The influence of riverbank filtration on regional water resources: a case study in the Second Songhua River catchment, China

Xueyan Ye, Ruijuan Cui, Lixue Wang and Xinqiang Du

ABSTRACT

Riverbank filtration (RBF) of river water recharging a groundwater system has been identified as a source of water supply that guarantees the quantity of abstracted water and reduces the cost of water treatment. This paper evaluates the safe yield of groundwater in suitable areas using a numerical model of groundwater flow and discusses the influence of RBF on the temporal variation of regional hydraulic heads, groundwater flow, river flow, and groundwater–surface water interaction (GSI) under different precipitation frequencies from 20% to 95% along the Second Songhua River in Northeast China. This study shows that the potential of RBF is enormous and that the total safe yield of groundwater abstraction was 29.56×10^4 m^3/day under the precipitation frequency of 95%. The direction of regional groundwater flow was not obviously changed except within the local groundwater flow field under the maximum safe yield pumping conditions. When the precipitation frequencies are higher than 75%, the direction of the GSI might be changed, and the rate of river recharge of groundwater is enhanced. The water quantity that would be captured from the river does not threaten the safety of the river ecology. It is concluded that there were no obvious adverse impacts of the large scale of RBF on regional water resources in the Second Songhua River area.

Key words | groundwater resources assessment, groundwater safe yield, groundwater–surface water interaction, precipitation frequencies, river bank filtration, visual MODFLOW

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INTRODUCTION

Riverbank filtration (RBF) occurs when the abstraction of groundwater near a river draws water from the river and filters it through the riverbank before it is abstracted for use. It is generally established on the banks of perennial rivers and is an effective way to ensure a long-term stable water supply. In general, RBF is effective in terms of water quality, water quantity, and cost considerations (Ahmed & Marhaba 2017).

In many European countries much of the drinking water is sourced from RBF wells, e.g. Switzerland – 80%, Serbia – 54% (Stauder *et al.* 2012), France and Slovakia – 50% (Hiscock & Grischek 2002), Finland – 48%, Hungary – 45% (Ahmed & Marhaba 2017), Germany – 17% (Ghodeif *et al.* 2016), especially in Berlin – 75% (Schubert 2002), and the Netherlands – 7% (Tyagi *et al.* 2013). In Düsseldorf in Germany, RBF has been used as the main source of drinking water since 1870 (Schubert 2002). In the United States, RBF has been used as a water supply for more than 70 years, and six RBF sites in Egypt produce more than 50% of the country's drinking water (Ghodeif *et al.* 2016). The RBF process has also been investigated in some cities in Egypt (Ahmed & Marhaba 2017), India, (Sandhu *et al.* 2011; Ojha 2012), and Delhi (Groeschke *et al.* 2017). South Korea has recently started to

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use RBF to supply drinking water (Ray 2008). According to the statistical data provided by the China Water Resources Bulletin in 2014, the quantity of water supplied from groundwater was 111.7×10^9 m^3, which represented 18.3% of China's total water supply (Hu *et al.* 2016). There are more than 300 RBF sites in China (Wang & Kong 2002), with approximately 50 RBF sites located in provincial capitals, as well as in some industrial zones along the Yellow River and its tributaries (Cao *et al.* 2004; Liao *et al.* 2004). All of these RBF systems have proven to be effective in terms of supplying water.

RBF is usually considered to be a water purification process in which river water is naturally filtered when it discharges through a riverbed or riverbanks into an aquifer. RBF has been proven to effectively reduce turbidity, total organic carbon, and dissolved organic carbon (Grünheid *et al.* 2005; Ahmed & Marhaba 2017), and the levels of high-molecular weight organics (Hamann *et al.* 2016; Ahmed & Marhaba 2017). It can also reduce the biological oxygen demand, chemical oxygen demand, heavy metal concentrations (Bourg & Bertin 1993, 1994; Sharma *et al.* 2012; Hamann *et al.* 2016), and the levels of inorganic substances, viruses, and microorganisms (Sandhu *et al.* 2011) in surface water. There have been several detailed studies of the quality of water subject to RBF (Sontheimer 1980; Jacobs *et al.* 1988; Kühn & Müller 2000). Some studies have identified the groundwater–surface water interaction (GSI) in RBF schemes by isotopic and water chemistry methods (Hu *et al.* 2016), but there have been few studies on the influence of RBF on regional water resources, particularly for schemes involving large-scale pumping of groundwater. This study mainly focuses on the influence of an RBF scheme on the regional groundwater flow field, river flow, and the interaction between groundwater and surface water under the conditions of different precipitation frequencies ranging from 20% to 95% along the Second Songhua River in Northeast China (20% = 80th percentile annual rainfall (i.e. a wet year); 50% = 50th percentile annual rainfall (i.e. mean annual rainfall); 75% = 25th percentile annual rainfall (i.e. a dry year); 95% = 5th percentile annual rainfall (i.e. a very dry year)).

BACKGROUND

The Second Songhua River is the largest river in Jilin Province, which is located in Northeast China (see Figure 1). The river originates in the Changbai Mountains, and has a total length of approximately 330 km and a total basin area of 7.3×10^4 km^2. According to data collected at the Songhuajiang Hydrologic Station, the average annual runoff is 1.56×10^{10} m^3, while the average annual runoff recorded at the Fuyu Hydrologic Station is 1.67×10^{10} m^3.

The study area for the RBF study was located in the plains of Jilin Province where the natural geographical conditions are suitable for the construction of an RBF scheme. Furthermore, the demand for water is strong. RBF is therefore being considered as a way of obtaining drinking water. The degree of hydraulic contact between the river and groundwater and the natural geographical conditions, were the two factors used to define the study area (see Figure 1) (Wang *et al.* 2016a).

The shallow unconfined groundwater in the study area is mainly recharged by the infiltration of rainfall, infiltration of irrigation water from paddy fields, and lateral groundwater runoff from mountain areas. The aquifers are formed in a range of soils, including glaciofluvial sand and gravel, alluvial–proluvial loessial soil, alluvial–proluvial sand and gravel, alluvial lacustrine sandy loam and mild clay, alluvial lacustrine loessal sand and sandy gravel, and alluvial lacustrine sand. The alluvial–proluvial sand and gravel aquifers are mainly located in the floodplains of the Second Songhua River, the Yinma River, and the Yitong River. The maximum production rate of a single well is 1,000–3,000 m^3/day. The loessial soil aquifers are mainly situated on both sides of the valley plains, and the maximum production rate of a single well is less than 100 m^3/day (see Figure 1).

In the study area, the spatial and temporal distribution of precipitation is uneven, and the average annual precipitation varies from 400 mm to 700 mm, decreasing from southeast to northwest (see Figure 1). The precipitation in July and August accounts for 70–80% of the total annual precipitation. The average annual evaporation increases from 1,200–1,500 mm in the west and northwest to 1,500–2,000 mm in the east and southeast.

Industrial and agricultural production and domestic water use in large and medium-sized cities, such as Jilin city and Songyuan city in Jilin Province, accounts

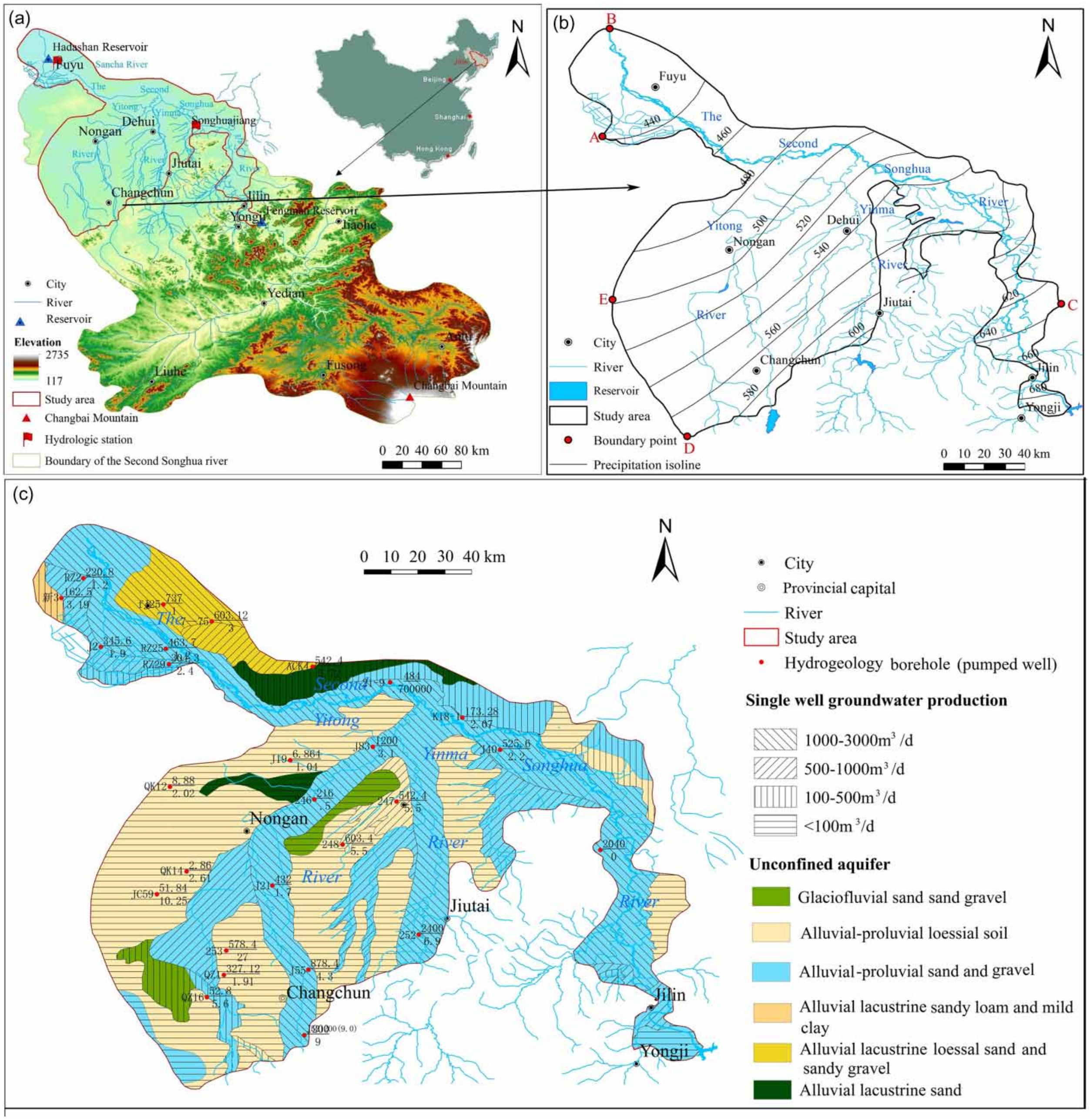

Figure 1 | The Second Songhua River catchment (a), precipitation (b), and geology (c).

for approximately 60% of the total urban water supply (Guo *et al.* 2013). Because groundwater resources in the area as a whole are not abundant (see Figure 2), it is very important to achieve the effective joint management of groundwater and surface river water along the largest river in region. Five RBF zones were selected for investigation, as shown in Figure 2 (Wang *et al.* 2016a).

METHODS

A regional-scale numerical transient two-dimensional groundwater flow model was developed for the Second Songhua River catchment using the Visual MODFLOW software and packages such as MODFLOW 2000, Zone Budget, and PEST. Based on the calibrated and verified numerical model,

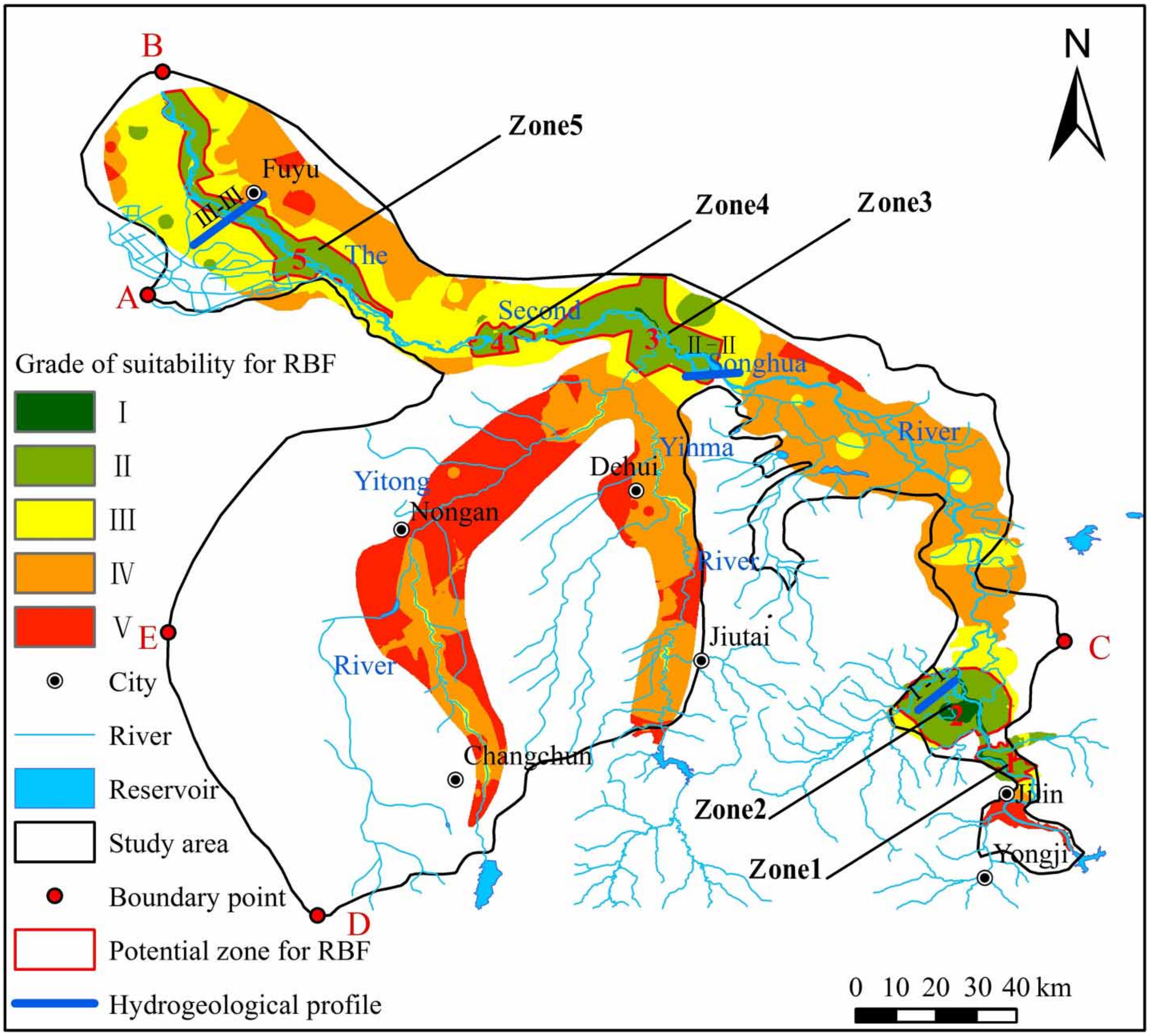

Figure 2 | Suitable zones for RBF along the Second Songhua River.

the safe yield of groundwater resources in each RBF zone was calculated, and the influence of RBF on the regional water resources was predicted and analyzed.

Conceptual model

The study area was the floodplain of the Second Songhua River Basin, with a total area of approximately $1.66 \times 10^4\ \mathrm{km}^2$. The northwest boundary (AB), the northeast boundary (BC), and the southwest boundary (DE) defined the watershed and were generalized as Neuman boundaries (the second boundary) (see Figure 2). The groundwater system in the study area accepts lateral recharge of groundwater from mountain areas, with the southern boundary (CD) and the western boundary (EA) serving as the dividing line between the mountainous and floodplain areas – this dividing line is generalized as a Cauchy boundary (Long *et al.* 2013). Within the study area, the Second Songhua River and its tributaries, the Yinma River and the Yitong River, are generally recognized as river boundaries (Cauchy boundaries). The unconfined aquifer was the target aquifer for modeling, which means that the hydrogeology and aquifer conditions in the study area were consistent with the hypothesis described in Darcy's Law.

Model calibration and verification

Each model's active cell area was 0.44 km^2, with a length and width of 660 m. The model generalizes the aquifer as a phreatic aquifer.

The numerical model of groundwater flow was based on a time series of observed hydraulic heads and groundwater sources/sinks, which were used to calibrate the hydrogeological parameters. The changes in the time series of groundwater hydraulic heads should be basically consistent with the actual observations, and the hydrogeological parameters should correspond to the hydrogeological conditions (Du *et al.* 2018). Model verification was based on the selection of another time period to verify the robustness of the parameter values. Calibration and verification were performed during 2011 and 2012, respectively.

Safe groundwater yield in suitable zones

Based on the numerical model of regional groundwater flow, a uniform arrangement of wells in the area suitable for RBF was established to evaluate the safe groundwater yield. By adjusting the number of wells and determining the single-well groundwater production and corresponding relationship curve between the abstraction rate and groundwater depth, the safe yield of groundwater was determined based on the turning point of the curve or the yield at the point where the constrained depth of the groundwater level was less than one-third of the aquifer thickness (Liu *et al.* 2011). One-third of the water-bearing sand layer thickness was adopted as the limit value of the groundwater head drawdown because, although this value is not a strict mathematical standard, it has been adopted in the general evaluation of groundwater resources in China.

Influence of RBF on regional water resources

According to the change in the river water stage under different precipitation frequencies (i.e. 20%, 50%, 75%, and 95%) and different abstraction plans (current abstraction intensity and safe yield intensity), the future groundwater level dynamics were modeled for the period 2014–2024, and the three influential aspects of regional groundwater flow direction, intensity, and direction of GSI and river flow were analyzed.

By comparing the groundwater flow fields between the current state and the modeled results at the end of the forecast period, the influence of RBF on regional groundwater flow direction and GSI was identified. The influence of RBF on river flow was analyzed as follows:

$$\delta = \frac{Q_{RG-A} - Q_{RG-C}}{Q_{RF}} \times 100\% \tag{1}$$

where δ is the degree of influence of RBF on the water flow under safe yield conditions (%); $Q_{RG\text{-}A}$ is the annual river water seepage to the aquifer under safe yield conditions (10^4 m^3/year); $Q_{RG\text{-}C}$ is the annual river water seepage to the aquifer under current conditions (10^4 m^3/year); and Q_{RF} is the annual river flow (10^4 m^3/year).

RESULTS AND DISCUSSION

Calibration and verification of the numerical model of groundwater flow

There are 37 observation wells in the study area, with six numbered wells selected here to show the fitting results for the relationship between the calculated and observed heads during calibration and verification (see Figures 3 and 4). Due to the limited number of observation wells, the hydraulic conductivity of the aquifer was calibrated against the observations of hydraulic heads in a trial estimation–correction method, and the model independent parameter estimation software, PEST, was used to obtain information, for approximately the 95% confidence intervals for the estimated parameters. The predictive RBF models were run using this parameter uncertainty.

The predictive models are transient models. The operation time is so long (10 years) that the hydraulic heads are close to a stable state at the end of running, which leads to a relatively steady decline of groundwater level with the safe yield. The local flow field in the study area is

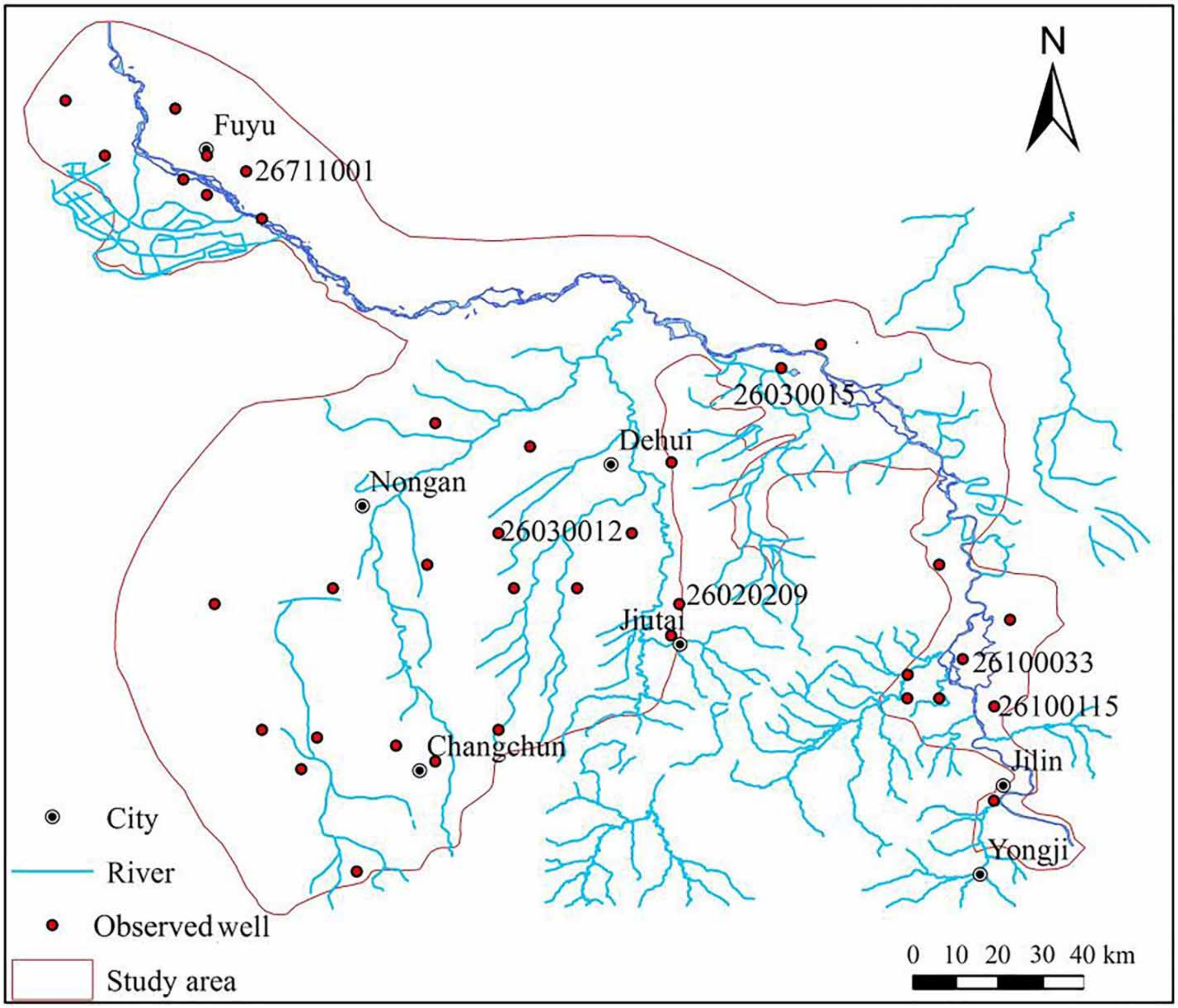

Figure 3 | Distribution map of the observation wells.

not sufficiently detailed, and the flow field varies greatly. The fitting of calculated values and observed values in the local observation wells was poorer in the area with large production where the variation of water head with time is not consistent with the trends in the observed groundwater level; however, this is a small part of the study area.

The fit of predicted to observed time series of groundwater heads during the calibration and verification periods achieved a correlation coefficient of 0.998, a Nash–Sutcliffe coefficient of 0.99. The results showed that the representation of the hydrogeological conditions, the treatment of groundwater sources/sinks, and the adopted values of hydrogeological parameters were all reasonable. The numerical model of groundwater flow could be used to predict the time series of the groundwater hydraulic heads in different groundwater abstraction scenarios in the study area.

Evaluation of the safe groundwater yield in the RBF zones

For the RBF Zones 1–5 under the 20% precipitation frequencies as examples, the safe groundwater yield was determined as follows.

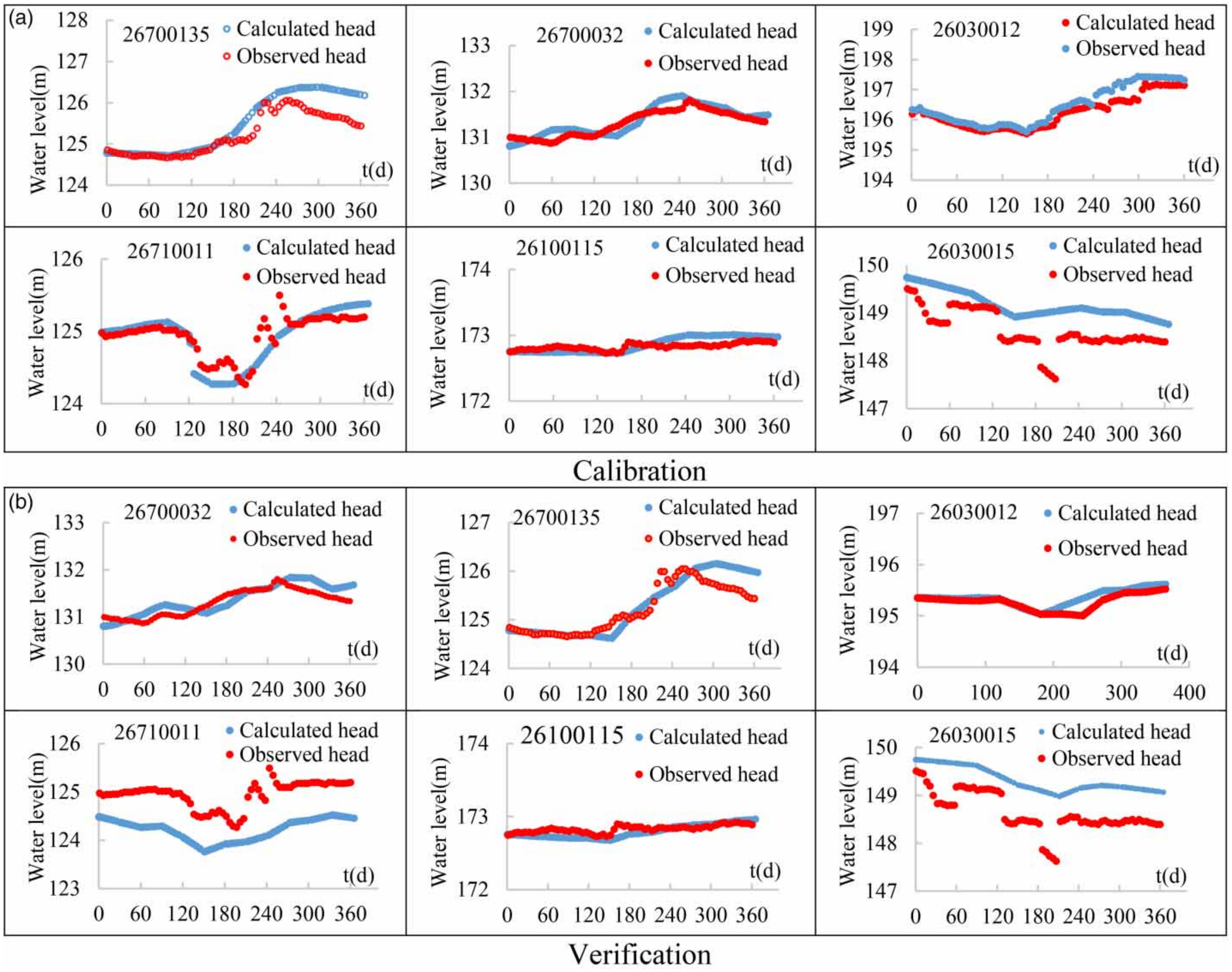

Figure 4 | Comparison of the calculated and observed heads of selected wells: (a) calibration period and (b) verification period.

RBF Zone 1

To establish a series of scenarios, with groundwater abstraction rates varying from 0.7×10^4 m^3/day to 2.83×10^4 m^3/day at intervals of 0.3×10^4 m^3/day, a relationship between the pumping rate and the stable hydraulic drawdown was determined. There was an obvious inflection point in the curve at a pumping rate of 1.61×10^4 m^3/day (see Figure 5(a)). The groundwater head drawdown increased in a linear rate of approximately 0.1 m in each pumping interval when the groundwater abstraction was less than 1.61×10^4 m^3/day, and the groundwater head drawdown increased by 0.69 m in each pumping interval when the groundwater abstraction rate exceeded 1.61×10^4 m^3/day. This result indicates that the environmental cost (where the adopted measure of environmental cost is the rate of drawdown for a given rate of daily abstraction) of groundwater pumping increases more rapidly when pumping rates exceed 1.61×10^4 m^3/day. This limit was determined to be the safe yield for RBF zone 1.

RBF Zone 5

When the groundwater abstraction was increased by approximately 1×10^4 m^3/day, the increase in the groundwater drawdown was linear at around 0.36 m per 1×10^4 m^3/day (see Figure 5(b)). There is no obvious inflection point in the relationship between groundwater pumping

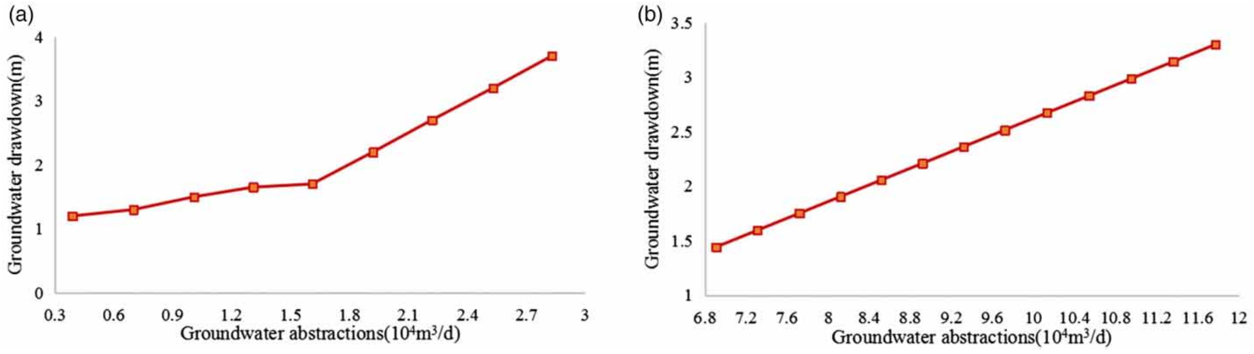

Figure 5 | Relationship between groundwater abstraction rate and groundwater drawdown in RBF Zone 1 (a) and RBF Zone 5 (b).

rate and the corresponding hydraulic drawdown. In this case a constrained drawdown standard of one-third aquifer thickness was used to assess the safe yield. Based on a total aquifer thickness of 9 m, a drawdown limit of 3 m was adopted and gave a safe yield for RBF Zone 5 of 10.99×10^4 m^3/day.

The adopted period of prediction was long, and a relatively steady groundwater level depression cone should be expected under each reasonable safe yield condition.

Similarly, the safe yield of groundwater in all RBF suitable zones was calculated separately for precipitation frequencies of 20%, 50%, 75%, and 95%, respectively. The results are shown in Table 1.

As shown in Table 1, there was a large potential for the abstraction of groundwater resources in the RBF zones along the Second Songhua River. Even under extreme drought conditions, the total safe yield was still approximately 29.34×10^4 m^3/day.

Table 1 | Estimated safe groundwater yield (10^4 m^3/day) in RBF Zones 1–5 under various levels of precipitation

RBF zone	Average thickness of the water-bearing sand (m)	Adopted groundwater drawdown limit (m)	Precipitation frequency			
			20%	50%	75%	95%
1	5	1.6	2.04	1.23	0.92	0.77
2	5	1.67	11.44	10.22	9.2	8.57
3	15	5.36	14.83	12.76	12.46	10.94
4	10	3.3	3.57	3.03	2.66	2.24
5	9	3	10.99	9.23	8.04	6.91

Influence of RBF zones on the regional groundwater flow field

Figure 6 uses the 20% precipitation frequency as an example and compares the groundwater flow field under the conditions of current abstraction and safe yield abstraction in the RBF zones. Figure 6 shows that the head difference between the safe yield scenario and current conditions at 20% annual precipitation is small, with differences ranging from −3.56 m to 1.02 m mainly in the RBF zones. It was concluded that abstraction in the RBF zones would not change the overall direction of the regional groundwater flow, but that abstraction in the RBF zones affects the local groundwater flow field only.

Influence of abstraction in RBF zones on river recharge

Due to the change in the local groundwater flow field, the direction and rate of recharge may change.

Using RBF Zone 2 as an example, the macroscopic pattern of groundwater flow was generally unchanged under all abstraction schemes; however, there were still some changes, including changes in the rate and direction of groundwater flow field near the river (see Figure 7). In RBF Zone 2, the aquifer thickness was approximately 5 m. Under the current conditions of abstraction and river water recharge of the ambient aquifer, there are groundwater level depression cones on the left and right riverbanks. Under the current abstraction regime, the groundwater level depression cone became slightly larger and the lowest groundwater level declined with an increase

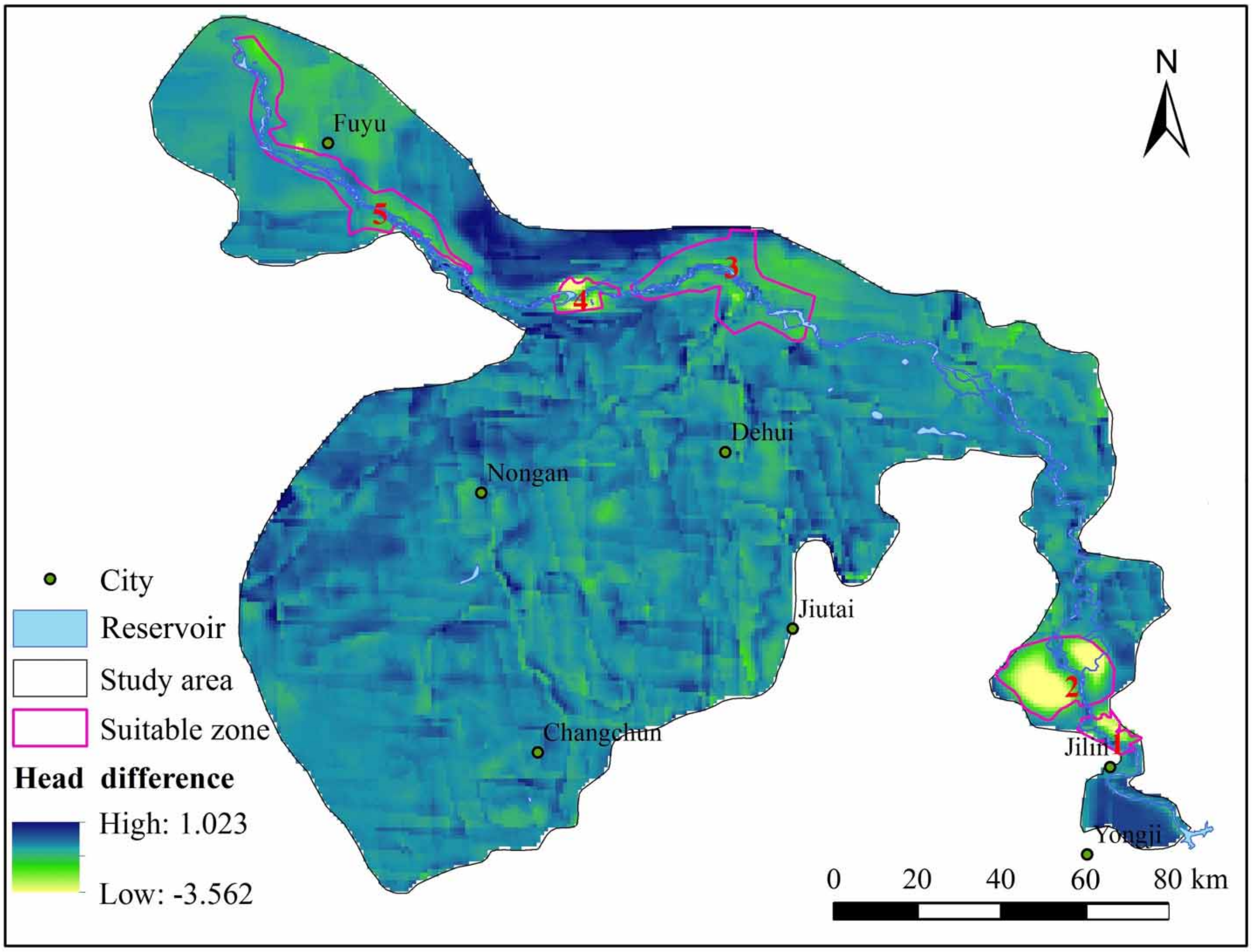

Figure 6 | The modeled equipotential contour map of unconfined groundwater.

in precipitation frequency. In comparison with the current abstraction regime, the groundwater level depression cones became larger and the lowest groundwater level declined from 4 m to 6 m under the safe yield abstraction conditions. Figure 6 shows that with an increase in the precipitation frequencies, the quantity of river water that recharges to the aquifer increases. Compared with the current abstraction regime, the recharge direction did not change significantly, but the rate of recharge clearly changed.

As shown in Table 2, the fraction of river water to the total amount of water abstracted increased as the precipitation frequency increased, and the proportion was 99.63% in RBF Zone 5 under a 95% precipitation frequency, indicating nearly all water abstracted was from river recharge. There was no river recharge in RBF Zone 3 under all conditions.

The river recharge varied to a certain extent in other RBF zones under the different precipitation frequencies, as shown in Table 3. Under higher precipitation frequencies, the recharge direction reversed from the river discharging groundwater to the river recharging the groundwater. Although there was no obvious change in the recharge direction under the lower precipitation frequencies, the recharge rate was definitively changed.

Influence of RBF on river flow

Under the existing hydraulic conditions in the study area, RBF abstraction first reduces the discharge of groundwater to the river. Furthermore, when the rate of abstraction was sufficiently high, the groundwater level was lower than the

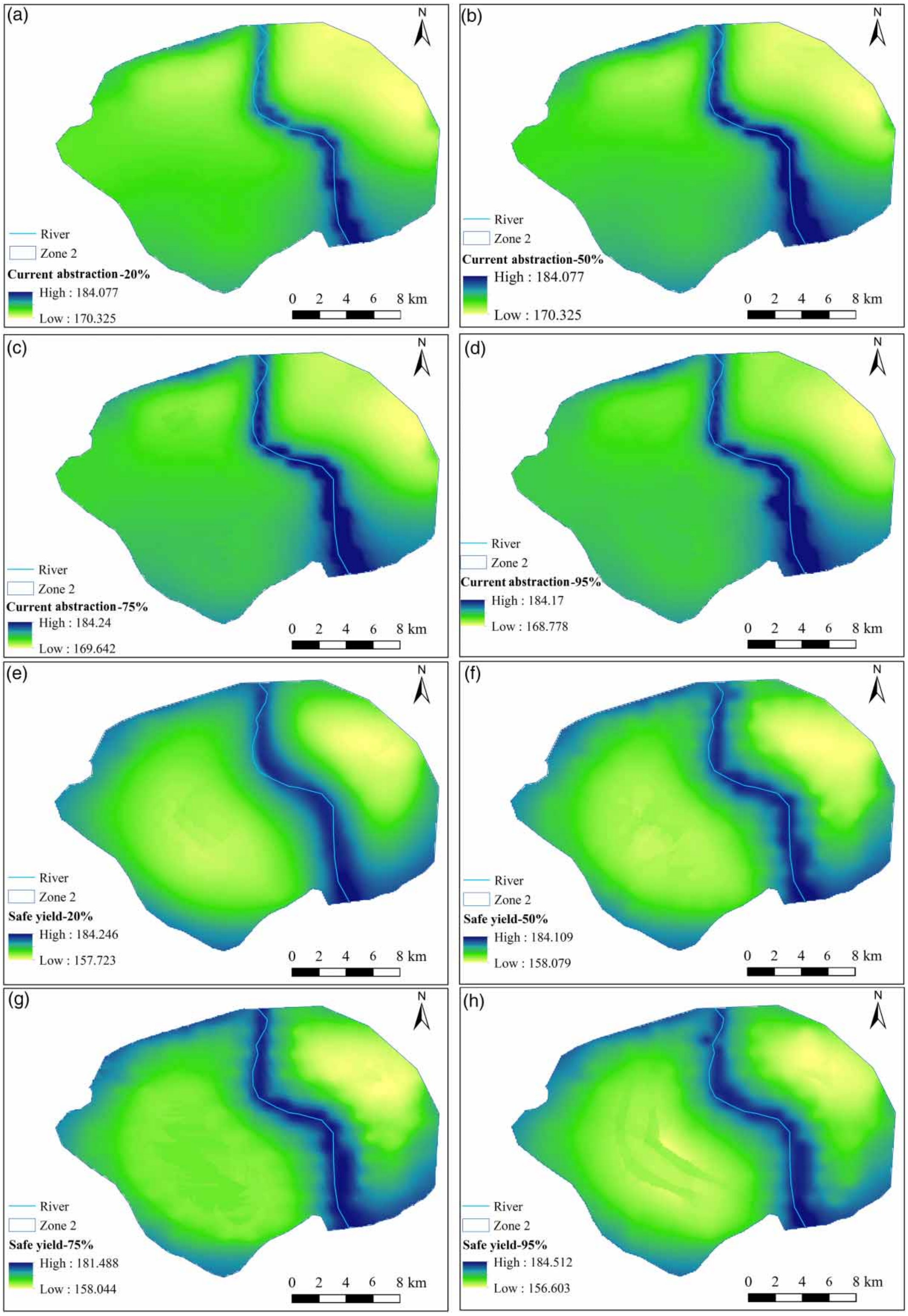

Figure 7 | The modeled equipotential contour map for RBF Zone 2: (a) current abstraction under 20% annual precipitation, (b) current abstraction under 50% annual precipitation, (c) current abstraction under 75% annual precipitation, (d) current abstraction under 95% annual precipitation, (e) safe yield abstraction under 20% annual precipitation, (f) safe yield abstraction under 50% annual precipitation, (g) safe yield abstraction under 75% annual precipitation, and (h) safe yield abstraction under 95% annual precipitation.

Table 2 | The fraction of river water to the total amount of water abstracted (10^4 m^3/year)

Precipitation frequency		**20%**	**50%**	**75%**	**95%**
Zone 1	River recharge	34.37	34.66	56.92	152.54
	Safe groundwater yield	744.60	448.95	335.80	281.05
	Proportion	4.62%	7.72%	16.95%	54.28%
Zone 2	River recharge	1,340.58	1,254.80	1,188.78	1,503.50
	Safe groundwater yield	4,175.60	3,730.30	3,358.00	3,128.05
	Proportion	32.11%	33.64%	35.40%	48.07%
Zone 3	River recharge	0.00	0.00	0.00	0.00
	Safe groundwater yield	5,412.95	4,657.40	4,547.90	3,993.10
	Proportion	0.00%	0.00%	0.00%	0.00%
Zone 4	River recharge	0.00	0.00	0.19	32.96
	Safe groundwater yield	1,303.05	1,105.95	970.90	817.60
	Proportion	0.00%	0.00%	0.02%	4.03%
Zone 5	River recharge	3,433.27	2,743.36	2,489.97	2,512.90
	Safe groundwater yield	4,011.35	3,368.95	2,934.60	2,522.15
	Proportion	85.59%	81.43%	84.85%	99.63%

Table 3 | Changes in GSI under different conditions

RBF zone	**Current abstraction condition**	**Safe yield abstraction**	**Impact of safe yield abstraction**
1	River discharges groundwater	River discharges groundwater	No change in recharge direction, but the rate decreased
2	River water recharges groundwater	River water recharges groundwater	No change in recharge direction, but the rate increased
3	River discharges groundwater	River discharges groundwater	No change in recharge direction, but the rate decreased
4	River discharges groundwater	At precipitation frequencies of 75% and 95%, river water mainly recharges the aquifer	Under higher precipitation frequencies the recharge direction reverses
5	The upper reaches of the river discharge groundwater; while the middle and lower reaches of the river water recharge groundwater. Overall, river water recharges groundwater	The river discharges groundwater upstream, while the river water recharges groundwater in the middle and lower reaches	No change in the recharge direction, but the length of river over which the river recharges the groundwater increased

river water level, which resulted in the river recharging the groundwater system, i.e. the RBF abstraction was capturing water from river. The water quantity changes between the river and groundwater system were calculated based on the modeled results and are given in Table 4.

Compared to the current abstraction regime, the amount of river flow recharged to the groundwater system (including the decreased groundwater discharge to the river) clearly increased, but there was an obvious difference in the range of increases in the zones. In RBF Zone 1, the impact of safe yield abstraction on river flow was least, ranging from 0.04% to 0.32% reductions in river flow, while the influence of safe yield abstraction on river flow was greatest in the downstream RBF Zone 5 where the

Table 4 | Impact of RBF abstraction on river flow (10^4 m^3/year)*

Precipitation frequency		**20%**		**50%**		**75%**		**95%**	
Abstraction regime		**Current**	**Safe yield**	**Current**	**Safe yield**	**Current**	**Safe yield**	**Current**	**Safe yield**
Flow in upstream reach		228,700		110,100		42,700		13,100	
Zone 1	River recharge	−53.4	34.37	−74.34	34.66	15.96	56.92	110.82	152.54
	Change in exchange	87.77		109		40.96		41.72	
	Proportion of river flow	0.04%		0.10%		0.10%		0.32%	
Zone 2	River recharge	788.38	1,340.58	827.5	1,254.8	1,007.65	1,188.78	1,156.11	1,503.5
	Change in exchange	552.2		427.3		181.13		347.39	
	Proportion of river flow	0.24%		0.39%		0.42%		2.65%	
Zone 3	River recharge	−1,792.32	−643.74	−1,466.41	−595.39	−1,172.96	−384.96	−886.09	−263.56
	Change in exchange	1,148.58		871.02		788		622.53	
	Proportion of river flow	0.50%		0.79%		1.85%		4.75%	
Zone 4	River recharge	−490.67	−53.43	−364	−6.21	−286.89	0.19	−197.98	32.96
	Change in exchange	437.24		357.79		287.08		230.94	
	Proportion of river flow	0.19%		0.32%		0.67%		1.76%	
Zone 5 upstream	River recharge	1,936.14	1,987.51	1,669.99	1,791.18	1,127.49	1,520.21	1,274.37	1,679.13
	Change in exchange	51.37		121.18		392.72		404.76	
	Proportion of river flow	0.02%		0.11%		0.92%		3.09%	
Flow in the middle and lower Reaches		13,000		6,300		4,500		2,300	
Zone 5 downstream	River recharge	1,337.79	1,913.54	1,101.04	1,438.35	1,168.67	1,547.95	1,194.30	1,454.70
	Change in exchange	575.75		337.32		379.28		260.40	
	Proportion of river flow	4.43%		5.35%		8.43%		11.32%	
Total amount of river lateral seepage		2,852.90		2,223.61		2,069.17		1,907.73	

*The upstream reach refers to the reach from the Fengman Reservoir to the Hada Shan Reservoir, while the middle and lower reaches refers to the reach from the Hada Shan Reservoir to the Sancha River. The positive river recharge values represents the river discharge to the groundwater, while the negative values represent groundwater discharge to the river.

river recharge ranged from 4.43% to 11.32% of river flow. The MinIEF (minimum in stream ecological water requirement) is the lower limit of flow below which the stability and health of river ecosystems cannot be maintained and aquatic creatures cannot survive (Li *et al.* 2018). Using the Tennant method for reference, if the MinIEF is 10% then it takes 10% of the annual average flow to maintain the river ecosystem health (Yang 2007; Wang *et al.* 2016b; Gillefalk *et al.* 2018). The estimated MinIEF is summarized in Table 5.

Table 5 | Estimated minimum instream ecological water requirement (10^4 m^3/year)

Precipitation frequency	**20%**		**50%**		**75%**		**95%**	
Abstraction regime	**Current**	**Safe yield**	**Current**	**Safe yield**	**Current**	**Safe yield**	**Current**	**Safe yield**
Flow in upstream reach	228,700	228,700	110,100	110,100	42,700	42,700	13,100	13,100
Total river recharge	2,724.5	2,718.7	2,497.5	3,080.6	2,151.1	2,381.1	2,541.3	3,368.1
Flow downstream of Zone 5	225,975	225,981	107,603	107,019	40,549	40,319	10,559	9,732
MinIEF			10,760					
Flow in the middle and lower reaches	13,000	13,000	6,300	6,300	4,500	4,500	2,300	2,300
Total river recharge	1,337.8	1,913.5	1,101	1,438.4	1,168.7	1,548	1,194.3	1,454.7
Flow downstream of Zone 5	11,662	11,086	5,199	4,861.7	3,331.3	2,952.1	1,105.7	845.3
MinIEF			520					

If safe yield abstraction is not exceeded in RBF Zones 1–5, then the current ecological health of the upstream and middle and lower reaches of the Second Songhua River is expected to be maintained.

CONCLUSIONS

To determine a suitable area of RBF, a numerical model of regional groundwater was constructed for the Second Songhua River floodplain, and a joint study of surface water and groundwater was conducted in the river basin to predict and analyze the impact of RBF schemes on regional water resources. The conclusions were as follows:

(1) Based on the assessed relationship between groundwater abstraction and hydraulic drawdown and limiting the drawdown to no more than one-third of the aquifer thickness, the safe yield of groundwater abstraction under different precipitation frequencies (20%, 50%, 75%, and 95%) was calculated and it was determined that it would be possible to increase abstraction across RBF Zones 1–5 by 570.0 to $1{,}087.2 \times 10^4$ m^3/year along the Second Songhua River depending on precipitation frequency.

(2) Safe yield abstraction in RBF Zones 1–5 would have little impact on the overall groundwater flow field in the region. Although it would not change the overall direction of the regional groundwater flow, it would have different impacts on the local groundwater flow fields.

(3) If safe yield abstraction is not exceeded in RBF Zones 1–5, then the current ecological health of the upstream and middle and lower reaches of the Second Songhua River is expected to be maintained.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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