Spatiotemporal groundwater recharge estimation for the largest rice production region in Sanjiang Plain, Northeast China

Xihua Wang, Guangxin Zhang and Y. Jun Xu

ABSTRACT

Accurate estimation of groundwater recharge is important for sustainable management of water resources in intensively irrigated agriculture. In this study, the water-table fluctuation (WTF) method, combined with statistical regression analysis, was used to understand the spatiotemporal variability of groundwater recharge in the largest rice production farming region on China's Sanjiang Plain. Monthly and annual groundwater recharge rates were estimated using the WTF method and simple kriging, respectively. Average annual recharge volumes were estimated for the entire region using the Thiessen polygon method. The study showed a large spatial and temporal variation of groundwater recharge in the region. Seasonally, the recharge rate was high during the spring and early summer when snowmelt occurred and heavier rainfall was concentrated. Nearly 68% of the total annual recharge took place during the 4 months from April to July. Annually, recharge volumes varied greatly, ranging from 7.9×10^8 m^3/yr (2005) to 9.9×10^8 m^3/yr (2006). There was a large spatial difference in recharge with the highest annual rate (191 mm/yr) in the south and the lowest (9 mm/yr) annual rate in the north. The findings demonstrated that the WTF is simple and very useful for shallow groundwater assessment for such a large alluvial plain.

Key words | groundwater recharge, irrigation management, Jiansanjiang Farming Bureau, Sanjiang Plain, water-table fluctuation method

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INTRODUCTION

Estimation of groundwater recharge at a variety of spatial and temporal scales is imperative for sustainable management of groundwater resources in terms of usage, water quality protection and aquifer water level restoration (Healy & Cook 2002; Scanlon *et al.* 2002; Chand *et al.* 2005; Dasilva *et al.* 2012; Obuobie *et al.* 2012). Although precipitation is one of the main sources for groundwater recharge and can be measured relatively easily, accurate estimation of groundwater recharge is a challenging task (De Vries & Simmers 2002) because of its complexity, which involves interactions between local climate, vegetation, soils and topography (McCallum *et al.* 2010; Ng *et al.* 2010; Okkonen & Klove 2010; Barron *et al.* 2012). As global climate change continues, more regions in the world's high latitude, such as China's Sanjiang Plain, are expected to become suitable for intensive rice cultivation, so accurate assessment of groundwater resources is becoming crucial for the development of strategies and plans for sustainable agriculture and environment.

Many methods have been used in groundwater recharge estimation, including baseflow separation (Rorabaugh 1964; Park *et al.* 1999; Halford & Mayer 2000), channel-water budgets (Lerner *et al.* 1990; Lerner 1997; Rushton & Ward 1997), heat tracers (Constantz *et al.* 1994; Ronan *et al.* 1998), isotopic tracers (Stuyfzand 1989), watershed modelling (e.g. Arnold *et al.* 2000), unsaturated-zone water balance (Delin *et al.* 2000; Delin & Herkelrath 2005), dating of groundwater (Delin *et al.* 2000) and RORA analysis of streamflow records

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using a recession-curve-displacement technique (Rutlege 1998, 2000). All these approaches have advantages and disadvantages, with some of them being data and computationally demanding and others being simple but generating less detailed information. Selection of these methods for local and regional groundwater recharge estimation needs to consider both accuracy and cost-effectiveness.

The water-table fluctuation (WTF) method is a simple method widely used to estimate groundwater recharge (Healy & Cook 2002; Crosbie *et al.* 2005; Delin *et al.* 2007; Healy & Scanlon 2010). The method requires information on only the water table and specific yield of an aquifer; however, there are three assumptions inherent in the method critical to its successful application (Healy & Cook 2002): (1) the observed well hydrograph depicts only natural WTFs caused by groundwater recharge and discharge; (2) specific yield is known and constant over the time period of the WTFs; and (3) the pre-recharge water level recession can be extrapolated to determine peak water level rise attributed to the recharge period. Therefore, factors that affect peak water level and spatiotemporal changes in specific yield can greatly influence accuracy of the groundwater recharge estimation for an aquifer using this method.

The Jiansanjiang Farming Bureau region is the largest rice production unit in the Sanjiang Plain, which is one of the most important rice production areas in China with intensive irrigation largely using groundwater. On average, a total of 1.3×10^5 m^3 of groundwater are used for irrigation annually in this region, accounting for 99.6% of the total groundwater pumped annually (Li 2007). However, continuously pumping of large amounts of groundwater has generated concerns. Zhao *et al.* (2008) reported a 5-m decline of the groundwater level over the past 50 years in Chuangye Farm and a large area of cone of depression at Qixing Farm. The high usage of groundwater, together with the large area of wetlands converted to rice cultivation in the region, have also been reported to have an impact on surface (Pan *et al.* 2011; Wang *et al.* 2012) and groundwater quality (Cao *et al.* 2012). Those problems possess a threat to long-term sustainable development of agriculture in the region. Previous studies focused on the whole annual recharge rate (Fu *et al.* 2002; Li 2007); however, the variability of spatiotemporal groundwater recharge in this region has not been researched before and its features and mechanisms remain unclear. Knowledge of the variability of spatiotemporal groundwater recharge is essential for devising groundwater mining strategies.

In this study, we used the WTF method combined with statistical regression to analyse spatial and temporal patterns of groundwater recharge in the Jiansanjiang Farming Bureau region in Northeast China. The primary goal of this study was to gain critical information on future groundwater resources in order to develop effective management strategies to support sustainable agriculture in the region. In addition, we sought to determine the applicability of the WTF method for such a large floodplain region.

STUDY AREA

The Jiansanjiang Farming Bureau region is located in the middle of the Sanjiang Plain (46°49′42″–48°13′58″N; 132°31′26″–134°22′26″E) in Heilongjiang Province, Northeast China (Figure 1). The Jiansanjiang Farming Bureau region is the largest rice production unit on the Sanjiang Plain and covers a total area of 12,400 km^2. This region is characterized by a cold temperate monsoon climate, with a long-term average annual temperature of 1.5 °C (Zhang & Ma 2008) and an average annual precipitation of 550–600 mm, much of which occurs within 3 months from June to August. Based on the long-term climatic records for Fujin station (station 50788), the Chinese Meteorological Data Sharing Service System, July has the highest monthly precipitation (158 mm) and February the lowest (2 mm). Land is used typically for agricultural and rice is the dominant crop in the region.

Much of the region is located on the low floodplain with an elevation range between 40 meters above sea level (m a.s.l.) in the north and 60 m a.s.l. in the south, with a slope gradient between 0.01% and 0.02%. The northwest edge of the Wanda Mountains extends into the southeast corner of the Jiansanjiang Farming Bureau region, producing the highest elevation (626 m a.s.l.) in the study area. The region is largely covered by Quaternary alluvial sediments (loam), where the major mining layers of groundwater are located. Based on geological age, geomorphology, lithology and burial depth, the aquifer formations can be classified as (1) Quaternary loose deposits of sand

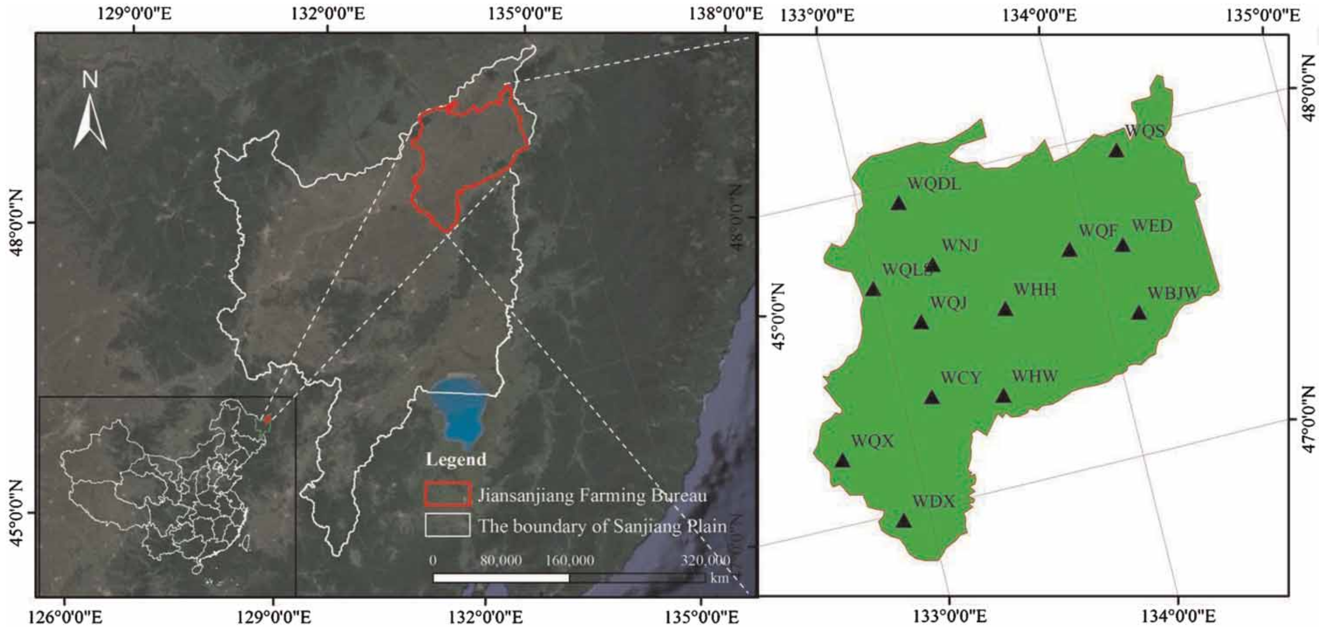

Figure 1 | Geographical location and the monitoring wells of the study region site in Jiansanjiang Farming Bureau, Sanjiang Plain, Heilongjiang Province, Northeast China.

gravel pore water formation, (2) Tertiary sandstone siltstone interlayer pore water formation and (3) Quaternary bedrock fissure water formation. The aquifer materials consist of loam, fine sand, medium sand (Li 2007). The shallow-water-bearing formation with high infiltration has frequent interactions with surface water (Li 2007). The flat topography and strong surface–groundwater connectivity provide good conditions for application of the WTF method (Healy & Cook 2002) to estimate groundwater recharge in the region, as described in the methodology section below.

METHODOLOGY

Groundwater data collection

In this study, we monitored groundwater level fluctuation from 13 monitoring wells across the Jiansanjiang Farming Bureau region (Figure 1). Water table depths in these wells were recorded with an automatic water level recorder (Odyssey, Dataflow Co., New Zealand). The groundwater levels were taken on the 10th, 20th, and the 30th day (or 28th for February) of each month for 4 years from 2005 to 2008.

WTF method

The WTF method is widely applied in groundwater recharge estimation for unconfined aquifers as it is simple in theory and needs only the groundwater level data and specific yield (Scanlon *et al.* 2002). The basic assumption of the WTF method is that the rise of groundwater level in unconfined aquifers is caused by the response to the aquifer infiltration of rainfall arriving at the groundwater table (Healy & Cook 2002). Recharge rate, R (mm/time), can therefore be quantified as follows (Healy & Cook 2002):

$$R = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \tag{1}$$

where S_y is the specific yield, Δh is the change in groundwater level (mm) during the recharge period and Δt is the time of recharge period.

The groundwater water level rise is equal to the difference between the peak of the rise and the corresponding point of the recession curve (Healy & Cook 2002) (Figure 2(a)). In general, there are three approaches for estimating the groundwater water level rise (Delin *et al.* 2007; Obuobie *et al.* 2012): (1) RISE program approach, (2) master recession curve (MRC) and (3) the graphical extrapolation method

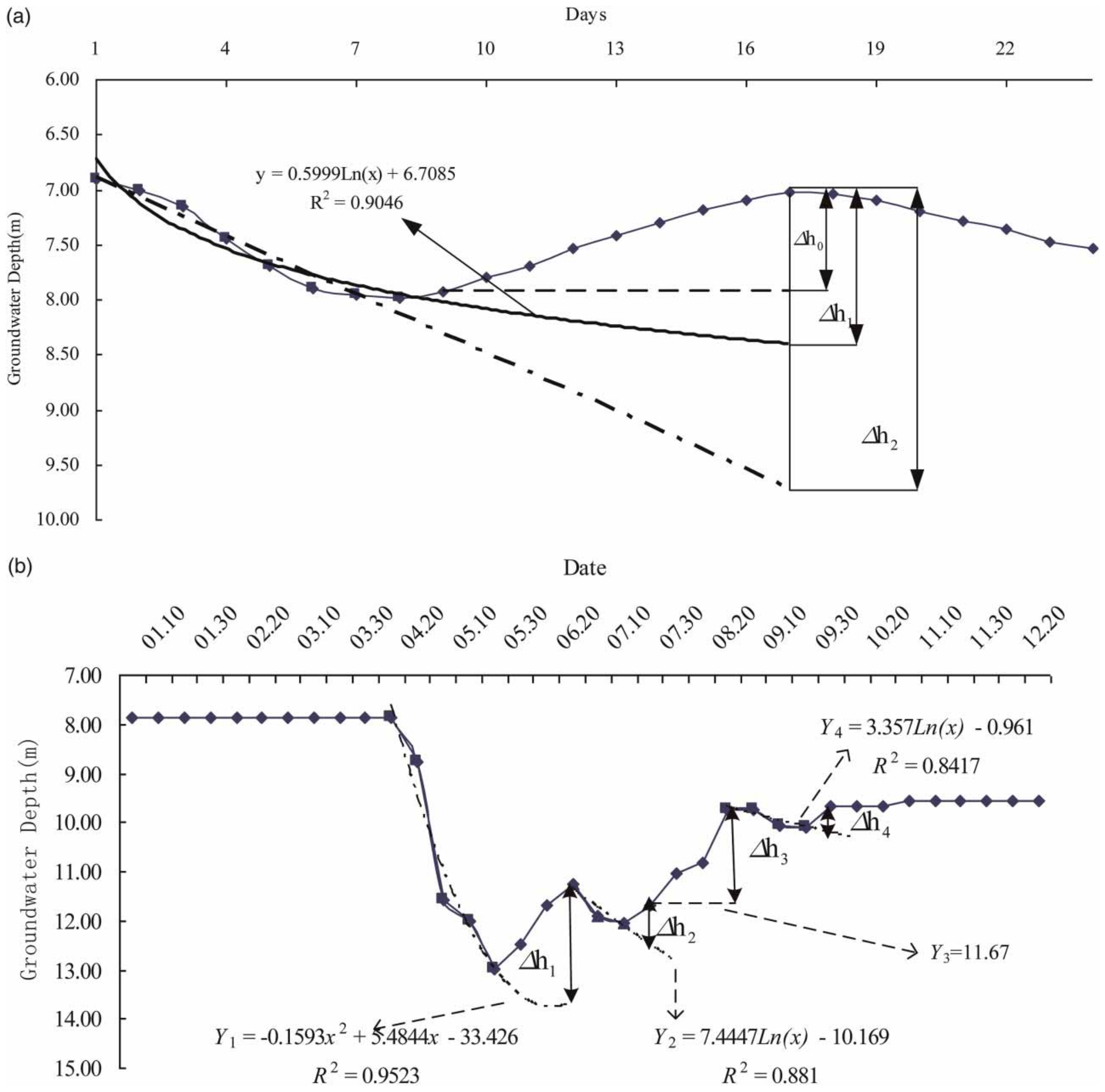

Figure 2 | (a) Hypothetical groundwater level fluctuation in a monitoring well. The groundwater level fluctuation is equal to the difference between the peak of the rise and low point of the extrapolated antecedent recession curve (dash line) at the time of peak. The GEM was combined with the RA to estimate the hypothetical groundwater rise. Δh_1 was calculated by the WTF method with the RA, and Δh_0, Δh_2 were calculated by the WTF with trend line manually. (b) The groundwater water level rise in WNJ in 2006 calculated using the GEM, combined with RA. Δh_1, Δh_2, Δh_3 and Δh_4 are the groundwater fluctuations.

(GEM). The RISE program approach has been reported to underestimate actual recharge rates, for no allowance is made for the hydrograph recession that would have occurred in the absence of recharge (Obuobie *et al.* 2012). The MRC method is less subjective, but it could be possible to miscalculate groundwater rise that is not caused by actual recharge, but by other factors, such as tides and earthquake. The GEM method is visual and simpler than the other two methods. However, GEM involves subjectivity in drawing the trend line by hand and could be time-consuming. In this study, we used regression analysis (RA) to fit the curve trend for each well and each month, in order to avoid errors caused by subjectivity as illustrated in Figure 2(b) for one well (WNJ in 2006).

As we observed, water level rise mainly occurred in June, July, August and October (Table 3(c)). Therefore, calculation for the water level fluctuation (Δh) was done for 4 different months, as given below for Well WNJ.

For June:

$$\begin{aligned}\Delta h_1 &= Y_1(x_{6.10}) - GWD(x_{6.10})\\ &= \left[-0.1593\times(18)^2 + 5.4844\times 18 + 8.1918\right] - 11.27\\ &= 13.68 - 11.27 = 2.41\,\text{m}\end{aligned}$$

For July:

$$\begin{aligned}\Delta h_2 &= Y_2(x_{7.20}) - GWD(x_{7.20})\\ &= [7.4447\times \text{Ln}(21) - 10.169] - 11.67 = 12.50 - 11.67\\ &= 0.83\,\text{m}\end{aligned}$$

For August:

$$\Delta h_3 = Y_3(x_{8.30}) - GWD(x_{8.30}) = 11.67 - 9.75 = 1.92\,\text{m}$$

For October:

$$\begin{aligned}\Delta h_4 &= Y_4(x_{10.10}) - GWD(x_{10.10})\\ &= [3.3570\times \text{Ln}(28) - 0.961] - 9.67 = 10.23 - 9.67\\ &= 0.56\,\text{m}\end{aligned}$$

For the entire water level fluctuation:

$$\begin{aligned}\Delta h &= \Delta h_1 + \Delta h_2 + \Delta h_3 + \Delta h_4 = 2.41 + 0.83 + 1.92 + 0.56\\ &= 5.72\,\text{m}\end{aligned}$$

where $GDW(x_{6.10})$ is the groundwater depth on 10 June; $Y_n(x_{6.10})$ is the regression curve value at the point on 10 June. $x_{6.10}$ is the sequence number for 10 June.

Similar water level fluctuations were calculated for other wells from 2005 to 2008 (Figure 2(b)).

Selection of specific yield

Specific yield (S_y) of rocks or soils soils is the quantity of water that a unit volume of an aquifer, after being saturated, will yield by gravity; it is expressed either as a ratio or as a percentage of the volume of the aquifer (Meinzer 1923) shown below:

$$S_y = \phi - S_r \tag{2}$$

where ϕ is the porosity of the rock or soil material, and S_r is the specific retention.

Generally, specific yield can be estimated by aquifer testing, water-budget methods or laboratory/field experiment (Lerner *et al.* 1990).

Many previous studies have estimated the range of the specific yield for different rock or soil materials (Johnson 1967). Many Chinese researchers also give different values for various materials. In this study, we selected specific yields for the Jiansanjiang Farming Bureau region by combining local experimental values with the range of previous studies for each individual well (Table 1).

RESULTS

Temporal trend of groundwater recharge

Inter-annual variation in recharge of wells WDX, WQLS, WCY, and WNJ was very high (Figure 3(a)). Much recharge of those wells occurred during April–July in 2005, April–July in 2006, April–August in 2007, and April–July in 2008. Inter-annual variation of recharge in wells WQJ, WED, WHW and WQX was moderately high (Figure 3(b)). Much recharge of these wells occurred in April–July in 2005, 2006, and 2007 and in March–June in 2008. Inter-annual variation in recharge of wells WQS, WQF, WHH, WQDL and WBJW was relatively small (Figure 3(c)). Much recharge of those wells occurred in April–July in 2005, March–July in 2006 and 2007), and March–June in 2008. For the entire region, much of groundwater recharge occurred from April to July, accounting for nearly 68% of the annual recharge (Table 2).

Based on the variability (i.e. coefficient of variation or CV) the 13 wells can be divided into three groups (Table 3): group 1 (WQS, WED, WHH, WQDL) with a CV >40%, group 2 (WQLS, WCY, WNJ, WBJW, WQJ) with a CV of 20–40% and group 3 (WDX, WHW, WQX, WQF) with a CV < 20%. Over 2005 and 2008, group 1, group 2, and group 3 wells showed an average annual recharge rate of 31, 77 and 141 mm/yr, respectively. Overall, the wells in the south showed much higher variation in recharge rate than the wells in the north.

Table 1 | Specific yields used for calculation of groundwater recharge at different locations in the Jiansanjiang Farming Bureau region, Northeast China

Well	Longitude	Latitude	Elevation (m)	Geology	Specific yield	Hydraulic conductivity (m/d)
WQS	134°12′54″	47°56′43″	41.5	Fine sand	0.155	15
WQJ	133°09′43″	47°34′16″	49.1	Fine sand	0.155	15
WDX	132°52′34″	46°58′57″	57.9	Fine sand	0.155	15
WQLS	132°58′30″	47°42′12″	41.8	Medium sand	0.181	25
WQF	133°53′58″	47°40′51″	46.1	Fine sand	0.155	15
WHW	133°26′48″	47°16′52″	57.4	Medium sand	0.181	25
WCY	133°07′41″	47°20′11″	52.8	Fine sand	0.155	15
WNJ	133°16′21″	47°44′04″	41.5	Fine sand	0.155	15
WED	134°08′23″	47°39′38″	48.8	Fine sand	0.155	15
WHH	133°32′46″	47°32′53″	47.6	Sandy clay	0.12	13
WJBW	134°08′13″	47°26′23″	59.2	Fine sand	0.155	15
WQX	132°39′39″	47°12′39″	49.4	Fine sand	0.155	15
WQDL	133°11′15″	47°56′58″	41.2	Sandy clay	0.12	13

For the entire Jiansanjiang Farming Bureau region, we estimated a total recharge volume of 7.9003×10^8 m^3 for 2005, 9.8933×10^8 m^3 for 2006, 9.7934×10^8 m^3 for 2007 and 8.7442×10^8 m^3 for 2008 (Table 4).

Spatial variability in groundwater recharge

Spatial annual recharge variation was high in the different years among the 13 wells. However, it was apparent that the lowest annual recharge occurred at Well WQS and the highest at Well WDX over the 4 years (Table 3). Specifically, the annual recharge in 2005 ranged from 3 mm/yr (WQS) to 155 mm/yr (WDX), accounting for 0.6% and 25.0% of rainfall, respectively. For 2006, annual recharge ranged from 5 mm/yr (WQS) to 231 mm/yr (WDX), accounting for 1.2% and 52.8% of rainfall, respectively. For 2007, annual recharge ranged from 10 mm/yr (WQS) to 195 mm/yr (WDX) (3.1% and 57.7% of annual rainfall, respectively). For 2008, annual recharge ranged from 17 mm/a (WQS) to 184 mm/yr (WDX), accounting for 3.9 and 42.0% of rainfall, respectively. The average annual recharge ranged from 54 mm/yr (2005) to 77 mm/yr (2006). Spatially, the southern part of the Jiansanjiang Farming Bureau region showed significantly higher variation in recharge than the northern part (Figure 3).

DISCUSSION

Temporal variability in groundwater recharge

Many factors can affect groundwater recharge variability, including climate factors, especially precipitation amount, intensity and duration, as well as soil factors, such as antecedent soil moisture and water table. In our study area, snowmelt began at the end of April and precipitation concentrated during June–August. The high recharge rate we found during April–July from all wells is a clear reflection of the seasonal climate patterns.

The high recharge in April and May could be partially attributed to the high level of irrigation activities in the season. For rice cultivation in this region, large amounts of water were supplied to keep the paddy fields inundated in April and May, which is the sowing and growing period. In the vegetative stage of rice (May and June), water consumption is highest. According to Li & Jia (2013), 47.2% of the entire arable land area of the Jiansanjiang Farming Bureau region is cultivated with rice so local farmers use a large amount of irrigation water to keep the rice paddies inundated. Li (2007) showed that about 1.38×10^8 m^3/yr irrigation water infiltrated into the groundwater, accounting for 14.2% of the whole groundwater recharge volume. Moreover, June and July

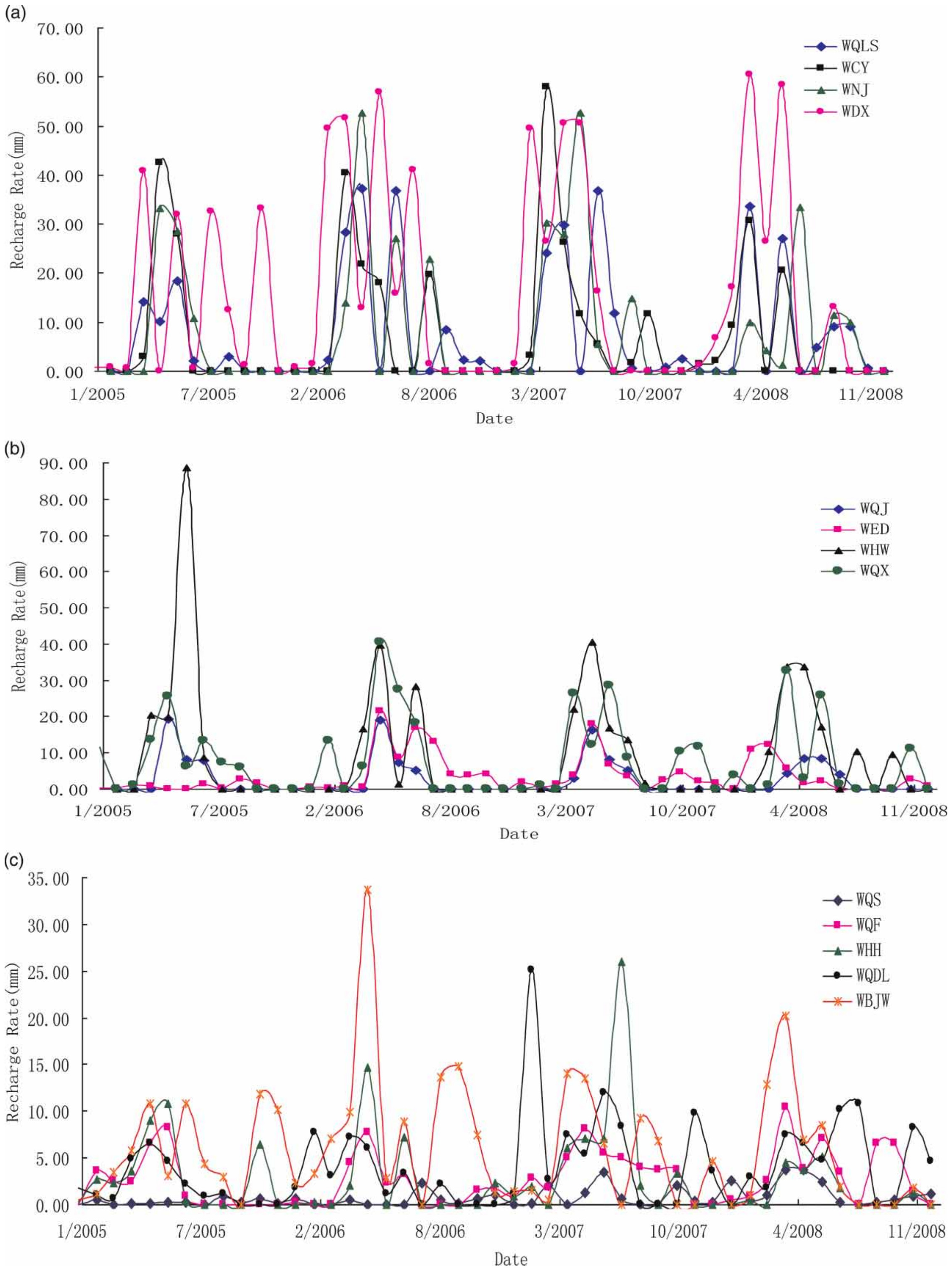

Figure 3 | The monthly groundwater recharge for the 13 wells, 2005–2008.

Table 2 | Average proportion of the monthly recharge in 13 monitoring wells in the Jiansanjiang Farming Bureau region, Northeast China, during 2005 and 2008

Well	1	2	3	4	5	6	7	8	9	10	11	12	*R* (4–7)(%)	*R* (4–7) × AW[a]
WQS	6.5	4.5	6.6	8.6	9.7	14.2	4.2	10.2	9.3	8.5	9.6	8.0	36.8	4.8
WQJ	0.0	0.0	0.0	6.7	49.6	26.1	17.6	0.0	0.0	0.0	0.0	0.0	100.0	3.0
WDX	0.4	1.4	14.1	23.8	11.5	25.7	3.9	9.7	3.9	0.2	5.3	0.0	65.0	5.8
WQLS	0.0	0.0	0.5	29.0	20.2	17.7	17.6	4.2	4.3	4.5	0.9	1.1	84.5	4.2
WQF	1.3	6.0	5.3	16.9	22.9	18.6	9.8	2.4	6.1	6.1	2.6	2.0	68.3	3.4
WHW	0.0	0.0	2.3	21.7	33.3	24.6	13.4	2.7	0.0	2.1	0.0	0.0	93.0	13.9
WCY	0.6	0.9	4.3	35.4	25.5	24.5	1.2	0.0	5.3	2.5	0.0	0.0	86.5	4.3
WNJ	0.0	0.0	0.0	12.3	29.6	20.3	22.5	0.0	11.8	3.5	0.0	0.0	84.7	2.5
WED	2.1	9.1	12.8	8.3	17.8	8.0	11.9	4.9	10.7	8.4	4.4	1.5	46.1	2.3
WHH	0.6	3.6	1.6	13.8	29.0	18.5	21.7	0.9	0.0	1.6	6.5	2.2	83.0	3.3
WJBW	1.3	2.4	9.3	20.0	21.3	8.7	7.2	5.7	7.3	3.5	7.2	6.1	57.1	8.6
WQX	4.7	3.5	0.7	22.5	21.2	23.8	10.8	2.1	1.8	2.6	6.5	0.0	78.2	3.9
WQDL	3.7	16.7	4.6	16.3	16.2	11.9	12.2	5.6	2.9	0.0	6.8	3.2	56.5	7.9
Average proportion (%)														68.1

[a]AW, area weighting calculated by the Thiessen polygon method; see Table 3.

Table 3 | Annual average recharge rates estimated for 13 monitoring wells in the Jiansanjiang Farming Bureau region, Northeast China, during 2005 and 2008

Group	Well	*R*(2005) (mm/yr)	*R*(2006) (mm/yr)	*R*(2007) (mm/yr)	*R*(2008) (mm/yr)	Average (A) (mm/yr)	Cv	Area of TP* (m^2)	Area weighting (AW)	A × AW (mm/yr)
Group 1	WQS	3	5	10	17	9	59.77	581,083,092	0.26	33
	WED	8	74	47	36	41	56.94	599,201,175	0.27	
	WHH	35	27	54	17	33	41.51	409,971,418	0.19	
	WQDL	24	32	76	58	47	43.12	622,285,489	0.28	
Group 2	WQLS	48	118	107	92	91	29.22	1,889,414,098	0.27	77
	WCY	73	100	118	64	89	23.86	1,054,208,061	0.15	
	WNJ	73	117	131	70	98	27.43	1,816,873,215	0.26	
	WJBW	65	105	58	53	70	29.05	647,983,760	0.09	
	WQJ	35	32	33	26	31	29.82	1,554,618,493	0.22	
Group 3	WDX	155	231	195	184	191	14.36	1,712,239,182	0.53	141
	WHW	138	86	94	115	108	18.47	536,671,758	0.17	
	WQX	85	106	99	79	92	11.46	630,256,174	0.20	
	WQF	24	21	40	44	32	11.75	345,194,086	0.11	

*TP, Thiessen polygon method; *R*, recharge rate.

are the main stage of precipitation recharge; there was about 5.2296×10^8 m^3/yr water infiltrated into the groundwater, which accounted for 53.5% of the whole groundwater recharge volume in the Jiansanjiang Farming Bureau region.

The annual recharge volumes estimated in this study are reasonable. Fu *et al.* (2002) and Li (2007) calculated groundwater recharge for this region based on a water balance method and reported a recharge rate of 8.2902×10^8 m^3 in 2002 and a recharge rate of 9.7709×10^8 m^3 in 2007. Our

Table 4 | Annual average recharge volumes of 13 monitoring wells in the Jiansanjiang Farming Bureau region, Northeast China, during 2005 and 2008

Well	Area of TP* (m^2)	Area weighting (AW)	R (2005) ×AW	R (2006) ×AW	R (2007) ×AW	R (2008) ×AW
WQS	581,083,092	0.13	0	1	1	2
WED	599,201,175	0.05	0	4	2	2
WHH	409,971,418	0.04	2	1	2	1
WQDL	622,285,489	0.14	3	4	10	8
WQLS	1,889,414,098	0.05	2	6	5	5
WCY	1,054,208,061	0.05	3	5	6	3
WNJ	1,816,873,215	0.03	2	4	4	2
WJBW	647,983,760	0.15	10	15	9	8
WQJ	1,554,618,493	0.03	0	1	1	1
WDX	1,712,239,182	0.09	13	20	17	16
WHW	536,671,758	0.15	21	13	14	18
WQX	630,256,174	0.05	4	5	5	4
WQF	345,194,086	0.05	1	1	2	2
Average annual recharge (mm/yr)			64	80	79	71
Annual volume (10^8 m^3/yr)			7.9003	9.8933	9.7934	8.7442

*TP, Thiessen polygon method; R, recharge rate.

estimates for the 4 study years were (2005–2008, respectively): 7.9003×10^8, 9.8933×10^8, 9.7934×10^8, and 8.7442×10^8 m^3, with an average of 9.0703×10^8 m^3, which was in close agreement with Fu's and Li's findings. The very small difference in the recharge estimation for 2007 between our approach (WTF) and Li's (WBM) (9.7709×10^8 m^3 vs 9.7934×10^8 m^3) provides confidence in using WTF for future groundwater recharge estimation for the region.

Despite the large recharge volumes, the groundwater storage in this region may continue to decline if more land is irrigated in the future, following the present trend. Future work is needed to determine the threshold of groundwater usage for agriculture irrigation that is sustainable for the region's environment and economic development.

Spatial variability in groundwater recharge

Generally, the recharge variability related to the variability of local soil property and surface topography (Delhomme 1979; Sharma *et al*. 1980; Russo & Bresler 1981; Delin *et al.* 2000). The southern part of Jiansanjiang Farming Bureau region showed significantly higher variation in groundwater recharge than in the northern part (Figure 4). This may also be explained by the difference of topography (elevation) and soil properties. The elevation of the region ranges from 40 m to 626 m. The low hills located in the southeast (WHW) and northwest (WQLS) generate a piedmont alluvial fan structure. Therefore, the permeability coefficient of hill soil (25 m/d) is also higher than others (15 m/d or 13 m/d). As for the low plain region, the elevation of the southern part (60 m) is higher than the northern (40 m), and the permeability coefficient of southern soil (WDX, 15 m/d) is also higher than the northern (WHH, 13 m/d) (Table 1). The high elevation region with the high infiltration rate is one of the most important groundwater recharge areas; the lower northern area is covered mainly by loam, which has low infiltration rate, and also low groundwater recharge (Figure 4).

In their study on surface–groundwater interaction, Cao *et al.* (2012) reported that 11.4% of the groundwater on the Sanjiang Plain showed severe pollution with nitrate, especially in rural areas, such as the Jiansanjiang Farming Bureau region. Furthermore, Pan *et al.* (2011) and Wang *et al.* (2012) showed that the shallow groundwater on the Sanjiang Plain was rich in iron. So local farmers who rely on the local groundwater should pump the deep groundwater and treat it if used as drinking water.

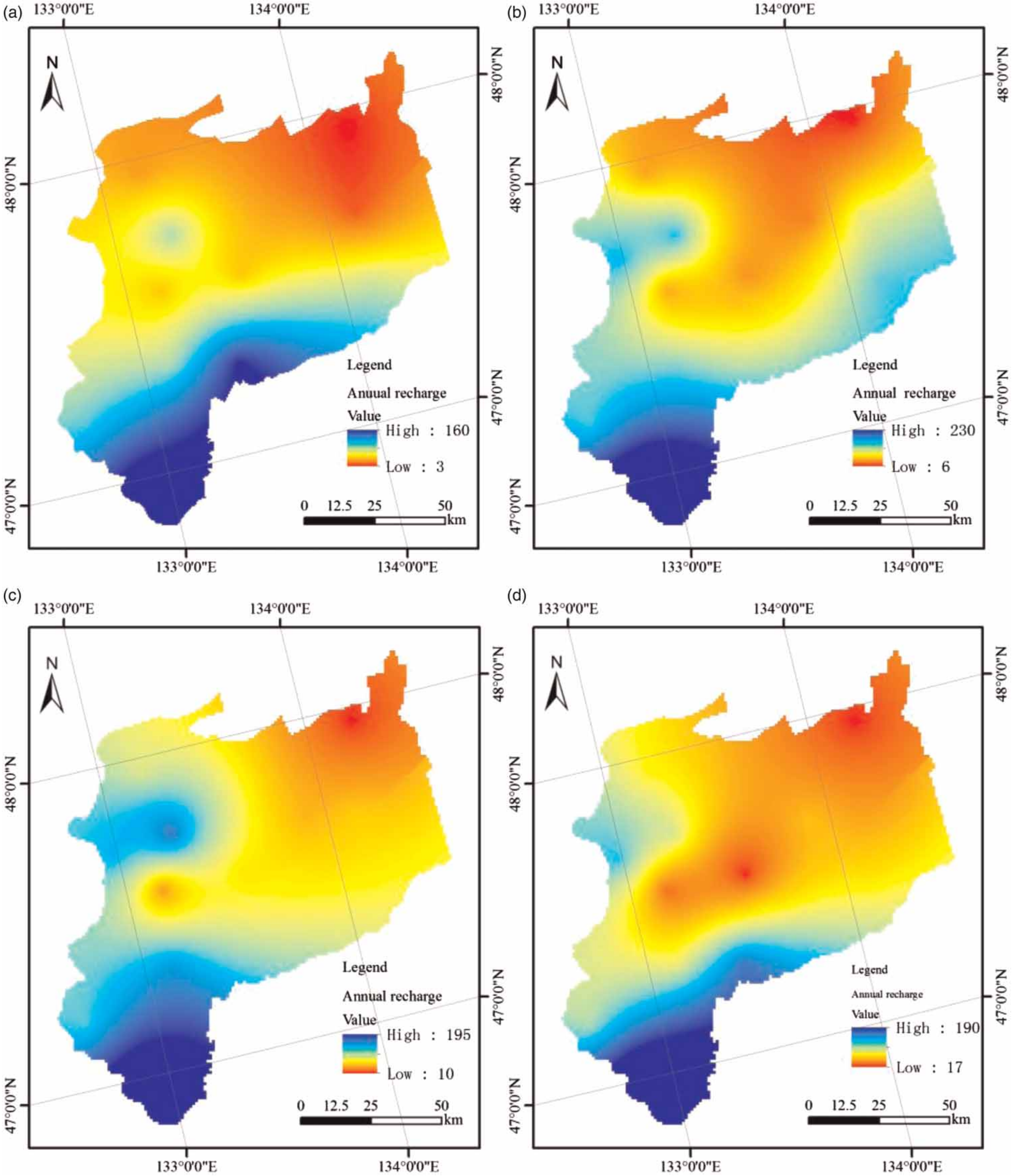

Figure 4 | Annual recharge isogram from 2005 to 2008 in the Jiansanjiang Farming Bureau Farming region. (a) 2005, (b) 2006, (c) 2007, (d) 2008.

CONCLUSION

This study is the first assessment of the spatiotemporal variability of groundwater recharge in the Jiansanjiang Farming Bureau region, a major rice production area on the Sanjiang Plain, Northeast China. The primary purpose of the study was to understand the spatial and temporal variation of groundwater recharge. Additionally, we intended to test the applicability of the WTF method in estimating groundwater recharge for the region. Based on our findings, we conclude that the WTF method is simple and very useful for shallow groundwater assessment for such a large alluvial plain. Our findings on variable groundwater levels and recharge rates in space and time suggest that groundwater pumping for agriculture irrigation should be preferred during April and May, allowing maximal recharge and storage in the following rainfall season.

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