	NSE	RMSE (10^8 m^3)
Jiamusi	2010	69.63	94.58	0.96	0.67	17.43
	2015	57.52	85.11			
	2020	87.97	105.94			
Shuangyashan	2010	20.68	38.06			
	2015	16.32	35.42			
	2020	29.63	41.37			
Hegang	2010	14.36	30.49			
	2015	12.36	28.36			
	2020	23.66	33.15			

Table note: Observed municipal data of total water resources are derived from the Heilongjiang Provincial Water Resources Bulletins issued by Heilongjiang Provincial Department of Water Resources in 2010, 2015 and 2020, which are authoritative official statistical datasets of regional native water volume within administrative divisions. Simulated water yield data are aggregated raster outputs of the baseflow-corrected InVEST model using zonal statistical tools in ArcGIS.

Overall, the model achieved a coefficient of determination (R^2) of 0.965, a Nash–Sutcliffe efficiency (NSE) of 0.677, and a root mean square error (RMSE) of $17.43 \times 10^8 \text{ m}^3$. The high R^2 indicates a strong linear relationship between the simulated and reported water resources, while the NSE value demonstrates that the model satisfactorily reproduces the temporal and spatial variations in regional water resources. Therefore, the modified InVEST model is considered sufficiently reliable for subsequent analyses of water yield dynamics and regional water supply–demand relationships in the Sanjiang Plain.

4.2. Spatiotemporal Evolution Characteristics of Water Yield

Figure 2 shows that the annual water yield of the Sanjiang Plain from 1990 to 2020 showed an overall fluctuating upward trend rather than a simple linear growth. Specifically, the water yield decreased rapidly from a high level from 1990 to 1994; it fluctuated and declined as a whole from 1995 to 1999, with a periodic low value around 1999; it rebounded significantly from 2000 to 2003 but then fell again from 2004 to 2008; it fluctuated at a high level and was relatively stable as a whole from 2009 to 2016; it rose significantly again from 2017 to 2020 and reached the highest value during the study period in 2019. Overall, the change in water yield has strong interannual fluctuation characteristics [45]. Annual water yield exhibited pronounced interannual fluctuations rather than a monotonic trend. According to Figure 2, the maximum annual water yield reached 23.28 billion m^3 in 2019, whereas the minimum value was 12.16 billion m^3 in 2011, representing an interannual difference of approximately 11.12 billion m^3 . These results indicate substantial temporal variability in regional water yield throughout the study period [46].

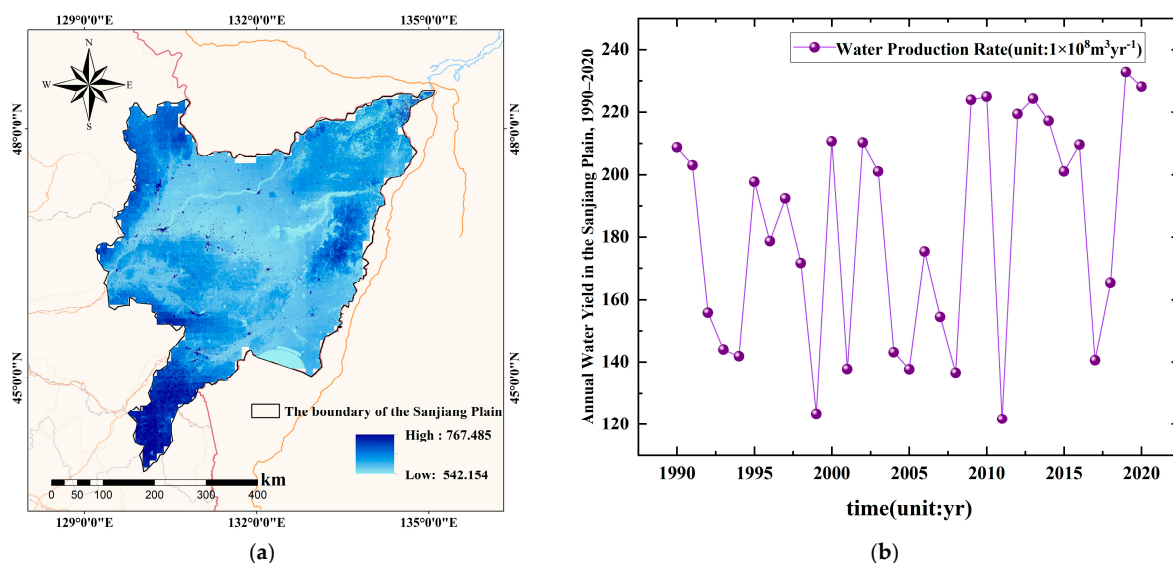


Figure 2. (a) Spatial distribution map of water yield. (b) Line chart of annual water yield from 1990 to 2020.

From the spatial distribution, the water yield of the Sanjiang Plain presents an obvious pattern of high at the edge and low in the center. The high-value areas are mainly concentrated in the southwest and local edge areas of the east and northeast of the study area, while the low-value areas are mainly distributed in the relatively continuous areas of the central and northern parts, showing a coexistence of patchy high-value and sheet-like low-value areas.

4.3. Spatiotemporal Evolution Characteristics of Water Demand

Based on the above methods, the spatiotemporal characteristics of water demand in the Sanjiang Plain from 1990 to 2020 were quantified (Figure 3). Overall, total water de-

mand exhibited a fluctuating but increasing trend during the study period. The minimum water demand occurred in 1997 (approximately 16.2 billion m^3), whereas the maximum was recorded in 2014 (approximately 32.0 billion m^3), representing an overall increase of 15.8 billion m^3 . According to the temporal variation, the evolution of water demand can be divided into three distinct stages. During 1990–2000, water demand fluctuated considerably, with frequent alternation between peaks and troughs. From 2000 to 2014, water demand increased rapidly, primarily driven by large-scale dryland-to-paddy conversion and the continuous expansion of paddy fields, which substantially increased irrigation requirements. After reaching its peak in 2014, water demand entered a relatively stable stage (2014–2020), remaining between 27.0 and 31.0 billion m^3 . This stabilization is likely associated with the implementation of regional water-resource management policies and the widespread adoption of water-saving irrigation technologies.

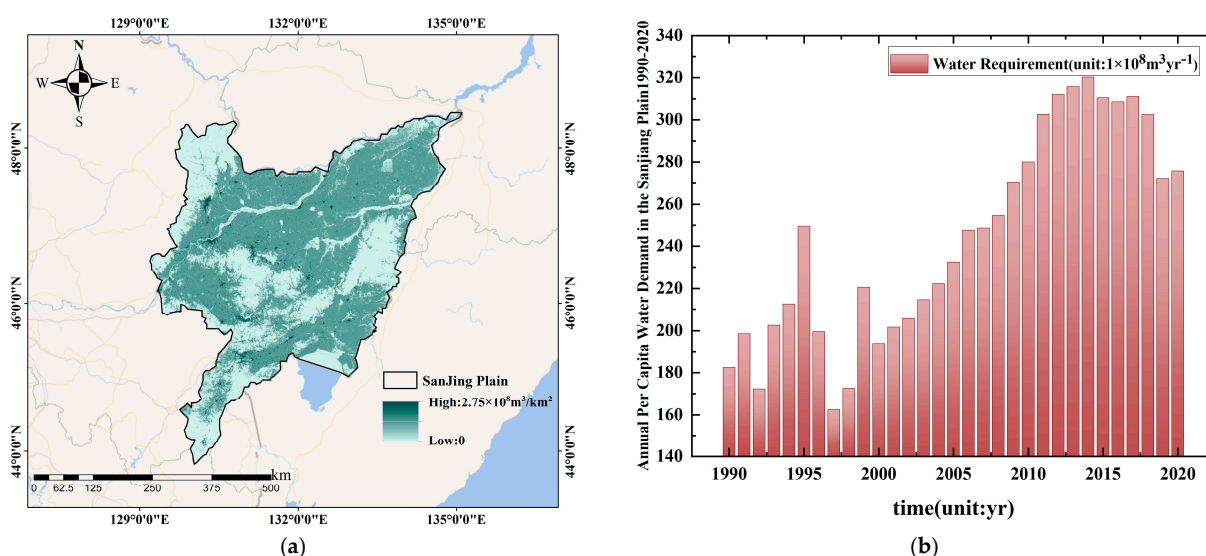


Figure 3. (a) Spatial distribution of water demand from 1990 to 2020. (b) Bar chart of water demand from 1990 to 2020.

Spatially, water demand exhibited pronounced heterogeneity across the Sanjiang Plain. High-demand areas, with values reaching up to $2.75 \times 10^8 \text{ m}^3 \text{ km}^{-2}$, were mainly concentrated in the central-eastern and northeastern parts of the plain, particularly in the major agricultural regions surrounding Jiamusi and Shuangyashan. These hotspots correspond to areas with intensive rice cultivation and high agricultural irrigation demand. In contrast, low-demand areas, with values approaching zero, were primarily distributed in the western and south-central mountainous and hilly regions, including the peripheral areas of Hegang and Jixi. These regions are dominated by forests and other natural ecosystems, where limited agricultural activities result in relatively low water demand.

4.4. Spatiotemporal Evolution of Water Supply–Demand Ratio, and Surplus and Deficit Areas

4.4.1. Spatiotemporal Differentiation Characteristics of Supply–Demand Ratio

Figure 4 illustrates the spatiotemporal distribution of the water supply–demand ratio (R) in the Sanjiang Plain. Overall, the spatial pattern of R exhibits a pronounced core–periphery gradient, accompanied by considerable spatiotemporal variability.

Spatially, low R values ($R < 0.9$; yellow areas) are primarily concentrated in the central, northeastern, and interior parts of the plain. These areas correspond to the region's major agricultural production zones, where extensive paddy cultivation has substantially increased irrigation water demand, resulting in relatively high water stress and pronounced imbalances between water supply and demand. In contrast, high R values ($R > 1.1$; cyan

areas) are mainly distributed in the western, southern, and southeastern mountainous and hilly regions along the periphery of the plain. These areas are characterized by extensive natural vegetation, relatively low levels of human disturbance, and comparatively lower water demand, resulting in a more favorable balance between water supply and demand.

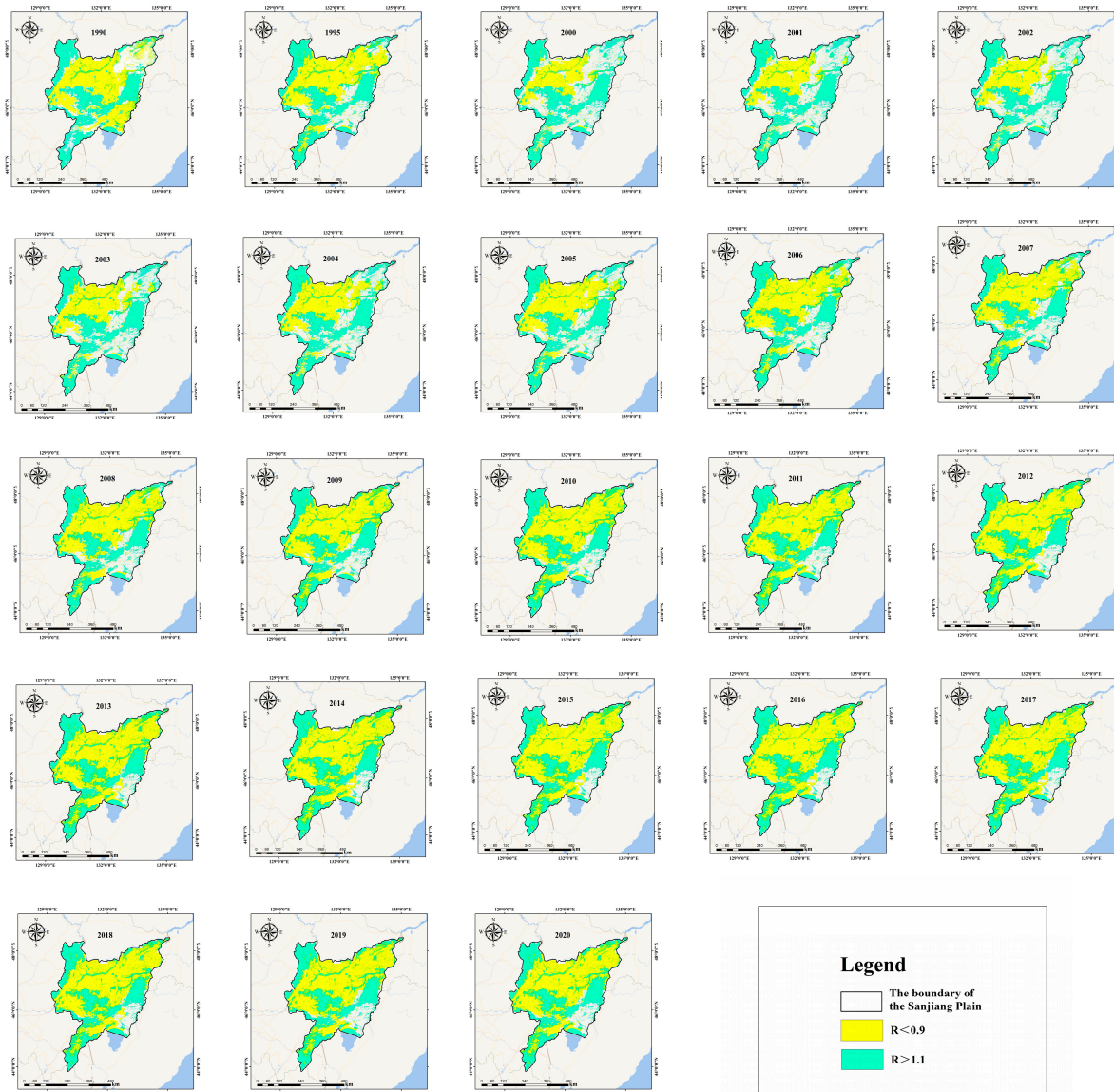


Figure 4. Spatial distribution map of supply–demand ratio from 1990 to 2020.

Overall, the spatial distribution of the water supply–demand ratio reflects the marked heterogeneity in the balance between regional water availability and water demand across the Sanjiang Plain.

4.4.2. Spatial Pattern and Area Change Trend of Surplus and Deficit Areas

Figure 5 illustrates the temporal evolution of water surplus and deficit areas from 1990 to 2020. Overall, the Sanjiang Plain maintained a persistent spatial pattern characterized by “surplus along the peripheral mountainous regions and deficit within the agricultural hinterland”. However, the areal extent of the two functional zones changed considerably over time. During 1990–2000, deficit areas gradually contracted, whereas surplus areas expanded and reached approximately 68,800 km², indicating an overall improvement in the regional water supply–demand relationship. This favorable pattern was mainly associated with relatively abundant precipitation and comparatively moderate agri-

cultural water demand. After 2003, deficit areas progressively expanded from the central plain toward the northeastern agricultural region, accompanied by a gradual contraction of surplus areas. This expansion became particularly pronounced during 2010–2015, when agricultural water demand increased rapidly owing to large-scale paddy-field expansion and increasing irrigation requirements. Since 2015, deficit areas have remained the dominant functional zone, accounting for approximately 63–70% of the Sanjiang Plain (about 56,000–68,800 km²), whereas surplus areas occupied only 25–32% of the total area (Figure 6). Overall, the deficit area exhibited an increasing trend after 2003, while the surplus area gradually decreased, indicating a progressive deterioration of the regional water supply–demand relationship.

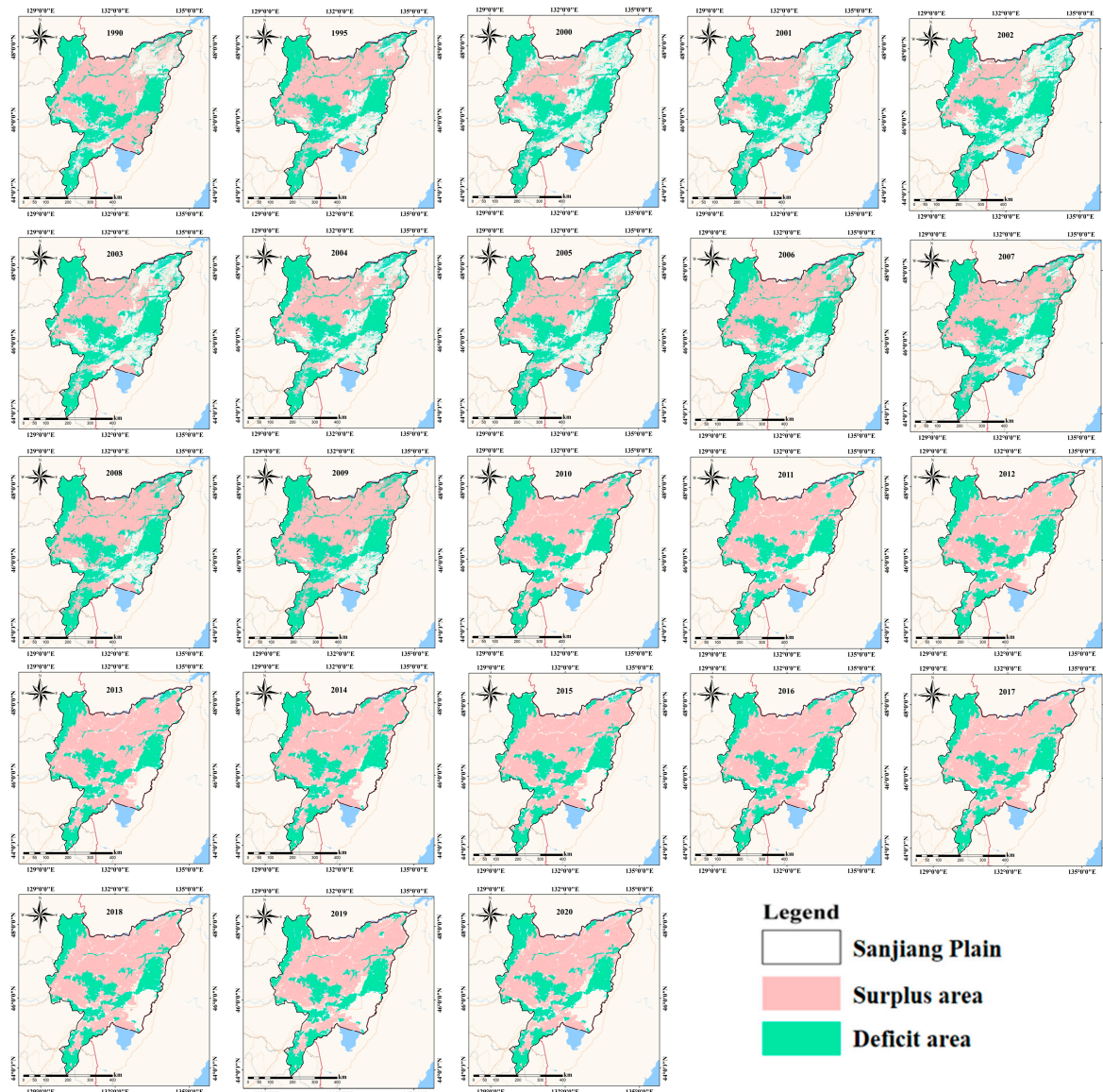


Figure 5. Changes in the surplus–deficit areas from 1990 to 2020.

4.4.3. Land Use of Surplus and Deficit Areas

Figure 7 shows the temporal evolution of land-use composition in the water surplus and deficit areas of the Sanjiang Plain from 1995 to 2020. In the water surplus areas, ecological land consistently dominated the landscape throughout the study period. Forest land accounted for more than 90% of the total area and increased slightly from approximately 93% in 1995 to 94% in 2020, indicating its dominant role in maintaining regional

water conservation and hydrological regulation. Wetlands and grasslands also exhibited an overall increasing trend. In particular, the proportion of wetlands increased from less than 2% in 1995 to approximately 5% in 2020, suggesting an enhancement of regional ecological buffering and hydrological regulation capacity. In contrast, cultivated land continuously declined from about 3% to below 2%, whereas other land-use types, including construction land, bare land, and water bodies, each remained below 2% and changed only marginally. The expansion of wetlands and other ecological land was the most evident during 2005–2015 and may be associated with the implementation of ecological restoration programs, such as the Natural Forest Protection Program and the Grain for Green and Wetland Restoration initiatives. In contrast, the water deficit areas were consistently dominated by agricultural land. Cultivated land accounted for more than 80% of the total area throughout the study period, decreasing slightly from approximately 83% in 1995 to 79% in 2000 before increasing to about 84% in 2020. The combined proportion of forests, shrublands, and grasslands remained between 10% and 20%, indicating relatively limited ecological land cover. Shrubland increased to approximately 9% in 2000 before gradually declining to around 6% in 2020, while forest and grassland exhibited only minor fluctuations. Wetlands and water bodies increased slightly, together accounting for approximately 5% of the total area by 2020. Impervious surfaces remained relatively stable at 3–5%, whereas bare land consistently accounted for less than 1%. Between 2005 and 2015, cultivated land expanded while ecological land declined, showing a contrasting land-use trajectory to that observed in the water surplus areas. During 2015–2020, cultivated land exhibited modest fluctuations, broadly corresponding to changes in the surplus areas.

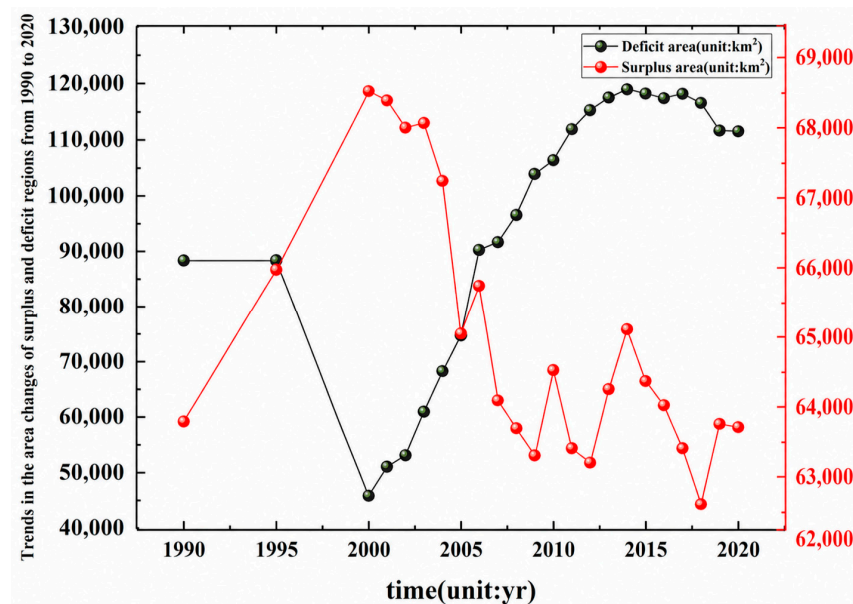


Figure 6. Trends of surplus and deficit area changes from 1990 to 2020.

4.4.4. Migration of Centroids in Surplus and Deficit Zones

This study employs the Standard Deviational Ellipse (SDE) model to identify the spatial centroids of water-resource surplus and deficit zones.

The two zones exhibit obvious zonal differences and directional complementarity in spatial activity ranges and urban relevance, with their core active areas overlapping in the south-central to east-central agricultural hinterland of the Sanjiang Plain. In 1990, the centroid of the water deficit zone (Figure 8) was located at approximately 132°40' E, 47°10' N, on the border of Jiamusi and Shuangyashan. Over the following 30 years, it underwent a tortuous southwest–northeast–southwest migration with an overall south-

westward shift, relocating to $131^{\circ}50'$ E, $46^{\circ}30'$ N near the Jiamusi–Qitaihe boundary by 2020. This migration demonstrates that water shortage pressure gradually transferred from the northeastern plain to the intensively cultivated central areas.

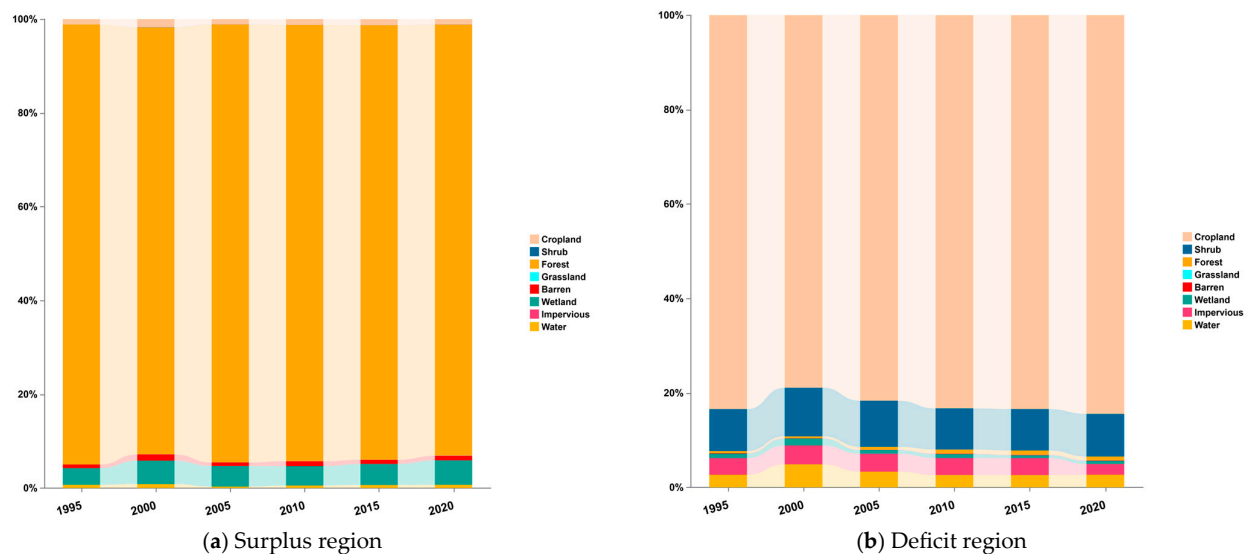


Figure 7. (a) Proportions of various land-use types in surplus regions. (b) Proportions of various land-use types in deficit regions.

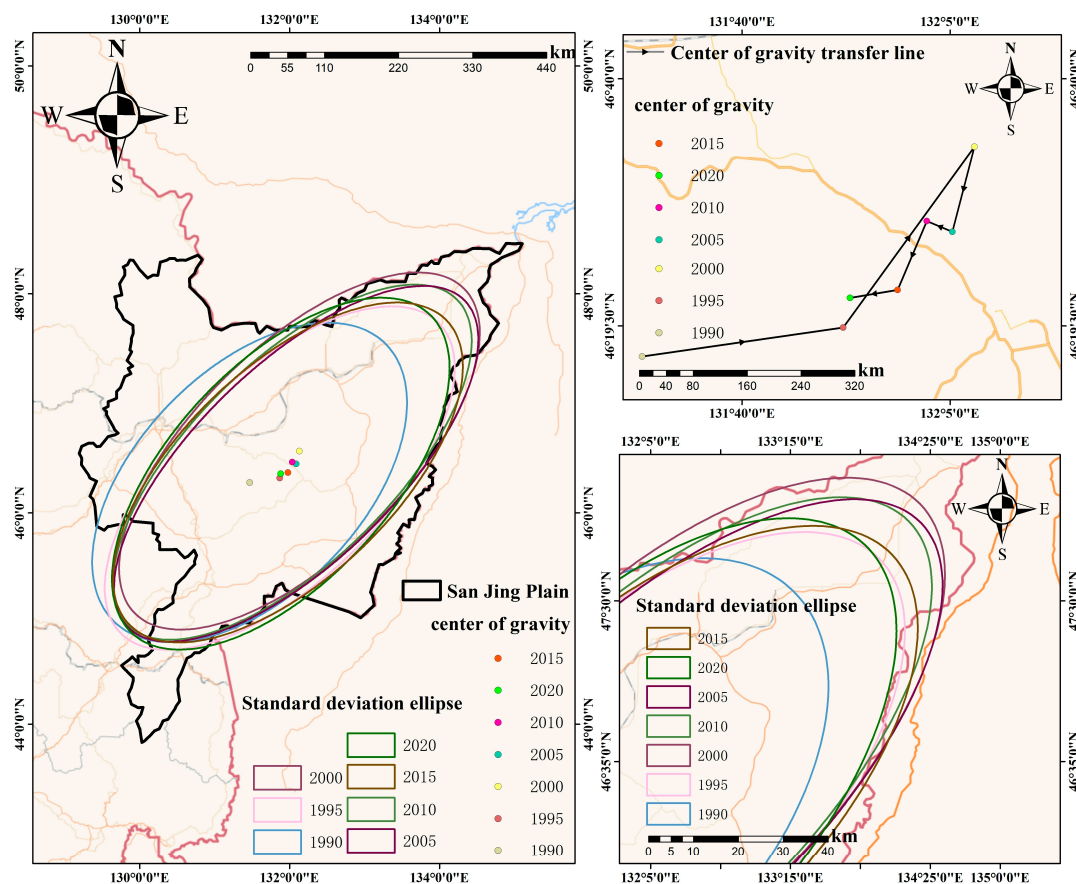


Figure 8. Centroid migration of water-resource deficit zones.

In comparison, the water surplus zone centroid (Figure 9) had a concentrated spatial activity scope, oscillating between the plain's western and southern margins and central hinterland. Its initial 1990 position was near Jixi City ($131^{\circ}30'$ E, $46^{\circ}20'$ N). The centroid

followed a complex migration path of northeast–southwest–northeast, presenting a general northeastward trend over three decades and finally settling near the Hegang–Jiamusi border ($132^{\circ}10' \text{ E}$, 47° N) in 2020.

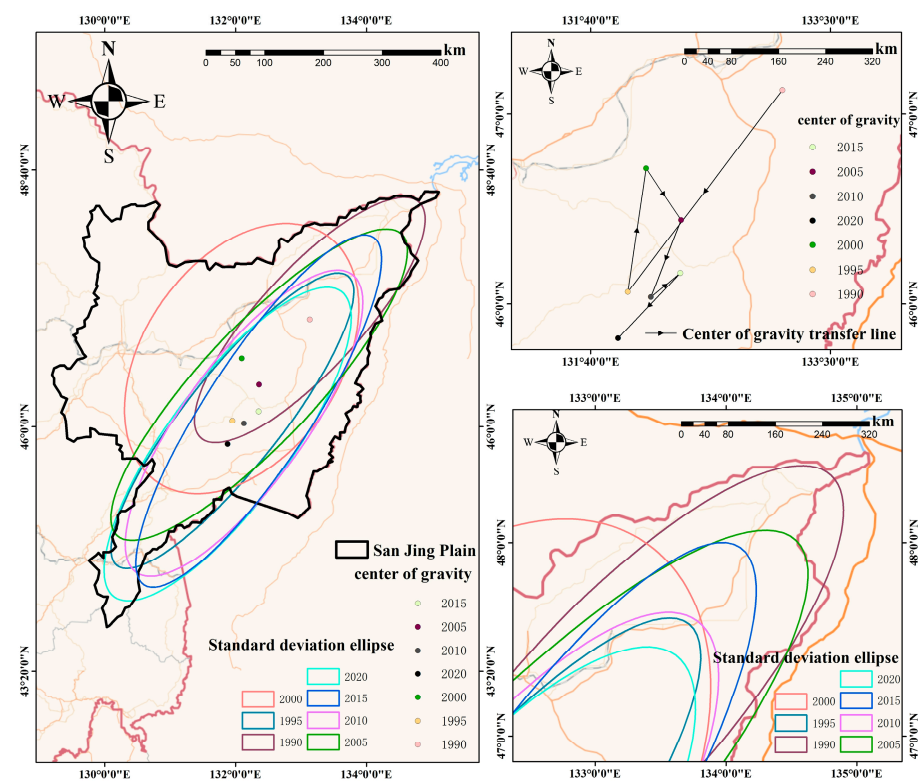


Figure 9. Centroid migration of water-resource surplus zones.

Significant disparities exist in the migration distance and speed of the two centroids, with the surplus zone centroid moving shorter distances but at a higher velocity. Long-term intensive agricultural development in the hinterland stabilized the spatial distribution of the deficit zone centroid, which only saw slight positional adjustments alongside agricultural layout changes, with an annual average migration distance of 10–15 km. In contrast, the surplus zone featured prominent spatial instability. Driven by the interaction of ecological conservation in the western and southern fringes and agricultural expansion in the central plain, its centroid experienced dramatic spatiotemporal fluctuations. Its annual average migration distance reached 15–20 km, exceeding 18 km in individual years.

4.4.5. Spatiotemporal Evolution Characteristics of Water-Resource Surplus and Deficit

Based on the spatial distribution of water ecological service grades (Figure 10) and the temporal variations in the area proportion of each grade from 1990 to 2020 (Figure 11), the regional water supply–demand relationship in the Sanjiang Plain was classified into five categories: stable surplus zone, mild surplus zone, water balance zone, moderate water shortage zone, and severe water shortage zone. The classification thresholds were determined using the Natural Breaks (Jenks) method, which minimizes within-class variance while maximizing between-class variance, thereby effectively reflecting the intrinsic distribution characteristics of the water supply–demand ratio. The resulting thresholds were further adjusted according to the regional characteristics of water supply and demand to improve the representativeness of the classification. Specifically, the severe water supply–demand conflict zone represents areas with severe water supply–demand conflicts, the moderate water supply–demand conflict zone indicates areas with moderate supply–demand conflicts, the water supply–demand buffer zone represents transitional ar-

areas where water supply approximately equals demand, the water supply–demand balance zone denotes areas with a slight surplus of water resources, and the water supply–demand surplus security zone represents areas with sufficient and stable water-resource availability.

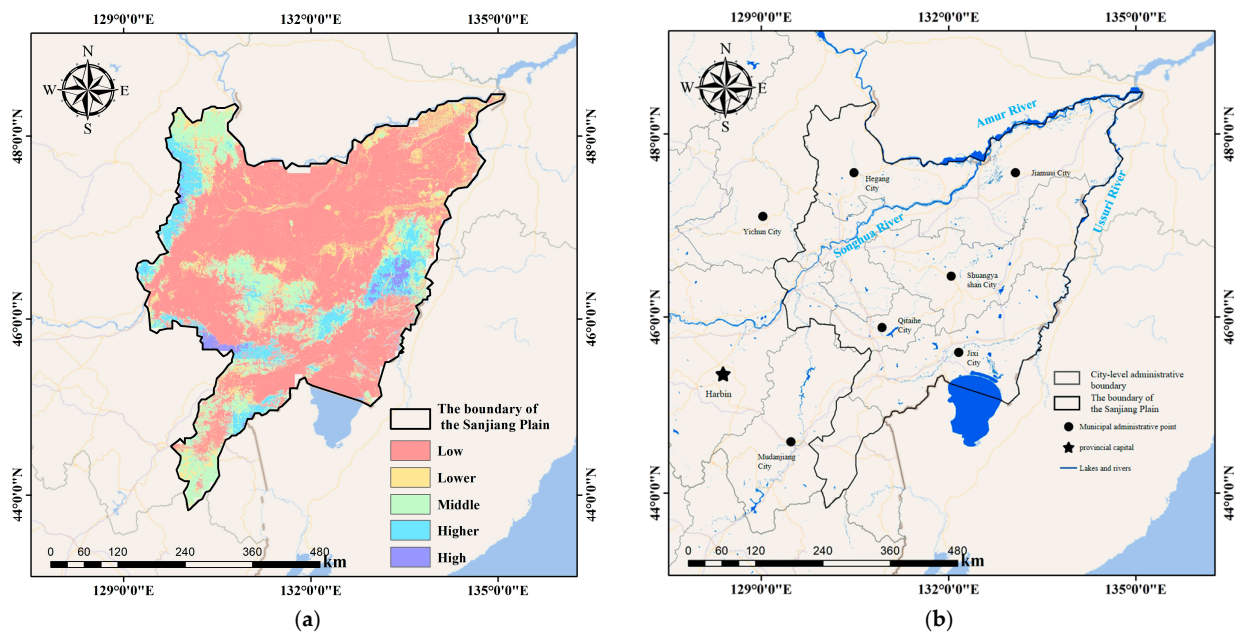


Figure 10. (a,b) Classification of water ecological service grades in the Sanjiang Plain.

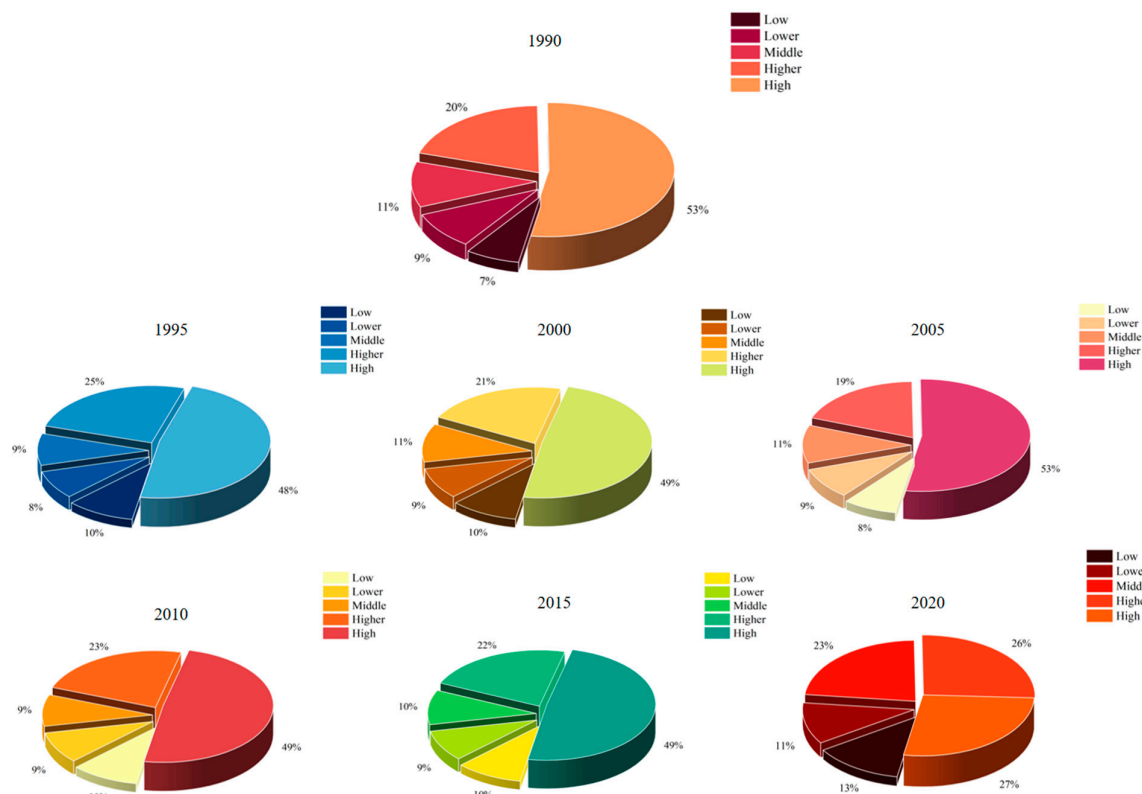


Figure 11. Changes in the proportion of water ecological service grades in the Sanjiang Plain (1990–2020).

In terms of spatial distribution, the areas with severe water supply–demand contradiction were the dominant type with the largest areal proportion and were continuously and extensively distributed across the central-western, northern and northeastern core

plain areas, covering nearly the main body of the Sanjiang Plain. The areas with moderate water supply–demand contradiction presented patchy and zonal patterns, embedded in the periphery of severe contradiction zones and mainly located at the transition zones between severe contradiction areas and central buffer zones. The buffer zones of water supply–demand contradiction were primarily distributed in the hilly–plain transition zones in the western and southern parts of the plain, as well as the extended areas from eastern mountains to the plain. Water supply–demand balanced areas were concentrated in the eastern, southeastern and western marginal mountainous and hilly regions. The secure areas with sufficient water-resource surplus appeared as concentrated patches, mainly located in the core ecological conservation areas in the central-eastern plain and small concentrated zones on the western margin. These areas functioned as core units with the strongest water conservation capacity and the most abundant ecological surplus.

From the perspective of temporal evolution, the overall pattern of regional water supply and demand remained stable from 1990 to 2015. The secure areas with sufficient water-resource surplus always accounted for the largest proportion, staying within the range of 48% to 53%. The water supply–demand balanced areas ranked second, with their proportion fluctuating between 19% and 25%. The total proportion of the three types of contradiction zones remained steadily at 25–30%, indicating a generally balanced water supply and demand across the region.

The period from 2015 to 2020 witnessed a critical transition of the water supply–demand pattern. The area of surplus zones decreased sharply, while that of contradiction zones increased comprehensively. The proportion of secure surplus areas plummeted from 49% in 2015 to 27% in 2020, dropping from the first- to the third-largest category. The proportion of balanced areas rose slightly to 26%, making it the dominant type in 2020. Meanwhile, the proportions of all contradiction zones increased remarkably. The share of buffer zones more than doubled from 10% to 23%, and the proportions of severe and moderate contradiction zones reached 13% and 11% respectively, both hitting the highest levels since 1990.

4.5. Quantitative Attribution of Driving Factors

To quantitatively evaluate the relative contributions of climate variability, agricultural expansion, and socio-economic development to regional water budget changes, partial correlation analysis was conducted using annual precipitation, cultivated land area, paddy-field area, population, and GDP as explanatory variables during 1990–2020. The results are summarized in Table 3.

Table 3. Water security zoning classification.

Grade	Description	Threshold
Severe Water Supply–Demand Conflict Zone	Severe supply–demand conflict	<82.6
Moderate Water Supply–Demand Conflict Zone	Moderate supply–demand conflict	82.6–146.3
Water Supply–Demand Buffer Zone	Water supply approximately equals demand	146.3–288.0
Water Supply–Demand Balance Zone	Slight water surplus	288.0–441.4
Water Supply–Demand Surplus Security Zone	Sufficient and stable water surplus	>441.4

As shown in Table 3, precipitation was the dominant climatic factor affecting regional water yield, with a partial correlation coefficient of 0.736 and a contribution rate of 36.8% ($r = 0.736$, $p = 0.0006$). This indicates that interannual precipitation variability exerted the strongest influence on annual water availability among all natural driving factors.

Among the anthropogenic factors, paddy-field area exhibited the highest partial correlation coefficient ($r = 0.790$) and the largest contribution (42.4%, $p = 0.0004$), indicating

that paddy-field expansion was the primary driver of increasing regional water demand. Cultivated land area showed a moderate contribution of 10.6% ($r = 0.395$, $p = 0.018$), whereas population contributed 7.7% ($r = 0.337$, $p = 0.031$). GDP exhibited the weakest relationship with regional water budget variation, with a contribution of only 2.5% ($r = 0.192$, $p = 0.087$), indicating that its independent effect was not statistically significant.

Overall, precipitation and paddy-field expansion together explained 79.2% of the total quantified contribution, demonstrating that climate variability primarily controlled regional water supply, whereas agricultural land-use change dominated the long-term evolution of regional water demand.

The Pettitt change-point test was applied to identify significant regime shifts in the temporal evolution of regional water yield, water demand, and water supply–demand ratio. The results are presented in Table 4.

Table 4. Partial correlation coefficients, contribution rates and significance levels of climate and human-induced driving factors for regional water budget changes from 1990 to 2020.

Driver	Partial Correlation	Contribution (%)	<i>p</i> -Value
Precipitation	0.736	36.8	0.0006
Paddy-field area	0.790	42.4	0.0004
Cultivated land area	0.395	10.6	0.018
Population	0.337	7.7	0.031
GDP	0.192	2.5	0.087 (ns)

As shown in Table 4, the water yield series exhibited a statistically significant abrupt change in 2000, with a Pettitt statistic (*K*) of 135 and a significance level of $p = 0.043$, indicating a transition in regional water supply conditions around the beginning of the 21st century.

Water demand experienced a significant change point in 2014 ($K = 138$, $p = 0.036$), suggesting that regional water consumption entered a new stage during the period of rapid agricultural expansion.

The water supply–demand ratio showed the most significant abrupt change in 2015, with a Pettitt statistic of 147 ($p = 0.003$), indicating a pronounced shift in the regional water security pattern (Table 5). This result is consistent with the observed expansion of water-deficit areas after 2014, suggesting that the regional water budget gradually entered a stage characterized by intensified supply–demand imbalance.

Table 5. Pettitt statistic, mutation year and significance *p*-value of water yield, water demand and water supply–demand ratio.

Variable	Statistic (<i>K</i>)	Change Point	<i>p</i> -Value
Water yield	135	2000	0.043
Water demand	138	2014	0.03
Supply–demand ratio	147	2015	0.011

5. Discussion

Different from traditional studies that only focus on either water supply or water demand alone, this research study emphasizes the long-term dynamic evolution and spatial heterogeneity of water supply–demand patterns. Based on long-term sequence data from 1990 to 2020, this paper systematically analyzes the spatiotemporal migration

of water-resource surplus and deficit zones in the Sanjiang Plain and further deepens the understanding of the evolution mechanism of regional water-resource patterns driven by climate change and human activities.

The water supply–demand contradiction in core agricultural areas is mainly distributed along the Songhua River from Jiamusi to Tongjiang, showing a spreading trend from the northeast to the southwest. This phenomenon is closely associated with the shift of agricultural development focus and the agglomeration of population and economic activities under the long-term policy of converting dry land to paddy fields. Meanwhile, potential high-risk areas are predominantly located within the supply–demand buffer zones, indicating that these zones are sensitive areas where surplus zones tend to transform into deficit zones and thus serve as key regions for future water-resource regulation and risk prevention.

Accordingly, this discussion mainly elaborates on the formation mechanism of water supply–demand patterns, the spatiotemporal evolution of surplus and deficit zones, and their driving factors. The findings are expected to provide scientific references for the optimal allocation of regional water resources and sustainable agricultural development.

The implementation of the Natural Forest Protection Program, the Grain-for-Green Program, and wetland restoration projects has effectively improved vegetation cover and regional water conservation capacity in northeast China. Nevertheless, these ecological restoration measures have mainly enhanced local ecosystem functions and have not fundamentally offset the rapid increase in agricultural irrigation demand caused by continuous paddy-field expansion. Consequently, although regional ecological restoration has alleviated water stress to some extent, it has not reversed the long-term spatial pattern of peripheral water surplus and central agricultural water deficit.

5.1. Evolution Characteristics of Water Supply and Demand Patterns in the Sanjiang Plain

The spatial distribution of water yield is primarily controlled by topography, precipitation, and ecosystem distribution. Mountainous and wetland regions exhibit strong water conservation capacity because of dense vegetation cover and relatively intact hydrological processes. By contrast, extensive agricultural reclamation in the central plain has reduced wetland area and weakened natural water retention capacity, resulting in persistently low regional water yield. These findings indicate that long-term land-use transformation has fundamentally altered the hydrological regulation functions of the regional ecosystem.

Regional water demand is mainly driven by agricultural irrigation associated with paddy-field expansion. Since the implementation of the dryland-to-paddy conversion policy after 2000, irrigation demand has increased substantially, making agriculture the dominant component of total water consumption. Compared with climatic factors, agricultural land-use change exerts a stronger and more persistent influence on regional water demand.

Water surplus and deficit zones maintained a relatively stable spatial pattern characterized by water surplus in peripheral mountainous regions and water deficits in the agricultural hinterland. However, the continuous expansion of irrigated paddy fields after 2000 accelerated the enlargement of deficit areas, suggesting that agricultural development has gradually exceeded the local carrying capacity of water resources.

Centroid migration further demonstrates the dynamic adjustment of regional water supply–demand patterns. Compared with deficit areas, surplus areas exhibited greater spatial variability, indicating that ecological conservation and precipitation variability jointly influenced the spatial redistribution of regional water resources.

Water ecological service grades remained generally stable before 2015 but deteriorated rapidly thereafter. The sharp reduction in secure surplus areas and simultaneous expansion

of conflict zones indicate that long-term agricultural expansion has progressively increased regional water stress and reduced overall water security.

Overall, the evolution of water supply and demand patterns in the Sanjiang Plain is jointly driven by precipitation variation, land-use transformation and agricultural expansion. Nevertheless, because the present study is conducted at annual and basin-wide scales, the identified driving mechanisms mainly represent long-term evolution trends rather than short-term seasonal responses. Therefore, seasonal irrigation water shortages and localized water stress within irrigation districts require further investigation using finer temporal and spatial resolutions. Precipitation changes cause interannual fluctuations in regional water yield, while the expansion of paddy fields under the dryland-to-paddy conversion policy is the fundamental reason for rising water demand and the expansion of deficit zones. The spatiotemporal evolution of water supply–demand patterns across the Sanjiang Plain is collectively governed by precipitation variability, land-use transitions, and large-scale agricultural expansion. Precipitation dominates interannual fluctuations in regional water yield, while the rapid proliferation of paddy fields drastically elevates irrigation demand and continuously expands the coverage of water-deficit zones. Prior research has verified that wetland restoration and ecological water replenishment initiatives effectively enhance ecosystem stability and landscape water retention capacity, optimizing local hydrological conditions [47]. Meanwhile, the implementation of water-saving agricultural management practices has partially relieved localized water shortages. Nevertheless, the growing irrigation pressure stemming from unceasing farmland reclamation largely counteracts the hydrological gains delivered by ecological remediation [48]. Our analysis further confirms that although ecological restoration and water conservation policies deliver tangible local hydrological improvements, they fail to fundamentally transform the enduring spatial differentiation pattern featuring water surplus in peripheral mountainous zones and chronic water scarcity within the agricultural hinterland. This conclusion aligns with existing research arguing that climate fluctuation and land-use shifts act as co-determinants of long-term hydrological ecosystem service dynamics [49].

5.2. Comparison with Other Major Agricultural Regions

The spatial pattern identified in the Sanjiang Plain shares several similarities with that reported for the North China Plain, one of China's most important grain-producing regions. Previous studies have shown that intensive agricultural irrigation and rapid expansion of cultivated land have substantially increased regional water demand and accelerated groundwater depletion. However, unlike the North China Plain, where groundwater overexploitation is the dominant water security issue, the Sanjiang Plain is characterized by abundant natural water resources but increasing spatial mismatch between water supply and agricultural demand due to large-scale paddy-field expansion. Therefore, regional water stress in the Sanjiang Plain is primarily controlled by supply–demand redistribution rather than absolute water scarcity [50].

Similar phenomena have also been reported in the High Plains Aquifer region of the United States. Long-term irrigation expansion has significantly enhanced grain production but simultaneously intensified groundwater depletion and ecosystem degradation. Nevertheless, unlike the groundwater-dependent irrigation system in the High Plains, agricultural production in the Sanjiang Plain relies mainly on surface water and precipitation, making climatic variability and land-use change the dominant drivers of regional water budget evolution [51].

Comparable land-use transitions have been observed in Brazil's Cerrado, where rapid agricultural expansion has altered regional hydrological processes by reducing evapotranspiration regulation and increasing irrigation demand. However, the cold-region climatic

conditions and seasonal frozen-soil processes in the Sanjiang Plain introduce additional hydrological complexity that is rarely observed in tropical agricultural regions [52].

In recent years, increasing attention has been devoted to the Water–Food–Ecosystem Nexus framework, which emphasizes the interactions among water resources, agricultural production, and ecosystem services. Unlike conventional water-resource assessments focusing only on either supply or demand, the nexus framework highlights the coupled evolution of ecological processes and human activities. The present study contributes to this emerging field by integrating ecosystem-service assessment, water supply–demand matching, spatial pattern analysis, and quantitative driver attribution into a unified analytical framework [53].

5.3. Freeze–Thaw Process Uncertainty Analysis

The Sanjiang Plain is located in the cold region of northeast China, where seasonal soil freeze–thaw processes strongly influence hydrological processes. Frozen soil reduces infiltration capacity during winter, whereas spring thaw rapidly increases surface runoff and groundwater recharge. Since the InVEST water yield model is based on the long-term Budyko water balance framework, it does not explicitly simulate seasonal frozen-soil dynamics or freeze–thaw-induced runoff generation.

To reduce this limitation, groundwater baseflow correction was introduced into the model through runoff coefficients and baseflow indices, which partially compensates for groundwater contributions to annual water yield. Because this study focuses on annual water budget characteristics over a 30-year period (1990–2020), the annual aggregation weakens the influence of seasonal hydrological fluctuations. Nevertheless, uncertainties caused by freeze–thaw processes still exist and may result in underestimation of runoff during spring snowmelt periods.

Future studies should integrate physically based cold-region hydrological models or couple seasonal freeze–thaw modules with the InVEST framework to further improve simulation accuracy in cold-region watersheds.

5.4. Temporal and Spatial Resolution Considerations

Although annual water supply and demand were adopted in this study to ensure consistency with long-term socio-economic and hydrological datasets from 1990 to 2020, it should be noted that annual aggregation cannot fully capture seasonal fluctuations in agricultural water demand. In the Sanjiang Plain, rice irrigation is concentrated mainly from May to July, during which agricultural water consumption reaches its annual peak. Consequently, annual water demand estimates may smooth short-term irrigation peaks and underestimate seasonal water stress.

Meanwhile, all calculations were conducted at a spatial resolution of 1 km × 1 km. Although this resolution is appropriate for basin-scale assessment and long-term regional analysis, it may obscure fine-scale heterogeneity within irrigation districts, river corridors, and agricultural management units.

5.5. Policy Implications for Regional Water-Resource Management

Based on the five-grade classification of water ecological service levels, differentiated management strategies should be adopted rather than applying uniform water-resource policies across the entire Sanjiang Plain. Such spatially explicit management can improve water-use efficiency while maintaining regional food production and ecological security.

Stable surplus zones are mainly distributed in mountainous and wetland ecosystems with high water conservation capacity. These areas should be designated as ecological conservation priority zones. Future management should strictly restrict agricultural reclamation and urban expansion, strengthen wetland restoration, maintain forest coverage, and

enhance ecological water storage functions. Mild surplus zones possess relatively sufficient water resources and can serve as ecological buffer areas. Moderate agricultural production can be maintained, while ecological restoration and water conservation projects should be promoted to prevent future degradation into water-deficit zones. Water balance zones represent transitional areas with relatively fragile supply–demand equilibrium. Priority should be given to improving irrigation efficiency through precision irrigation scheduling, canal lining, and water-saving irrigation technologies. These areas require continuous monitoring because they are most likely to shift toward deficit conditions under future climate change. Moderate deficit zones should implement agricultural water-saving measures, including alternate wetting and drying (AWD) irrigation for paddy fields, optimized irrigation quotas, and adjustment of planting structures according to local water availability. Severe deficit zones should be regarded as high-priority water management regions. Strict groundwater abstraction control, irrigation quota regulation, and optimization of high-water-consuming crop distribution should be implemented. Engineering measures such as recycled irrigation water utilization and digital irrigation scheduling should also be promoted to alleviate long-term water stress.

The results indicate an inherent trade-off between agricultural production and ecosystem water conservation in the Sanjiang Plain. Continuous expansion of paddy fields substantially improves grain production but simultaneously increases irrigation demand and reduces regional water security. Conversely, ecological restoration projects such as wetland recovery enhance water regulation capacity but may reduce the available cultivated land. Therefore, future land-use planning should balance national food security objectives with regional ecological sustainability through optimized spatial allocation of agricultural and ecological land.

Recommended water-saving technologies include alternate wetting and drying irrigation (AWD), low-pressure pipeline irrigation systems, intelligent irrigation scheduling based on soil moisture monitoring, canal seepage control, and precision fertilization combined with irrigation management. These technologies have been widely demonstrated to reduce irrigation water consumption while maintaining rice yield under cold-region agricultural conditions.

Accordingly, a tiered water-resource management framework is proposed, in which ecological conservation is prioritized in stable surplus zones, adaptive management is implemented in balanced zones, and intensive water-saving interventions are concentrated in severe deficit zones. Such differentiated management strategies are expected to improve regional water security while maintaining sustainable agricultural production.

5.6. Suggestions

The water-resource deficit zones of the Sanjiang Plain are persistently concentrated in the agricultural core areas of the central and northeastern plain, with a continuous expansion of deficit areas from 2000 to 2014. This phenomenon is fundamentally attributed to the rapid expansion of paddy fields caused by large-scale dryland-to-paddy conversion, which leads to a prominent spatial mismatch between intensive agricultural irrigation demand and the weak regional water yield capacity. Accordingly, differentiated agricultural management measures should be implemented according to local water-resource carrying capacity for regions with long-term groundwater overexploitation and severe water supply–demand contradictions. It is necessary to strictly restrict the reclamation of new high-water-consumption paddy fields, appropriately reduce rice planting scales in water-deficient areas, and promote the transformation of regional agriculture toward water-saving dry farming. Meanwhile, water-saving irrigation technologies such as sprinkler irrigation, drip irrigation, and shallow wet irrigation should be widely popularized to

improve agricultural water use efficiency and fundamentally alleviate the excessive growth of agricultural water demand.

Regions with high water supply–demand ratios are mainly distributed in the western, southern, and southeastern mountainous and hilly areas of the Sanjiang Plain, where water-resource surplus relies heavily on the stable water conservation function of forest and wetland ecosystems. In contrast, deficit zones are concentrated in the plain hinterland with intensive agricultural development, forming a typical spatial mismatch pattern of water supply in highland areas and water consumption in lowland areas. Therefore, core surplus areas including mountain woodlands and wetlands should be listed as key ecological protection zones. The destruction of ecological land must be strictly controlled to maintain regional water yield capacity and ecological regulation and storage functions. Furthermore, the construction of a unified regional water-resource allocation system should be strengthened, and water diversion and storage projects in irrigation districts should be improved to enhance the water supply capacity of surplus zones for deficit zones and mitigate the spatial imbalance of regional water supply and demand.

From 2015 to 2020, the area of water surplus security zones in the Sanjiang Plain decreased significantly, while the proportion of high-risk areas including severe and moderate water supply–demand contradiction zones continued to increase. This indicates that long-term agricultural development combined with climate fluctuations has triggered a rapid rise in regional water security pressure. Consequently, a water security early warning mechanism based on the dynamic monitoring of water supply–demand ratios should be established. Precipitation variations, groundwater levels, agricultural irrigation scales, and the degree of water supply–demand imbalance should be incorporated into the real-time monitoring system to implement dynamic early warning and hierarchical management for high-risk regions. In addition, the total water-resource quantity control system and groundwater exploitation redline policy should be strictly enforced. It is essential to strengthen agricultural water allocation and risk emergency management in extreme-drought years, so as to improve the adaptability of the regional water-resource system to climate fluctuations and human disturbance.

5.7. Innovation, Uncertainties and Prospects

This study addressed three major research gaps in previous investigations of water supply and demand in cold-region agricultural watersheds by integrating water supply and demand assessment, refined spatial analysis, and long-term evolution analysis. A coupled analytical framework based on the optimized InVEST model, water supply–demand ratio, and spatial statistical methods was developed to characterize regional water-resource dynamics in the Sanjiang Plain from 1990 to 2020. Compared with conventional administrative-unit analyses, the proposed framework provides a more detailed representation of the spatial evolution of water surplus and deficit patterns. Furthermore, the five-grade classification system of water ecological services improves the assessment of regional water security and supports targeted water-resource management.

Despite these contributions, several limitations remain. First, although baseflow correction improved the applicability of the InVEST model, seasonal freeze–thaw processes and groundwater–surface water interactions were not explicitly represented, introducing uncertainty into water yield estimation. Second, annual-scale analysis cannot fully capture seasonal water shortages during the rice irrigation period. Third, the spatial resolution adopted in this study is suitable for regional analysis but cannot adequately describe local hydrological heterogeneity within irrigation districts. Finally, although the annual raster-based analysis effectively reveals long-term evolution patterns, it requires substantial computational resources.

Future studies should couple physically based hydrological models with freeze–thaw and groundwater modules to improve process representation in cold regions. Monthly or seasonal analyses combined with high-resolution remote sensing data and irrigation scheduling information would provide a better understanding of seasonal water stress. In addition, advanced quantitative methods, including geographical detectors and structural equation models, could be employed to further quantify the interactions among climate change, land-use transformation, and agricultural development. Future work should also incorporate CMIP6 climate scenarios to evaluate future water security risks and support adaptive water-resource management under climate change.

Overall, this study provides a practical framework for identifying regional water supply–demand mismatches and offers scientific support for sustainable water-resource management in the Sanjiang Plain and other cold-region agricultural watersheds.

6. Conclusions

This study systematically investigated the spatiotemporal evolution of water supply–demand patterns in the Sanjiang Plain from 1990 to 2020 by integrating water yield, water demand, water supply–demand ratio, surplus–deficit analysis, centroid migration, and water ecological service zoning. The main conclusions are as follows.

- (1) Water yield exhibited significant interannual fluctuations, whereas water demand showed an overall increasing trend before stabilizing after 2014. Consequently, the regional water supply–demand relationship gradually shifted from relative balance to increasing imbalance.
- (2) Water surplus areas were mainly distributed in the western, southern, and southeastern mountainous regions, while water deficit areas were concentrated in the central agricultural hinterland. A pronounced transition occurred during 2015–2020, when the proportion of surplus security areas sharply decreased from 49% to 27%, indicating a critical deterioration in regional water security.
- (3) Partial correlation analysis revealed that paddy-field expansion (42.4%) and precipitation variability (36.8%) were the dominant drivers of regional water budget changes. Pettitt change-point analysis further confirmed that the regional water supply–demand pattern experienced a statistically significant transition around 2015.
- (4) The proposed five-grade water ecological service zoning effectively identified areas with different levels of water supply–demand conflict and provided a scientific basis for differentiated water-resource management. The results provide practical guidance for ecological conservation, agricultural water-saving management, and sustainable water-resource allocation in the Sanjiang Plain.

Limitations

This study has several limitations. First, the analyses were conducted at the annual scale and therefore could not fully capture seasonal variations in water supply and irrigation demand. Second, the spatial analysis focused on the regional scale and did not explicitly consider groundwater dynamics or irrigation district-level management practices. Third, future climate scenarios and socio-economic development pathways were not incorporated into the analysis. Future studies should integrate coupled hydrological models, groundwater processes, and climate change scenarios to improve the prediction of regional water security and support adaptive water-resource management.

Author Contributions: Conceptualization, Y.Z. (Yongxuan Zhang); Methodology, Y.Z. (Yongxuan Zhang); Software, Y.Z. (Yongxuan Zhang); Validation, Y.Z. (Yongxuan Zhang); Formal analysis, Y.Z. (Yongxuan Zhang); Resources, Y.Z. (Yongxuan Zhang); Writing—original draft, Y.Z. (Yongxuan Zhang); Writing—review & editing, Y.Z. (Yongxuan Zhang), X.Y., R.Z., W.X. and Y.Z. (Yuan Zhong); Visualization, Y.Z. (Yongxuan Zhang); Supervision, C.D.; Project administration, C.D.; Funding acquisition, C.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the findings of this study are publicly available from the corresponding public repositories. The annual land-use dataset is available from Zenodo (<https://doi.org/10.5281/zenodo.8176941>). Meteorological, soil, and water-related datasets are available from the Resource and Environment Science and Data Center, Chinese Academy of Sciences (<https://www.resdc.cn/>). The DEM data are available from the Geospatial Data Cloud (<https://www.gscloud.cn/>). Population data are available from Figshare (<https://figshare.com/>). Additional data generated or analyzed during this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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