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Assessment of Shallow Groundwater Recharge from Extreme Rainfalls in the Sanjiang Plain, Northeast China

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Abstract: Groundwater recharge from rainstorms can be vital for regional water resources. With the expansion of the need for more water in some specific regions under global climate change, groundwater is being pumped at a far greater rate than it can be naturally replenished. Considering that excess rainstorms could be utilized for groundwater recharge to lessen the declining tendency of regional groundwater level in the Sanjiang Plain, Northeast China, we analyzed groundwater changes in the quantity of a regional shallow aquifer in the region following extreme rainfall in 2013. The results show that shallow groundwater table in the north and central Sanjiang Plain increased following the 2013 extreme rainfall. Most of the annual maximal change of groundwater depth (MCGD) was in the range of 1 m to 3 m, occupying 72.1% of the study area. The average MCGD was 1.73 m in 2013, about 0.4 m higher than the mean value during the last five years (1.33 m). Spatially, the overall average groundwater depth showed an increasing trend from the southeast to the midwest and northeast. We estimated a total recharge of approximately 41.14×10^8 m^3 from the 2013 extreme rainfall across the north and central Sanjiang Plain. This large quantity of recharge demonstrates the important role that large rainstorms can play in regional shallow groundwater resources.

Keywords: extreme rainfall; groundwater-surface water interaction; groundwater storage; recharge; Sanjiang Plain

1. Introduction

Groundwater from shallow aquifers is a life-sustaining resource that is integral to sustaining regional agriculture, economic development, and ecological integrity in many parts of the world [1–3]. However, groundwater is often being pumped at far greater rates than it can be naturally replenished, which poses a far greater threat to global water security than is currently acknowledged [4]. The rate of global groundwater depletion was estimated at 113 km^3/year during 2000–2009, and has likely more than doubled since the period of 1960–2000 [5]. With the increased demand of water resources due to intensive agriculture and urban development, groundwater in many regions of the world now faces a crisis of exhaustion. Recent studies have exposed excessive rates of groundwater depletion resulting from a lack of intra- or international oversight [6,7]. The excessive use of groundwater resources can have serious consequences, such as land subsidence, uplifting and seismic activities, vegetation degradation, ecological environment deterioration, livelihoods for rural poor and food security implications [8,9]. In view of the shrinking groundwater resources, it is important to develop effective techniques and methods to study the trend of groundwater storage (increase/decrease) and its recharge-discharge relationship, which can support the mitigating measures of over-pumping shallow groundwater to ensure the sustainable utilization of groundwater resources.

Previous research has shown that the continuously decreasing of shallow groundwater table is not only closely related with increased local exploitation but also with the greatly reduced supply of regional rainstorm floods [10–12]. For storm floods, most studies focused on flood disasters and forecast [13,14], flood risk and efficiency [15,16], and floodwater utilization [17,18], which has been extended such that rain-flood can be one of the main recharge sources for groundwater in some regions [19,20]. Despite the disaster of floods, under positive circumstances, flood water can be used to constitute a considerable amount of a region's water resources [21], especially in a groundwater system. Doble et al. [22,23] reported that inundated floodplains always had high recharge rates for shallow groundwater. In a study on the relation between river stage and groundwater table in Russia, Belousova [24] found that floods with different intensities caused different levels of groundwater. Simpson et al. [20] showed that floods with different sizes and durations could affect riparian shallow groundwater systems, and that larger flood events could result in much higher groundwater recharge. Wang et al. [25] assessed the flooding's impact mainly on shallow groundwater table and quality in the Sanjiang Plain. A few recent studies found that flood events could supplement groundwater; however, the complex hydro-meteorological processes and insufficiency data limit this effort. Compared with conventional water resources (namely, the water resource is stable and reliable which can be sustainable used, such as water supply from reservoirs, rivers, and groundwater wells), the floodwater has complexities and particularities. In addition, its monitoring data and information is usually insufficient over a long time period, which raises difficult challenges in evaluating the impacts of the extreme flood on regional groundwater storage. In this context, how to quantitatively calculate and assess the extreme rainfall's impact on groundwater recharge while only relying on limited data is worthy of further research.

This paper aims to combine spatial analysis and water table fluctuation method to estimate groundwater recharge following a heavy rainstorm in the Sanjiang Plain, northeast China, providing a basis upon which future researchers and decision-makers can use to achieve the main goals of groundwater management and the sustainable use of water resources.

2. Study Area

The Sanjiang Plain (literally in Chinese: three-river floodplain) is located in Heilongjiang Province, northeast China, covering a total land area of approximately 10.9×10^4 km^2 (Figure 1). The climate of this region can be characterized by a temperate continental monsoon climate, with a long-term annual average temperature of 2.8 °C and the annual evaporation of 550–840 mm. The annual average precipitation is 500–650 mm, more than 60.0% of which falls within three months from June to August. A study [26] found that annual temperature showed a rising trend of 0.26 °C/10a in the region; the annual precipitation showed slight changes, but the rainy period and the dry period showed decreased and increased trends, respectively; the runoff of the main rivers showed a significantly downward trend in the annual.

The topography of the Sanjiang Plain is flat, as much of the region is located on the floodplain with a slope gradient between 0.01% and 0.02%. It is a large alluvial plain formed in the lower reach of three rivers—the Songhua, Heilong and Wusuli Rivers. The Heilong and Wusuli Rivers are international rivers draining China's and Russia's territorial lands with an annual average yield of 3.47×10^{11} and 6.19×10^{10} m^3, respectively. Flowing across the Sanjiang Plain, the Songhua River yields a long-term annual average of 7.27×10^{10} m^3. The discharges of the Songhua and Heilong Rivers decreased continuously over the past 60 years [27]. The Sanjiang Plain is largely covered by Quaternary alluvial sediments, where the major mining layers of groundwater are located. 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 a mix of loam, fine sand, medium sand, sandy clays, silts and volcanic rocks [25].

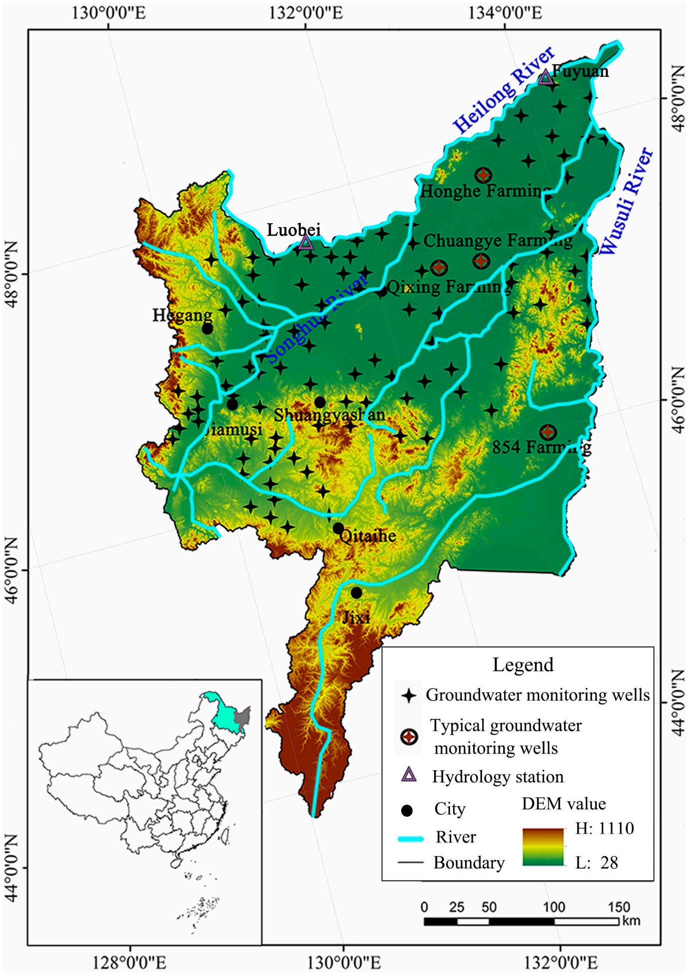

Figure 1. Geographical location of the Sanjiang Plain, Northeast China, and the monitoring wells used in this study.

According to the official reports on water resources in 2014, groundwater supply accounts for 64% of the total water consumption in the Sanjiang Plain. The study area has traditionally supported its agriculture, which makes up over 80% of the total water consumption, leading to a continual descent of the groundwater table. The falling groundwater table is a serious issue in the Sanjiang Plain, because it strengthens the water leakage of wetlands, intensifying the water shortage and ecological service degradation of wetlands. With the development of National Grain Implementation Production Plan in the Sanjiang Plain, the irrigation area extends, increasing the demand for water resources, which will change the regional water cycle and water resources conditions [28].

In 2013, heavy rainfall occurred in the Heilong River basin between China and Russia lasting from the end of July to early September. This has caused many areas of the Sanjiang Plain to experience flooding. The average rainfall of Heilongjiang Province reached 453 mm in this summer, 33% more than the normal [29]. The feature of the precipitation distribution appeared on a diminishing scale from east to the middle and from south to the north across the Sanjiang Plain (Figure 2). The heaviest and lightest rainfall occurred in the east and northeast of the study area, respectively. From 15 to

17 August, heavy rainfall exacerbated the situation, causing the worst flooding in the region in more than a decade. On 25 August, the Heilong River's water level has hit 99.85 m in Luobei County, 2.05 m above the warning level, surpassing the previous record set in 1984 [30]. The water level exceeding warning line lasted 28 days at Luobei station. By 2 September, water levels at the hydrologic station of Fuyuan reached 89.88 m, 2.38 m above the warning level, exceeding the highest record in 1984. The water level above warning line lasted 46 days at Fuyuan station (Figure 3, Table 1). The event was reported as a 118-year highflow [31]. This extreme rainfall event provided an opportunity to investigate the impact of a major rainstorm on regional shallow groundwater. Extreme weather and heavy rain is expected to take a greater toll in the future as global warming intensifies. Climate change has led to more frequent rainstorms in Heilongjiang Province [29], which may play an important role in the regional groundwater resources. In this context, it is efficient to make full use of rain floods resources, which can mitigate the continuous declination trend of groundwater in the Sanjiang Plain. Therefore, determining how to reasonably use the pass-by rainstorm resource to curb the rapid decline of groundwater table and improve the efficiency of water utilization becomes a critical issue. Assessing the impacts of extreme rainfall on regional groundwater storage is the priority of this effort.

Table 1. Information of hydrologic stations in the Heilong River.

Station	Warning Level (m)	Highest Record in 2013		Highest Record in History	
		Water Level (m)	Time	Water Level (m)	Time
Luobei	97.80	99.85	25 August	99.57	23 August 1984
Fuyuan	87.50	89.88	2 September	88.33	29 August 1984

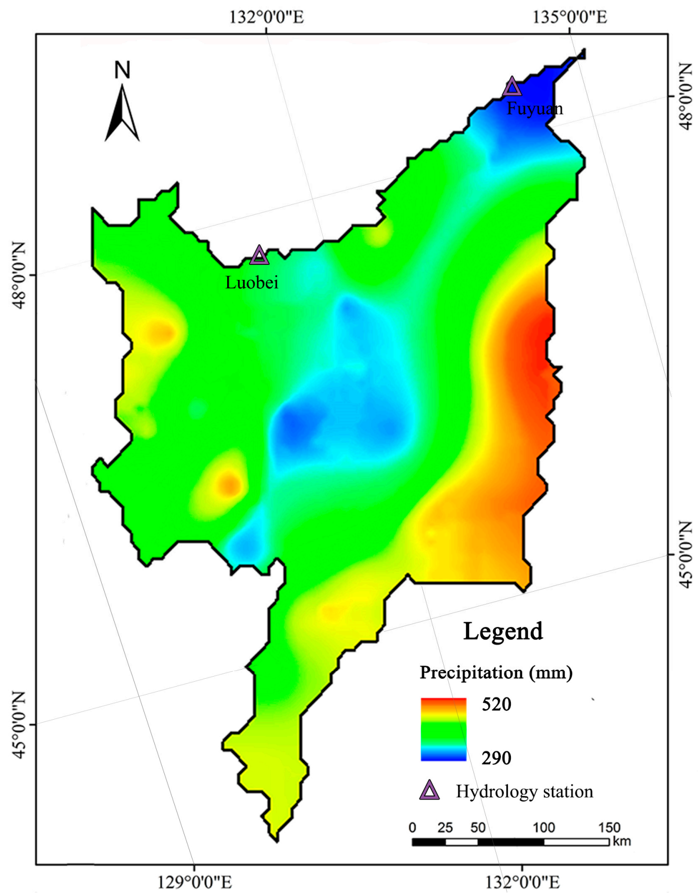

Figure 2. The distribution of the precipitation in the summer of 2013.

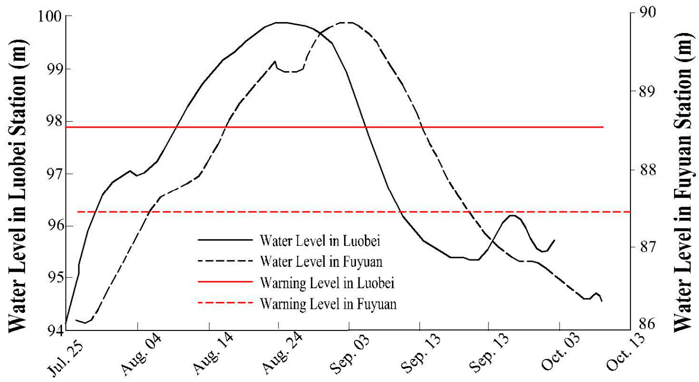

Figure 3. Water levels at the Luobei and Fuyuan station during the heavy rainfall period.

3. Data and Methodology

3.1. Data

The meteorological data mainly come from four sources in this paper: Chinese Geo-environmental Monitoring Groundwater Level Yearbook, Heilongjiang Province Statistics Yearbook, Jiamusi Water Resources Bureau, and statistic information and monitoring data of field investigation in the Sanjiang Plain from this study team. Collectively, we obtained data on shallow groundwater depths of 102 wells during 2008–2013, typical observation of groundwater depths of four wells during 1997–2012 (Figure 1). Water table depths in these wells were recorded with an automatic water level recorder (Odyssey, Dataflow Co., Christchurch, New Zealand).

3.2. Methodology

Kriging provides the best linear unbiased estimation for spatial interpolation [32,33]. We estimated regional shallow groundwater table depths by Kriging interpolation method. The computation was executed with Golden Surfer 9.0 (Golden Software, LLC, Golden, CO, USA) based on its spatial analysis. The general equation of kriging estimator is:

$$Z\left(x_p\right) = \sum_{i=1}^{n} \lambda_i Z\left(x_i\right) \quad (1)$$

where $Z(x_p)$ is the kriged value at location x_p; $Z(x_i)$ is the known value at location x_i; λ_i is the weight associated with the data. The Spherical variogram model was used during the interpolating computation.

We used Water Table Fluctuation Method [34] to assess the impacts of the 2013 extreme rainfall on regional groundwater storage, the equation is as follows:

$$\sum Q = \Delta H \mu F \quad (2)$$

where $\sum Q$ is groundwater storage; ΔH is the change of groundwater depth; μ is the specific yield of aquifer; F is the calculating area.

Equation (2) shows that the change of groundwater depth is critical to the estimation for the groundwater recharge of rainstorms. Suppose that the extreme rainfall didn't occur in 2013, the groundwater depth would decrease continuously with pre-existing trend, while it would be lower than the monitored value when the extreme rainfall occurred. Therefore, the groundwater recharge of rainstorms could be calculated by the difference of the groundwater depth between the two conditions. We cannot accurately determine the groundwater depth on the assumed conditions, especially in the condition of insufficient data. Even with this difficulty, however, we found that the multi-year change of groundwater storage is relatively stable (except in the extreme situation, e.g., extreme hydrological conditions) which means that the annual change of groundwater depth in rainy season and dry season remains within a fairly fixed range. Then, comparing the maximum change of groundwater storage in many years with 2013, this difference between them can be approximated as the groundwater recharge of the 2013 extreme rainfall. We used Golden Surfer 9.0 (Golden Software, LLC, Golden, CO, USA) with the spatial analysis and volume calculation to assess the change of groundwater storage in the Sanjiang Plain. During this computation, the annual maximal change of groundwater depth (ΔH, MCGD) is firstly calculated as the difference between the maximum and minimum of each monitoring well from 2008 to 2013, respectively.

The specific yield of aquifer (μ) can be referenced from relevant hydrogeological parameter data in the Sanjiang Plain (Table 2, initial value), and subsequently determined by the simulation and calibration based on Groundwater Modelling System (GMS) software. The GMS software is a comprehensive package, which is widely used to model groundwater flow in the world [35,36]. The procedure for applying to a groundwater flow model includes four steps: (1) in-situ information collection; (2) conceptual model construction; (3) simulation and calibration of groundwater flow model; (4) predictive simulation. More details and computing processes of this groundwater simulation for the Sanjiang Plain can be seen in the cited literature [26]. The distribution of the hydrogeology parameters and values of μ are listed in Table 2 and Figure 4 [37].

Table 2. The specific yield of aquifer (μ) in the distribution regions by GMS.

ID	1	2	3	4	5	6
Initial value	0.3	0.24	0.21	0.1	0.05	0.03
Certificated value	0.25	0.14	0.21	0.11	0.05	0.03

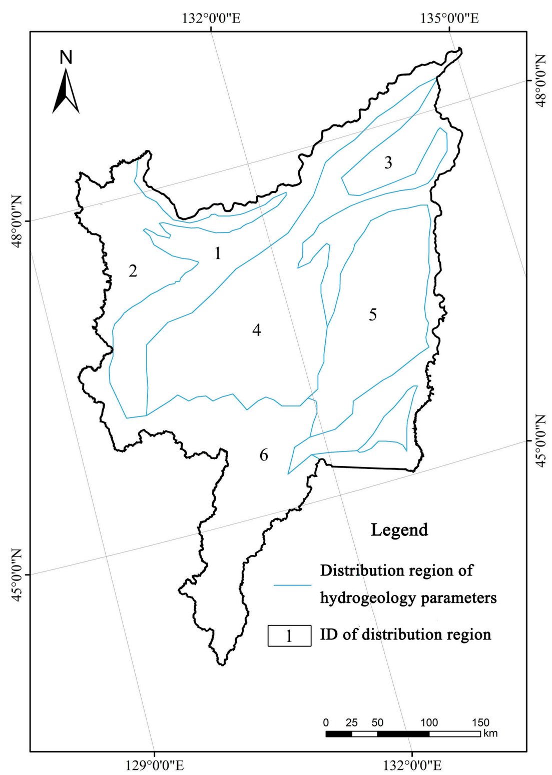

Figure 4. The distribution of the hydrogeology parameter.

Then, we interpolated and transformed the above data into grids. Finally, submitting ready-processed data of ΔH and μ into Equation (2), the annual change of groundwater storage can be obtained by Golden Surfer 9.0. A flow diagram summarizes this methodology (Figure 5).

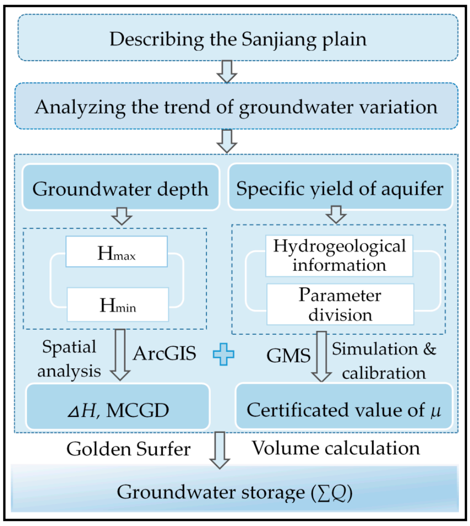

Figure 5. The flow diagram of the methodology.

4. Results

4.1. Trend of Groundwater Depth before the 2013 Extreme Rainfall

The overall average groundwater depth during 2008–2012 in the Sanjiang Plain ranged from 1 m to 20 m with distinct spatial difference, which showed an increasing trend of water table depth from the southeast to the mid-west and northeast (Figure 6). Figure 6a–c showed that the groundwater tables across the region have dropped from 1997 to 2012, with the sharpest drop in the north. The rate of the groundwater drops appeared to be also land use and distance-to-river dependent (Figure 6d–f). Spatially, the groundwater change in the irrigated area was greater than in the non-irrigated area; the fluctuations in the area near a river were smaller than a considerable distance from a river.

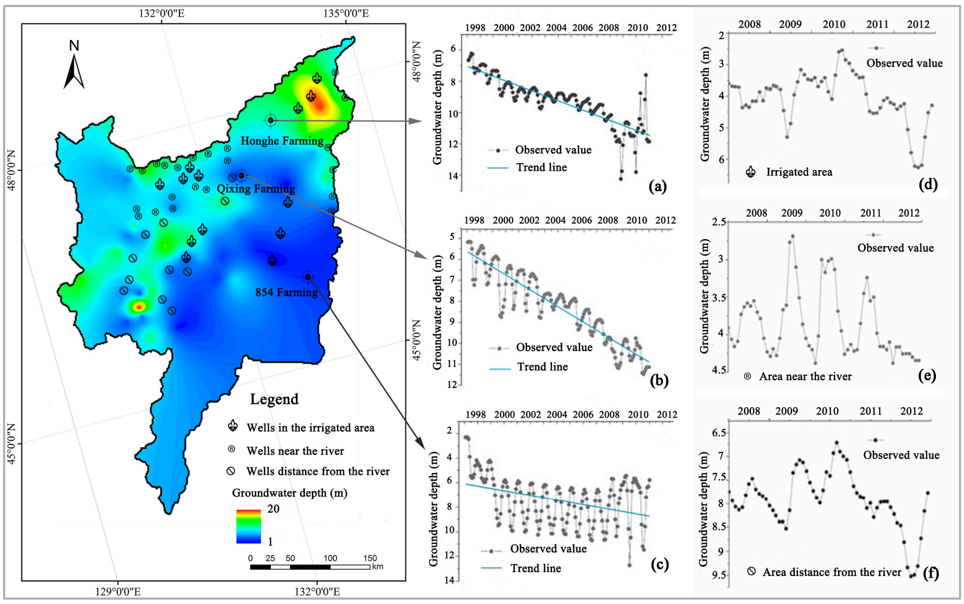

Figure 6. Spatial characteristics of groundwater depth in the Sanjiang Plain during 2008–2012 (left); trends of groundwater depth of three typical groundwater monitoring wells from 1997 to 2012 (**a**–**c**); the groundwater depth variation of 48 groundwater monitoring wells in different areas from 2008 to 2012 (**d**–**f**).

The difference value of groundwater depth between 2008 and 2012 in the Sanjiang Plain ranged from −3.5 m to 5.5 m, most of which was in the range of 0 m to 2 m. Spatially, the groundwater tables in the east dropped greater than the west (Figure 7a). Figure 7b showed that the groundwater rose about 0 m to 3 m from 2012 to 2013 in the whole, with a diminishing scale from north to the south.

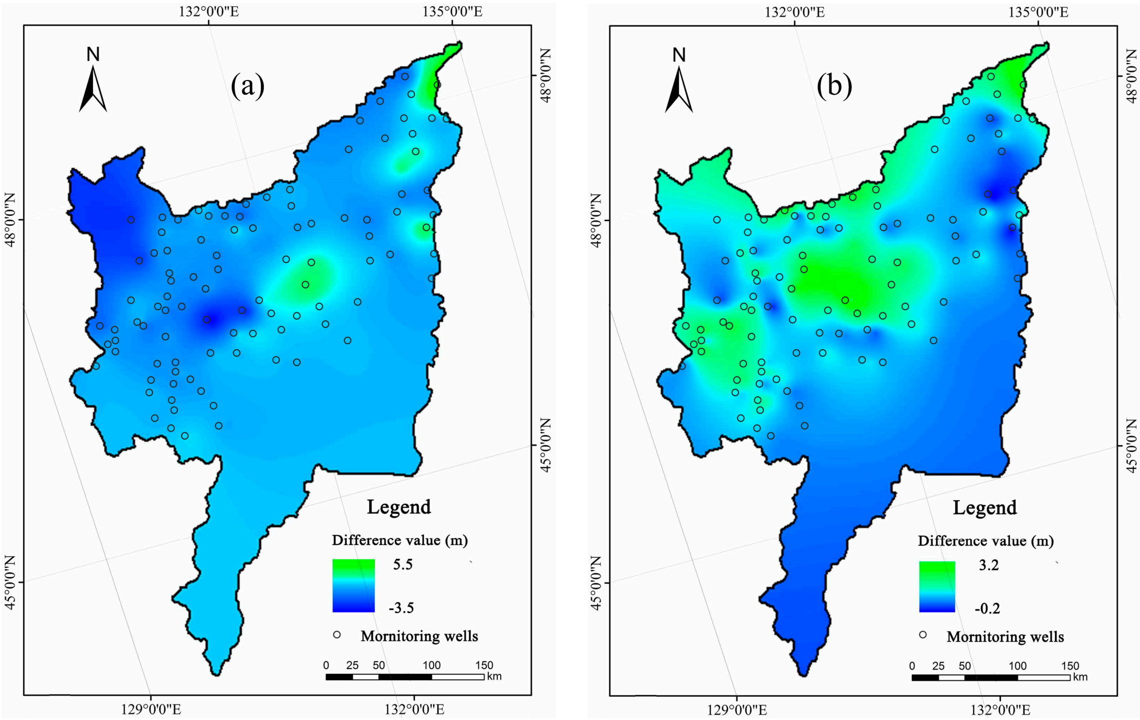

Figure 7. Spatial characteristics of the difference groundwater depth between 2008 and 2012 in the Sanjiang Plain (**a**); the difference value of groundwater depth between 2012 and 2013 (**b**).

4.2. Groundwater Storage Change following the 2013 Extreme Rainfall

Using the methods mentioned above, we estimated changes of the groundwater depth and storage based on the monitoring data of 102 wells during 2008–2013 in the Sanjiang Plain. Considering 102 wells were mostly distributed in the north and central Sanjiang Plain, we chose this part of area to assess the impacts of rainstorms on regional groundwater storage, which can avoid great interpolation error in the computational process.

The shallow groundwater table in the north and central Sanjiang Plain increased following the 2013 extreme rainfall (Table 3 and Figure 8). Before the extreme rainfall, most of the average MCGD was in the range of 0 m to 2 m during 2008–2012, and the shallowest and deepest annual average change of groundwater table were 1.13 m (2011) and 1.53 m (2009). After the extreme rainfall, most of the MCGD was in the range of 1 m to 3 m, occupying 72.09% of the study area. The average MCGD was 1.73 m in 2013, about 0.4 m greater than the mean of last five years (1.33 m). Spatially, the MCGD tended to be high in the middle area and low in the north and south (Figure 8).

The total groundwater storage in the north and central Sanjiang Plain increased following the 2013 extreme rainfall (Table 3). The average groundwater storage was 166.53 × 10^8 m^3 from 2008 to 2012, about 41.14 × 10^8 m^3 lower than that 2013 (207.67 × 10^8 m^3). In other words, we estimated a total recharge of approximately 41.14 × 10^8 m^3 from the 2013 extreme rainfall across the north and central Sanjiang Plain.

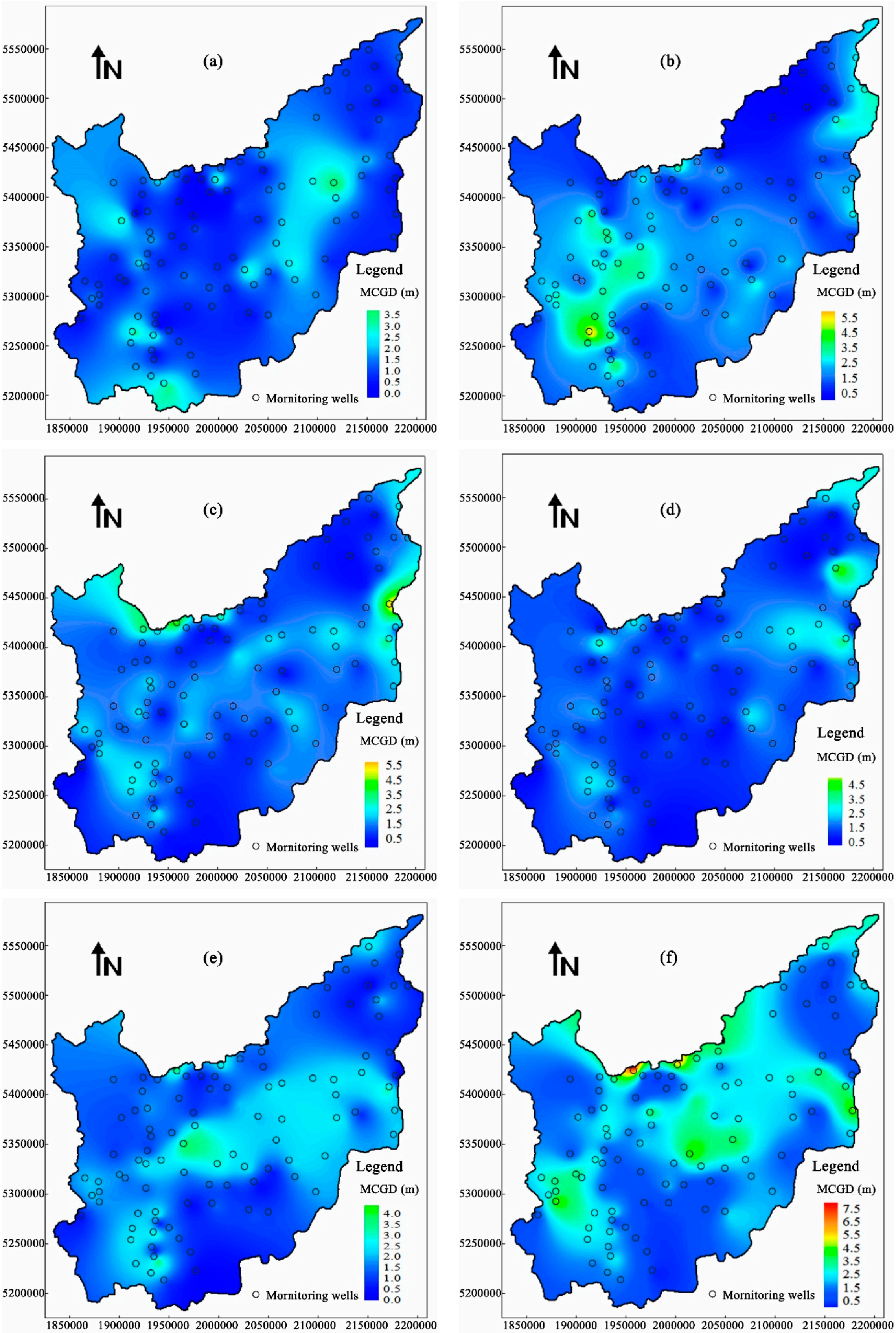

Figure 8. Maximal change of groundwater depth (MCGD) in the north and central Sanjiang Plain from 2008 to 2013: (**a**) 2008; (**b**) 2009; (**c**) 2010; (**d**) 2011; (**e**) 2012; (**f**) 2013.

Table 3. Groundwater storages by depth and year in the north and central Sanjiang Plain.

Year	MCGD (m)	Area (×10^8 m^2)	Percentage (%)	Total Groundwater Storage (×10^8 m^3)
2013	0–1	156.43	19.64	207.67
	1–3	574.11	72.09	
	>3	65.83	8.27	
	1.72	796.36	100.00	
2012	0–1	176.26	22.13	174.0
	1–2	458.19	57.54	
	>2	161.91	20.33	
	1.42	796.36	100.00	
2011	0–1	311.26	39.09	152.52
	1–2	431.37	54.17	
	>2	53.73	6.75	
	1.13	796.36	100.00	
2010	0–1	212.45	26.68	173.97
	1–2	492.30	61.82	
	>2	91.60	11.50	
	1.38	796.36	100.00	
2009	0–1	178.28	22.39	174.61
	1–2	420.88	52.85	
	>2	197.20	24.76	
	1.53	796.36	100.00	
2008	0–1	314.18	39.45	157.53
	1–2	393.50	49.41	
	>2	88.68	11.14	
	1.18	796.36	100.00	

5. Discussion

5.1. Factors Influecing the Groundwater Storage Change

The groundwater storage is affected, to a great extent, by the level of precipitation. The relationship between groundwater storage and precipitation revealed a significant positive correlation in the north and central Sanjiang Plain with a positive correlation coefficient of 0.68 ($p < 0.05$, two-tailed). Within a short period of time (several months), an increase of groundwater storage is the direct cause of extreme rainfalls.

In addition, the total groundwater storage is closely related to the agricultural structure of the study area. Currently, the sum of the rice paddy and other crop land occupy 53.6% (or 5.57 × 10^4 km^2) in the Sanjiang Plain [25]. As a hygrophilous food crop, rice is the dominant plant in the study area requiring the largest water consumer in agriculture, especially in the growth period of July and August. Therefore, the groundwater system can be self-restoring to a degree if we reduce the pumpage of groundwater while utilizing rain flood resources in the growth season. For a long time (several decades), human activity has been the main influencing factor of groundwater storage. According to the statistical development report on paddy fields and annual official report on water resources, the paddy field acreage was enlarged more than 25 times over the last three decades, and in addition to that, 10 times more groundwater was pumped [26,36,38].

The recharge volume estimated during this extreme rainfall in the north and central Sanjiang Plain was 41.14 × 10^8 m^3, which is about two thirds of the estimated annual average recharge (65.16 × 10^8 m^3; [39]) or more than 90% of the annual irrigation water use (45.6 × 10^8 m^3; [40]), nearly equivalent of the annual groundwater pumpage for irrigation on the Sanjiang Plain. As a note, this recharge volume of 41.14 × 10^8 m^3 is an approximate value, slightly lower than the actual total extreme rainfall recharge for groundwater. It also indicates the important role of large rainstorms for regional shallow groundwater. Extreme rainfalls are often considered as a natural hazard, which is deemed to have negative effects on human health or life. However, floods have a positive side from a groundwater recharge standpoint and should be considered in regional water resources management [25].

5.2. Uncertainties of this Study

The present study has explicitly illustrated the changes of groundwater depth and storage before and after the 2013 extreme rainfall. The results revealed that storm water can be one of the main recharge sources for groundwater. The groundwater storage is heavily influenced by the precipitation, agricultural structure and local water recourse management level. Although the calculation was not accurate enough due to the lack of sufficient data, it can help to provide scientific evidence for decision making on groundwater management. This is a new effort to quantitatively calculate and assess the extreme rainfalls' impact on groundwater recharge relying on insufficient data (groundwater depths of 102 wells in five years). However, there are several challenges that have limited a complete and elaborate analysis. First, the lack of long sequences of statistical information and monitoring data has limited a verifying analysis that could help determine the relationship between groundwater depth and storage. Second, the limited availability of spatially detailed data has constrained our ability to determine accuracy and error range of our estimations. Additionally, it is difficult to quantitatively assess the real recharge of groundwater from an extreme rainfall. Combining other methods based on hydrological modelling with monitoring at a finer scale would obtain better estimation results. These limitations are gaps that need to be addressed in future research into extreme rainfall effects on shallow groundwater recharge.

6. Conclusions

Groundwater storage is increasingly acknowledged as an important component of regional water resources. This study analyzed the groundwater table change across a large floodplain region in northeast China following a major extreme rainfall in 2013, in order to determine positive effects of floods on shallow groundwater recharge. Results gained from this study revealed a nearly 20% increase of shallow groundwater storage across the region caused by the extreme rainfall, and that the change was greater in the areas near the rivers. This large quantity of recharge demonstrates the important role that large extreme rainfalls can play in regional shallow groundwater resources. The study provided scientific evidence for the local government to make decisions and gives macro guidance about developing integrated strategies and plans for agricultural production and groundwater management. For instance, there are a large area of swamps in Sanjiang Plain, so it is efficient that making full use of extreme rainfall resources by storing rainwater in swamps connected with river system by channels associated with other reservoirs or lakes in the rain season. Rain flood stored in them for increasing the retention time could gradually recharge groundwater and will release to rivers in dry season or be pumped to irrigate the farmland in growing seasons, which can partly replace the sum of groundwater withdrawal. Meanwhile, the risk of extreme flood should be utilized under control. In addition, the regulation and storage of rain-flood water by artificial groundwater recharge is another attempt on comprehensive utilization of the surface water and groundwater to mitigate the continuous decline of groundwater in the Sanjiang Plain.

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

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