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Article

Study on Suitable Rice Planting Scale Based on Balance of Groundwater Recharge and Discharge in Sanjiang Plain

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Abstract: In addition to implementing active water resource allocation measures to solve the serious groundwater overexploitation problem caused by large-scale rice planting in the Sanjiang Plain, the reasonable adjustment of rice planting areas is another method of doing so. From the perspective of groundwater recharge and discharge balance, this paper carries out a novel assessment of suitable rice planting areas in the Sanjiang Plain, which is expected to provide a new method for the implementation of land exploitation according to water resource conditions. The technical scheme is as follows: by adjusting the water resource allocation data and rice spatial distribution data in the surface water–groundwater coupled model (baseline model with dynamic land use) in the Sanjiang Plain, static land-use models under different rice planting scales were established. Through simulation and comparison, the rice area that could achieve the balance of groundwater recharge and discharge was considered the suitable rice planting scale in the Sanjiang Plain. The results showed that the average annual change in groundwater storage from 2000 to 2014 simulated by the baseline model was −0.313 billion m^3, indicating that there was space for further optimization and adjustment of the rice planting scale in the Sanjiang Plain. By comparing the static land-use models of each year under the current water resource allocation pattern, the rice area of 1.021 million hm^2 in 2005 could effectively realize the balance of groundwater recharge and discharge. Under the new water resource allocation pattern of 2035, the water resource conditions in the Sanjiang Plain will be greatly improved, which can support a rice planting scale of 3.058 million hm^2 on the basis of ensuring the balance of groundwater recharge and discharge. Our research results can provide a reference for water resource allocation and land-use optimization regulation in the Sanjiang Plain.

Keywords: suitable rice area; balance of groundwater recharge and discharge; surface water and groundwater coupled model; Sanjiang Plain

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1. Introduction

The Sanjiang Plain is a significant grain production base in China, whose rice planting area accounts for approximately 55% of the cultivated land area in the region [1]. Since the 1990s, groundwater exploitation has risen dramatically with the expansion of rice-growing areas, resulting in the formation of large groundwater depression cones [2]. As a result, comprehending the dynamic change law of groundwater and its influencing factors in the Sanjiang Plain is essential for determining the scale of rice cultivation in this region.

Currently, there are more diverse assessment approaches for optimal rice planting size. The main approaches are: (1) calculating the exploitable modulus of groundwater and agricultural water demand [3,4]; (2) the development of GIS and DNDC models to estimate crop water consumption [5]; (3) the development of a mathematical model for simulation analysis [6]; (4) the development of an optimization model based on linear programming and designed to maximize irrigation benefits [7]; (5) the calculation of limitations on ecological water demand [8]; and (6) the analysis of land suitability using multi-criteria evaluation of MCE and GIS technologies [9] to create a plan for an appropriate rice planting size. Many researchers have also conducted studies on the best rice-growing scale in the Sanjiang Plain. Wang Shaohua et al. [3] examined and assessed the exploitable modulus of groundwater and agricultural water demand in the Sanjiang Plain, as well as the area appropriate for rice production, while taking environmental water into consideration. A decision-making framework for Farm 597 and the well-irrigated rice in Sanjiang Plain as a whole was created by Liu Wei et al. [10] through the construction of the groundwater burial depth prediction model of Farm 597 in Sanjiang Plain. Fu et al. [11] used a stochastic process to simulate the dynamic groundwater change in well-irrigated rice in Chuangye Farm of Sanjiang Plain and devised plans for the appropriate scale of well-irrigated rice in Sanjiang Plain.

However, the published literature has not shown that the reasonable rice planting scale in the region is determined through the adjustment of groundwater recharge and discharge balance. With the background that China is actively carrying out ecological civilization construction and optimizing land exploitation according to water resource conditions, it is of great practical significance to replace part of the rice planting area with rain-fed food crops, reduce groundwater exploitation, achieve a dynamic balance of groundwater, and gradually repair the over-exploited groundwater and deteriorated ecological environment while ensuring food security.

In the Sanjiang Plain, the factors affecting the balance of groundwater recharge and discharge are not only the scale of rice planting but also other hydrological processes, such as precipitation and surface water [12,13]. However, in order to exclude the interference of other factors on groundwater and achieve the research objectives of this paper, the general groundwater simulation and assessment methods may not be sufficient. Therefore, this paper adopts the surface water–groundwater coupling model [14,15] to simulate the process of groundwater recharge and discharge in Sanjiang Plain and determines the appropriate rice planting scale for groundwater recharge and discharge balance by transforming the rice planting area data in the model while keeping the data and parameters of other models unchanged. It provides a reference for water resource allocation and planting structure regulations in the Sanjiang Plain.

2. Overview of the Study Area

The Sanjiang Plain, located in the northeast of Heilongjiang Province, is a triangle formed by the convergence of the Heilongjiang, Songhua, and Wusuli rivers (Figure 1a). The region covers a total land area of approximately 105,700 km^2, of which plain regions constitute 56.5% and are the major areas of human activity [1,16]. The land-use types in the Sanjiang Plain are diverse. Influenced by human activities, obvious mutual transformation has been observed between different land-use types. Among them, paddy fields have changed the most acutely from 2000 to 2014 (Figure 1b), accounting for 22.8% of the total area of the region from 9.0% [2,17], leading to the expansion of groundwater depression cones and increasing the impact on groundwater year by year.

The plain areas are the main planting areas for rice, and also the areas where the groundwater changes violently. The total area of the two major plains, the Sanjiang Low Plain and the Xingkai Lake Plain, is approximately 51,700 km^2, and their rice area accounts for approximately 90% of that of the Sanjiang Plain (2014). This study focuses on the relationship between groundwater balance and rice area in the two plain areas of the Sanjiang Plain. Aquifers in the plain areas consist of Quaternary loose sediments with a grain size between sand and gravel and no aquifuge. The thickness of the Quaternary aquifer is 50~300 m, covered with a 5~20 m clay layer in the eastern part of the Sanjiang Low Plain, which sometimes confines the groundwater under the clay layer [18]. Groundwater in the aquifers has good recharge conditions and is a reliable water source for the Sanjiang Plain. The amount of groundwater exploited in the Sanjiang Plain has increased from

1.176 billion m^3 in the 1980s to 10.15 billion m^3 in 2017 [19,20], causing the groundwater level in the plain to decline continuously.

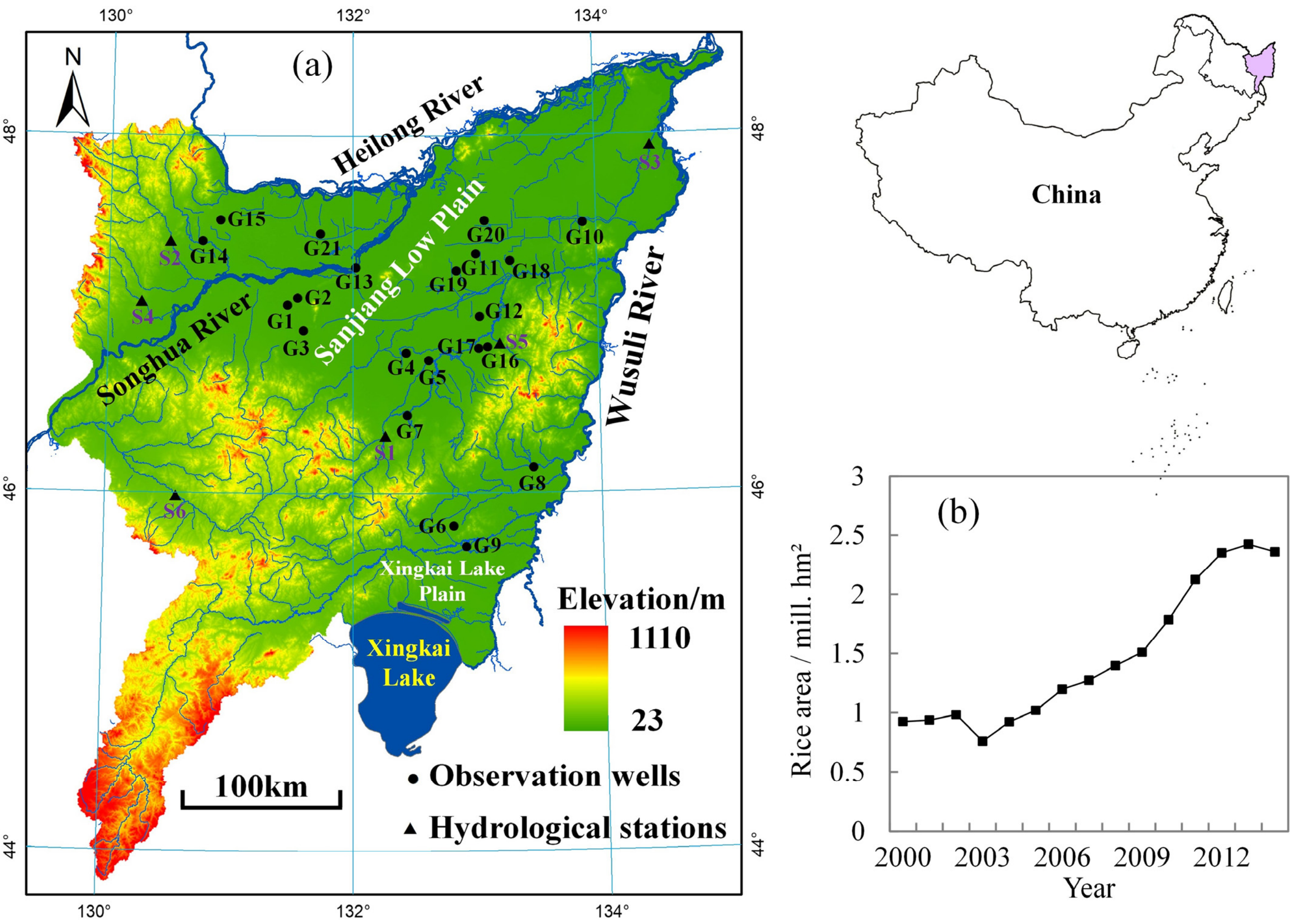

Figure 1. (**a**) Overview of Sanjiang Plain; (**b**) rice area change.

3. Materials and Methods

3.1. Technical Scheme

Using the land-use data of 2000, 2005, 2010, and 2014, we built a 2000~2014 water cycle model of the Sanjiang Plain under the dynamic land-use mode (baseline model), which has been calibrated and verified [21]. The baseline model was used to analyze groundwater balance in the Sanjiang Plain at the current rice planting scale. The current year's groundwater is overexploited, indicating that the current rice planting area is not the appropriate rice planting scale in Sanjiang Plain. Based on the baseline model, the corresponding water cycle model under the static land-use mode was built using the annual land-use data (including land-use data interpolated by the baseline model) during the simulation period (static models). The appropriate rice planting scale under the current water resource allocation pattern was obtained by comparing the simulated groundwater balance from 15 static models. Sanjiang Plain actively carries out surface water engineering construction, increases the surface water utilization rate, and lowers reliance on groundwater to strengthen the water resource guarantee capacity and minimize the over-exploitation of groundwater. A new water resource allocation pattern will be established in 2035, by which time a larger rice planting scale will be used in the Sanjiang Plain. Based on the 2014 static model (the water cycle model built using the 2014 LU), we also built a prediction model by replacing its corresponding input data with the 2035 water allocation and rice area data [22], and simulated the groundwater recharge and discharge in the Sanjiang Plain.

If the groundwater in plain areas does not reach a balance between recharge and discharge, rice areas will continue to be adjusted until the groundwater reaches a dynamic balance. This helps determine how much rice should be planted under the new pattern of water resource allocation. The technical scheme can be represented by the flow chart shown in Figure 2.

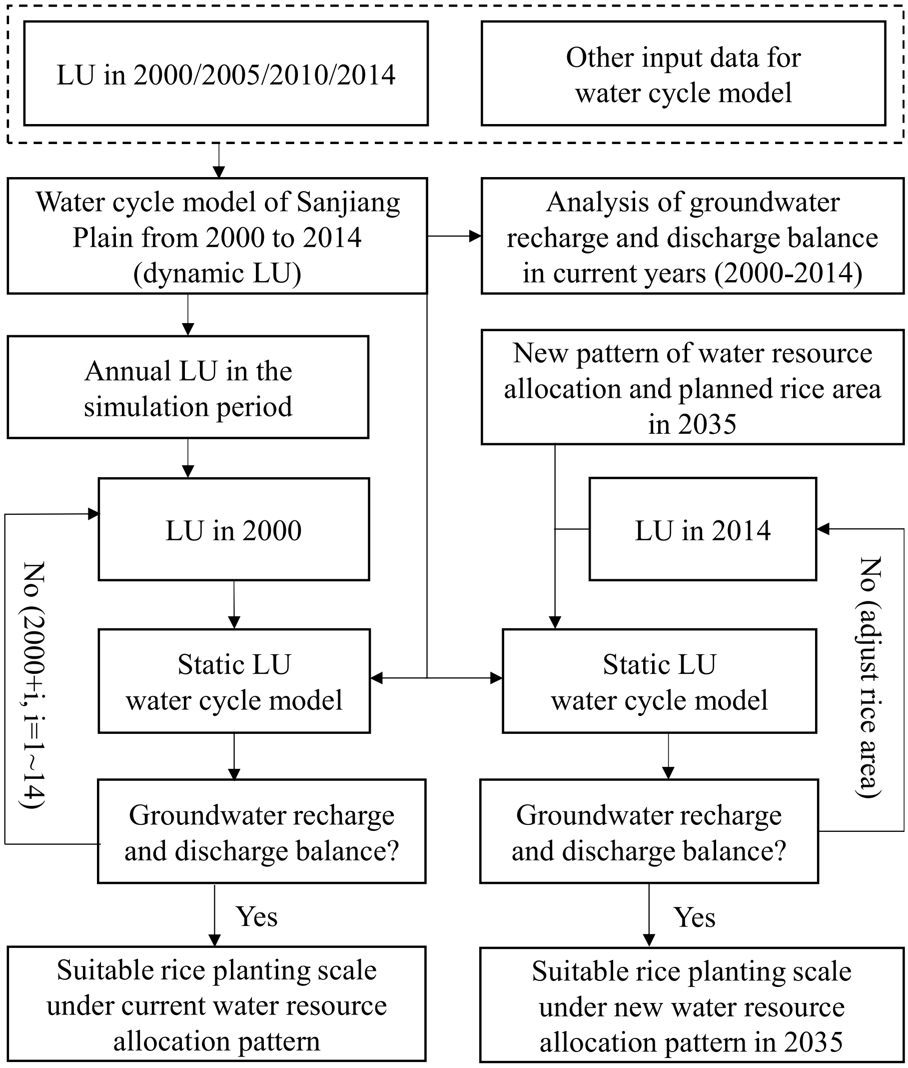

Figure 2. Flow chart of the technical scheme (LU: land use).

3.2. Model Principle

MODCYCLE is a distributed hydrological model tightly integrated with the numerical simulation of groundwater that has been successfully applied in many regions [21–25]. Its hydrological process simulation can be divided into two parts. On the one hand, the hydrological process of the land surface is mostly utilized to construct sub-basins and mesh units through DEM, and HRU is divided by soil type, land use, and other data. The model can also simulate surface water network processes, which include the cascade confluence and diversion processes of main rivers, reservoirs, channels, etc., as well as the inflow, consumption, etc., of rivers running into the local region from outside and point sources. The two are linked by the confluence of surface runoff, water diversion for irrigation, surface-groundwater interaction, etc. [21].

The hierarchical water balance verification mechanism is the underlying principle of MODCYCLE [23]. The verification of the water balance at an independent level is carried out using hydrological response units, channels, reservoirs, major rivers, grid cell groundwater, sub-basin groundwater, etc., in accordance with the principle of independence before integrity. The water balance of the aquifer sub-basin in the plain area is then performed at the intermediate comprehensive level. Finally, a water balance verification mechanism with a high correlation is formed by conducting the water balance verification of the numerical simulation area and the whole basin at a comprehensive level.

The MODCYCLE model simulates irrigation in the same way that it simulates precipitation arriving at the surface, that is, starting from the soil surface of the hydrological response unit and simulating the processes of ponding, runoff producing and infiltration, interlayer infiltration, subsurface runoff, deep percolation, etc. [22]. In terms of planting, the difference between rice or other aquatic crops and ordinary dry crops is that the aquifer must be kept in the field during the growth period, and whether irrigation is required is determined by the depth of water accumulation on the surface, resulting in the "automated rice irrigation" operation [22].

One of MODCYCLE's characteristics is its close coupling with numerical groundwater simulation. The MODCYCLE model uses numerical algorithms in the simulation of groundwater in the plain area to calculate the replenishment, drainage, and equilibrium of groundwater in the form of grid cells. The groundwater aquifers are no longer restricted to shallow and deep aquifers, but can be divided into at least two layers, if not indefinitely. Other than the first aquifer, which is a phreatic aquifer, the remaining aquifers are confined. In plain regions, it is not essential to compute all replenishment and drainage items for the sub-basin; rather, through the spatial nesting relationship between the sub-basin in the plain area and the grid cell, statistics can be generated on the change in replenishment, drainage, and storage of the sub-basin based on the simulation data of the grid cell [26].

MODCYCLE also performs key functions, such as dynamic land-use updates. The missing years of land-use data are supplemented by linear interpolation, and the annual land-use data are dynamically updated in the process of water cycle simulation using the annual scale as the time unit and the sub-basin as the fundamental simulation unit. To preserve the continuity of hydrological cycle simulation before and after the land-use update, the HRU divided by the new land-use data in the following year will inherit the HRU water storage simulated in the previous year [21].

3.3. Model Construction

A large amount of data was used to construct the model (Table 1), which can be roughly categorized as spatial distribution data (sub-basin, river network, land use, soil type, etc.), numerical groundwater simulation data (hydrogeological parameters, boundary conditions, initial conditions, etc.), meteorologically driven data (precipitation, wind speed, temperature, etc.), and human-driven data (agricultural water, non-agricultural water, etc.). In this study, 1705 sub-basins were divided based on the actual river network and DEM data of the Sanjiang Plain (Figure 3a). Meanwhile, the Sanjiang Low Plain and the Xingkai Lake Plain were used for the numerical groundwater simulation. The groundwater aquifer was divided vertically into shallow and deep layers and horizontally into 206 $\times$ 206 grid cells (2000 m $\times$ 2000 m) to split the plain area into 13,076 effective cells (Figure 3b).

Table 1. Model input parameters and data.

Data Type	Input Data
Spatial distribution data	Sub-basin, river network, land use, soil type, agricultural planting structure, etc.
Numerical groundwater simulation data	Hydrogeological parameters, boundary conditions, initial conditions, etc.
Meteorological driven data	Rainfall, wind speed, temperature, air humidity, radiation, etc.
Human driven data	Agricultural water, non-agricultural water, reservoir regulation, external water transfer, human exploitation, etc.

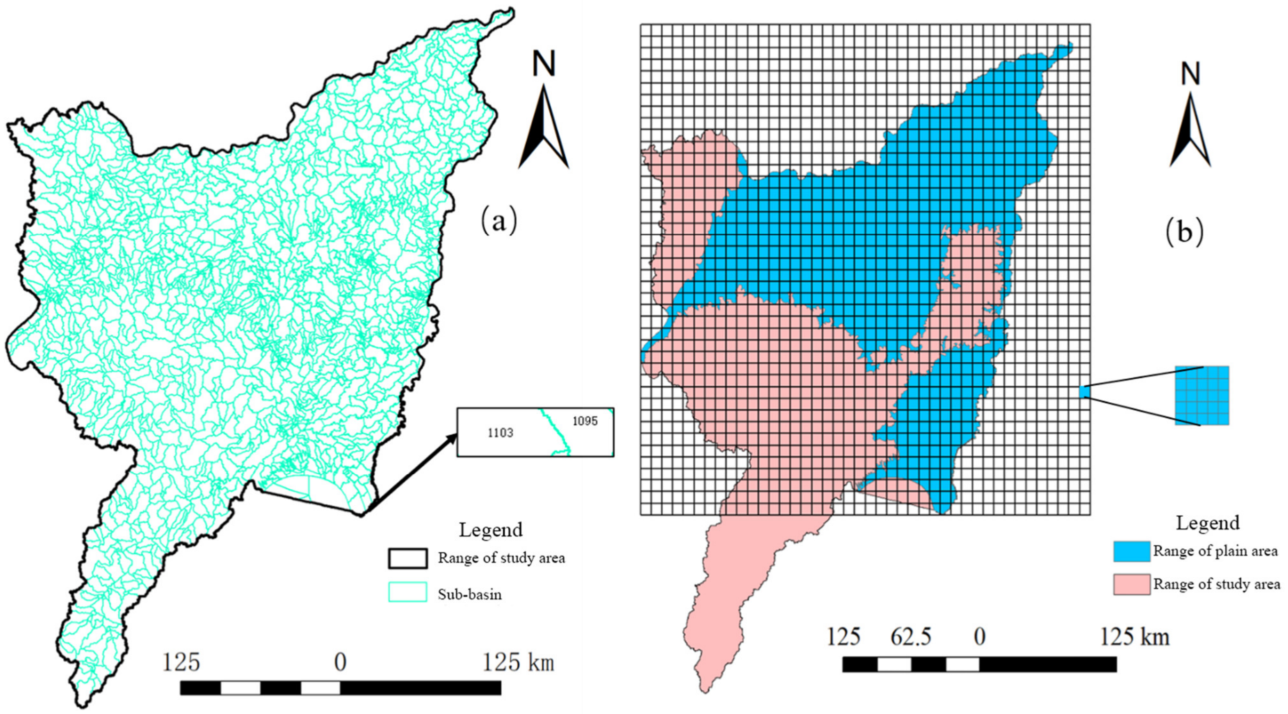

Figure 3. Unit division of the hydrological cycle and groundwater numerical simulation. (**a**) Sub-basins of the Sanjiangping; (**b**) groundwater grid cells in plain areas.

4. Results, Analysis, and Discussion

We calibrated and validated the model, and then analyzed the current (2000–2014) dynamic change in groundwater using the baseline model. Employing the static models under different LUs, we evaluated the groundwater water balance under the current water resource allocation pattern and the new water resource allocation pattern to explore suitable rice planting scales in the Sanjiang Plain for the purpose of groundwater recharge and discharge balance.

4.1. Model Calibration and Validation

To calibrate and validate the model, the flow data from six representative hydrological stations and the groundwater level data from 21 observation wells in the plain area (Figure 1a) were selected. The performance of the model was assessed by R^2 (coefficient of determination) and NSE (Nash–Sutcliffe efficiency coefficient), with 2000–2008 as the calibration period and 2009–2014 as the validation period. Tables 2 and 3 show the parameters calibrated and the fitting effects of hydrological stations and observation wells. More information on the model calibration and validation can be found in other literature [21,22].

Table 2. Selection of key parameters for hydrological cycle and groundwater numerical simulation.

Parameters	Meaning (Unit)	Recommended Scope	Final Calibrated Value
Hydrological cycle			
MXSURPOND	Maximum surface ponding depth/mm	0.0–150.0	1–100
ALPHA_BF	Base flow factor/d	0.0–1.0	0.05–0.08
ESCO	Soil evaporation compensation factor	0.01–1.0	0.9–0.92
SURLAG	Retardation coefficient of surface runoff	1.0–24.0	5.0–5.0
SOL_AWC	Effective water supply capacity of soil layer	0.0–1.0	0.01–0.25
SOL_K	Saturated permeability coefficient/(mm/h)	0.0–25.0	0.018–25
GWDMN	Water level threshold of shallow aquifer of base flow (m)	0.0–5.0	2.5–2.5

Table 2. *Cont.*

Parameters	Meaning (Unit)	Recommended Scope	Final Calibrated Value
Numerical Simulation of Groundwater			
HY	Hydraulic conductivity/(m/d)		0.25–7.5
SC1	Type 1 storage coefficient		0.008–0.175
SC2	Type 2 storage coefficient		0.004–0.175

Table 3. NSE and R^2 at representative observation wells and hydrological stations. The locations of wells and stations can be found in Figure 1.

Fitting Effect of Groundwater Level						Fitting Effect of Surface Runoff				
No.	Calibration Period R^2	Validation Period R^2	No.	Calibration Period R^2	Validation Period R^2	No.	Calibration Period		Validation Period	
							NSE	R^2	NSE	R^2
G1	0.55	0.63	G12	0.65	0.76	S1	0.64	0.71	0.60	0.80
G2	0.58	0.60	G13	0.54	0.70	S2	0.63	0.75	0.70	0.81
G3	0.56	0.64	G14	0.83	0.76	S3	0.55	0.70	0.59	0.75
G4	0.67	0.61	G15	0.75	0.66	S4	0.68	0.73	0.75	0.85
G5	0.72	0.66	G16	0.43	0.47	S5	0.60	0.71	0.63	0.67
G6	0.45	0.63	G17	0.49	0.67	S6	0.64	0.80	0.65	0.78
G7	0.50	0.57	G18	0.75	0.80					
G8	0.68	0.75	G19	0.73	0.58					
G9	0.49	0.62	G20	0.84	0.90					
G10	0.36	0.55	G21	0.55	0.69					
G11	0.82	0.58								

4.2. Dynamic Analysis of Current Groundwater

The change in the groundwater table can reflect the recharge and discharge relationship of groundwater to some extent. The groundwater level of the Sanjiang Plain has a large variation range; in particular, the decrease in the groundwater level is widely distributed in the northeast of the plain area. During 2000–2014, the decrease in the groundwater level was generally greater than 2 m, and the maximum decrease was more than 16 m (Figure 4). This was seen in the area where the surface water diversion project was backward and groundwater-irrigated rice was widely planted. More than 90% of rice was irrigated by exploiting groundwater, resulting in groundwater discharge far greater than recharge, which is the main cause of the imbalance of groundwater recharge and drainage in the Sanjiang Plain.

Under the dynamic land-use mode, the groundwater recharge and discharge fluxes in the Sanjiang Plain from 2000 to 2014 were evaluated using the baseline model. On the whole, the fluxes of groundwater in the plain area increased. Generally, the increase in precipitation can reduce the irrigation amount per unit area of rice, thus, reducing the amount of groundwater exploitation. However, the area of rice in the Sanjiang Plain has increased too rapidly, so that although precipitation is increasing, groundwater exploitation is also increasing. As a result, the changes in groundwater storage were in deficit in most years. While there were also some years in which the storage changes were positive values, the groundwater storage at the end of 2014 showed a large depletion compared with storage at the beginning of 2000 (Figure 5).

From the simulation values, the average annual recharge of groundwater in plain areas (51,700 km^2) from 2000 to 2014 was 6.355 billion m^3. Many institutions have evaluated the amount of groundwater recharge and groundwater resources in the Sanjiang Plain. The total groundwater recharge assessed by the Heilongjiang Provincial Water Conservancy and Hydroelectric Power Investigation, Design and Research Institute in 2002 was 7.032 billion m^3 (assessed area 57,300 km^2) [27]. The total recharge of groundwater in the Sanjiang Low Plain assessed by the Heilongjiang Provincial Geological Survey and Research Institute was 5.145 billion m^3 (assessed area 39,400 km^2) [28]. Researchers from the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences evaluated the total recharge of groundwater as 6.516 billion m^3 [29]. Our simulation results are similar to the results calculated by other institutes, and the error may be due to the difference in the evaluated area and time. These can reflect the rationality of our model to a certain extent.

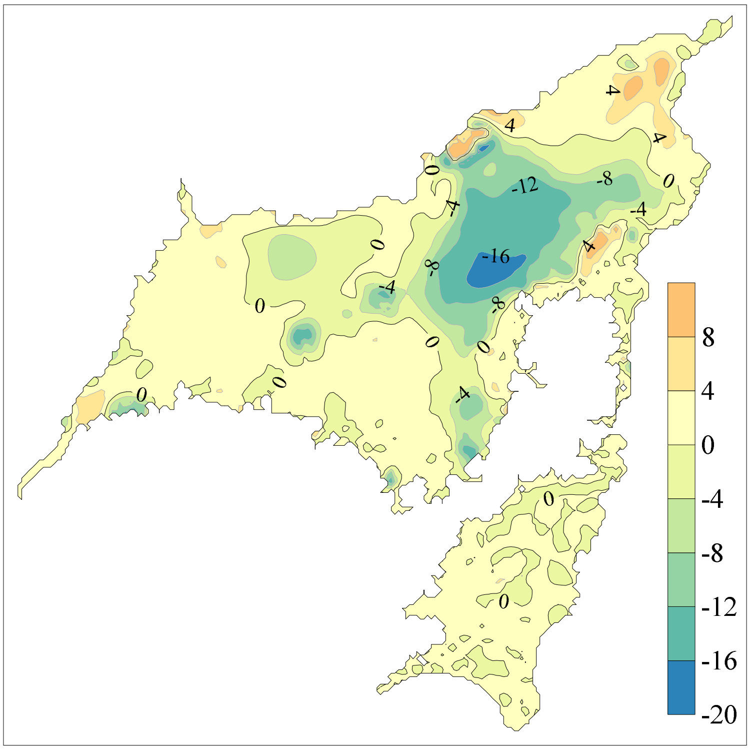

Figure 4. Variation of groundwater level from 2000 to 2014 in the plain areas. Negative values mean that the groundwater level drops (unit: m).

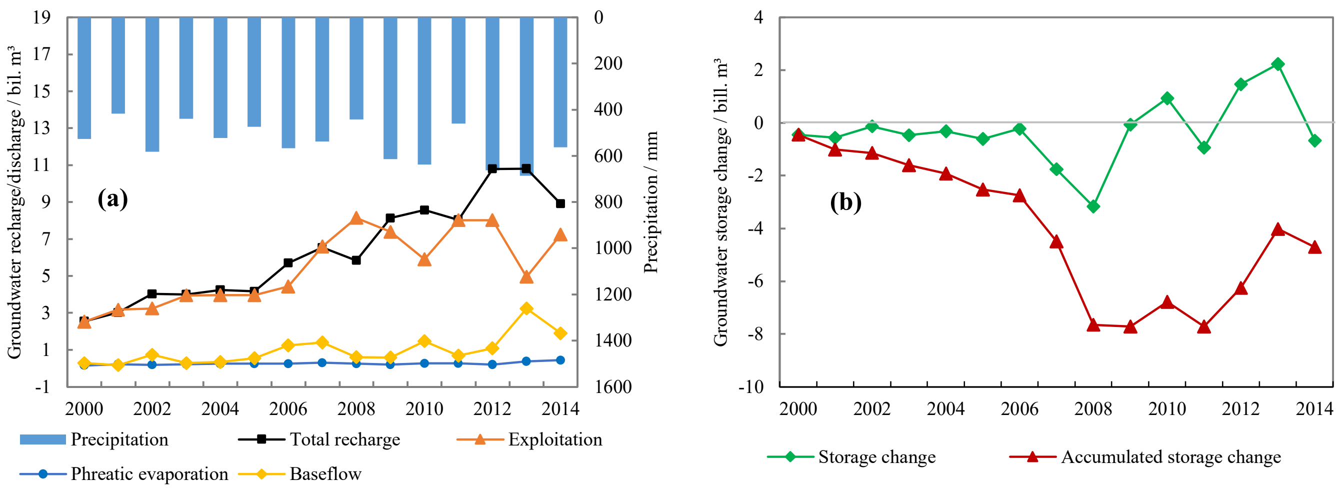

Figure 5. Dynamic change in groundwater under dynamic land-use mode. (**a**) Groundwater fluxes and precipitation; (**b**) groundwater storage change.

The average annual discharge of groundwater in plain areas is 6.668 billion m^3, which is 0.313 billion m^3 more than the average annual recharge, indicating that the groundwater storage is in a deficit trend. At this deficit rate, storage at the end of 2014 decreased by 4.699

billion m^3 compared with that at the beginning of 2000. In terms of the discharge of groundwater, the average annual exploitation of groundwater can reach up to 5.437 billion m^3, accounting for 81.5% of the total discharge. It can be seen that in order to achieve a balance between groundwater recharge and drainage, reducing groundwater exploitation is the key, so reducing the rice planting area can be an alternative method of achieving this.

4.3. Suitable Rice Planting Scale under the Current Water Resource Allocation Pattern

Based on the baseline model, with other parameters and data unchanged, the corresponding static LU model was established using the annual land-use data (including the land-use data obtained by interpolation) during the simulation period, and the representative static LU models of 2000, 2002, 2005, and 2007 were selected for comparative analysis of the main fluxes and storage of groundwater (Figure 6). The rice areas of the four LU patterns were 0.924, 0.985, 1.021, and 1.275 million hm^2. From the trend of total groundwater recharge (Figure 6a), the recharge of the four LU patterns showed a trend of fluctuating and increasing year by year. In the static LU model, the land use remained unchanged, so the trend of increasing recharge was mainly caused by the increase in precipitation. Comparing the total recharge of the four LU patterns, it can be seen that the larger the rice area, the greater the groundwater recharge. The increased recharge is mainly due to the percolation of rice irrigation water. Among the patterns, the total recharge of the 2007 LU pattern was significantly greater than that of other LU patterns. Due to the increasing trend of precipitation, the groundwater exploitation of the four LU patterns fluctuated and decreased year by year (Figure 6b). Similar to the total recharge, exploitation also increases with the increase in rice area in different LU patterns.

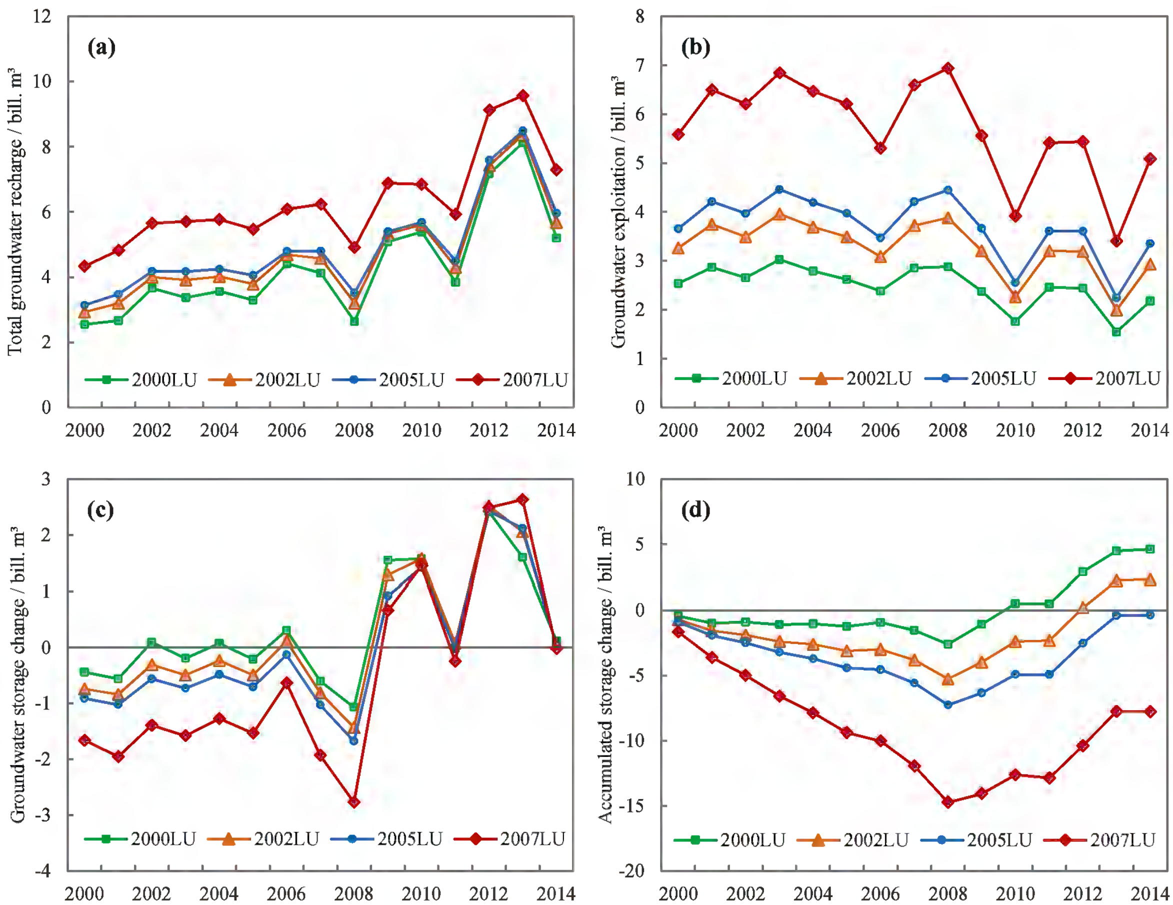

Figure 6. Comparison of main groundwater fluctuations and storage under LU in 2000, 2003, 2005, and 2007. (**a**) Total groundwater recharge, (**b**) groundwater exploitation, (**c**) groundwater storage change, and (**d**) accumulated storage change.

From the annual storage change (Figure 6c) and accumulated storage change (Figure 6d) of groundwater, the storage under the 2007 LU pattern changed greatly in most years. Of these, the first nine years showed states of serious loss. Although recharge in the last six years increased significantly and showed a large positive change, the accumulated storage changed greatly, and the groundwater loss over the past 15 years was the most serious. The groundwater storage was the smallest under the 2000 LU pattern; particularly in the first seven years, the groundwater was basically in dynamic balance. In the last six years, abundant precipitation infiltration recharge was received, and the storage increased rapidly. By the end of 2014, the groundwater storage had increased in general. This situation is most conducive to the recovery of groundwater to a state before the large-scale expansion of rice, but there are also some disadvantages to this situation, such as inadequate utilization of groundwater resources, endangering food security and local farmers' economic income due to the small rice area and leading to secondary soil salinization because of the high phreatic table. The storage under the 2005 LU pattern also changed greatly, which showed a trend of loss until 2008, but gradually recovered afterwards. By the end of 2014, the groundwater had basically recovered to its state at the beginning of 2000.

From the values of accumulated storage changes, the overall changes in groundwater storage during the simulation period under the four LU patterns in 2000, 2002, 2005, and 2007 were 4.615, 2.308, −0.378, and −7.78 billion m^3, respectively, and the annual average storage changes were 0.308, 0.154, −0.025, and −0.519 billion m^3, respectively, which indicate that the 2005 LU pattern is the closest to achieving a balance between groundwater recharge and drainage. If the rice area continues to increase, the depletion of groundwater storage will be greater than that under the 2007 LU pattern, and therefore it will be more difficult to achieve a dynamic balance of groundwater. Therefore, 1.021 million hm^2 in 2005 is the most suitable rice area for realizing the balance of groundwater recharge and drainage under the current water resource allocation pattern.

4.4. Suitable Rice Planting Scale under the New Water Resource Allocation Pattern

According to relevant planning of the Sanjiang Plain, the rice planting scale is expected to increase from 2.356 million hm^2 in 2014 to 3.004 million hm^2 by 2035, and the demand for water resources will further increase. Therefore, the local government plans to increase water supply by 11.3 billion m^3 through the construction of more surface water diversion projects to supply water to 43 planned irrigation areas, which can cover most of the cultivated land in the two plain areas and realize further replacement of groundwater exploitation [22].

Based on the 2014 LU static water cycle model, by replacing the initial groundwater level with that at the end of 2014, replacing the water use data with the new pattern of water resource allocation of 2035, replacing the rice area with the planned rice area of 2035, and keeping the other data unchanged, we established the prediction model. The simulation results show (Figure 7a) that the groundwater recharge was greater than discharge in most years, demonstrating that the groundwater storage in the Sanjiang Plain will recover rapidly on the basis of the groundwater status at the end of 2014. After 15 years, the groundwater storage will increase by 6.8 billion m^3, and the annual average change in the groundwater storage is 0.453 billion m^3. If this trend is followed, the depletion of groundwater caused by long-term over-exploitation in the Sanjiang Plain will be quickly repaired, but it will also cause many problems, particularly the secondary salinization of soil due to the high groundwater level. At this time, we can consider further developing the area of rice, increasing the amount of groundwater exploitation, and realizing the balance of the recharge and drainage of groundwater.

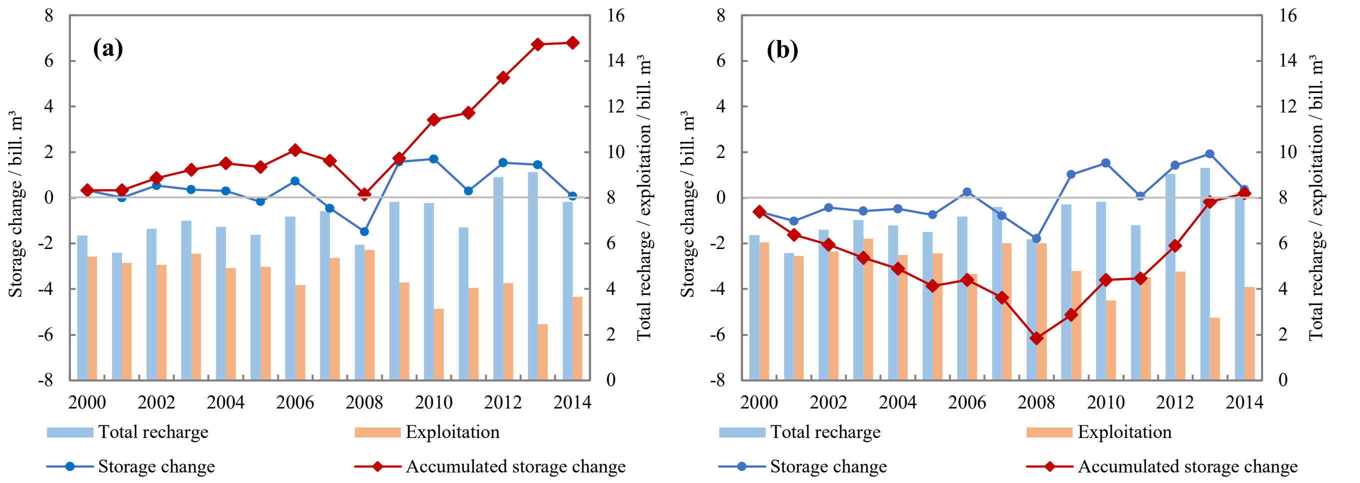

Figure 7. Main groundwater fluxes and storage change under planned rice area (**a**) and suitable rice area (**b**). All data of the two models are the same, except for the rice area; (**b**) is 0.054 million hm^2 more than (**a**). The meteorological data are from 2000 to 2014, so the abscissa still uses this simulation period.

On the basis of the prediction model, we continued to increase the rice area (the increased area of the rice irrigated by groundwater) until the groundwater simulated by the model achieved a balance between recharge and discharge. The results of the model trial calculation (Figure 7b) show that when the rice area increases from the planned 3.004 million hm^2 to 3.058 million hm^2, the annual average storage change in groundwater decreases to 0.013 billion m^3, and the accumulated storage change over 15 years is only 0.192 billion m^3, meaning that the groundwater reaches a dynamic balance state. Thus far, 3.058 million hm^2 can be considered a suitable rice area to ensure the balance of groundwater recharge and discharge under the new pattern of water resource allocation in 2035.

5. Conclusions

The rapid increase in rice area in the Sanjiang Plain has led to serious over-exploitation of groundwater and an imbalance in recharge and discharge. Adjusting the rice area to restore the dynamic balance of groundwater is an alternative method for repairing groundwater over-exploitation. Therefore, we use the surface water and groundwater coupled model to explore the suitable rice area under different water resource allocation patterns in order to achieve the balance of groundwater recharge and discharge. The main conclusions are as follows:

(1) Current rice areas are not conducive to balancing the recharge and discharge of groundwater and need to be adjusted. The simulation results of the dynamic LU water cycle model (baseline model) from 2000 to 2014 show that although the areas of rice in the first few years were relatively small, the increase was too rapid, resulting in an increase in groundwater exploitation despite precipitation increasing. The annual average groundwater storage change was -0.313 billion m^3, and the accumulated groundwater storage change reached 4.699 billion m^3 in 15 years. Obviously, the current rice areas are not suitable for the Sanjiang Plain.

(2) Under the current water resource allocation pattern, the suitable rice area for realizing the balance of groundwater recharge and discharge was the rice area seen in 2005, i.e., 1.021 million hm^2. On the basis of the baseline model, we changed the land-use data to the LU of each year and established the corresponding static LU model. Through the comparison of the groundwater simulation results of each model, it was found that the annual average storage change in groundwater under the 2005 LU pattern was -0.25 billion m^3, and the accumulated storage change over 15 years was -0.378 billion m^3, which is smaller than the absolute values of those under other LU patterns.

This shows that the rice area in 2005 was the most conducive to the realization of groundwater balance.

(3) Under the new pattern of water resource allocation, the planned rice area (3.004 million hectares) is not sufficient for the use of groundwater resources. An additional 0.054 million hm^2 of well-irrigated rice can achieve the balance of groundwater recharge and discharge. Under the new pattern of water resource allocation, surface water replacement groundwater irrigation is realized in the planned rice area, but the groundwater utilization is insufficient, and the annual groundwater storage change is 0.453 billion m^3. Although this will be useful for the restoration of historical groundwater deficits, it is not conducive to agricultural production (soil secondary salinization) in the long run. By increasing the area of well-irrigated rice, the average annual change in groundwater storage will be gradually reduced to 0.013 billion m^3, and the dynamic balance of groundwater will be achieved. Currently, the suitable rice area of the Sanjiang Plain is 3.058 million hm^2.

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