

Article

Evaluation of the Impact of Ecological Water Supplement on Groundwater Restoration Based on Numerical Simulation: A Case Study in the Section of Yongding River, Beijing Plain

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Abstract: Ecological water supplement relies on river channels to introduce surface water, to make a reasonable supplement of groundwater, to repair the regional groundwater environment and urban river ecosystem. Evaluating the degree of groundwater restoration after ecological water supplement (by taking appropriate measures) is a critical problem that needs to be solved. Thus, based on the Yongding River ecological water supplement in 2019 and 2020, we analyzed the groundwater monitoring situations in the ecological water supplement region. We established an unstructured groundwater flow numerical model in the study area through the quadtree grids. The model was calibrated with the measured water level. The simulated results could accurately reflect the real groundwater dynamic characteristics, and it showed that the water level rise was concentrated in the 3–6 km range of the Yongding River after the ecological water supplement. In 2019, the calculated ecological water infiltration amount was $101.28 \times 10^6 \text{ m}^3$, the affected area was 265.19 km², and the average groundwater level rise in the affected area was 2.10 m. In 2020, the calculated ecological water infiltration amount was $102.64 \times 10^6 \text{ m}^3$, the affected area was 506.88 km², and the average groundwater level rise in the affected area was 1.25 m. While the ecological water supplement had a positive impact on groundwater level restoration, the groundwater level around the typical buildings within the study area, including Beijing West Railway Station and Beijing Daxing International Airport, would not be significantly affected.

Keywords: Yongding River; groundwater numerical simulation; artificial ecological water supplement; groundwater recharge resources amount evaluation



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1. Introduction

Yongding River is located in the western suburbs of Beijing and is known as the “Mother River” of Beijing. Since 1950, due to the long-term impact of numerous water conservancy projects built in the river, the ecological environment of the river basin has been continuously deteriorating [1,2]. In addition, due to the influence of social development, the over-exploitation of groundwater and the gradual seriousness of water pollution led to the deterioration of water volume and water quality in the Yongding River Basin [3,4]. In recent years, more attention has been placed on the study of river ecological restoration. Some investigators focus on the study of restoration methods [5,6], and others focus on the study of water pollution treatment [7,8]. For the ecological environment in the Yongding River Basin, some investigators also summarize the progress of the restoration and put forward specific restoration methods [9] and restoration goals [10]. Since the beginning of this century, the Beijing Municipal Government has carried out many countermeasures to restore and control the ecological environment of the Yongding River Basin. In 2016, it

launched the ecological water supplement project of the Yongding River, with the three provinces of Tianjin, Hebei, and Shanxi; this project has achieved ideal governance effects so far [11].

After implementation of the Yongding River ecological water supplement project, there has been concern over the amount of ecological water needed for the river basin. In-depth studies have provided a certain theoretical basis for solving the problem of water allocation in the process of the ecological water supplement. For instance, Wei Jian et al. used the environmental water demand method and the ecological water demand method to study the ecological water demand at different stages of the Yongding River mountain section [12]. Du Yong et al. also calculated the ecological water demand, which could meet the continuous flow of the entire Yongding River based on the monitoring of the groundwater level, flow, and infiltration data of the ecological water supplement in 2019 [13].

Researchers have also evaluated the impact of the ecological water supplement on the groundwater quality and quantity of the basin. Through numerical simulation, Hu et al. found the lining constructed with the geomembrane in the Yongding River can effectively control the seepage of water and the diffusion of solutes in the aquifer. They also confirmed the diffusion of potential pollutants increases with the infiltration of the Yongding River ecological water supplement [14]. Using the principal component analysis method, Luo et al. analyzed the temporal and spatial changes of 11 water quality parameters at 10 monitoring points of Yongding River in April 2011 and September 2016. Based on this, they evaluated the impact of river restoration projects on groundwater quality [15]. Based on the ecological water supplement work of the Yongding River in 2020, Hu Litang et al. used many technical methods, such as groundwater balance analysis, correlation analysis, and cluster analysis to discuss the leakage loss, groundwater dynamic changes, and control factors of each river section [16]. Ma Yao et al. used the groundwater balance analysis method to calculate the amount of groundwater supplements in different sections of the Yongding River during the ecological supplement period in 2019. They also carried out an analysis of the impact on the regional groundwater after the ecological water supplement of the Yongding River (Beijing section) [17]. Kangning Sun et al., by developing a coupled model, integrating a Muskingum method-based open channel flow model and machine learning-based groundwater model, described the dynamic changes in streamflow and groundwater levels in response to the ecological water supplement of the Yongding River [18].

In summary, many researchers have conducted relevant studies on the ecological restoration of the Yongding River Basin and have obtained many instructive study results. Studies have shown that the implementation of the ecological water supplement work in the Yongding River can significantly alleviate the problem of regional groundwater overexploitation. As a result, the quantity and quality of regional groundwater have significantly improved. Moreover, the development of ecological water supplement work can also improve the ecological environment of the Yongding River Basin and promote the re-flow of the river. However, most studies on the impact of groundwater level restoration are based on groundwater balance methods and mathematical statistics methods, and the results are insufficient to characterize the spatial variability of groundwater level restoration or forecast the repair effect. The most complete and reliable method to solve the problem is by the numerical simulation of groundwater; moreover, the simulation of groundwater by the widely used MODFLOW. Gert Ghysels et al. and A. A. El-Zehairy et al. have successfully applied MODFLOW to the simulation study of the relationship among rivers, lakes, and groundwater [19,20]. They proposed a feasible method for simulating the interaction between surface water and groundwater. In addition, MODFLOW has also been used in numerical simulation studies of saline water encroachments in coastal areas [21,22] and groundwater in complex karst areas [23]. MODFLOW is widely used in different fields and different depths of research, which also further demonstrates its full reliability.

In this paper, we analyze the dynamic characteristics of groundwater and establish a numerical model of groundwater under ecological water supplement conditions by MODFLOW, to reveal the degree of regional groundwater restoration. Meanwhile, the impact of ecological water supplement on typical buildings within the study area is also taken into account. The study conclusions can provide suggestions to identify the extent of groundwater restoration in the region, and provide a reference for future ecological water supplement work.

2. Methods

2.1. Ecological Water Supplement Information in the Study Area

The Yongding River ecological water supplement plains region (Beijing section) is located in the southwest side of Beijing (China) (Figure 1a), with a total area of about 888.72 km². Under the influence of climate drought, irrational exploitation, and utilization of groundwater, the Yongding River channel was in “cut-off” states for a long time [24,25]. Since the Yongding River Comprehensive Management and Ecological Restoration Project launched, two large-scale ecological water supplement tasks were carried out in 2019 and 2020. The ecological water supplement was from the Guanting Reservoir (Beijing, China) all the way to the south, by the San Jiadian barrage, into the plain region. In 2019, it only reached the 12 km downstream of the Lugouqiao barrage. However, in 2020, it flowed through the Men Tougou, Shi Jingshan, Fengtai, Fang Shan, and Da Xing, five districts, in Cui Zhihuiying town (Da Xing, China), out of Beijing’s administrative boundary. Therefore, it went through the entire Beijing Plain region in 2020. In 2019 and 2020, a total volume of 313 × 10⁶ m³ and 166.42 × 10⁶ m³ was discharged from the Guanting Reservoir. The ecological water supplement volume in the plains and the duration are shown in Table 1.

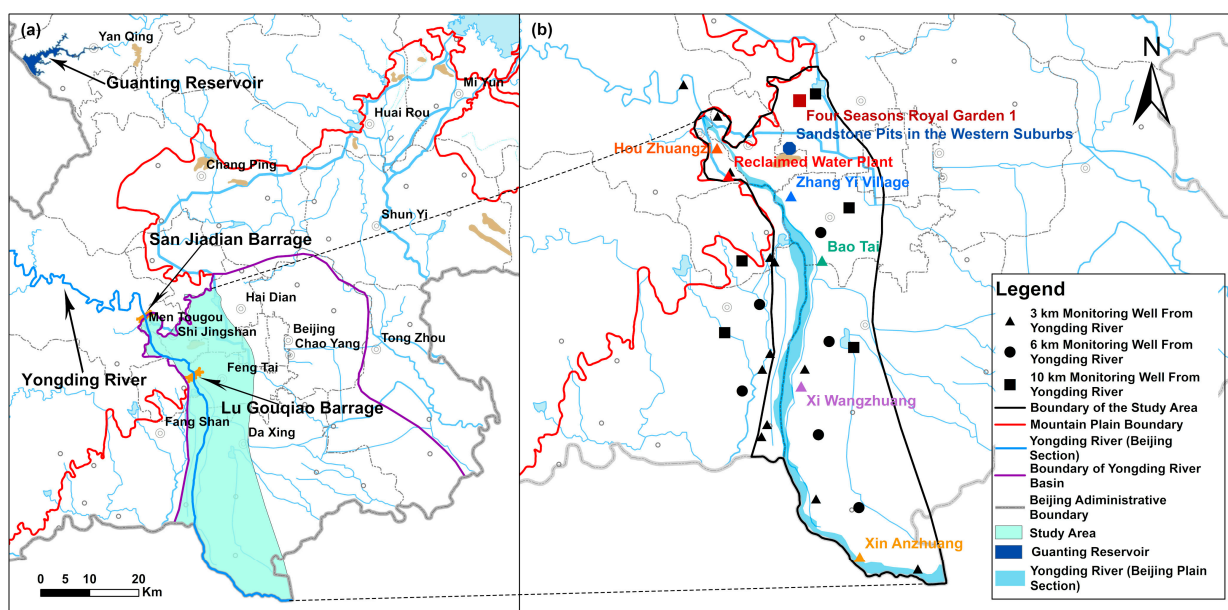


Figure 1. (a) Location map of the Yongding River ecological water supplement plains region (Beijing section). (b) Distribution map of the groundwater monitoring wells.

Table 1. Ecological water supplement in the plain region of the Yongding River in 2019 and 2020.

Ecological Water Supplement Year (a)	Start Time of Water Supplement	Lastest Times (d)	Amount of Water Supplement in San Jiadian Barrage (m ³)
2019	22 March	77	128.18 × 10 ⁶
2020	22 April	32	142.38 × 10 ⁶

To observe the influence of the ecological water supplement on groundwater in Yongding River, 32 automatic observation wells of groundwater within 10 km of Yongding River are shown in this study. The locations of the observation wells are shown in Figure 1b. From upstream to downstream, within 3 km of the Yongding River, the observation wells data were selected to draw the groundwater level process lines during 2018–2019 (Figure 2a). Since the Yongding River water supplement started on 22 March 2019, the groundwater table in the upper and middle reaches of Yongding River rose in early April 2019. The delay effect on the groundwater level rising in the region could be used to explain this phenomenon. After the ecological water supplement, the water table gradually decreased. Xi Wangzhuang and Xin Anzhuang were located in the middle and lower reaches of Yongding River. Because the ecological water supplement head of Yongding River did not reach here, not all were affected by the ecological water supplement. Therefore, the water table could remain unchanged. Zhang Yi village, located near the Lugouqiao barrage, affected by the San Jiadian barrage—to release water, the water level changed greatly. Hou Zhuangzi and the reclaimed water plant are located close to the San Jiadian barrage, so the ecological water supplement affected them much earlier. Compared to the Bao Tai observation well, which was located in the midstream, the water table also rose earlier. Finally, compared to the non-ecological water supplement time, the water level of the four groundwater monitoring wells located upstream recovered significantly during the ecological water supplement period. The water level gradually returned to the pre-ecological water level state after the ecological water supplement period. Only a small increase in the water level had been maintained.

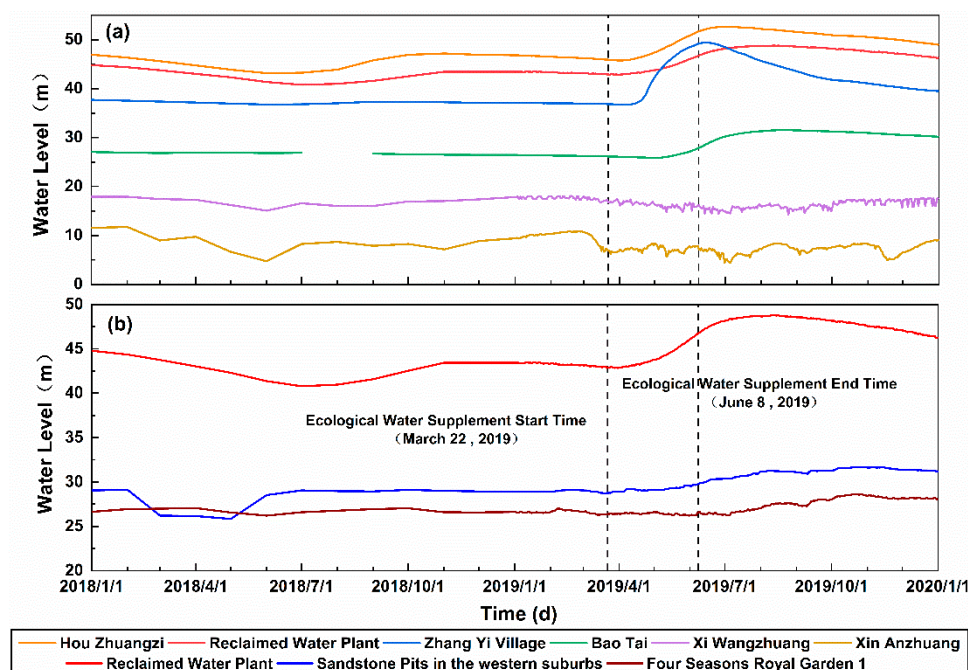


Figure 2. (a) Dynamic curve of the groundwater level of the monitoring wells along Yongding River. (b) The dynamic curve of the groundwater level of monitoring wells at different distances, with a perpendicular arrangement to the Yongding River.

According to the “principle of perpendicular” to the Yongding River, from near to far, observation well data were used to draw the groundwater level process line diagram during 2018–2019 (Figure 2b). As the distance increased, this influence was gradually weakened. For example, the Sandstone Pits in the western suburbs observation well, which was 6 km away from the Yongding River, only had a little impact on the ecological water supplement. The groundwater level between the selected monitoring wells had more obviously risen compared to the non-ecological water supplement period.

2.2. Hydrogeological Conditions in the Study Area

The study area is located in the southwestern part of the alluvial fan of the Yongding River, which is high in the northwest and low in the southeast (Figure 3a,b). The annual average atmospheric rainfall is 571.2 mm. The river in the region is mainly the Yongding River. The regional aquifer is mainly a single phreatic aquifer on top of the alluvial fan. The average thickness of the aquifer varies from 50 to 240 m, in which Quaternary sand and gravel dominate its lithology, and the hydraulic conductivity varies from 10 to 250 m/d [26,27]. The hydrogeological profile in the Yongding River alluvial fan is shown in Figure 4, which is adapted from Figure 2 in the study by Huan et al. [28]. The aquifer is mainly recharged by means of lateral runoff in the piedmont zone, precipitation infiltration, and water infiltration of the Yongding River; it is discharged by means of artificial mining and lateral outflow of the aquifer. For the water diversion channels in cities, most of them have a lining effect, and the surface water flow has no obvious replenishment effect on the groundwater. Therefore, it is not included in the source and sink items in our study. Recently, due to the continuous increase of exploiting groundwater, the depth of groundwater has been greater than 10 m, so the evaporative water loss of the diving surface can be ignored. The regional groundwater migrates from northwest to southeast and from the mountain front to the alluvial plain. The runoff intensity gradually weakened from the top to the bottom of the alluvial fan and from the upstream to the downstream of the river channel.

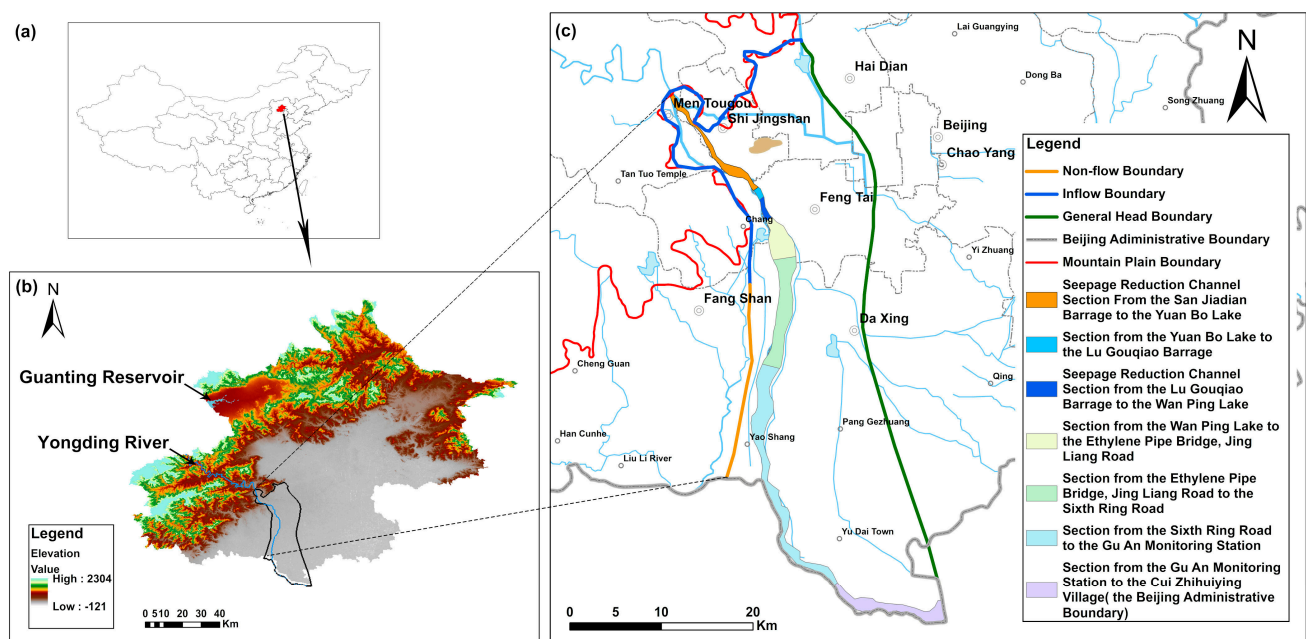


Figure 3. (a,b) Location and terrain distribution of the alluvial fan of the Yongding River. (c) Schematic diagram of generalization of the model boundary and each Yongding River ecological water supplement monitoring section.

2.3. Groundwater Flow Numerical Model

The northern model boundary was extended to the mountain-plain boundary and treated as an inflow boundary. The southern side of the western boundary was consistent with the boundary lines of the Dashi-Juma River groundwater system and the Yongding River groundwater system, divided, which was treated as a non-flow boundary. The eastern boundary considered of the impact range of groundwater restoration to artificially delimit the model boundary, and treated it as a general head boundary (Figure 3c). Based on the study objectives and the distribution characteristics of the aquifer, we generalized the model as a single-layer model. The upper boundary was the phreatic surface, which accepted external replenishment. The lower boundary considered the vertical influence

of the Yongding River's ecological water supplement. Therefore, we selected the bottom boundary of the phreatic aquifer as the model boundary and regarded it as a non-flow boundary.

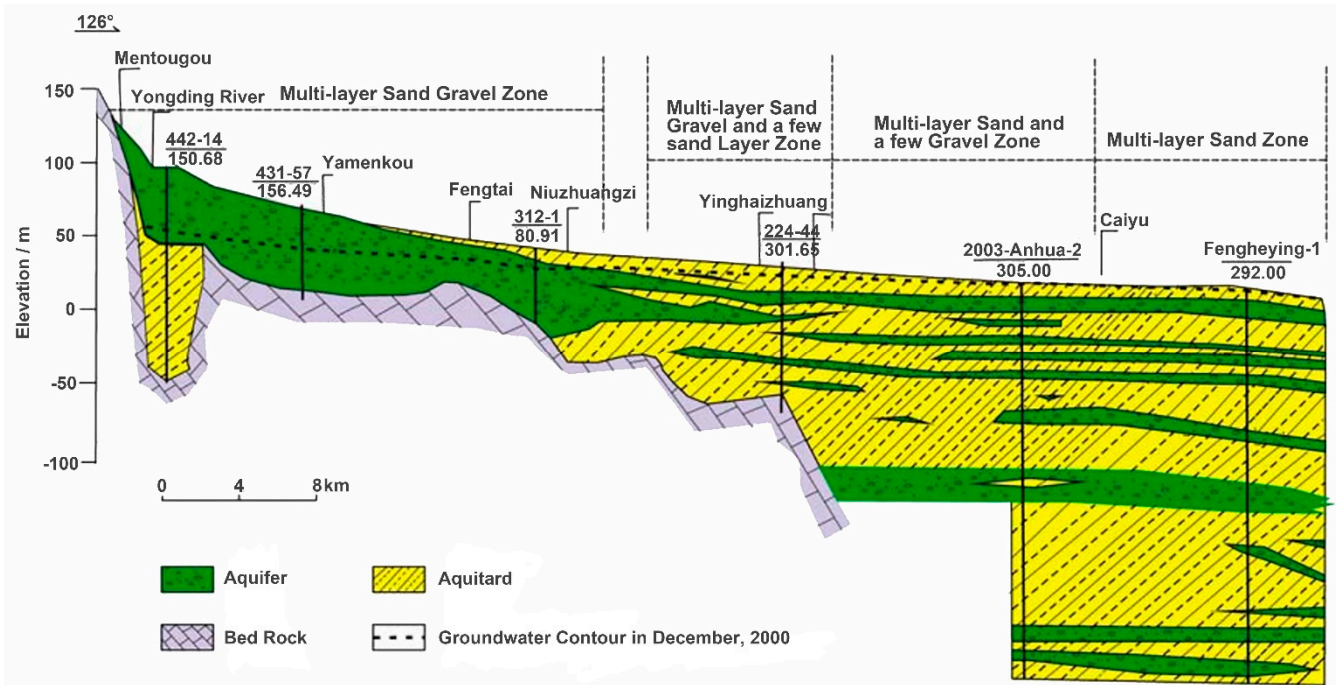


Figure 4. Hydrogeological profile in the Yongding River alluvial fan (adapted from Figure 2 in the study by Huan et al. [28]).

According to the achievements of previous studies, using quadtree grids to mesh the model could improve the calculation accuracy based on ensuring the calculation efficiency of the model [29–31]. Therefore, we also selected the quadtree grids provided by the MODFLOW-USG module in the GMS software. We set the basic grid size of the model to 200×200 m and carried out two different levels of local encryption. The meshing of the model was shown in Figure 5. Referring to the analysis of the dynamic characteristics of groundwater, we preliminarily estimated the impact range of Yongding River's ecological water supplement was about 3–6 km from both sides of the river. Moreover, the groundwater table within a 3 km area had obvious uplift. Thus, we refined the grids within 3 km along the Yongding River with a 50×50 m size. Then, we segmented the ecological water supplement infiltration volume of the Yongding River with the distribution of each monitoring section (Figure 3c). Moreover, we took the water volume, and multiplied the identified and corrected infiltration coefficient to add to the model in the form of an injection well. Therefore, the grids where the injection well was located were refined twice, and the grid size after refinement was 25×25 m. A total of 136,721 grids existed in the model.

The simulation period was from 1 January 2019 to 31 December 2019. During the simulation period, we allocated the ecological water supplement from April to July to the “stress period” of days, and the rest of the non-refill months to each natural month, as a stress period. Each stress period was processed by the corresponding software package according to the actual source and sink data, and then assigned to each time step. The initial values of hydrogeological parameters referred to the parameter partition values generated by previous work experience and fine-tuned through fitting correction.

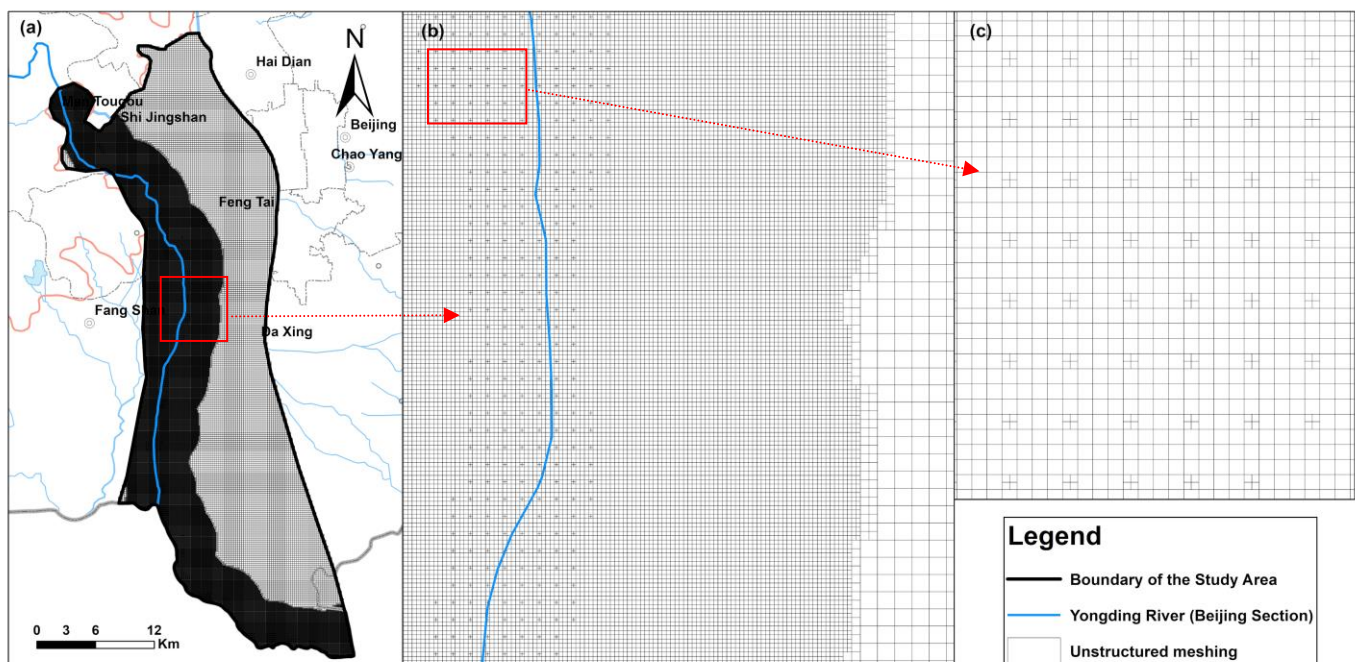


Figure 5. (a) Model quadtree grids division diagram. (b) Schematic diagram of a partial enlargement of the first-level encryption in a 3 km range along the Yongding River. (c) Schematic diagram of partial enlargement of secondary intensification of ecological water injection wells.

2.4. Model Calibration and Validation

The measured groundwater flow field on 31 December 2019, was used as the identification and verification flow field, and the model was identified and verified by trial-and-error calibration. The results showed that the simulated flow field and the measured flow field were (basically) the same in trend and flow patterns. Except for the piedmont zone on the north side and the Pang Gezhuang area in the Daxing district, which had a poor simulation effect, the other parts all reflected the actual groundwater flow trend (Figure 6a). The simulated groundwater level process line of the typical observation wells was consistent with the measured groundwater level, which accurately reflected the change process of groundwater before and after water replenishment (Figure 6b). The parameter partition after identification and correction is shown in Figure 6c. The hydraulic conductivity changes showed a clear trend of gradually decreasing from the upper part of the alluvial fan to the downstream plain region, and the parameter was not much different from the initial value. Therefore, the established numerical model could reflect the variation characteristics of the groundwater after the Yongding River ecological water supplement. We could use it to simulate and predict the impact of groundwater restoration after the Yongding River ecological water supplement.

Through the calibration and validation of the model, we obtained the results of the groundwater zone budget in the study area in 2019 (Table 2). During the simulation period, the total recharge of groundwater in the study area was $359.79 \times 10^6 \text{ m}^3$, the total discharge was $238.17 \times 10^6 \text{ m}^3$, and the recharge difference was $121.62 \times 10^6 \text{ m}^3$. The groundwater was in a positive equilibrium state as a whole. Among the recharge items, the rainfall infiltration was $143.28 \times 10^6 \text{ m}^3$, followed by the Yongding River ecological water supplement infiltration, $101.28 \times 10^6 \text{ m}^3$. They accounted for 67.97% of the total groundwater recharge in the study area. The discharge was mainly assembled by artificial mining, which was $188.97 \times 10^6 \text{ m}^3$, accounting for 79.34% of the total discharge.

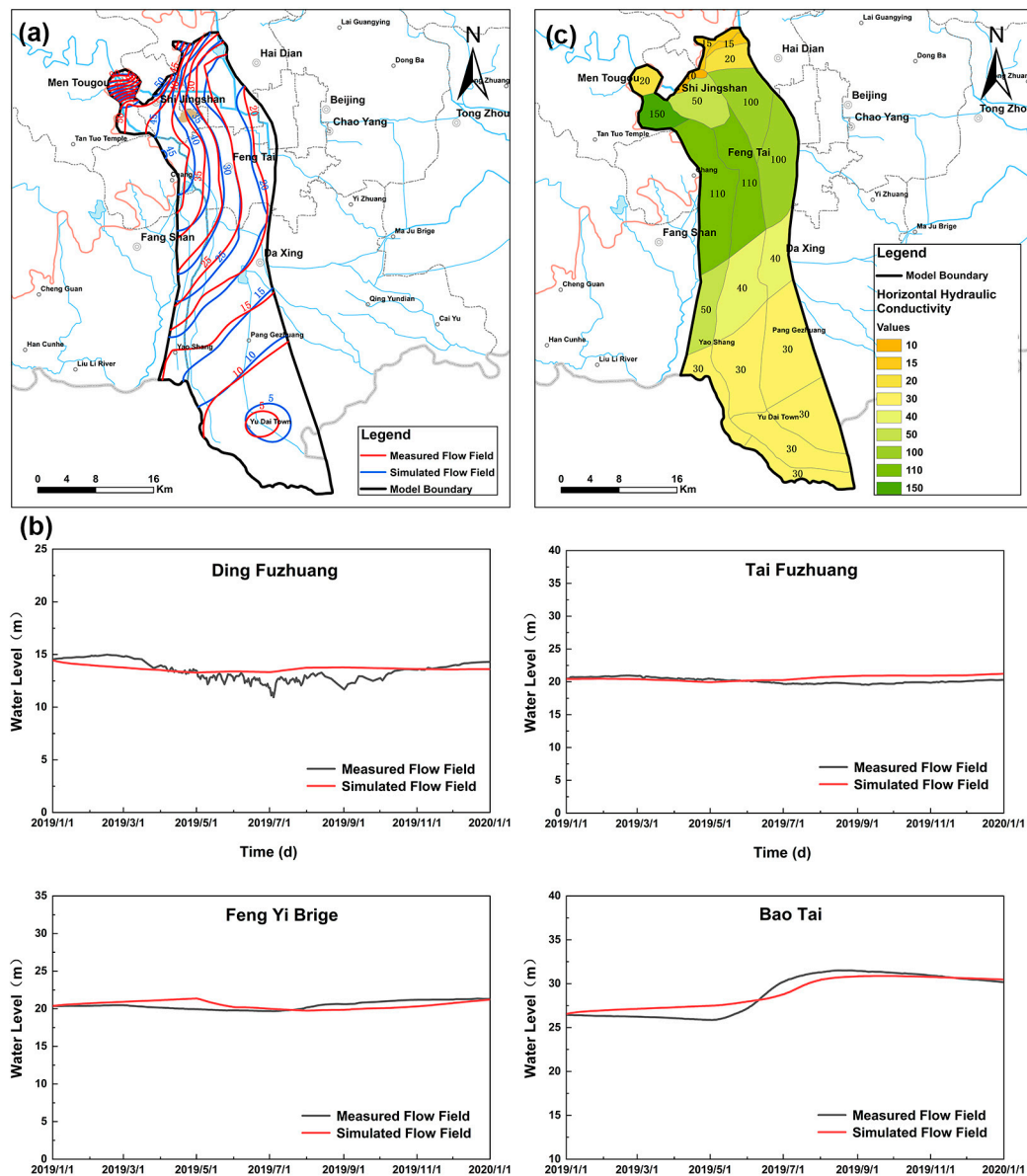


Figure 6. (a) Flow-field fitting diagram at the end of the simulation period. (b) The fitting curve of typical observation well in the ecological water supplement region. (c) Identification verified the aquifer parameter-zoning diagram (m/d).

Table 2. Groundwater zone budget in the study area in 2019.

Zone Budget Terms		Volume ($\times 10^6$ m ³)	Percentage
Recharge	Rainfall infiltration	143.28	39.82%
	Lateral inflow	92.82	25.80%
	Pipe network infiltration	22.41	6.23%
	Ecological water supplement infiltration	101.28	28.15%
	Total recharge	359.79	100%
Discharge	Artificial mining	−188.97	79.34%
	Lateral outflow	−49.20	20.66%
	Total discharge	−238.17	100%
Recharge and discharge difference		121.62	

3. Results and Discussion

3.1. Identification of Infiltration Volume and Leakage Coefficient in the Yongding River Channel

The artificially ecological water supplement infiltration volume in each section of the Yongding River was calibrated and validated by the corrected model. Therefore, we also obtained the accurate leakage coefficients to provide calculation parameters for the groundwater flow prediction model of the Yongding River ecological water supplement in 2020. The ecological water supplement “head” of the Yongding River, in 2019, only reached 12 km downstream of the Lugouqiao barrage. The calculation only included the section of the river from below Wanping Lake to the point where the final hydraulic head reached. Due to the runoff interception effect of the Lugouqiao barrage causing the water level to rise, the infiltration capacity of the sandy gravel river channel had tremendously improved. Therefore, the section from the Yuan Bo lake to the Lugouqiao barrage was significantly larger than other river sections. Finally, we list the calculated infiltration amount and leakage coefficient of the Yongding River ecological water supplement in Table 3. About 21% of the total ecological water supplement volume was lost in 2019, and only 79% of the ecological water supplement volume successfully infiltrated and recharged groundwater. The loss of ecological supplement water could be explained as the water loss due to wetting of the river and intercepted by the soil during the infiltration of the ecological water supplement head through the river. The daily evaporation and infiltration of urban rivers and lakes could also occupy some ecological water supplement flow. Moreover, the lost volume, because the water surface of the entire river course evaporated, and was lost in the process of the ecological water supplement, was also included.

Table 3. Ecological water supplement infiltration volume and leakage coefficient for each section of Yongding River in 2019.

Section	Ecological Water Supplement Volume of Each Section ($\times 10^6 \text{ m}^3$)	Ecological Water Supplement Infiltration Volume of Each Section ($\times 10^6 \text{ m}^3$)	Leakage Coefficient
Seepage reduction channel section from the San Jiadian barrage to the Yuan Bo lake	68.64	5.49	0.08
Section from the Yuan Bo lake to the Lugouqiao barrage		51.13	0.72
Seepage reduction channel section from the Lugouqiao barrage to the Wanping Lake	59.54	8.93	0.15
Section of natural river course from below Wanping Lake to the point where the water head reaches		35.73	0.60
Total	128.18	101.28	0.79

3.2. Impact Range Analysis of Ecological Water Supplement in Yongding River in 2019

To obtain the impact range under the single factor of the ecological water supplement infiltration, the simulation results of the model with ecological water supplement conditions and the model without water supplement conditions were compared. We also used the groundwater level data on 31 December 2019, simulated by the two models to map the uplift variation of the groundwater level in the ecological water supplement region (Figure 7). It was shown that, by the end of 2019, the ecological water supplement head would gradually spread outward. Considering the model interpolation errors and the small fluctuations in the groundwater level, we finally selected the groundwater level rise value greater than 0.25 m as the standard to quantitatively calculate the impact range. The calculated affected area was about 265.19 km², accounting for 29.86% of the study area. It was distributed within about 6 km on both sides of the Yongding River channel; the widest impact range was located near the Lugouqiao barrage, reaching 9.7 km. Due to the

the simulated groundwater level data on 31 December, 2020, with or without ecological supplement conditions, the groundwater level restoration impact range of the ecological water supplement in 2020 was obtained, as shown in Figure 8. The overall distribution concentrated in the range of about 6–7 km on both sides of the Yongding River. The affected area was about 506.88 km², which accounted for 57.01% of the study area. Obviously, only the Fengtai water plant was within the delineated area of impact range, and the remaining typical buildings, including the no. 3 water source plant, Shi Jingshan water plant, BWRS, and BDIA, were not included in it.

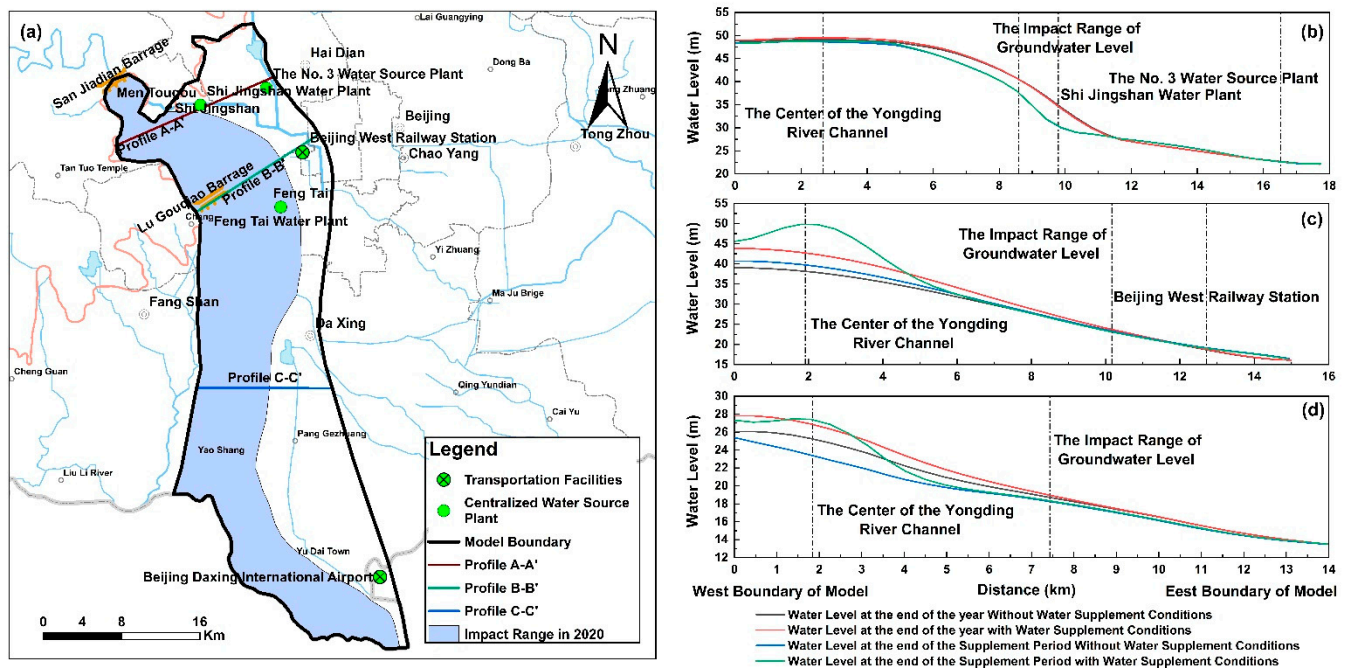


Figure 8. (a) Impact range of groundwater level restoration in the Yongding River supplement region in 2020. (b) Profile A–A' water level change map for the upper reaches of the Yongding River. (c) Profile B–B' water level change map for the middle reaches of the Yongding River. (d) Profile C–C' water level change map for the lower reaches of the Yongding River.

We set three calculation sections perpendicular to the Yongding River, along the upper, middle, and lower reaches of the Yongding River, to analyze the changes in the width of the impact range affected by the ecological water supplement. The position of the calculation section is shown in Figure 8a, and the groundwater level process lines of each profile are shown in Figure 8b–d. In regard to the upper reaches of the Yongding River, most of the river channels had seepage reduction effects, and the impact range of groundwater level rise was only about 7–9 km. In the middle reaches of the area, affected by the runoff interception effect of the Lugouqiao barrage, the impact range could be up to 9–11 km. In the downstream area, due to the decrease of the ecological water supplement, the width of its impact range was merely about 6–7 km.

3.4. Prediction of the Restoration Degree of the Groundwater Level in Yongding River in 2020

The maximum restoration degree of the groundwater level under the influence of the ecological water supplement infiltration in 2020 was obtained by the data at the end of the ecological water supplement period (12 June 2020) (Figure 9a). Identically, the restoration degree of the groundwater level at the end of the year, was obtained by the data on 31 December 2020 (Figure 9b). Combined with the calculated impact range of the Yongding River ecological water supplement in 2020, we also got the average groundwater level restoration degree.

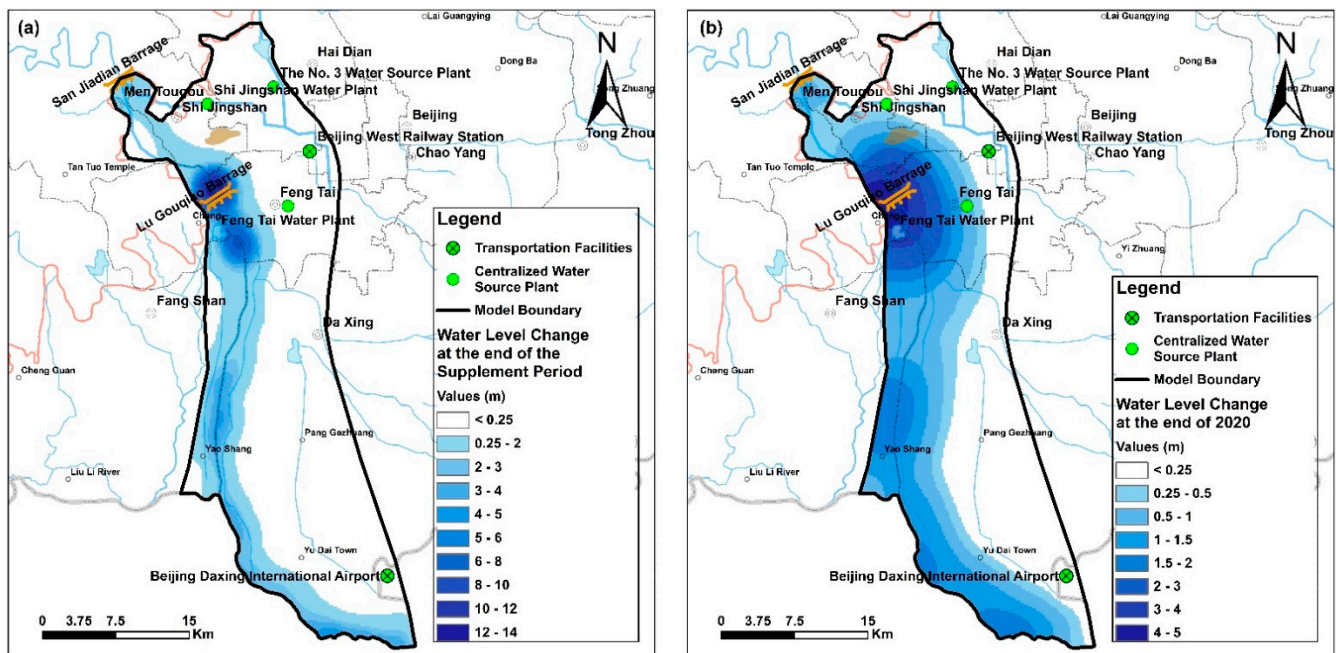


Figure 9. (a) Variation map of groundwater level in the study area at the end of the supplement period in 2020. (b) Variation map of groundwater level in the study area at the end of 2020.

The largest restoration degree of the groundwater level rise at the end of the ecological water supplement period in 2020 occurred at the center of the channel near the Lugouqiao barrage, which was about 12–14 m. We explained this by the runoff interception effect of the Lugouqiao barrage, which caused the water level to rise and then led to the increased infiltration of the sandy gravel channel. Similarly, because of the general seepage reduction effect in the upper reaches of the Yongding River, the water level rise was generally smaller than the middle and lower natural river sections. Until the end of 2020, the water level gradually dissipated outwards and the water level at the center of the river channel gradually decreased. The change range of the high water level region near the Lugouqiao barrage dropped to 4–5 m, with the rest of the river channel generally declining to below 2.0 m. Moreover, the average groundwater level restoration degree of the impact range was 1.25 m.

For typical buildings, they were not affected by the ecological water supplement head at the end of the ecological water supplement period in 2020. However, with the gradual spread of the ecological water supplement head, only the Fengtai water plant was not significantly affected at the end of 2020. The groundwater level rose about 0.5 m. Outside of the range of the groundwater level restoration, although the Shi Jingshan water plant was unaffected, it was already at the edge of the groundwater level restoration area. When the next large-scale ecological water supplement occurs, it will be affected to a certain extent. However, the no. 3 water source plant, BWRS, and BDIA, were still more than 2–3 km away from the groundwater level restoration area. In the future, the ecological water supplement process would be relatively less susceptible to the impact of groundwater level restoration.

3.5. Analysis on the Ecological Water Supplement Infiltration Volume of Yongding River in 2020

By analyzing the simulation results, the ecological water supplement infiltration volume of each section of the Yongding River in 2020 is given in Table 4. Compared with 2019 (Table 3), in order to accomplish the ecological water supplement demand of the downstream reaches, the ecological water supplement of the two river sections above the Lugouqiao barrage was reduced by 32%. For the river channel below the Lugouqiao barrage, there was no runoff interception effect, and the amount of the ecological water supplement was inversely related to the distance from the section to the Lugouqiao barrage.

The leakage coefficients of each channel segment were selected from the leakage coefficients after calibration and validation of the ecological water supplement's numerical model in 2019. The ecological water supplement infiltration volume of Yongding River in 2020 was about $102.64 \times 10^6 \text{ m}^3$, accounting for about 80% of the total ecological water supplement volume, which was roughly equivalent to the ecological water supplement infiltration volume in 2019.

Table 4. Ecological water supplement infiltration volume for each section of Yongding River in 2020.

Section	Ecological Water Supplement Volume of Each Section ($\times 10^6 \text{ m}^3$)	Ecological Water Supplement Infiltration Volume of Each Section ($\times 10^6 \text{ m}^3$)
Seepage reduction channel section from the San Jiadian barrage to the Yuan Bo lake	46.69	3.74
Section from the Yuan Bo lake to the Lugouqiao barrage		33.62
Seepage reduction channel section from the Lugouqiao barrage to the Wanping Lake	38.26	3.06
Section from the Wanping Lake to the Ethylene Pipe Bridge, Jing Liang Road		27.55
Section from the Ethylene Pipe Bridge, Jing Liang Road to the Sixth Ring Road	10.00	8.00
Section from the Sixth Ring Road to the Gu An monitoring station	21.82	17.45
Section from the Gu An monitoring station to the Cui Zhihuiying village (the Beijing administrative boundary)	11.53	9.22
Total	128.30	102.64

4. Conclusions

By establishing a groundwater flow model, this article studied the ecological water supplement infiltration volume, groundwater level restoration, and the impact of water level rise on typical buildings under different water supplement scenarios in the Yongding River in 2019 and 2020. The numerical model could accurately reflect the dynamic change characteristics of groundwater and predict the effect of the ecological water supplement. The conclusions were as follows:

(1) The total recharge of groundwater in the study area was $359.79 \times 10^6 \text{ m}^3$, the total discharge was $238.17 \times 10^6 \text{ m}^3$, and the recharge difference was $121.62 \times 10^6 \text{ m}^3$. The groundwater was in a positive equilibrium state as a whole. The ecological water supplement infiltration volume of the Yongding River reached a 28.15% proportion in the recharge items, which was $101.28 \times 10^6 \text{ m}^3$ in 2019 and $102.64 \times 10^6 \text{ m}^3$ in 2020, accounting for 80% of the total ecological water supplement.

(2) The total impact range of the ecological water supplement of the Yongding River in 2019 was 265.19 km^2 , which was concentrated in the 6 km range on both sides of the Yongding River. The maximum groundwater level restoration was located at the center of the river channel near the Lugouqiao barrage, in which the groundwater level rose up to 7–8 m. Moreover, the average groundwater level rise was 2.10 m in the affected area.

(3) The predicted area affected by the ecological water supplement of the Yongding River in 2020 was 506.88 km^2 , and the maximum groundwater level restoration range was up to 9–11 km. The upstream section of the river had a smaller impact range due to the seepage reduction effect, merely about 7–9 km. The largest groundwater level rise rose at the end of the ecological water supplement period, which was up to 12–14 m. Moreover, the average groundwater level rise was 1.25 m at the end of 2020.

(4) For the groundwater level around the typical buildings, such as Beijing West Railway Station, Beijing Daxing International Airport, and the centralized water source plant within the study area, only the Fengtai water plant was slightly affected by the two ecological water supplements in 2019 and 2020. The rest were not significantly affected.

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