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Groundwater and Surface Water Availability via a Joint Simulation with a Double Control of Water Quantity and Ecologically Ideal Shallow Groundwater Depth: A Case Study on the Sanjiang Plain, Northeast China

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Abstract: Joint assessment of groundwater-surface water resources can help develop sustainable regional water management plans for intensive agriculture. In this study, we estimated allowable groundwater and surface water quantities using a water balance model, WetSpass-GMS, for the Sanjiang Plain (10.9×10^4 km^2), one of the most important grain production bases in China. We then applied a double control based on the groundwater availability and the concept of an ecologically ideal shallow groundwater depth (EISGD) to three different water use scenarios: (A) continuation of the current water use management; (B) maximal use of water resources under a double control; and (C) irrigation of 266.7×10^4 hectares that are suitable for rice cultivation. We found an annual allowable surface water quantity of 4.71 billion cubic meters for the region and an annual exploitable groundwater quantity of 4.65 billion cubic meters under full consideration of water requirements, i.e., sustaining river base flow, necessary riverine sediment transport, and ecological water supplies for wetlands and reservoirs. Our simulation results showed that for Scenario A, groundwater level in the region would continue falling, and that the groundwater levels in wet, normal and dry years would drop below the EISGD level in 2028, 2023 and 2019, respectively. For Scenario B, groundwater and surface water would be able to support rice paddies of 219.7×10^4 hectares, 212.7×10^4 hectares, and 209.3×10^4 hectares during wet, normal and dry years, respectively. For Scenario C, future demands on groundwater and surface water under wet, dry and normal years would all exceed their allowable supplies. Overall, this study indicates that integrated management plans promoting an increase of surface water use and a reduction in irrigation with groundwater should be developed for sustainable agriculture and ecological preservation on the Sanjiang Plain.

Keywords: allowable water resources; coupled simulation and regulation; surface-groundwater interaction; double control of water quantity and water level; Sanjiang Plain

1. Introduction

Groundwater and surface water resources in a region are often physically connected. The interaction between the two water resources is complex, and understating their regional availability and connectivity can be crucial in sustaining economic development, ecological functions, and social stability [1–5]. For many regions in the world, groundwater is a main source for agricultural irrigation, counting about 70% of all global irrigated land. This has led to a number of ecological and environmental stresses including continuous decline of groundwater levels and increase of cone of depression, which often causes land degradation [6–9]. Although many regions have abundant river and lake water resources, local agriculture still replies on groundwater use due to easy exploitation and low expense, which further causes groundwater decline. It is therefore important that the quantity and availability of groundwater and surface water be jointly assessed to develop plans and strategies for long-term sustainable water resources management.

Several studies have been done on joint regional regulation of surface water and groundwater in China. For instance, in order to solve the water shortage for agriculture and the uneven spatial distribution of water resources in the Shiyang River basin in Northwest China, Quan and Dong [10] develop a groundwater-surface water joint regulation model; In a study on the joint regulation of groundwater-surface water for the Huangshui River and Dagu River, Meng [11] and Wang [12] applied a quantity control approach to restrict local water resource withdrawal; from a study on the control of water level during the joint simulation groundwater-surface water, Liu [13] presented an ideal joint regulation schedule under control of the groundwater level. Similar studies on joint groundwater-surface water regulation have also been conducted in other geographical regions. For instance, Querner [14] used Modflow to analyze surface water and groundwater interactions in the Netherlands; To obtain more accurate results, researchers [15–18] presented a surface water and groundwater conjunctive plan used minimum depth standard for fish passage in California, USA, average surface water flow deficits in Australia, Darcy's law and statistical regression analysis of historic data for relating environmental river flow targets to groundwater levels in India, combined clustering method in the High Plain, USA, a support vector machines (SVMs) model as a simulator of surface water, and a genetic algorithm (GA) as the optimization mode in west central Iran. Collectively, these studies have demonstrated the importance of joint assessment of groundwater-surface water for regional water resources management. However, these studies mainly focused on a single water quantity or water level control. Few studies used a double control approach of water quantity and level in joint groundwater-surface water analysis.

As one of China' most important grain production areas, the Sanjiang Plain in Northeast China is the largest, most intensively irrigated agricultural region in the country. The region is also planned by the Chinese government to become the country's most important rice culture base in the future. For agricultural irrigation in this region, a total of 2.57×10^9 m^3 of groundwater is used annually accounting for 60% of the total groundwater usage of the Sanjiang Plain [19]. Continuous withdrawal of the large quantity of groundwater has generated serious environmental concerns, a significant decrease of the regional shallow groundwater level has been found. For example, Zhao et al. [20] reported a 5-m decline of the shallow groundwater level over the past 50 years in the central Sanjiang Plain and a large area of cone of depression in the northwest Sanjiang Plain. Intensive groundwater use, together with extensive conversion of wetlands to rice paddy fields, has had a significant impact on the quality of surface water [21,22] and groundwater [23] due to accelerated ground-surface water interactions, where the rate of surface water infiltrate into groundwater has become far less than the rate of exploited, causing ecological land deterioration, especially in natural wetlands. At the same time, when the level of a shallow groundwater decreases, more wetland water recharges the groundwater, resulting in direct wetland degradation. Song et al. [24] reported that about 80% of the wetlands in the Sanjiang Plain disappeared in the past 60 years. Such problems pose a threat to the long-term sustainable development of food security and regional ecological security. Hence, studying the jointed regulation of groundwater and surface water in this region is a key measure of progress for the sustainable development under continuously decreasing groundwater level, which leads to wetland degradation. In addition, previous studies focused on the large basin scale, few studies have investigated a large flat plain area like the Sanjiang Plain (10.9×10^4 km^2) with intensive agricultural irrigation activities.

In this study, we performed a joint regulation assessment of groundwater and surface water under a double control of water quantity and a concept of ecologically ideal groundwater depth recently developed by Wang and others [25] for the Sanjiang Plain. The EISGD is a depth range of shallow groundwater that is necessary for sustaining present vegetation ecosystems, and have the upper and lower boundary. The concept of determining the boundaries for an ecologically ideal shallow groundwater depth is based on preservation of the present vegetation. When shallow groundwater level rises to the surface or near-surface, plant roots switch to an anoxia environment. Most xeric plants cannot tolerate extended period of saturation. In addition, if the surface soil is rich in salt, rising of shallow groundwater level may lead to surface salt accumulation in some climate regions degrading soil quality. On the other hand, when the shallow groundwater level declines to deeper depths, it becomes inaccessible to plant roots and groundwater transpiration is nearly zero. Over a long period of time with shallow groundwater decline, surface vegetation communities (e.g., farmland, woodland, meadow, and wetlands) will degrade or shift to different communities. We created a joint simulation model considering both groundwater and surface water to analyze the effects of three water management scenarios on future water resources. The assessment and modeling are to help develop effective water management strategies to support sustainable agriculture irrigation and wetland preservation in the region.

2. Study Area

Covering a total low land area of 10.9×10^4 km^2 between 43°49′55″–48°27′40″ N and 129°11′20″–135°05′26″ E, the Sanjiang Plain is located in Heilongjiang Province, Northeast China. It is a large alluvial floodplain formed in the lower reach of three rivers—the Songhua, Heilong and Wusuli Rivers (Sanjiang in Chinese literally means three rivers, Figure 1). The Heilong and Wusuli Rivers are international rivers draining China's and Russia's territorial lands with an annual average yield of 346.5 billion m^3 and 61.9 billion m^3, respectively. Flowing across the Sanjiang Plain, the Songhua River yields a long-term annual average of 72.7 billion m^3. The discharges of the Songhua and Heilong Rivers decreased continuously in the past 60 years [26].

Climate of this region can be characterized by a cold temperate continental monsoon climate, with a long-term annual average temperature of 2.8 °C and an annual average precipitation of 500–650 mm, more than 60% of which occurs within three months from June to August [26]. Topography of this region is flat and much of the region is located on the floodplain with a slope gradient between 0.01% and 0.02%. The western edge and southeastern edge of the Sanjiang Plain are Xiaoxinganling Mountain and Wanda Mountain with the elevation 1429 m a.s.l. and 831 m a.s.l., respectively. The region is largely covered by Quaternary alluvial sediments, where the major mining layers of groundwater are located. Based on the geological age, geomorphology, lithology and burial depth, the aquifer formations can be classified as: (1) quaternary loose deposits of sand gravel aquifer; (2) tertiary sandstone siltstone interlayer aquifer; and (3) quaternary bedrock fissure aquifer. The aquifer materials consist of medium sand, a mix of loam, fine sand, sandy clays, silts and volcanic rocks [22].

The Sanjiang Plain has a large area of wetlands. In the past half-century, many of the wetlands have been converted into agricultural farmland [27]. In the last decade, the area of woodland, meadow and wetlands further decreased by 0.58%, 12.53% and 4.41%, respectively, but the rice farming area increased by 2.08% [28]. Currently, major land use and land cover types in the Sanjiang Plain include wetland, rice paddy, corn, woodland, and meadow. The wetlands occupy 9.2% (or 1.00×10^4 km^2), the arable land (sum of the rice paddy and other corn land) 53.6% (or 5.57×10^4 km^2), the woodland 33.1% (or 3.40×10^4 km^2), and the meadows 4.1% (or 0.40×10^4 km^2). Rice is the dominant crop in the region [24,28].

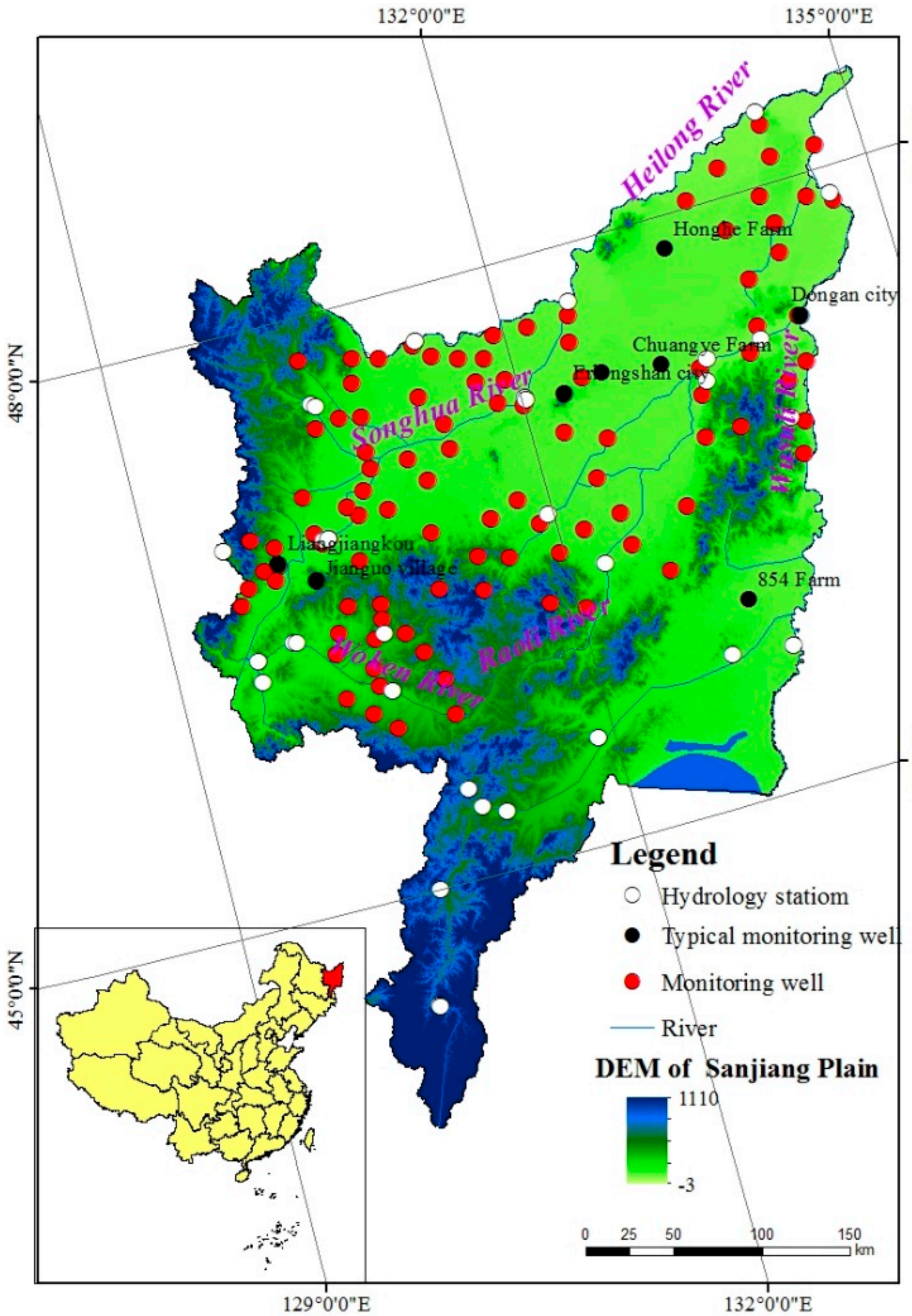


Figure 1. Geographical location of the study area, monitoring wells, and hydrologic stations in the Sanjiang Plain, Northeast China.

3. Methodology

3.1. Conceptual Model, Mathematical Model and Joint Model

3.1.1. Surface Water Conceptual Model

Rivers in the Sanjiang Plain showed slow flow due to the gentle landscape. The boundary conditions: the two boundary river (Heilong River and Wusuli River) were assigned to be a specific head and the other two boundary were assigned to be a specific quantity (Figure 2).

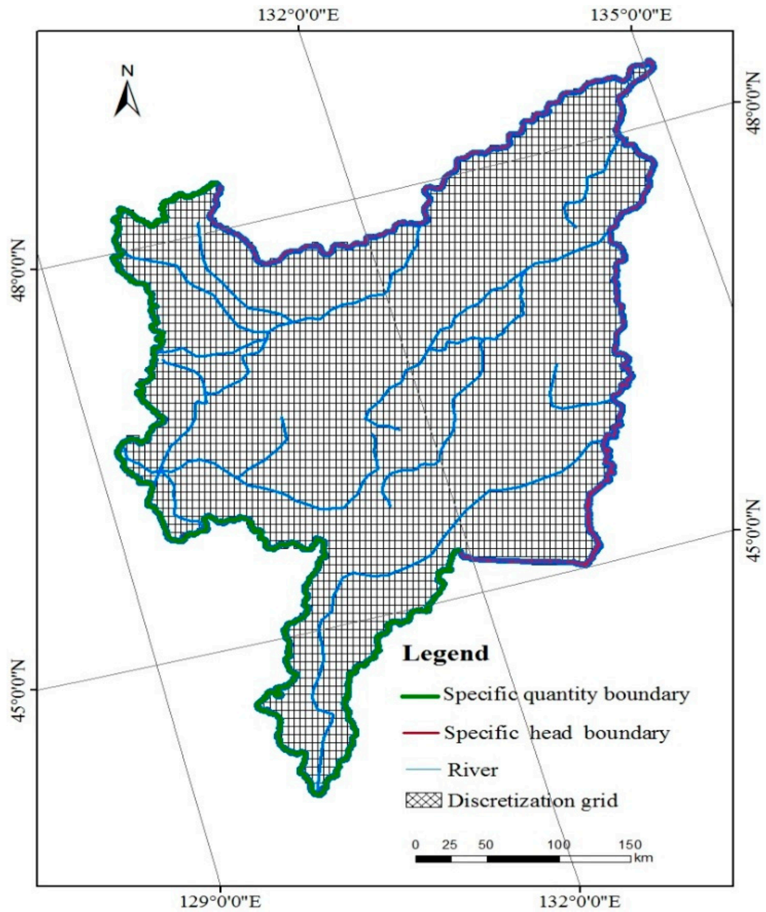


Figure 2. River network and discretization grids of the Sanjiang Plain.

3.1.2. Mathematical Model

$$\begin{cases} \frac{\partial \phi_o h_o}{\partial t} - \frac{\partial}{\partial x}\left(d_o K_{ox} \frac{\partial h_o}{\partial x}\right) - \frac{\partial}{\partial y}\left(d_o K_{oy} \frac{\partial h_o}{\partial y}\right) + Q_o = 0 & (x,y) \in D_o \\ h_o\,(x,y,t)|_{\Gamma 1} = h\,(x,y,t) & (x,y) \in \Gamma_1 \\ K_n \frac{\partial h_o}{\partial n}\Big|_{\Gamma 2} = q_o\,(x,y,t) & (x,y) \in \Gamma_2 \\ h_o\,(x,y,t)|_{t=0} = h\,(x,y,0) & (x,y) \in D_o \end{cases} \quad (1)$$

where [29] ϕ_o is the surface porosity; h_o is the river elevation (m) ($h_o = d_o + z$); d_o is the depth of river (m); and D_o is the scope of surface water. $h_o\,(x,y,t)$ is the specific head boundary; Q_o is the source sink term (LT^{-1}), $q_o\,(x,y,t)$ is the specific quantity boundary; K_{ox}, K_{oy} is the surface conductivity of x, y direction (LT^{-1}); K_n is the surface conductivity of n direction (LT^{-1}); and $h\,(x,y,0)$ is the initial conditions.

$$K_{ox} = \frac{d_o^{2/3}}{n_x} \frac{1}{[\partial h_o/\partial s]^{1/2}}, K_{oy} = \frac{d_o^{2/3}}{n_y} \frac{1}{[\partial h_o/\partial s]^{1/2}} \quad (2)$$

$$\phi_o = \begin{cases} 1 & (d_o \geq H_{ds} + H_{rs}) \\ \frac{4[H_{ds}+H_{rs}]d_o - 3{d_o}^2}{[H_{ds}+H_{rs}]^2} & (d_o < H_{ds} + H_{rs}) \end{cases} \quad (3)$$

where n_x, n_y are the manning coefficient in the x, y direction [$L^{-1/3}T$], H_{ds} is the depression storage (m), and H_{rs} is the reduced storage (m).

3.1.3. Groundwater Conceptual Model

Groundwater in the Sanjiang Plain mainly storage in quaternary loose deposits of sand gravel aquifer, and the groundwater flow was defined as heterogeneity, unsteady and three dimensional flow. The boundary condition: the west, south and southeast part of Sanjiang Plain are low hills with the weak permeable strata and defined as the specific quantity boundary. The other two boundaries (Heilong River and Wusuli River) were assigned to be a specific head (Figure 2).

3.1.4. Mathematical Model

$$\begin{cases} \frac{\partial}{\partial x}(k\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(k\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(k\frac{\partial h}{\partial z}) + \varepsilon = s\frac{\partial h}{\partial t} & (x,y,z) \in \Omega, t \geq 0 \\ k(\frac{\partial h}{\partial x})^2 + k(\frac{\partial h}{\partial y})^2 + k(\frac{\partial h}{\partial z})^2 - \frac{\partial h}{\partial x}(k+p) + \varepsilon = \mu\frac{\partial h}{\partial t} & (x,y,z) \in \Gamma_0, t \geq 0 \\ h\,(x,y,z)|_{\Gamma o} = h_1\,(x,y,z) & (x,y,z) \in \Gamma_1, t \geq o \\ K_n \frac{\partial h}{\partial n}\Big|_{\Gamma 2} = q_2\,(x,y,z,t) & (x,y,z) \in \Gamma_2, t \geq o \\ h_o\,(x,y,z,t)|_{t=0} = h_o & (x,y,z) \in \Omega \end{cases} \quad (4)$$

where [30] Ω is the flow area; Γ_0 is the upper boundary of flow area; Γ_1, Γ_2 are the specific head boundary and specific quantity boundary, respectively; q is the discharge per unit width of the specific quantity boundary (m^3/day/m); h_0 is the initial water level (m); h_1 is the water level of the specific head boundary (m); n is the total amount of well; K is the permeability coefficient of aquifer (m/day); x, y is the coordinates (m); s is the residual saturation; ε is the source and sink term (m^3); p is the precipitation item (m); and μ is the storage coefficient.

3.1.5. Joint Model

We used the FOEC [31] method to combine the surface water model and groundwater model.

$$\begin{aligned} q_{ss} &= \alpha\,(h_{sb} - h_s) \\ \alpha &= k_r \frac{K_{sat}}{l_e} \end{aligned} \quad (5)$$

where α is the FOEC conductance; l_e is the coupling length between surface water and groundwater (L); q_{ss} is the exchange capacity of surface water and groundwater ($L^3L^{-3}T^{-1}$); k_r is the relative permeability of upstream nodes; K_{sat} is the permeability coefficient of aquifer surface medium (LT^{-1}); h_{sb} is the groundwater level (L); and h_s is the surface water level (L).

3.2. Input Data

We collected monthly data on shallow groundwater depths of 120 monitoring wells across the Sanjiang Plain during 2008 and 2013 (Figure 1). We also collected monthly water table data from 26 hydrologic stations administered by the Jiamusi Bureau of Hydraulics for the same period. Water table depths in these wells were recorded with an automatic water level recorder (Odyssey, Dataflow Co., Christchurch, New Zealand). Those water data were used for establishing jointing simulation model of groundwater-surface water and calibration and validation.

3.3. Model Discretization, Calibration and Validation

We used the WetSpass-GMS [32,33] software to develop a joint model of groundwater-surface water.

3.3.1. Model Discretization

Spatial Discretization

The entire study area (10.9×10^4 km^2) was gridded into 0.1 km × 0.1 km squares (i.e., 0.01 km^2), making a total of 109,000 cells (Figure 2).

Temporal Discretization

In this study, the joint model of groundwater-surface water used the same spatial and temporal discretization. The temporal discretization period for the Sanjiang Plain was one month, and each period included three time steps.

3.3.2. Model Calibration

A total of 120 observation wells and 26 hydrology stations were used in the calibration process. The initial time of model recognition was 1 January 2008, and the end time of model recognition was 30 December 2010.

The model parameters that have been calibrated in this process included groundwater parameters such as hydraulic conductivity (K), storage coefficient (μ), the bottom of air pressure in a vadose zone ($\alpha(m^{-1})$), porosity size distribution index (β), residual saturation (Sγ), and pore connection index (Lp) (Figure 3 and Table 1), as well as surface water parameters such as manning roughness coefficient, depression storage (m), reduced storage (m) and coupling length (m) (Table 2).

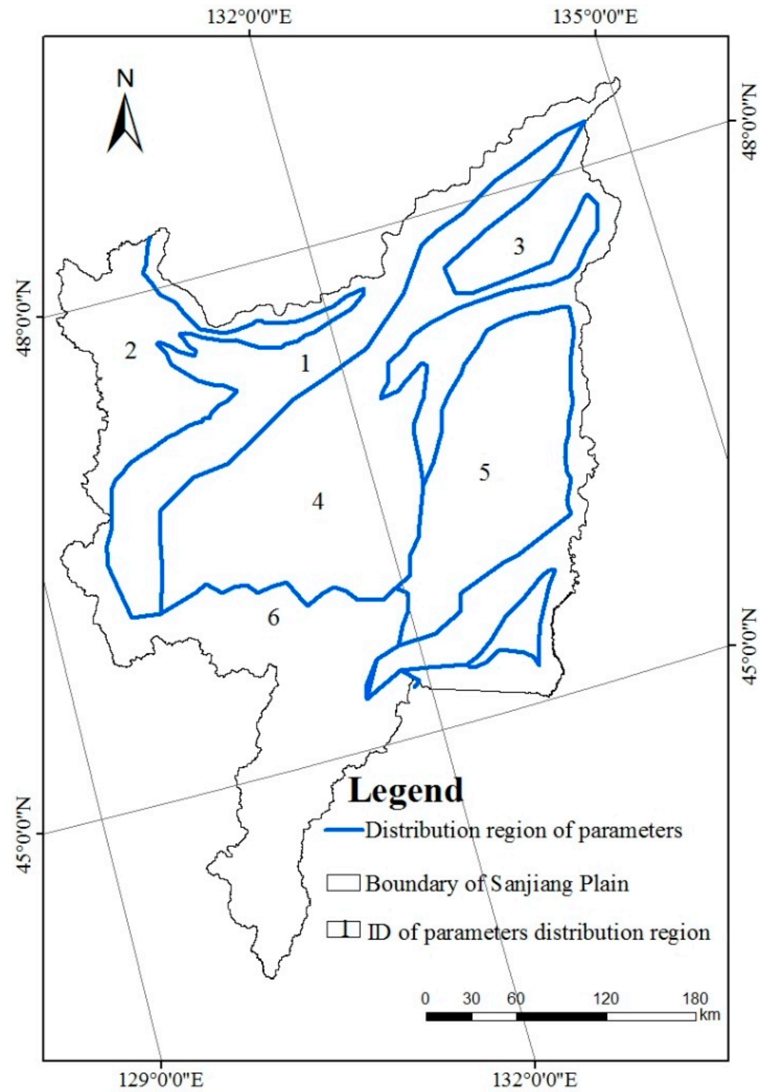


Figure 3. Spatial application of six sets of hydrogeology parameters for modeling (see Table 1).

Table 1. Calibrated hydrogeology parameters within the numerical model. The values in the parenthesis "( )" is the initial values of hydrogeology parameters before calibration.

ID	K(m/d)	μ	α(m^{-1})	β	Sγ	Lp
1	30 (32)	0.25 (0.3)	4.23 (4.21)	1.16 (1.15)	0.032 (0.046)	1.42 (0.41)
2	15 (18)	0.14 (0.20)	4.17 (4.07)	1.32 (1.28)	0.025 (0.032)	1.32 (1.36)
3	20 (20)	0.21 (0.21)	2.04 (1.78)	1.21 (1.04)	0.0.21 (0.024)	1.26 (0.25)
4	16 (20)	0.11 (0.10)	1.26 (1.3)	1.28 (1.30)	0.096 (0.097)	1.34 (1.42)
5	1 (2)	0.05 (0.05)	1.62 (1.56)	1.04 (1.19)	0.065 (0.065)	1.64 (1.82)
6	1 (1.5)	0.03 (0.03)	2.43 (2.43)	1.64 (1.64)	0.042 (0.056)	1.01 (0.64)

Table 2. Calibrated hydraulic parameters within the numerical model. The values in the parenthesis "( )" is the initial values of hydrology parameters before calibration.

Name	Woodland	Meadow	Wetland	Rice	Corn
Manning roughness coefficient	0.52 (0.62)	0.01 (0.04)	0.08 (0.06)	0.04 (0.05)	0.7 (0.2)
Depression storage (m)	0.031 (0.03)	0.002 (0.003)	0.0001 (0.002)	0 (0)	0.008 (0.002)
Reduced storage (m)	0.0002 (0.002)	0.0001 (0.0002)	0 (0)	0 (0)	0.0001 (0.001)
Coupling length (m)	0.4 (0.2)	0.7 (0.5)	0.05 (0.02)	0.02 (0.02)	0.56 (0.3)

3.3.3. Model Validation

We used two years of data collected between 1 January 2011 and 30 December 2012 to validate the reliability of the model. The relative error (RE), the absolute error (AE) and Nash–Sutcliffe efficiency (NSE) [34] were used to evaluate modeling results against the measurements. Comparisons between observed and simulated values for surface water (the relative error was less than 20%, and the NSE were more than 0.80) and groundwater (the absolute error was less than 0.5 m, and the NSE of Lianjiangkou, Jianguo village, Erlongshan city and Dongan city were 0.99, 0.98, 0.97 and 0.86, respectively; all more than 0.85) demonstrated satisfactory application of the groundwater-surface water joint modeling (Figures 4 and 5 and Table 3). Thus, the established joint model is capable to reflect the surface water and groundwater flow conditions in the Sanjiang Plain.

Table 3. River stage validation results of Baoan station.

Year		2008				2009				2010			
Station	**Month**	**OBV**	**SMV**	**RE (%)**	**NSE**	**OBV**	**SMV**	**RE (%)**	**NSE**	**OBV**	**SMV**	**RE (%)**	**NSE**
Baoan station	1	0.02	0.021	5	0.99	0.23	0.19	17.4	0.99	0.019	0.022	15.8	0.99
	2	0.1	0.11	10	0.99	0.21	0.24	14.3	0.99	0.02	0.017	15	0.99
	3	1.54	1.78	15.6	0.99	0.012	0.01	16.7	0.99	0.053	0.045	15.1	0.99
	4	5.13	4.23	17.5	0.96	4.11	3.46	15.8	0.99	15.1	13.86	8.2	0.98
	5	11.8	12.56	6.4	0.99	2.44	2.04	16.4	0.99	31.6	29.36	7.1	0.99
	6	5.22	4.63	11.3	0.98	6.04	5.89	2.5	0.99	4.69	4.15	11.5	0.90
	7	3.07	3.61	17.6	0.98	19.1	18.32	4.1	1.00	6.14	5.96	2.9	0.89
	8	1.57	1.68	7	0.98	23.6	21.56	8.6	0.99	11	9.6	12.7	0.91
	9	1.02	1.16	13.7	0.98	7.61	7.02	7.8	0.99	3.6	3.15	12.5	0.97
	10	1.2	1.36	13.3	0.98	3.12	2.98	4.5	0.99	2.65	2.34	11.7	0.99
	11	0.73	0.82	12.3	0.98	1.44	1.18	18.1	0.99	1.48	1.36	8.1	0.99
	12	0.145	0.163	12.4	0.98	0.488	0.402	17.6	0.99	0.34	0.28	17.6	0.99

Note: RE stands for relative error; NSE stands for Nash–Sutcliffe efficiency; OBV stands for observed values; SMV stands for simulated values.

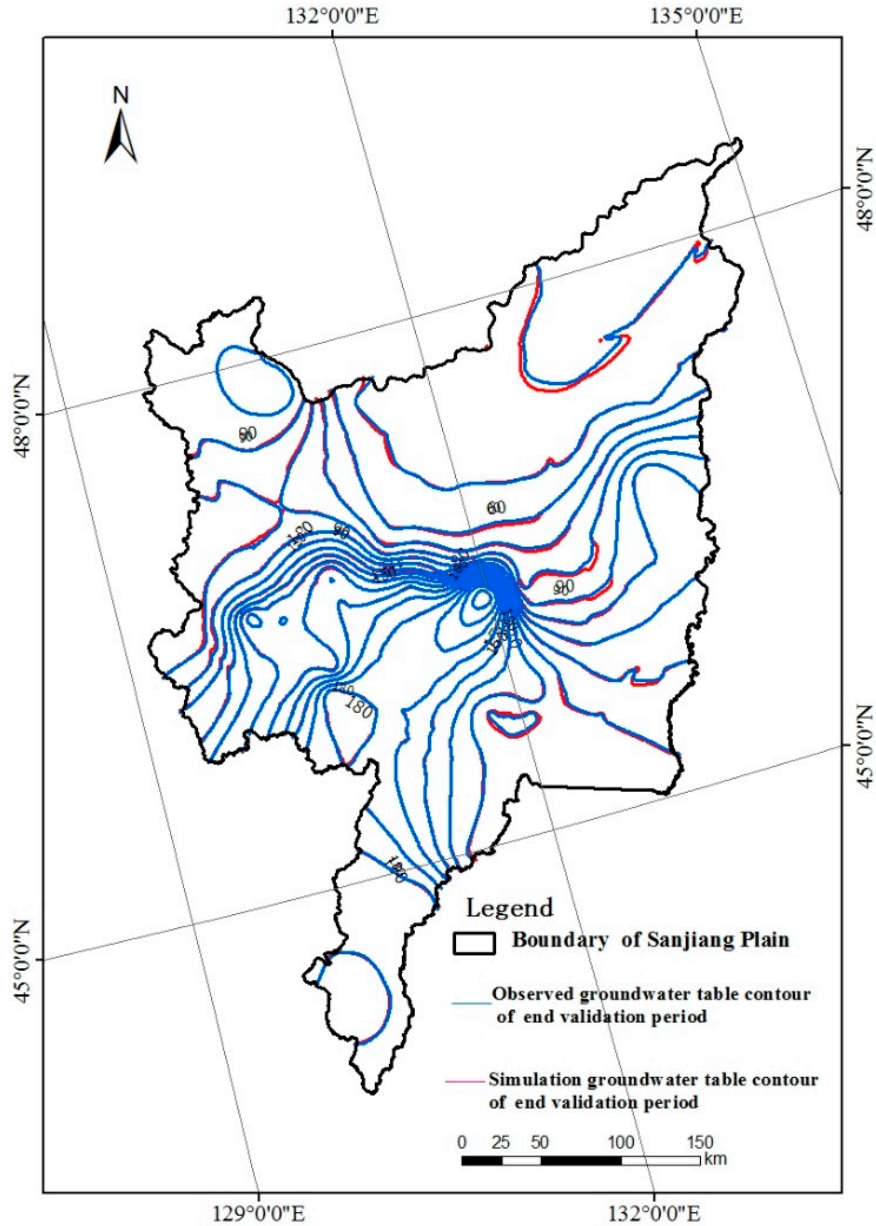


Figure 4. Comparison between the simulated and observed groundwater depths at the end date of the validation period.

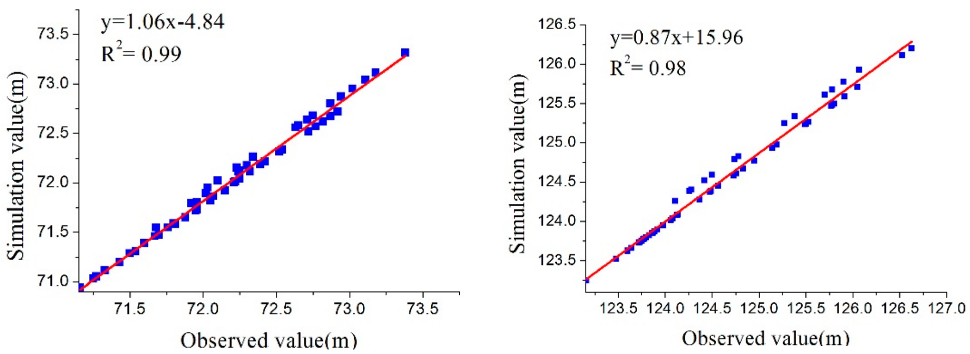
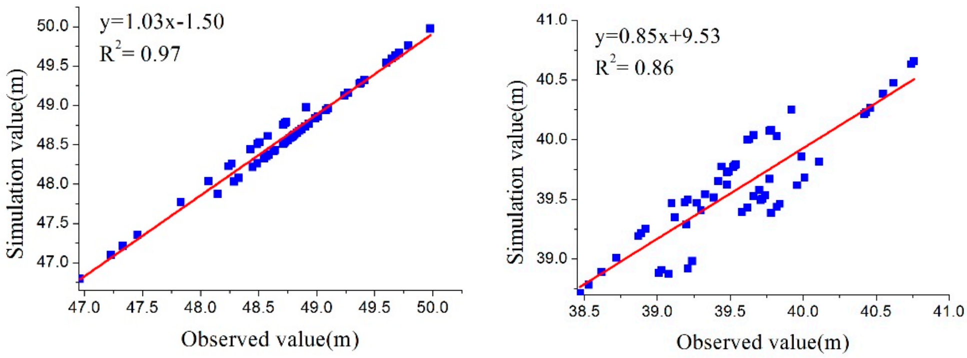


Figure 5. *Cont.*



(**c**) (**d**)

Figure 5. The calibration scatterplot between the simulated and observed groundwater depths. Solid red line is the best fit line: (**a**) Lianjiangkou; (**b**) Jianguo village; (**c**) Erlongshan city; and (**d**) Dongan city (Figure 1).

3.4. Simulation Scenarios

We proposed the following three scenarios for future groundwater use on the Sanjiang Plain.

Scenario A: An exploitation of groundwater use of 57.2 × 10^8 m^3/year and surface water use of 18.3 × 10^8 m^3/year. Industry and domestic uses have a proportion of 15%, while the rest 85% is designed for farmland irrigation. It is also consider for three different hydrological years: wet years, the years with 25% precipitation exceedance; normal years, the years with 50% precipitation exceedance; and dry years, the years with 75% precipitation exceedance. Scenario A plausibly represents the current water use situation on the Sanjiang Plain.

Scenario B: In this case, an exploitation of 46.54 × 10^8 m^3/year groundwater and 47.14 × 10^8 m^3/year surface water is proposed for the Sanjiang Plain. This water consumption scheme is based on the concept of ecologically ideal shallow groundwater depth proposed by Wang et al. [25]. Similarly, 15% of the consumption is for industrial and domestic uses, while 85% is for farmland irrigation; the calculation is done for wet, normal, dry years.

Scenario C: An exploitation of 46.54 × 10^8 m^3/year groundwater and 151.11 × 10^8 m^3/year surface water for irrigating all suitable farmland for rice culture (i.e., 266.7 × 10^4 hectares) on the Sanjiang Plain. Similarly, industrial and domestic uses count 15% and the rest 85% is for farmland irrigation; the calculation is done for wet, normal, and dry years.

4. Results and Discussion

4.1. Current Allowable Groundwater and Surface Water Resources of the Sanjiang Plain

The entire surface water resource in the Sanjiang Plain was 153.35 × 10^8 m^3/year, which included discharges of the Songhua River (69.19 × 10^8 m^3/year), Naoli River (34.92 × 10^8 m^3/year), and Woken River (49.24 × 10^8 m^3/year) (Figure 1). The allowable water resource for the Sanjiang Plain was actually only about one third (47.14 × 10^8 m^3/year) of the total surface water, taking out the river ecological water requirement. The allowable quantity of shallow groundwater for the Sanjiang Plain was 46.54 × 10^8 m^3/year (Table 4).

Table 4. The allowable quantity of surface water and groundwater of the Sanjiang Plain.

River	Average Runoff per Year (10^8 m^3)	River Ecological Water Requirement (10^8 m^3)			Allowable Surface Water Resources (10^8 m^3)	Allowable Groundwater Resources (10^8 m^3)
		Baseflow	Sand Washing	Water Requirement of Aquatic Life		
Songhua	69.19	13.84	6.57	27.68	38.05	-
Naoli	34.92	6.98	3.14	13.97	19.21	-
Woken	49.24	9.85	4.48	19.7	27.08	-
Total	153.35	30.67	14.2	61.34	47.14	46.54

4.2. Projections of Future Groundwater-Surface Water Resources

Scenario A: Under this scenarios, the estimates of groundwater storage for wet year, normal year and dry year on the Sanjiang Plain would decrease 38.30 × 10^8 m^3, 53.98 × 10^8 m^3 and 64.84 × 10^8 m^3, respectively (Table 5). Spatially, the groundwater table of Honghe farm for wet year (Figures 1, 6 and 7), normal year (Figures 8 and 9) and dry year (Figures 10 and 11) would occur far below the lower boundary of EISGD in 2028, 2023 and 2019, respectively. The results indicate that continuation of the current water use on the Sanjian Plain would cause continued decline of groundwater beyond the lower boundary of EISGD, which would lead to the surface ecological degradation and severe water shortage for semi-arid areas in the region.

Table 5. Groundwater storage change under three different scenarios.

Scenarios	Precipitation Assurance	The Change of Aquifer Water Storage (×10^8 m^3)
Scenario A	25%	−38.3
	50%	−53.98
	75%	−64.84
Scenario B	25%	18.36
	50%	6.23
	75%	−5.72
Scenario C	25%	22.61
	50%	11.2
	75%	4.77

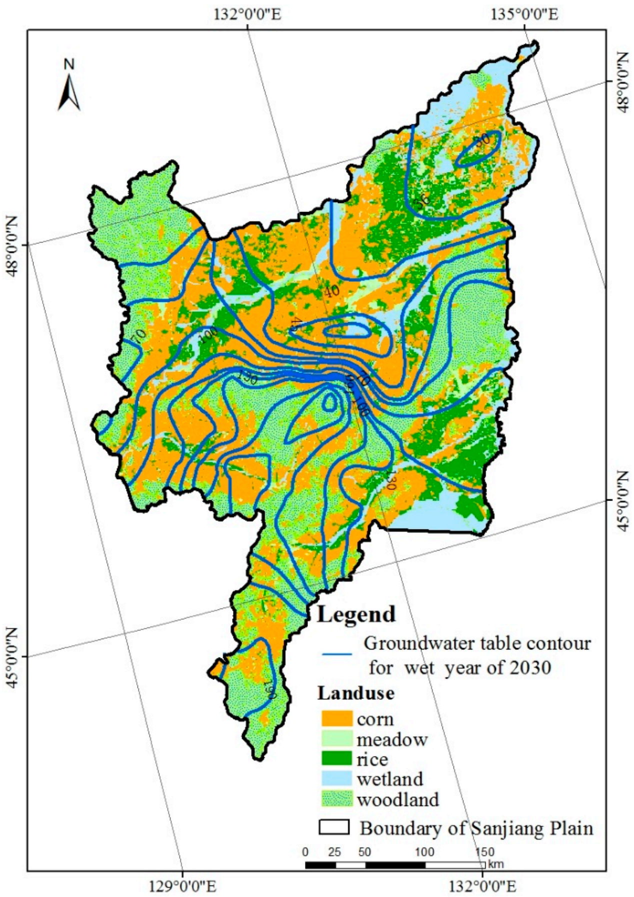


Figure 6. Groundwater table contour for a wet year (25%) of Scenario A of the Sanjiang Plain during 2030.

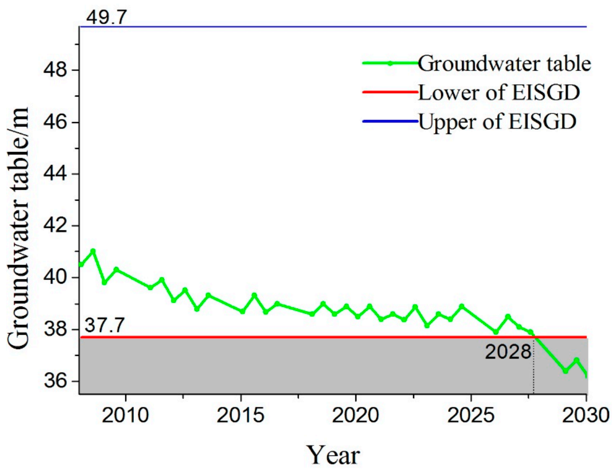


Figure 7. Groundwater table and ecologically ideal shallow groundwater depth (EISGD) for a wet year (25%) for Scenario A of the Honghe farm from 2008 to 2030. The gray background stands for the groundwater table that is below the lower boundary of EISGD.

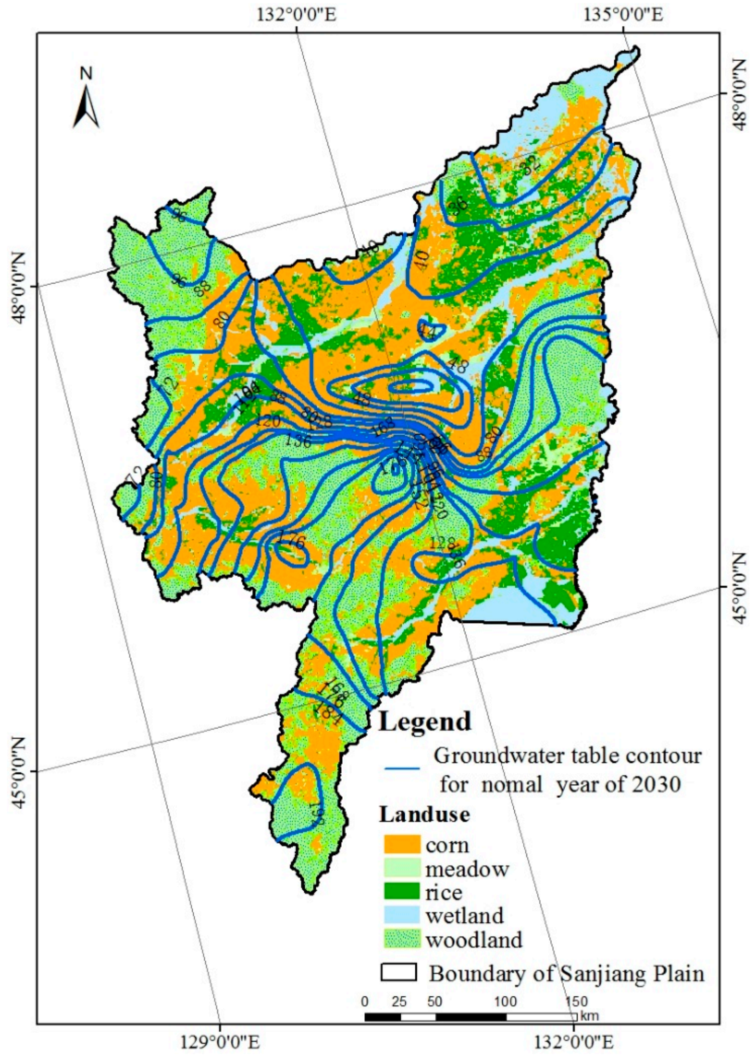


Figure 8. Groundwater table contour of a normal year (50%) for Scenario A of the Sanjiang Plain during 2030.

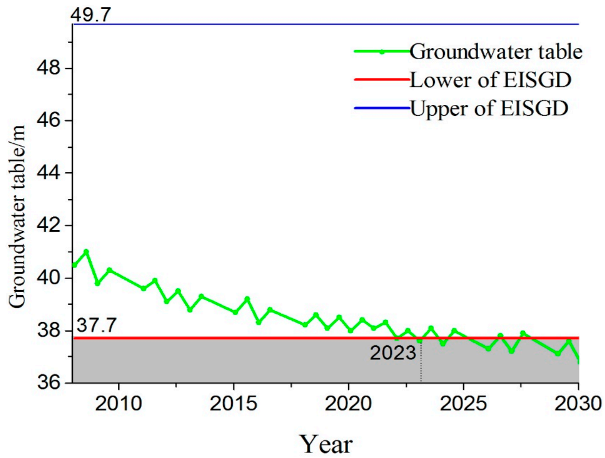


Figure 9. The groundwater table and ecologically ideal shallow groundwater depth (EISGD) for a normal year (50%) of Scenario A of the Honghe farm from 2008 to 2030. The gray background stands for the groundwater table that less than the lower boundary of EISGD.

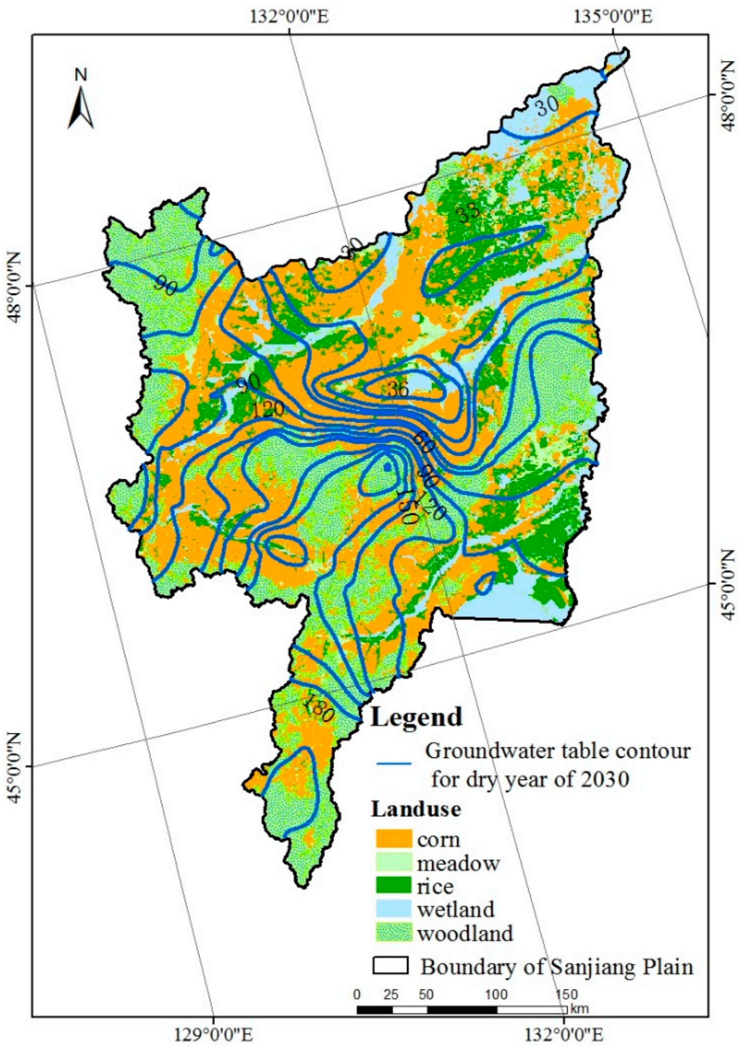


Figure 10. Groundwater table contour of the dry year (75%) of Scenario A of the Sanjiang Plain during 2030.

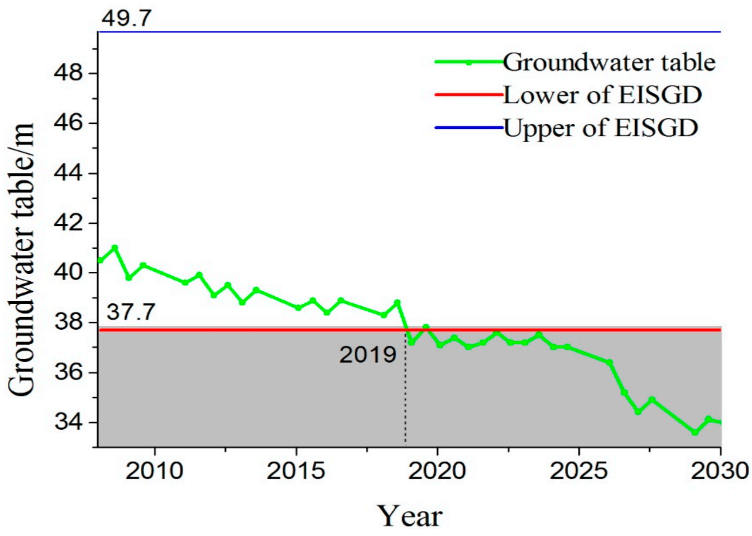


Figure 11. Groundwater table and ecologically ideal shallow groundwater table for a dry year (75%) of Scenario A of the Honghe farm from 2008 to 2030. The gray background stands for the groundwater table that is below the lower boundary of EISGD.

Scenario B: Aquifer storage of the Sanjiang Plain for wet year and normal year increased 18.36×10^8 m^3 and 6.23×10^8 m^3, respectively (Table 5). However, the aquifer storage of the Sanjiang Plain for dry year decreased 5.72×10^8 m^3 (Table 5). Meanwhile, the estimates for groundwater exploitation under the restriction of EISGD for wet year, normal year and dry year on the Sanjiang Plain were 53.61×10^8 m^3, 48.64×10^8 m^3 and 46.34×10^8 m^3, respectively (Table 5). The estimates for using surface water under restriction of EISGD for wet, normal and dry years on the Sanjiang Plain were 43.49×10^8 m^3, 45.05×10^8 m^3 and 45.05×10^8 m^3, respectively (Figures 1 and 12, Figures 13–17 and Table 5). Moreover, according to the irrigation quantity of the Sanjiang Plain for conventional (6300 m^3/hectare) and irrigation saving (3700 m^3/hectare), the water quantity can support the maximum rice areas under conventional irrigation for wet year, normal year and dry year on the Sanjiang Plain were 1.97 million hectares, 1.90 million hectare, 1.85 million hectare, respectively. However, the water quantities that are needed to support the maximal rice culture expansion under irrigation reduction for wet year, normal year and dry year on the Sanjiang Plain were 3.30 million hectares, 3.19 million hectares, and 3.11 million hectares, respectively (Table 6). The area for irrigation reduction amount to 1.5 times of the area of conventional irrigation, suggesting that promoting irrigation reduction on the Sanjiang Plain is ultimately important.

Table 6. Supporting rice areas of groundwater and surface water under Scenario B.

Scenario	Precipitation Assurance (%)	Allowable Using Water Resources (10^8 m^3)		Conventional Irrigation			Saving Irrigation		
		Groundwater	Surface Water	Supporting Rice Area by Groundwater (10^4 Hectare)	Supporting Rice Area by Surface Water (10^4 Hectare)	Total	Supporting Rice Area by Groundwater (10^4 Hectare)	Supporting Rice Area by Surface Water (10^4 Hectare)	Total
B	25	53.61	43.49	72.0	59.3	131.3	121.0	98.7	219.7
	50	48.64	45.04	65.3	61.3	126.6	110.0	102.7	212.7
	75	46.34	45.04	62.7	60.7	133.4	105.3	102.0	207.3

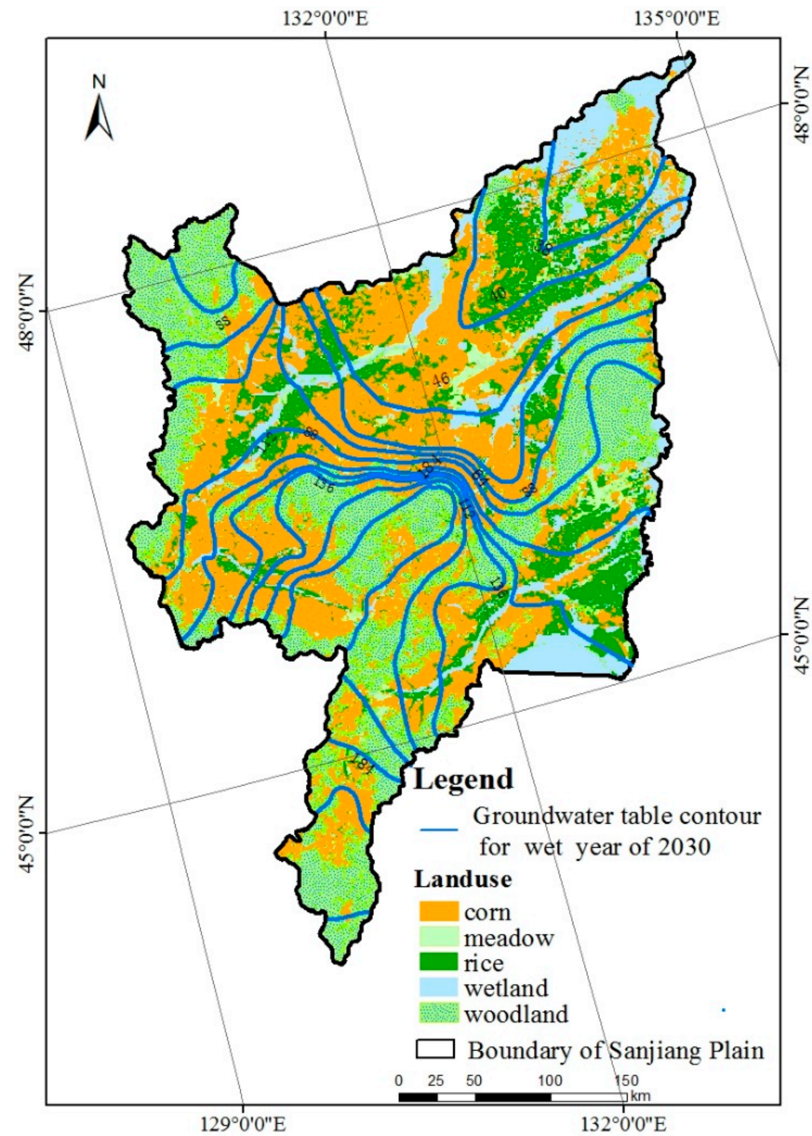


Figure 12. Groundwater table contour of a wet year (25%) of Scenario B of the Sanjiang Plain during 2030.

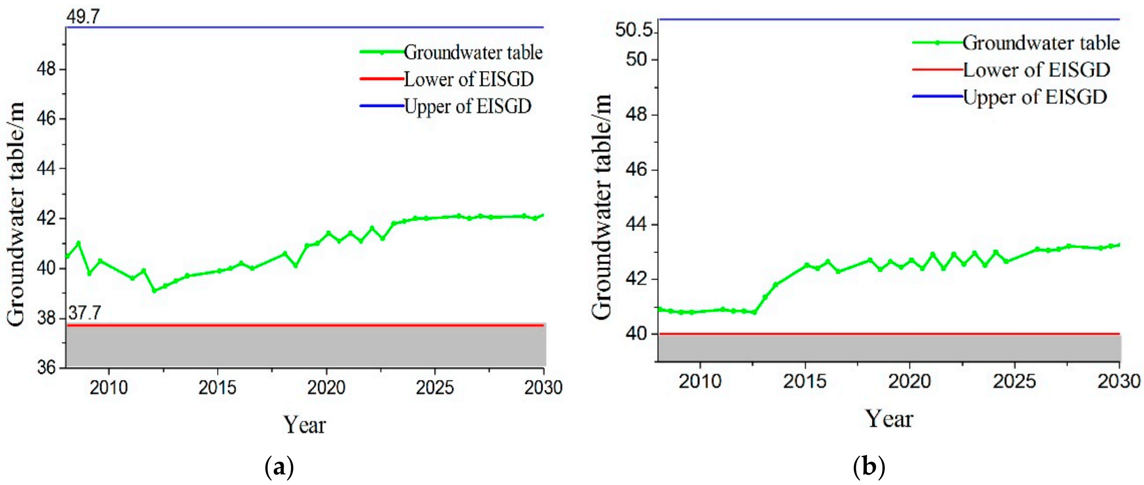
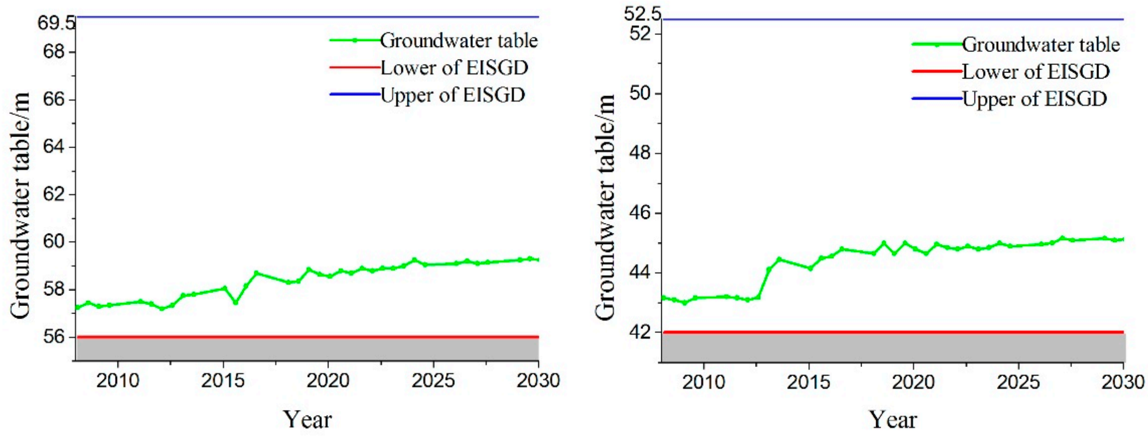


Figure 13. *Cont.*



(**c**) (**d**)

Figure 13. Groundwater table and ecologically ideal shallow groundwater depth (EISGD) for a wet year (25%) of Scenario B of the typical wells from 2008 to 2030: (**a**) Honghe F arm; (**b**) Chuangye Farm; (**c**) 854 Farm; and (**d**) Qixing Farm (Figure 1). The gray background stands for the groundwater table below the lower boundary of EISGD.

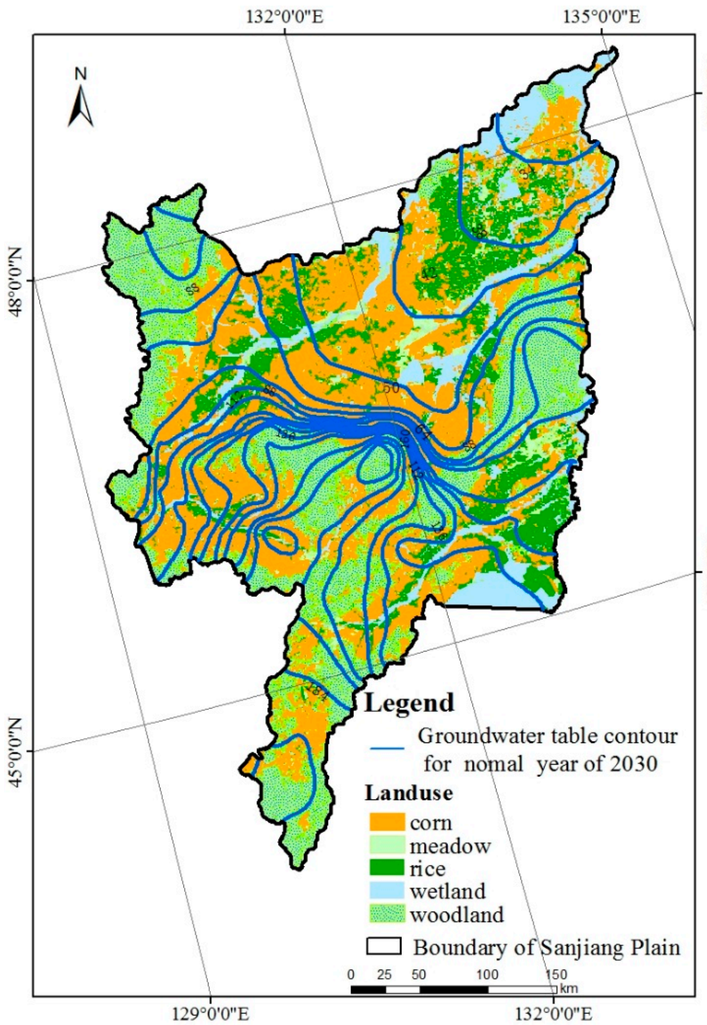


Figure 14. Groundwater table contour of a wet year (50%) of Scenario B of the Sanjiang Plain during 2030.

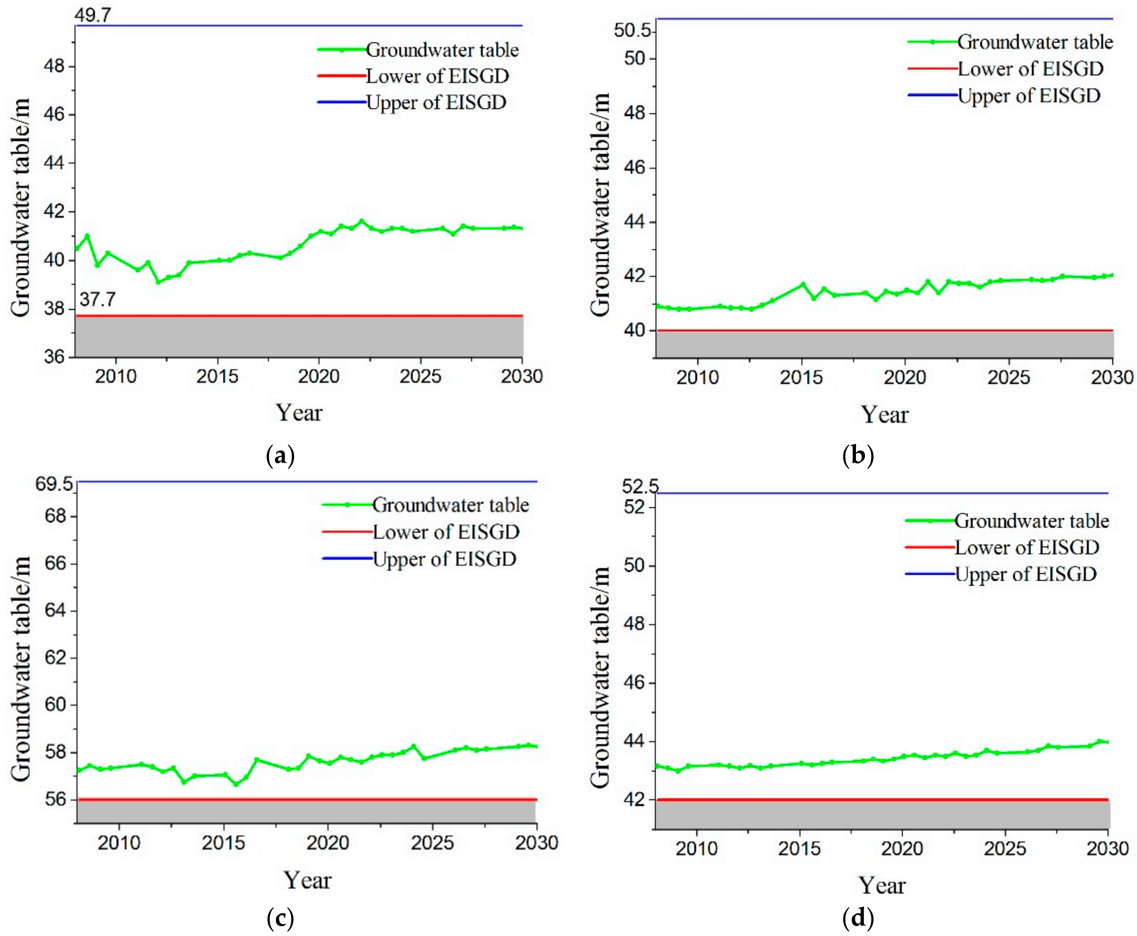


Figure 15. Groundwater table and ecologically ideal shallow groundwater table for a normal year (50%) of Scenario B of the typical wells from 2008 to 2030: (**a**) Honghe F arm; (**b**) Chuangye Farm; (**c**) 854 Farm; and (**d**) Qixing Farm (Figure 1). The gray background stands for the groundwater table below the lower boundary of EISGD.

Scenario C: Aquifer storage of the Sanjiang Plain for wet year and normal year increased 11.20×10^8 m^3, 4.77×10^8 m^3 and 6.23×10^8 m^3, respectively (Table 5 and Figures 16 and 17). However, the aquifer storage of the Sanjiang Plain for dry year decreased 5.72×10^8 m^3 (Table 7). Meanwhile, the exploitation groundwater under the restriction of EISGD for wet year, normal year and dry year on the Sanjiang Plain were 65.01×10^8 m^3, 58.46×10^8 m^3 and 50.35×10^8 m^3, respectively (Table 7), and using surface water under restriction of EISGD for wet year, normal year and dry year on the Sanjiang Plain were 86.10×10^8 m^3, 92.65×10^8 m^3 and 100.76×10^8 m^3, respectively (Table 5 and Figures 16 and 17). More water is needed for irrigating the 266.67×10^4 hectares of rice paddies on the Sanjiang Plain. Therefore, a need for using more surface water under the restriction of EISGD would be 38.96×10^8 m^3 for a wet year, 45.51×10^8 m^3, for a normal year, and 53.62×10^8 m^3 for a dry year on the Sanjiang Plain (Table 7). However, the quantities are large and it is a serious problem to divert river waters in the region. The Heilong River and Wusuli River are international rivers bordering China and Russia with an annual average yield of 346.5 billion m^3 and 61.9 billion m^3, respectively (Figure 1). If China plans to use the river water for irrigation, negotiations would be necessary between the two countries.

From Scenario A to Scenario B, it showed that the groundwater table increased with the increasing use of surface water. This suggests that Scenario B would benefit ecological protection of local wetlands and reservoirs. On the other hand, high shallow groundwater in the region could be detrimental to some vegetation for possibly accumulating salts in the upper soil layer [25]. Therefore, the EISGD and allowable groundwater and surface water resources on the Sanjiang Plain were used to control the groundwater table.

Reducing irrigation can help reduce pressure on groundwater use, which is especially important for sustainable agriculture in the semi-arid areas on the Sanjian Plain. In fact, reduced irrigation schedules have been used widely on the Sanjiang Plain. Peng [35] reported an effective irrigation schedule named “controlled irrigation”, which would keep water table only in the returning stage of rice growing and could save nearly 50% of water use [36]. Therefore, the schedule has been wildly adopted in rice paddy irrigation on the Sanjiang Plain [37,38] and its promotion is still needed in the future.

The change from Scenario B to Scenario C suggests that the water resources (i.e., groundwater and surface water) of the Sanjiang Plain cannot meet the requirement for irrigating all the areas that are suitable for rice culture. For the Sanjiang Plain, designed by the Chinese government to become the largest rice production region in the future, the most challenging question how to solve the water resource shortage and how to expand rice culture while not further increasing groundwater use.

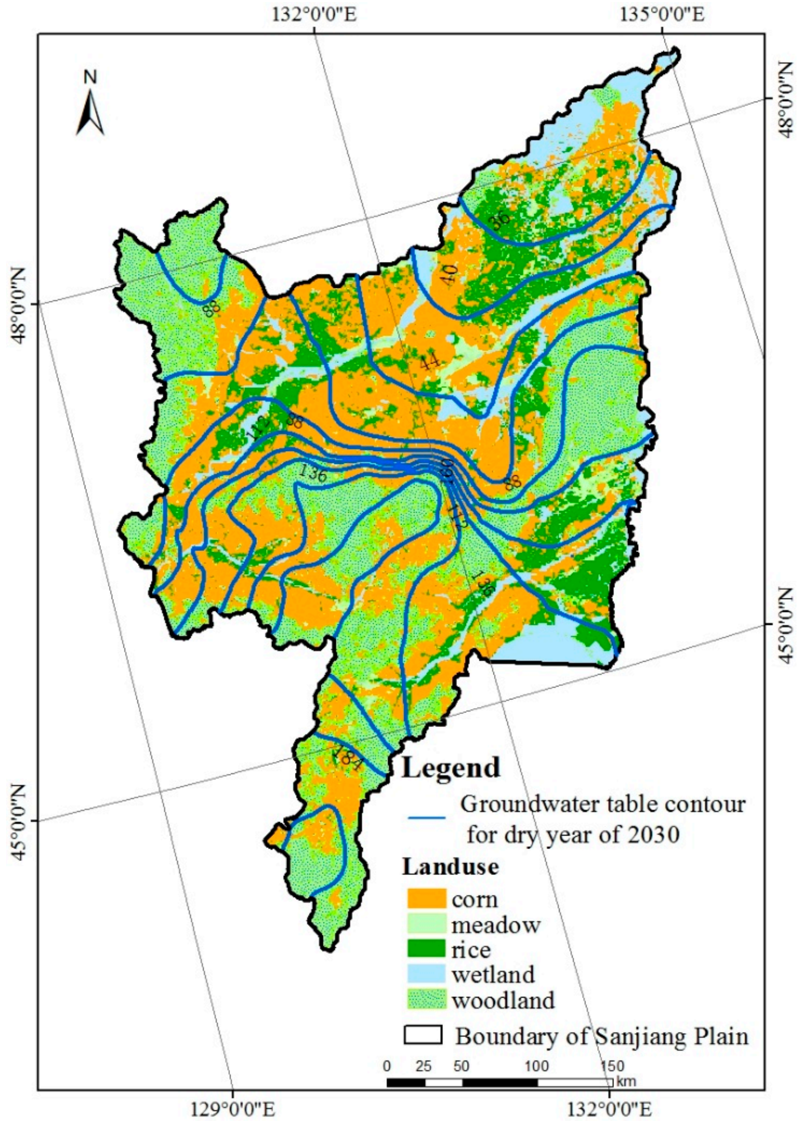


Figure 16. Groundwater table contour of the wet year (75%) of Scenario B of the Sanjiang Plain during 2030.

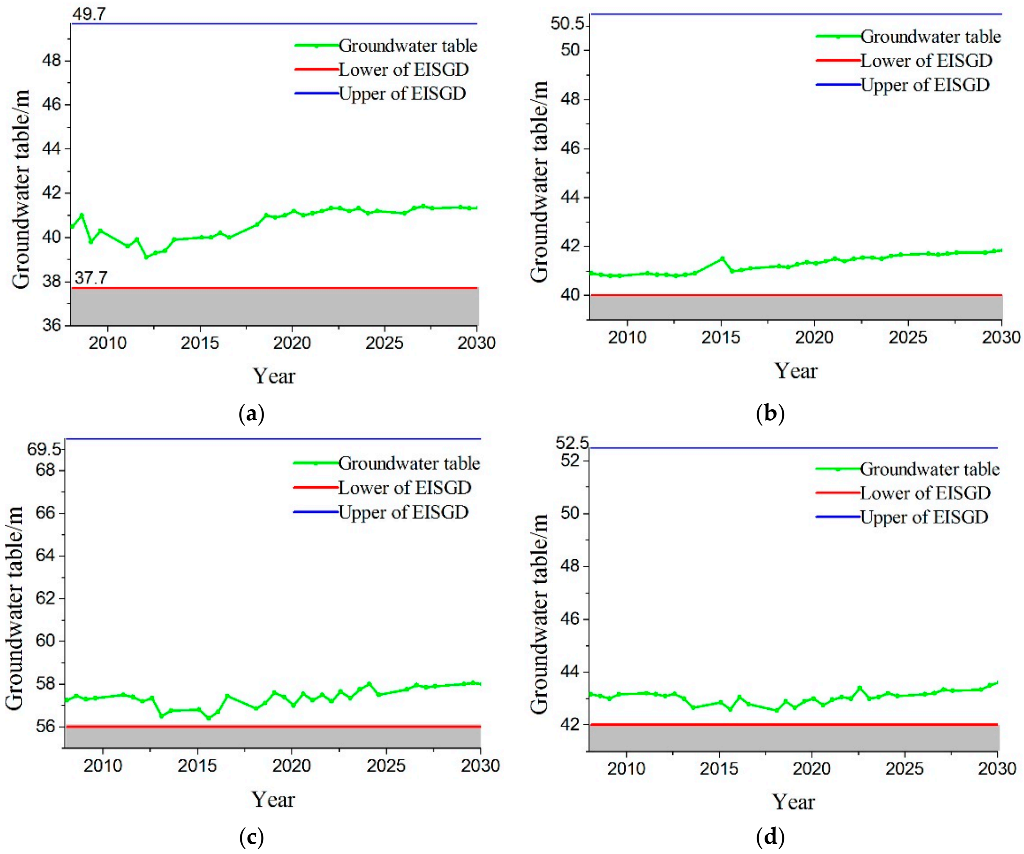


Figure 17. Groundwater table and ecologically ideal shallow groundwater depth (EISGD) for a dry year (75%) for Scenario B of the typical wells from 2008 to 2030: (**a**) Honghe Farm; (**b**) Chuangye Farm; (**c**) 854 Farm; and (**d**) Qixing Farm (Figure 1). The gray background stands for the groundwater table below the lower boundary of EISGD.

Table 7. The groundwater and surface water exploitation quantity for irrigation of 266.7 × 10^4 hectares under Scenario C of the Sanjiang Plain.

Scenario	Precipitation Assurance (%)	Allowable Using Water Resources (10^8 m^3)		Needing More Water Quantity (10^8 m^3)
		Groundwater	Surface Water	
C	25	65.01	86.1	38.96
	50	58.46	92.65	45.51
	75	50.35	100.76	53.62

5. Conclusions

This study is the first assessment of a joint simulation of groundwater and surface water based on a double control of water quantity and water level for the Sanjiang Plain in Northeast China, one of China's most important grain production regions and the country's largest inland freshwater wetland area. The study found that the allowable surface water and groundwater resources were 47.14 × 10^8 m^3 and 46.54 × 10^8 m^3, respectively. If water exploitation continues under the current water use, groundwater table in the region would decrease continuously, which may cause regional degradation of terrestrial ecosystems. The study also found that fully using the allowable surface water and groundwater can only support approximately 83% of the area that are suitable for rice culture on the Sanjiang Plain. Based on the findings, we suggest that local and regional authorities develop integrated water resources management plans that promote increase of surface water use and reduction in irrigation with groundwater in order to ensure sustainable agriculture and ecological preservation of the Sanjiang Plain.

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

References

1. Winter, T.C. *Ground Water and Surface Water: A Single Resource*; DIANE Publishing Inc.: Denver, CO, USA, 1998.
2. Stonestrom, D.A.; Jim, C. *Heat as a Tool for Studying the Movement of Ground Water near Streams*; U.S. Department of the Interior: Washington, DC, USA; U.S. Geological Survey: Reston, VA, USA, 2003.
3. Vandersteen, G.; Schneidewind, U.; Anibas, C. Determining groundwater-surface water exchange from temperature-time series: Combining a local polynomial method with a maximum likelihood estimator. *Water Resour. Res.* **2015**, *51*, 922–939. [CrossRef]
4. Irvine, D.J.; Cranswick, R.H.; Simmons, C.T.; Shanafield, M.A.; Lautz, L.K. The effect of streambed heterogeneity on groundwater-surface water exchange fluxes inferred from temperature time series. *Water Resour. Res.* **2015**, *51*, 198–212. [CrossRef]
5. Wang, W.K.; Dai, Z.X.; Zhao, Y.Q.; Li, J.T.; Duan, L.; Wang, Z.F.; Zhu, L. A quantitative analysis of hydraulic interactin processes in stream-aquifer systems. *Sci. Rep.* **2016**, *6*, 1–12.
6. Herrea-Pantoja, M.; Hiscock, K.M.; Boar, R.R. The potential impact of climate change on groundwater-fed wetlands in Eastern England. *Ecohydrology* **2012**, *5*, 401–413. [CrossRef]
7. Crosbie, R.S.; Scanlon, B.R.; Mpelasoka, F.S.; Reedy, R.C.; Gates, J.B.; Zhang, L. Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA. *Water Resour. Res.* **2013**, *49*, 3936–3951. [CrossRef]
8. Zeng, R.; Cai, X. Analyzing streamflow changes: Irrigation-enhanced interaction between aquifer and streamflow in the Republican River Basin. *Hydrol. Earth Syst. Sci. Discuss.* **2014**, *10*, 7783–7807. [CrossRef]
9. Wang, X.H.; Zhang, G.X.; Xu, Y.J.; Sun, G.Z. Assessing the regional-scale groundwater-surface water interaction on the Sanjiang Plain, Northeast China. *Environ. Sci. Pollut. Res.* **2015**, *22*, 16951–16961. [CrossRef] [PubMed]
10. Quan, J.; Dong, Z.C. Study on the joint regulation model of groundwater-surface water in the Shiyang river, China. *Yellow River* **2008**, *5*, 39–40.
11. Meng, X.M. *Couple Simulation and Predicting Study of Groundwater-Surface Water Model in the Jining City, China*; Hehai University: Nanjing, China, 2007.
12. Wang, L. *Couple Simulation of Groundwater-Surface Water in the Jilin City, Northeast China*; Jilin University: Changchun, China, 2014.
13. Liu, X.G. *Study on the Joint Regulation of Groundwater-Surface Water in the Huangshui River Basin, China*; Jinan University: Guangzhou, China, 2010.
14. Yang, X.; Yang, W.; Zhang, F.; Chu, Y.; Wang, Y. *Investigation and Assessment of Groundwater Resources Potential and Eco-Environment Geology in Sanjiang Plain. China Geology Survey*; Geological Publishing House: Beijing, China, 2010.
15. Querner, E.P. *The Combined Surface and Groundwater Flow Model MOGROW Applied to the Hupselse Beek Drainage Basin*; IAHS Publ.: Maastricht, The Netherlands, 1994.
16. Fleckenstein, J.; Michael, A.; Graham, F.; Jeffrey, M. Managing Surface Water-Groundwater to Restore Fall Flows in the Cosumnes River. *J. Water Resour. Plan. Manag.* **2004**, *130*, 301–310. [CrossRef]

17. Danie, L.; Hector, M.; Justin, C. Conjunctive Management of Groundwater and Surface Water Resources in the Upper Ovens River Valley. In Proceedings of the Irrigation and Drainage Conference 2009: Irrigation Today—Meeting the Challenge, Swan Hill, Australia, 18–21 October 2009.
18. Kevin, B.M.; David, P.A. Model reduction for combined surface water-groundwater management formulations. *Environ. Model. Softw.* **2016**, *8*, 102–110.
19. Hamid, R.S.; Mahdieh, E. Conjunctive Use of Surface Water and Groundwater: Application of Support Vector Machines (SVMs) and Genetic Algorithms. *Water Resour. Manag.* **2013**, *27*, 2623–2644.
20. Zhao, Q.; Han, Y.M. Analysis of stimulated recharge of groundwater on the Jiansanjiang Farming Bureau, Sanjiang Plain. *J. Heilongjiang Hydraul. Eng. Coll.* **2008**, *3*, 1–4.
21. Pan, X.F.; Yan, B.X. Effects of land use and changes in cover on the transformation and transportation of iron: A case study of the Sanjiang Plain, Northeast China. *Sci. China Earth Sci.* **2011**, *54*, 686–693. [CrossRef]
22. Wang, X.; Yan, B.X. The spatial variation and factors controlling the concentration of total dissolved iron in rivers, Sanjiang Plain. *Clean Soil Air Water* **2012**, *40*, 712–717. [CrossRef]
23. Cao, Y.J.; Tang, C.Y.; Song, X.F.; Liu, C.M.; Zhang, Y.H. Characteristics of nitrate in major rivers and aquifers of the Sanjiang Plain, China. *J. Environ. Monit.* **2012**, *14*, 2624–2633. [CrossRef] [PubMed]
24. Song, K.; Liu, D.; Wang, Z.; Zhang, B.; Jin, C.; Li, F.; Liu, H. Land use change in Sanjiang Plain and its driving forces analysis since 1954. *J. Geogr. Sci.* **2008**, *63*, 93–104.
25. Wang, X.H.; Zhang, G.X.; Xu, Y.J. Defining an ecologically ideal shallow groundwater depth for regional sustainable management: Conceptual development and case Study on the Sanjiang Plain, Northeast China. *Water* **2015**, *7*, 3997–4025. [CrossRef]
26. Li, F.P.; Zhang, G.X.; Xu, Y.J. Spatiotemporal variability of climate and streamflow in the Songhua River Basin, Northeast China. *J. Hydrol.* **2014**, *514*, 53–64. [CrossRef]
27. Li, Y.F. Study on the eco-environmental changes in Sanjiang Plain during recent years. *Environ. Sci. Manag.* **2013**, *38*, 42–46.
28. Wang, X.; Zhang, G.; Xu, Y.J. Spatiotemporal groundwater recharge estimation for the largest rice production region in Sanjiang Plain, Northeast China. *J. Water Supply Res. Technol.* **2014**, *63*, 630–641. [CrossRef]
29. Pandy, S.; Huyakorn, P.S. A full coupled physically-based spatially-distributed model for evaluating surface/subsurface flow. *Adv. Water Resour.* **2004**, *27*, 361–382. [CrossRef]
30. Jon, P.J. Simulating Hydrologic System Using a Physically Based, Surface-Subsurface Model: Issues Concerning Flow, Transport and Parameterization. Ph.D. Thesis, University of Waterloo, Toronto, ON, Canada, 2005.
31. Liggett, J.E.; Werner, A.D.; Simmons, C.T. Influence of the first-order exchange coefficient on simulation of coupled surface–subsurface flow. *J. Hydrol.* **2012**, *414*, 503–515. [CrossRef]
32. Batelaan, O.; Smedt, D.F. WetSpass: A flexible, GIS based, distributed recharge methodology for regional groundwater modelling. In Proceedings of the Sixth IAHS Scientific Assembly on Impact of Human Activity on Groundwater Dynamics, Maastricht, The Netherlands, 18–27 July 2001; pp. 11–18.
33. Zhang, X.B. Groundwater modeling system (GMS) software. *Hydrogeol. Eng. Geol.* **2003**, *5*, 53256.
34. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Trans. ASABE* **2007**, *50*, 885–900. [CrossRef]
35. Peng, S.Z.; Xu, J.Z.; Huang, Q.; Liu, F.L. Controlled irrigation of paddy rice and environmental multifunctionality. *J. Shenyang Agric. Univ.* **2004**, *35*, 443–445.
36. Wang, X.H.; Lu, W.X.; Xu, Y.J.; Zhang, G.X.; Qu, W.; Cheng, W.G. The positive impacts of irrigation schedules on rice yield and water consumption: Synergies in Jilin Province, Northeast China. *Int. J. Agric. Sustain.* **2016**, *14*, 1–12. [CrossRef]
37. Nie, X.; Wang, Y.Y.; Liu, X.T.; Zhao, Z.C.; Ma, T.T. Water consumption and water use efficiency of rice of Sanjiang plain under control irrigation. *Syst. Sci. Compr. Stud. Agric.* **2011**, *27*, 228–232.
38. Sun, D.W.; Yu, H.Y. Effect analysis on water control irrigation technology of rice in Heilongjiang reclamation area. *J. Northeast Agric. Univ.* **2008**, *39*, 104–107.