

Article

Quantification and Regionalization of the Interaction between the Doumen Reservoir and Regional Groundwater in the Urban Plains of Northwest China

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Abstract: Groundwater and artificial reservoirs are in a continuous dynamic interaction that can affect not only water quantity but the quality. In this paper, taking the DR (Doumen Reservoir) as an example, the level dynamic changes between the DRTS (Doumen Reservoir Test Section) and groundwater were discussed, and the water quality used by SFE (single-factor evaluation) and WQI (water quality index) method were analyzed. A coupling model is presented to quantify the leakage impact range and groundwater budget and regionalize the impact of surface water on regional groundwater quality. The results show that the level dynamics of the reservoir and groundwater are highly consistent, with a cross-correlation coefficient of 0.85 and a lag time of about 7 days. The reservoir recharges the groundwater with an increase-decrease-stationary wave dynamic potential. After 3 years of operation of the DR, the groundwater still is recharged, the groundwater level will rise obviously, with a maximum of 8.5 m. The amount of surface water recharged is always 0. NH₃-N, and COD will have varying degrees of impact, both of which are mainly the pollution halo around North Lake. The results can provide support for water resources management and environmental protection of urban plain reservoirs.

Keywords: groundwater and surface-water interaction; WQI; numerical modeling; solute transport; urban plain reservoirs; China



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1. Introduction

Many places in the world, such as Israel, central Australia, and northwest China, cover a wide area have the common characteristics of low precipitation, high evaporation, and less surface water resources [1–3]. Therefore, groundwater is an extremely precious water sources [4], but it is not sustainable.

The surface water and groundwater (SW-GW) interaction is one of the most critical hydrological processes [5–7]. The interaction is often complicated by human intervention, including groundwater pumping, irrigation, hydropower stations, dams, and artificial reservoirs, as they could significantly alter the flow regimes of both surface water and groundwater [8–10]. Understanding the complex behavior of the integrated SW-GW system is very important to the regional water resources management and is of great significance for maintaining ecosystem diversity and stability [11].

In recent years, studies on the SW-GW interaction have received extensive attention [12–19]. El-Zehairy et al. [20] studied the interactions of surface water and groundwater applying an integrated MODFLOW solution in Turawa, Poland. Chu et al. [21] selected a typical karst region, Fangshan in northern China, to characterize the interaction of groundwater and surface water in the karst aquifer of Fangshan, Beijing. Lin et al. [22]

discussed the groundwater/surface-water interaction in arid Dunhuang Basin by establishing a three-dimensional transient groundwater flow model and using MODFLOW 2000. But, in fact, studies on the SW-GW interaction mainly focuses on hydraulic connection, and few studies have been conducted on new urban plain reservoirs [23], especially in northwest China.

Compared with natural lakes and rivers, artificial reservoirs are regulated bodies of water with large periodic fluctuations, and, due to the hydrodynamic conditions of the reservoir, low-permeability silt in the reservoir bottom sediments accounts for the majority, so the interaction between reservoir and groundwater is much weaker than river and groundwater [24]. However, the groundwater system still affects the water balance and nutrient balance of the reservoir, and the reservoir also affects the groundwater flow field and chemical field in the area [25].

Doumen Reservoir (DR) is a newly built urban plain reservoir in northwest China, and also a comprehensive artificial reservoir, which has diverse functions, including incoming water regulation, urban water supply, urban flood control, and the ecological environment improvement. However, in most places on the Earth, groundwater and artificial reservoirs are in a continuous dynamic interaction that can affect not only water quantity but also the quality of both, and DR is no exception.

Reservoir leakage causes water loss and groundwater level to rise, as well as causes waterlogging and secondary salinization, which ultimately leads to environmental degradation. However, it is worth noting that in water-scarce plains, reservoir leakage is also a source of recharge for soil water and groundwater, which play a positive role in maintaining groundwater level and protecting groundwater resources. The other is water quality. As the groundwater level rises, water quality will definitely be affected, but it is not clear how the water diversion source will ultimately affect the regional groundwater quality after the DR is completed. Therefore, the questions of recharge and water quality are key issues in quantification and regionalization of the interaction between DR and groundwater, as well as one of the important links in water resources utilization and water environmental protection.

In this paper, the water level dynamics between the Doumen Reservoir Test Section (DRTS) and the groundwater were discussed, and the water quality used by single-factor evaluation (SFE) and water quality index (WQI) method were analyzed. An integrated SW-GW model by using MODFLOW-NWT model and MT3DMS V.5.2 module was established to assess the hydrogeological effects of the DR in the early stage of the reservoir construction and impoundment, specifically with the aims to: (1) discuss the level dynamic changes and effects of the water quality between DRTS and groundwater, (2) quantify the leakage impact range and groundwater budget of the DR, and (3) evaluate the impact of DR quality on groundwater regionally. The study will provide a reference for the follow-up construction and management of DR, as well as insights for the related research of other newly-built urban plain reservoirs.

2. Materials and Methods

2.1. Study Area

DR ($108^{\circ} 45' - 108^{\circ} 48' \text{ E}$, $34^{\circ} 11' - 34^{\circ} 13' \text{ N}$) is located in the southern part of Fengdong New City, Xixian New District, Shaanxi Province, China, which is established on the site of the Kunming Pool in the Han dynasty (Figure 1). The DR is arranged according to the North-South Lake. The North Lake serves as the flood diversion area of the Fenghe River and simultaneously supplies ecological water to Xi'an City, while the South Lake serves as the urban drinking water source and supplies water to Fengdong and Fengxi New District. The DRTS is part of North Lake. The construction of the reservoir began in 2017. The DRTS has a storage capacity of only 1.55 million m^3 and a storage area of 0.47 km^2 . The North Lake and South Lake will be constructed, in turn, later. It is planned that the DR will be fully completed in 2022. After the completion of the DR, the planned storage area is 10.4 km^2 , and the storage capacity will reach 50.52 million m^3 .

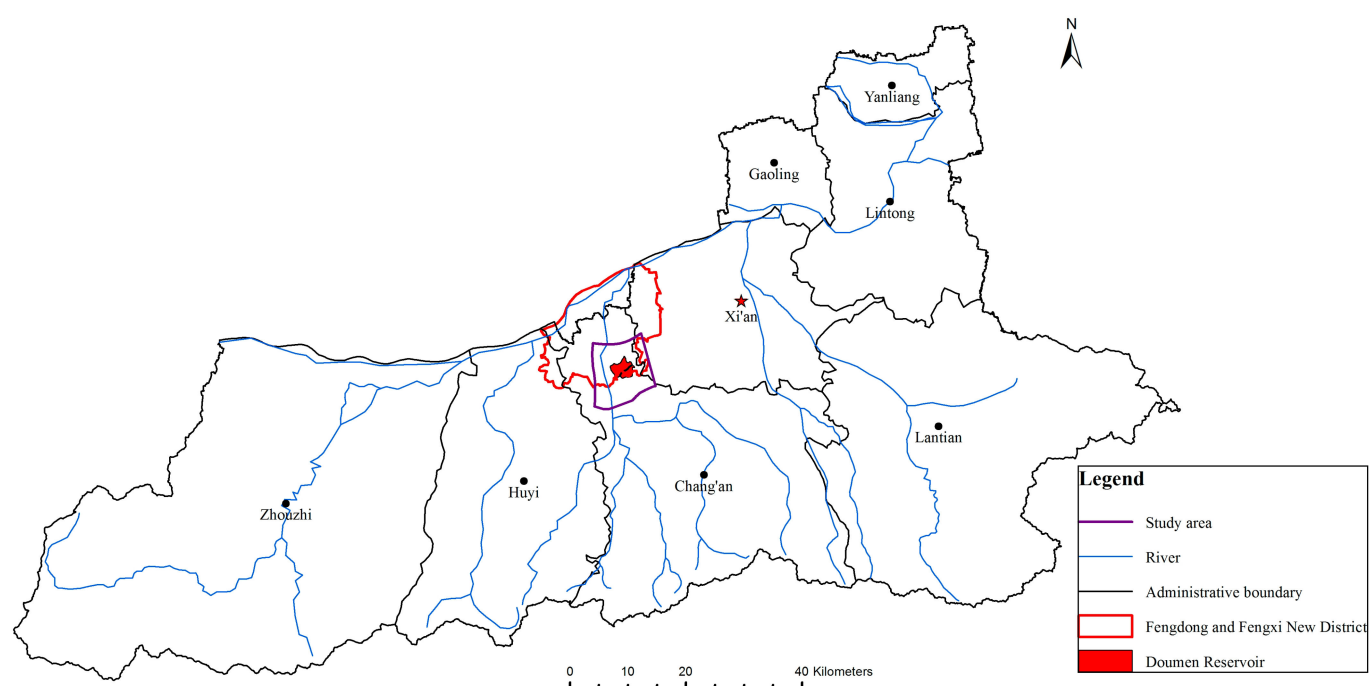


Figure 1. Location of the Doumen Reservoir (DR) and study area.

DR is located in the middle of Guanzhong Plain. The annual average precipitation in the study area is 5.08×10^2 mm, mainly concentrated in June to September, accounting for 78.55%, the precipitation of winter is very small, and the proportion of precipitation is less than 2%. The annual average surface evaporation is 1.04×10^3 mm. Surface evaporation in spring is relatively large, accounting for 32.1%, and, in November, surface evaporation accounts for only 2.63%. The annual average temperature is 15.9°C . The terrain of the study area is relatively flat, high in the southeast and low in the northwest, ground elevation is 380–420 m, and the flow direction of groundwater is consistent with it [26,27].

The groundwater in the study area belongs to unconfined water, which occurs in alluvial sand, gravel, and water-bearing rock groups. The water-abundance is generally good, increasing from south to north. The surface of the Fenghe floodplain contains a sand layer of 20–25 m. The first-level alluvial river terraces become thicker with a coarser grain size, the thickness is 30–50 m and a sandy gravel layer below. The thickness of the aquifer in floodplain and first-level terraces in the north is about 40–60 m, and the groundwater depth is 2–20 m, with the unit water inflow of $18\text{--}44\text{ m}^3/\text{h}\cdot\text{m}$. The unit water inflow in the south is $10\text{--}18\text{ m}^3/\text{h}\cdot\text{m}$, which is a strong water-rich unconfined aquifer. Some secondary alluvial terraces areas have groundwater depths of 25–30 m, aquifer thickness of about 30–40 m, permeability coefficient of about 5–10 m/day, and unit water inflow of $4\text{--}7\text{ m}^3/\text{h}\cdot\text{m}$.

Groundwater in the area occurs in sediments and these sediments form an unconfined aquifer that is recharged by rainfall infiltration, by Fenghe River recharge, by seepage from rivers and canals, by lateral runoff of upstream groundwater, by the return of irrigation, and by mountainside seepage. Groundwater discharge takes place mainly by extraction from farmland and by lateral runoff of down-stream groundwater, followed by evapotranspiration.

2.2. Data

In order to explore the reservoir water and groundwater interaction in the early stage of DR construction, 7 groundwater monitoring wells were drilled on the north side of the DRTS, with a depth of 20 m and a diameter of 10 cm. The monitoring wells were arranged in two rows, the interval between wells is 235 m on average, and the row spacing is 150 m on average. The distribution diagram is shown in Figure 1. The groundwater self-counting

instrument uses the Solinst 3001 Levellogger Edge series instrument of Canada to record groundwater level data, and the monitoring frequency is 0.5 h/time. The groundwater quality results were obtained from 7 wells.

The surface water level data is monitored by the automatic monitor and the artificial water gauge together, and the recording frequency is once a day. In addition, a total of 9 surface water monitoring points are deployed according to the layout principle of the lake monitoring section (Figure 2).

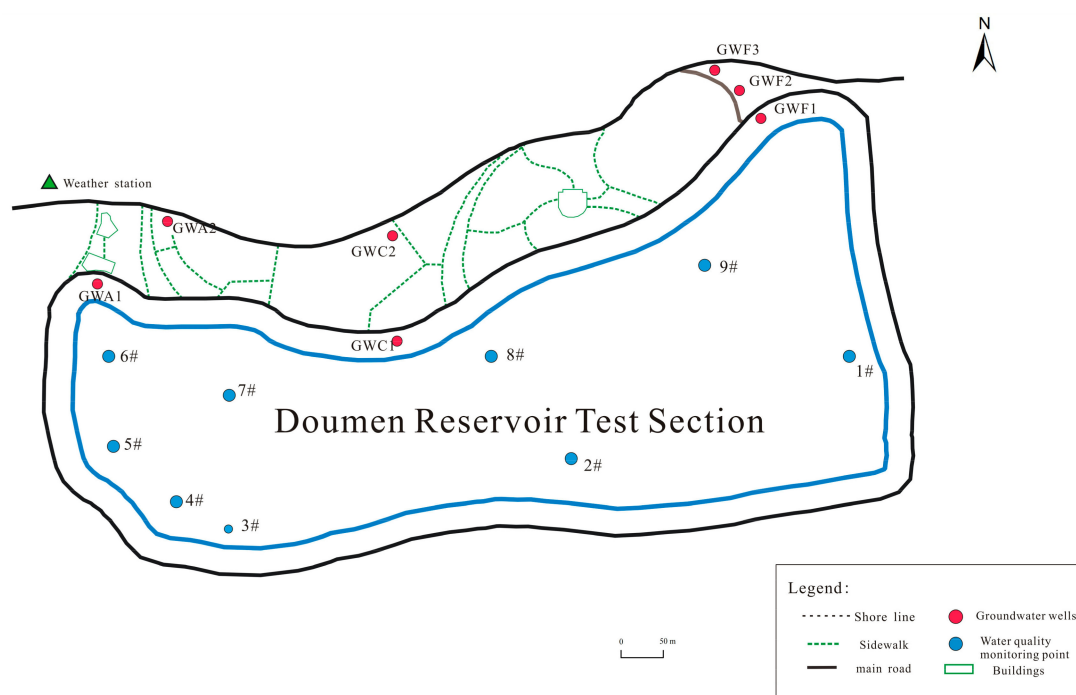


Figure 2. Schematic diagram of monitoring distribution of surface water and groundwater in the Doumen Reservoir Test Section (DRTS).

The precipitation and evaporation data in the study area are monitored by the KME series of portable automatic weather stations, using ELO 105 data collectors, powered by solar systems, and all sensors are designed in accordance with WMO standards and comply with ISO 9001 standards. The recording time step is 0.5 h once.

2.3. Methods

Visual MODFLOW 2000 provides the most complete simulation environment for the practical application of 3D groundwater flow and pollutant transport simulation. It is a standard visualization professional software system that has been unanimously recognized by counterparts in various countries. The main simulation functions include optimizing irrigation pumping volume, determining exposure pathways for risk assessment, and evaluating the safe water supply of groundwater and groundwater repair system. The applied MODFLOW-NWT model [28] is used to simulate groundwater flow and reservoir leakage, and MT3DMS V.5.2 module is used to simulate solute transport path in this study.

3. Results and Discussion

3.1. Groundwater and DRTS Water Level Dynamics

Groundwater level is a dynamic indicator that characterizes the recharge or discharge of groundwater [29]. The monthly average of the DRTS water level and groundwater level from March 2018 to August 2019 were calculated, as shown in Figure 3. In Figure 3, RWL represents the reservoir water level, and Mean represents the average groundwater level. The reservoir water level and the groundwater level show obvious seasonal changes,

rising from June to October, and falling from November to May of the following year. The reservoir water level is significantly higher than the groundwater level, with an average water level of 400.15 m. The average groundwater level is 393.50–395.19 m, and the average water level varies by 1.68 m. The groundwater level of Wells GWA1 and GWA2 rose significantly in June compared to May 2018. The reason is that the study area is located in the urban scenic area. Ornamental plants were planted near wells GWA1 and GWA2. Manual intervention (watering) in mid-June caused the groundwater level to rise occasionally. The monthly average groundwater level trends of other observation wells are basically the same.

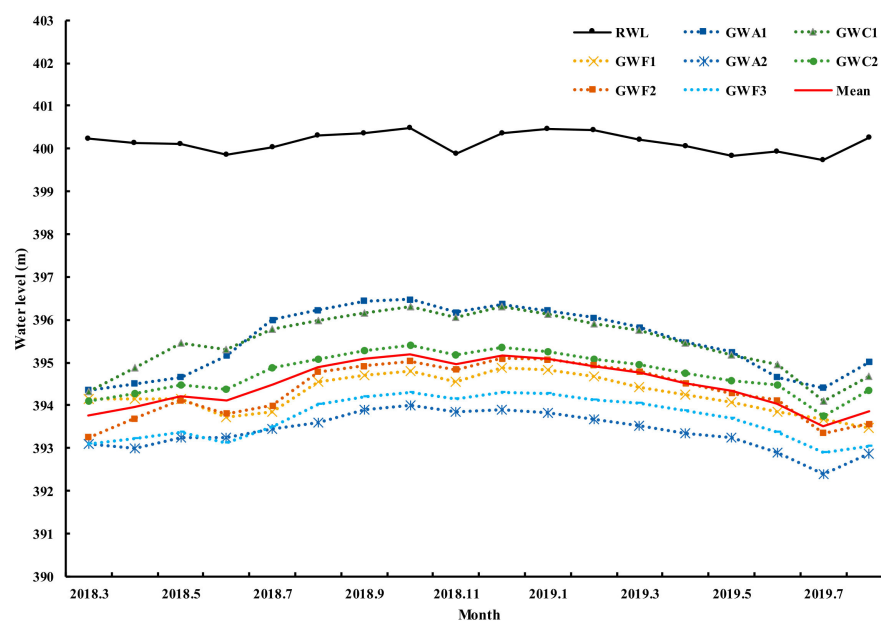


Figure 3. The level changes of reservoir water and groundwater.

For two time series, regardless of whether the sampling scales or their variability are similar, as long as the two are synchronized in time, the co-correlation function can be used to describe the correlation between the two time series, which is called time-lag cross-correlation analysis. This method takes into account the time lag of the interaction between different time series elements, and there is a reaction delay process [30,31].

The cross-correlation between the reservoir water level and the groundwater level is discussed. From Figure 4, there is a significant correlation between the reservoir water level and the groundwater level of the 7 monitoring wells. The correlation coefficient between the reservoir water level and the average groundwater level is 0.85. The correlation coefficient of the coastal well GWC1 is the highest, 0.88, and the far shore well GWA2 has the lowest correlation coefficient, which is 0.71. The correlation between the reservoir water level and the groundwater level in the middle of the reservoir bank is greater than that of the two sides, and the east side is greater than the west side. The lag time of the correlation between the reservoir water level and the groundwater level is about 7 days, and the precipitation and groundwater level are about 14 days. Combined with the dynamics of the lake level and the groundwater level, the two show a high degree of consistency, indicating that there is a close hydraulic relationship between the reservoir water level and the groundwater level in the study area, and the groundwater level changes are mainly affected by the reservoir water level rather than meteorological factors, such as precipitation.

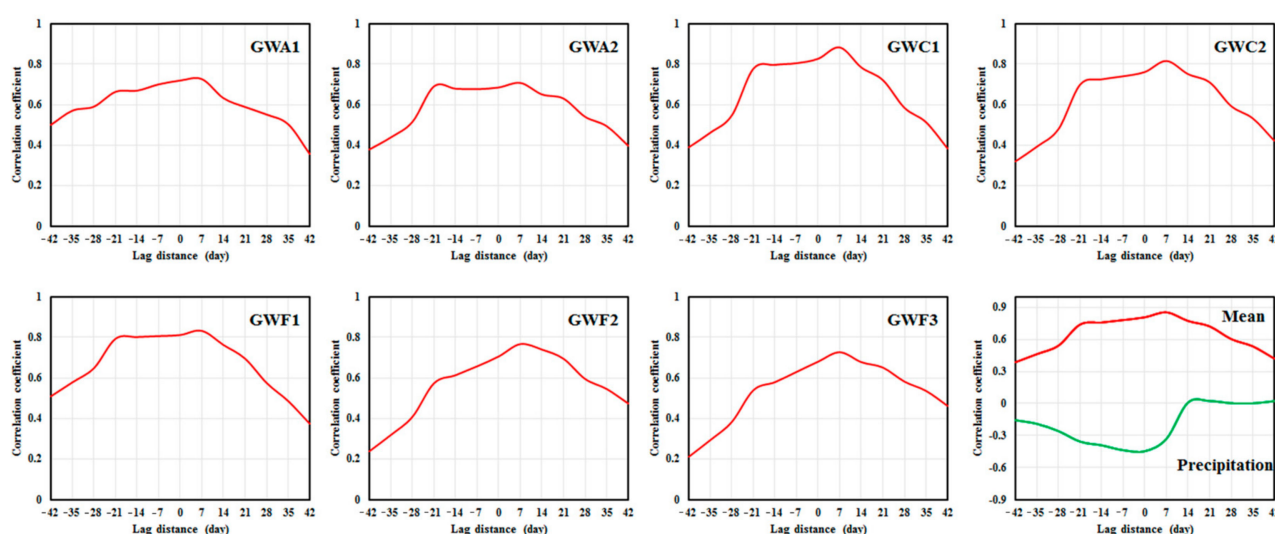


Figure 4. Cross-correlation between the reservoir water level and the groundwater level.

3.2. DRTS Water and Groundwater Quality

When there are multiple results from different monitoring points, the arithmetic mean of each index concentration of each point in the time series is calculated first; then, the arithmetic mean of each index concentration of all points in the spatial sequence is calculated, and, finally, the SFE method is used to evaluate water quality [32]. The method is that if the index exceeds the standard value of the corresponding function, it means that the water body has not fully met the functional requirements. It is a commonly used way in water environmental impact assessment, regardless of surface water or groundwater, but obviously the results are susceptible to extreme indicators. Therefore, the WQI method proposed by Pesce and Wunderlin [33] was also used in this study. Briefly, each water quality parameter was assigned a weighting factor that reflects its importance as an indicator of the overall water quality, and then WQI values are used to classify water bodies [34]. The WQI value ranges from 0 to 100, which is classified into five levels (i.e., 0–25, 26–50, 51–70, 71–90, 91–100) corresponding to very poor, poor, moderate, good, and excellent, respectively.

Twenty-one surface water indicators, such as pH, permanganate index, COD, BOD, DO, petroleum, ammonia nitrogen, total phosphorus, Cr^{6+} , F^- , CN^- , S^{2-} , volatile phenol, anionic surfactant, fecal coliform, mercury, arsenic, selenium, zinc, copper, lead, and cadmium, were selected, and 15 groundwater indicators, such as pH, total hardness, TDS, manganese, mercury, arsenic, cadmium, lead, E. coli, ammonia nitrogen, S^{2-} , Cl^- , SO_4^{2-} , NO_3^- , NaNO_2 , from March 2018 to August 2019, were compared with the standard for water quality to judge the water environment quality of the water area. The SFE results show that the total phosphorus, COD, and BOD indicators of the surface water all exceed the standard, and the water quality reaches 4 or 5 standards, which is a light or moderate pollution. The groundwater quality has reached three or more water quality standards. The results of the WQI method are shown in Figure 5. The results show that, in the same period, the groundwater quality is generally better than the surface water quality, and the groundwater quality is at a good level. The WQI value gradually rises in the later stage, while the surface water quality deteriorates in the later stage, which is inferior to the diversion water quality. In summary, DRTS water quality will not have a great impact on groundwater quality.

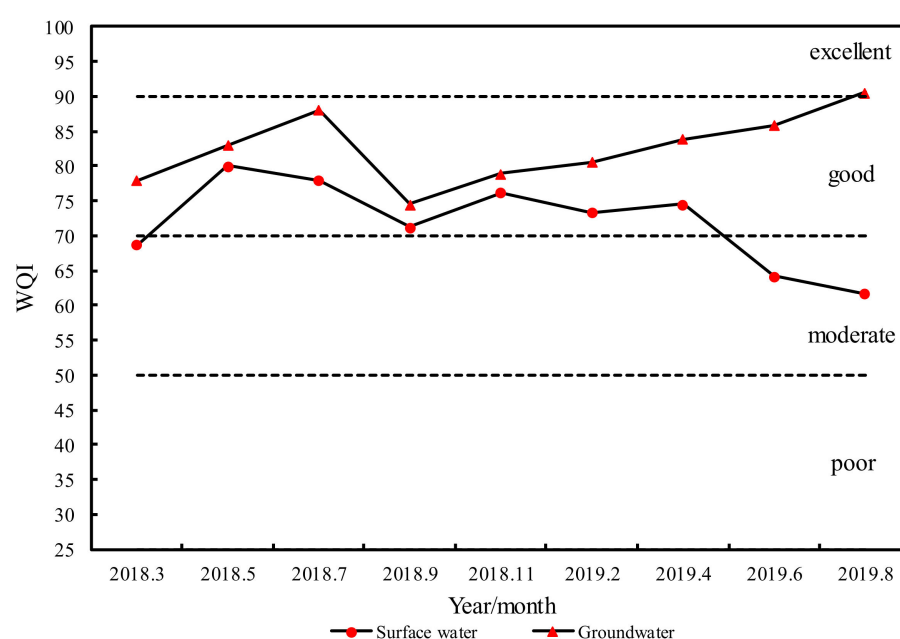


Figure 5. The evaluation results of the water quality index (WQI) method.

3.3. Reservoir Leakage and Groundwater Level Variation

3.3.1. Unsteady Groundwater Flow Model

Boundary range and conditions: According to regional hydrogeological conditions, a buffer zone of 3.0 km away from DR is the simulation area, as shown in Figure 6. The projected coordinate system is WGS_1984_UTM_Zone_49N. The simulation area is generalized into a three-dimensional heterogeneous non-steady flow system. The boundary conditions are summarized as follows: the surface receiving rainfall infiltration is generalized as an unconfined surface, and the bottom clay layer is treated as an impervious boundary. DR is generalized as the third type of flow boundary, which simulated by the MODFLOW RIV package. The riverbed bottom is 396.8 m, and the calibrated conductance is $7.83 \text{ m}^2/\text{day}$. The Fenghe River is simulated by the MODFLOW RIV package, the riverbed bottom is about 380.5 m, and the permeability coefficient is 3.48 m/day . The Taiping River has a small flow rate and is simulated by MODFLOW Recharge package, and the recharge is 496 mm/year . The aquifer in the area has a hydraulic connection with the outside in the horizontal direction, so the surrounding areas are generalized as flow boundaries. The eastern and western boundaries are perpendicular to the groundwater level, which is generalized as a zero-flow boundary, and the southern and northern boundaries have lateral runoff recharge, which is generalized as a flow boundary and simulated by the MODFLOW GHB package. The GHB water level is set according to the monitoring water level, and the calibrated GHB conductivity is $10 \text{ m}^2/\text{day}$. If there is no measured water level at the general water head boundary, the instantaneous record of the boundary is used to establish a time series to make it the same as the latest measured water level time series change pattern (phase and amplitude), but the groundwater level matches the instantaneous record.

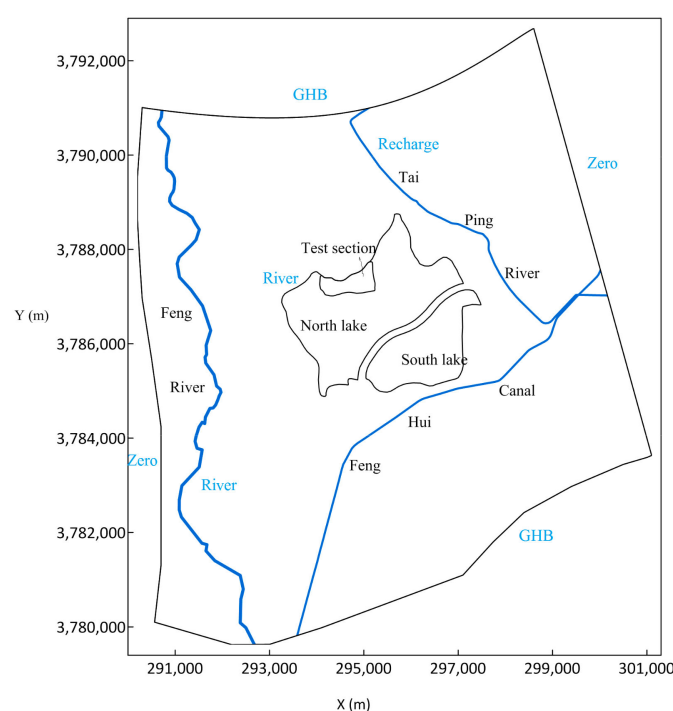


Figure 6. Boundary range and conditions.

Model design: The simulation area is divided into 270 rows $\times$ 266 columns and two layers vertically according to the stratum distribution characteristics. The first layer is mainly clay, loess, loam, and silty clay, and the second layer is sand layer of 20–40 m. In order to better characterize the hydrodynamic changes, it is refined to the five layers. The model spatial discretization is shown in Figure 7 (Take the first layer and column 25 as an example.), the first four layers are the first main layer, and the fifth layer is the second main layer, in Figure 7b. The ground elevation uses the DEM of ASTGTM3, and the elevation of each layer is derived from geological survey data and is obtained by interpolation using surfer 17 kriging. The simulation has a total of 2 years and 7 months, divided into 31 time periods, and each time period takes 10 days as a time step. The model uses the MODFLOW-NWT solver to run, the complexity is set to complex, and other parameters are default values.

The division of rainfall infiltration coefficient is determined according to the soil type and topography of the unsaturated zone, which is consistent with the second-level parameter partition (Figure 8b). The landform type close to the Fenghe River is floodplain, the soil types of which are loam, fine sand, and silt, and the larger area is the first-level alluvial river terraces where the soil type is clay with fine sand; the other areas are second-level alluvial river terraces, the soil types of which are loam and loess. The rainfall infiltration coefficients based on measured data are 0.45, 0.35, and 0.24, respectively. Rainfall infiltration varies with monthly precipitation from Doumen Weather Station, which is a surface recharge that can be added to the model through the MODFLOW Recharge package. The hydrogeological parameters of the simulation area are shown in Figure 8a,b. The initial values are obtained from the stratum lithology data and the test results.

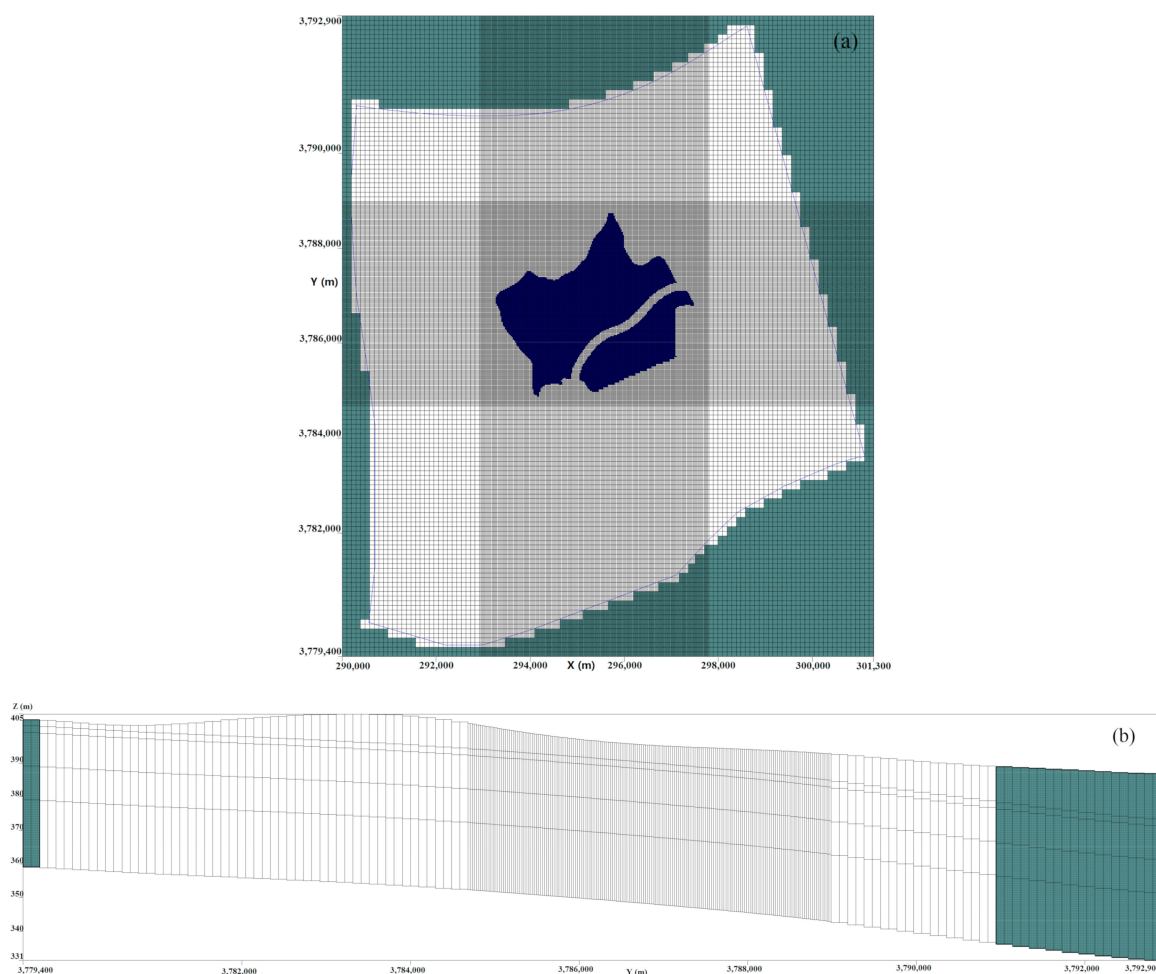


Figure 7. Model spatial discretization in (a) horizontal; (b) vertical.

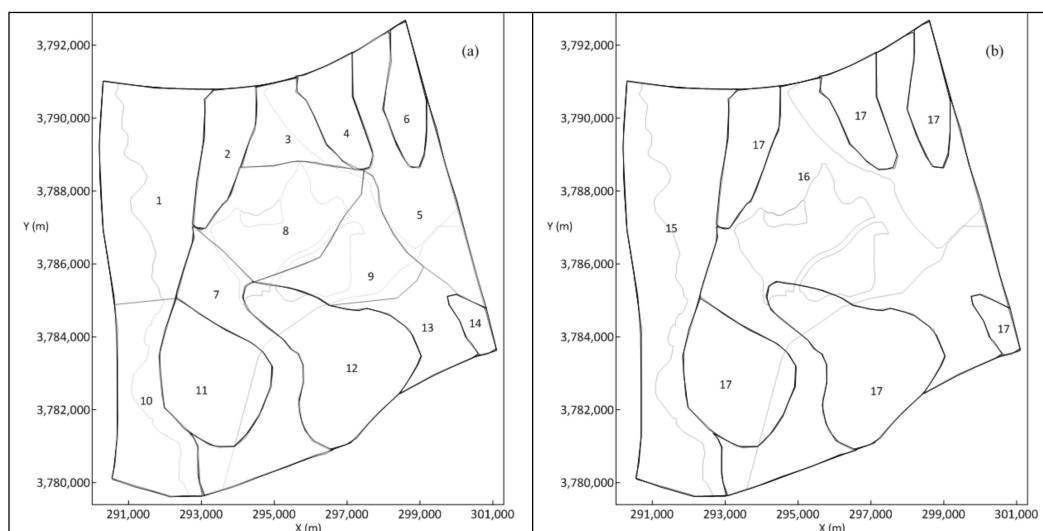


Figure 8. (a) The first-level parameter partition. (b) The second-level parameter partition.

Model calibration and validation: The detailed calibration of the model from February 2017 to February 2018 using groundwater level measured in monitoring wells. The trial-and-error method was selected for calibration. During the calibration process, hydraulic conductivity was calibrated to match the measured groundwater level contours, the recharge

rates were calibrated to fit the seasonal variations in groundwater level measured, and the permeability coefficient and specific yield were calibrated to fit the observed groundwater level changes; the final results are shown in Table 1. The simulated groundwater levels are generally consistent with the observed values in 11 monitoring wells, including 4 old wells (Table 2), after the model was calibrated. The correlation coefficient is 0.94, the mean absolute error (MAE) between simulated and measured water levels is 0.58 m, and the root mean square error (RMSE) is 1.15 m. The calibrated model results were considered reasonable for simulating the groundwater flow. The 95% confidence interval was applied to evaluate the model uncertainty, as shown in Figure 9. The range is narrow and very close to the 1:1 line, which indicates a relatively small uncertainty of the model.

Table 1. Zoning results of hydrogeological parameters.

No.	1	2	3	4	5	6	7	8	9
	10	11	12	13	14	15	16	17	/
Permeability coefficient (m/day)	5.1	4.2	2.4	4.0	2.8	4.8	3.4	2.1	3.2
	6.7	4.4	4.6	4.1	5.3	26.6	15.5	17.9	/
Specific yield	0.16	0.13	0.17	0.12	0.18	0.14	0.16	0.15	0.17
	0.18	0.13	0.14	0.17	0.16	0.18	0.18	0.15	/

Table 2. The baseline information of four old wells.

Well Number	Drilling Year	X (m)	Y (m)	Well Height (m)
A-152	1981	296,449	3,787,740	399.48
A-178	1981	293,268	3,788,640	399.90
C-22	2000	294,449	3,784,120	407.07
A-154	1983	290,794	3,783,790	407.09

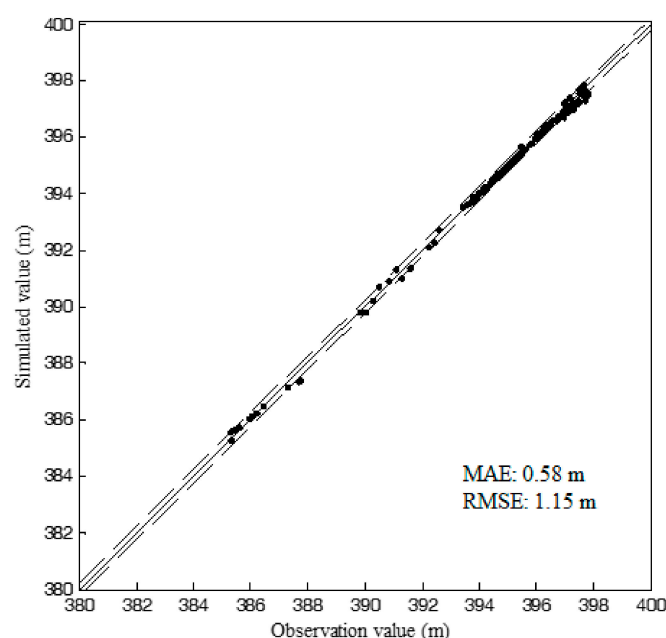


Figure 9. Comparison between observed and simulated water levels. Dotted lines indicate the 95% prediction intervals.

The calibration model was validated using groundwater levels measured from March 2018 to August 2019. The initial and boundary conditions in the validation model remained the same as the calibration model [20]. During the model validation period, the variations of simulated water level trends were in agreement with the observed values. Given that the

simulated groundwater level were validated by the observed values, and the model precision meets the requirements, this model was considered to be appropriate for predicting the effects of the DR.

3.3.2. Model Results and Discussion

MODFLOW ZBud was used to extract the supply of the groundwater and the DRTS from February 2017 to August 2019. From Figure 10, the leakage rate presents an increase-decrease-stationary wave dynamic potential. The leakage rate in the DRTS after water storage is 4.59×10^3 – 1.36×10^4 m³/day, with an average of 6.86×10^3 m³/day, and the average leakage intensity is 1.5×10^{-2} m³/m², which means that the leakage per square meter of the DRTS is 1.5×10^{-2} m³.

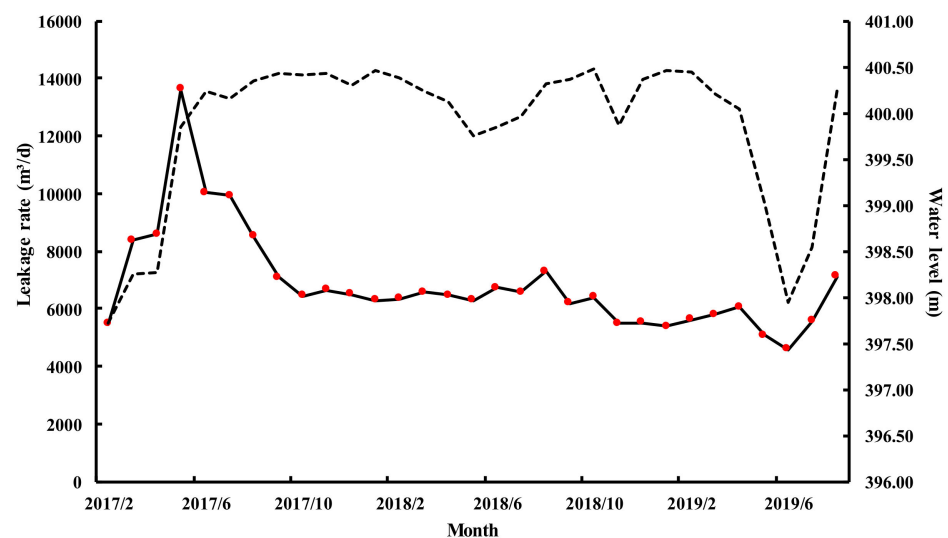


Figure 10. The reservoir water level and leakage process of the DRTS.

The DRTS began to store water in 2017, and the leakage rate is constantly changing in Figure 10. In the initial stage of water storage, saturated gravity drive is the main way of water movement. After the surface water seepage reaches the unsaturated soil layer, the wet front gradually advances to the lower layer and finally reaches the unconfined water surface. In the process, as the depth of wetting increases, the infiltration rate gradually decreases, and the leakage rate also decreases. Generally, the leakage rate is the largest during this period, reaching 1.36×10^4 m³/day.

When the wet front reaches the unconfined water, surface water and groundwater are hydraulically connected, and part of the unsaturated zone begins to gradually turn into a saturated zone. After the unconfined water receives recharge from the surface water, the groundwater recharge is greater than the outflow to the surroundings in the initial stage due to the small hydraulic slope, the groundwater level will rise gradually, forming a groundwater mound, and produce a horizontal migration velocity extending to the surrounding. When the outflow is equal to the recharge, the leakage rate is basically stable at this time. The amount of surface water recharged is always 0, indicating that the reservoir water always recharges groundwater.

The predicted leakage rate calculated according to the confined-unconfined flow formula [35] is 3660 m³/day when the clayey aquifer overlying the sandy aquifer is excavated. The reason for the inconsistency between the two methods is that the analytical method only considers the lateral leakage of the reservoir water. In other words, through the investigation of regional hydrogeological conditions, the artificial reservoirs that were initially constructed mainly have vertical leakage.

The study area has a strong vertical recharge effect. Therefore, rainfall, evaporation, and reservoir water level are the main driving forces affecting groundwater level and

leakage rate. The correlation was analyzed, and it was found that the reservoir water level and the leakage rate pass the 95% significance test, and the person correlation coefficient is 0.61. The results show that the reservoir water level and the leakage rate in the DRTS have a clear correlation. From Figure 10, the reservoir water level change is basically the same as the leakage rate, the reservoir water level rises, and the leakage rate increases. The peak value corresponds to the actual situation.

According to the latest Preliminary Construction Plan for DR, after DR is completed, the storage area of the North Lake will reach 7.0 km², the storage depth will be 3.7 m, the storage area of the South Lake will reach 3.4 km², and the storage depth will be 9.9 m. The three-year operation (2023–2025) of the DR was simulated.

The results show that the groundwater level around the reservoir will rise obviously, forming a groundwater mound. At this time, the groundwater at the bottom of the reservoir is directly hydraulically connected with the lake water, and the reservoir leakage is much higher than the regional precipitation infiltration when the reservoir was not built. Leakage has become the main driving factor of the groundwater level in the water storage area. After receiving the vertical replenishment of the surface water, the groundwater in the reservoir area spreads around, but the groundwater flow direction remains unchanged, and it still flows from southeast to northwest.

The groundwater flow field between the unbuilt reservoir area and after the completion of DR was compared (Figure 11), within the simulation area (100 km²), the impact range of groundwater level variation greater than 0.5 m is 56.2 km², accounting for 56.2% of the total area, and the impact range greater than 1 m is 38.4 km², the impact range greater than 2 m is 23.5 km², and the impact range greater than 5 m is 9.7 km², accounting for only 9.7% of the total area. The most obvious rise of groundwater level is at the bottom of the reservoir area center, with a maximum of 8.5 m.

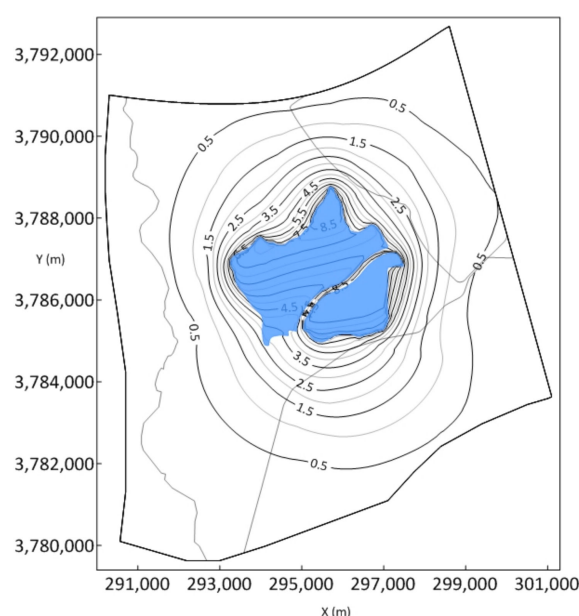


Figure 11. Comparison of groundwater flow field before and after water storage in DR.

The leakage rate results are shown in the Table 3. After 3 years of operation of the reservoir, the stable leakage rate will be 4.48×10^4 m³/day, the leakage intensity will be 4.3×10^{-3} m³/m², the annual leakage rate will be 16.35 million m³/a, and the storage capacity of DR will account for 0.32. Obviously, the leakage rate cannot be ignored. According to the geological survey data, it is known that the permeability coefficients of the north-central North Lake, the northeast corner of North Lake, the west of North Lake, and the south of South Lake are relatively large. Therefore, in the subsequent construction of DR, the above four areas are recommended to adopt anti-seepage measures. Horizontal

bedding and drainage facilities are used to prevent the continuous leakage and prevent groundwater environmental problems, such as reservoir immersion and salinization.

Table 3. DR leakage.

Partition		North Lake	South Lake
Storage area (km ²)		7.0	3.4
Storage depth (m)		3.7	9.9
Leakage rate (10 ⁴ m ³ /day)	1 year	5.64	3.53
	2 year	2.53	2.02
	3 year	2.42	1.98
stable leakage (10 ⁴ m ³ /day)			4.48
Leakage intensity (10 ⁻³ m ³ /m ²)			4.3
Annual leakage (million m ³ /year)			16.35
Ratio of storage capacity			0.32

3.4. Water Quality Impact Range

Water quality issues are equally important in the study of the interaction between reservoirs and groundwater. NH₃-N and COD were selected as solutes to analyze the impact of reservoir storage on regional groundwater quality, which can provide technical support for groundwater environmental protection.

3.4.1. Groundwater Solute Transport Model

The MODFLOW MT3DMS module can simulate a series of complex physical migration processes (convection, dispersion, adsorption, etc.) and chemical reactions in the solute transport process, as well as has wide applicability in solving typical solute transport problems in groundwater under various conditions [36,37]. Therefore, on the basis of the unsteady flow numerical model established above, the MT3DMS module is used to establish the unsteady movement trend prediction model of NH₃-N and COD migration.

The spatial distribution of typical solutes is obtained through simultaneous solution of water flow equation and solute transport equation. The parameters of the model mainly include effective porosity (n_e), soil density, and dispersion coefficient. The first two are determined by porosity. The longitudinal dispersion, the lateral dispersion, and the vertical dispersion are considered according to $a_T:a_L:a_V = 100:10:1$. The longitudinal dispersion a_T is taken as 10 m.

The behavior of pollutants in the SW-GW system is summarized as migration and transformation. Migration mainly means that the pollutants move down to the aquifer in leaching with the infiltration water flow and then spread horizontally along the groundwater flow. Transformation mainly includes adsorption-desorption, nitrification-denitrification, and other processes. When the solute transport model was established, linear isotherm adsorption was adopted, and the partition coefficient and the reaction rate constant are used to measure the adsorption and biochemical reactions (such as nitrification, anammox) of pollutants in groundwater. These two parameters are obtained through empirical constants from literature [38–41], first, and model calibration, finally. The calibrated partition coefficients of NH₃-N and COD are $3 \times 10^{-3} \text{ cm}^3/\text{mg}$ and $5 \times 10^{-3} \text{ cm}^3/\text{mg}$, respectively, and the reaction rate is 0.01 day^{-1} .

The simulation range, simulation time, and boundary conditions of the solute transport model are basically the same as those of the water flow model. DR is generalized as a surface leakage source. The water of North Lake is drawn from Fenghe River. The surface water environmental quality standard is Class IV. The concentration of NH₃-N and COD is 0.83 mg/L and 20.9 mg/L. The water from South Lake comes from the project to transfer water from the Hanjiang River to the Weihe River. The surface water environmental quality standard is Class II, and the concentration of NH₃-N and COD is 0.16 mg/L and 1.7 mg/L. Taking groundwater quality Class III as the standard, the exceeded limits of NH₃-N and COD are 0.5 mg/L, 3 mg/L. Therefore, the pollution source mainly comes from North Lake.

3.4.2. Model Results

The transport results of $\text{NH}_3\text{-N}$ and COD are shown in Figures 12 and 13. The results show that the range of $\text{NH}_3\text{-N}$ exceeding groundwater quality Class III standard after 3 years of storage in the reservoir will be 6.14 km^2 , the impact range will be 9.56 km^2 , and the maximum transport distance will be 90 m. After 10 years of storage, the range of exceeding the standard will reach 6.98 km^2 , and the impact range will be 11.55 km^2 , the maximum transport distance will reach 225 m. After 20 years of impoundment, the exceeding range will reach 13.01 km^2 , the impact range will reach 20.82 km^2 , and the maximum transport distance will be 775 m. After 50 years of impoundment, the exceeding range will be 18.18 km^2 , and the impact range will be 25.30 km^2 , the maximum transport distance is 1016 m.

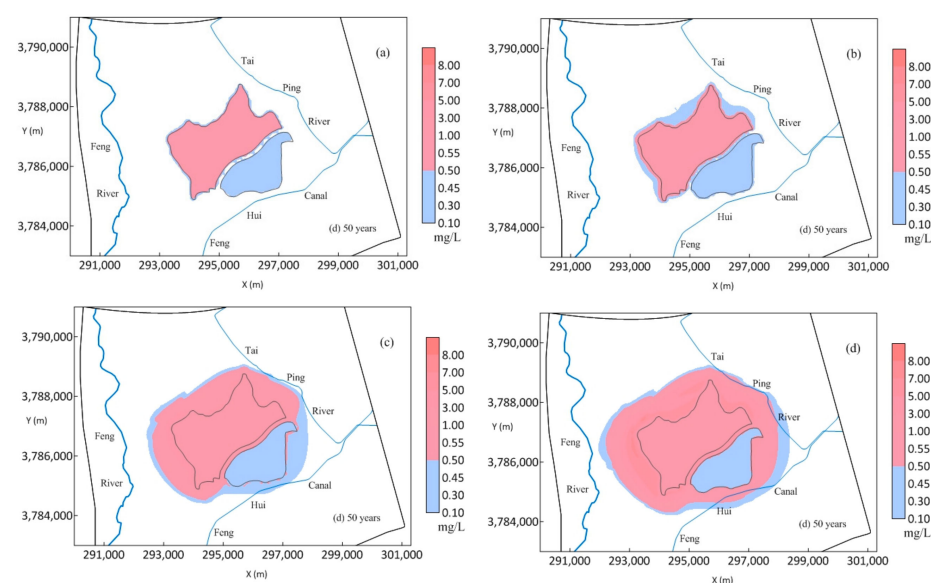


Figure 12. $\text{NH}_3\text{-N}$ transport of (a) 3 years; (b) 10 years; (c) 20 years; (d) 50 years after water storage in DR.

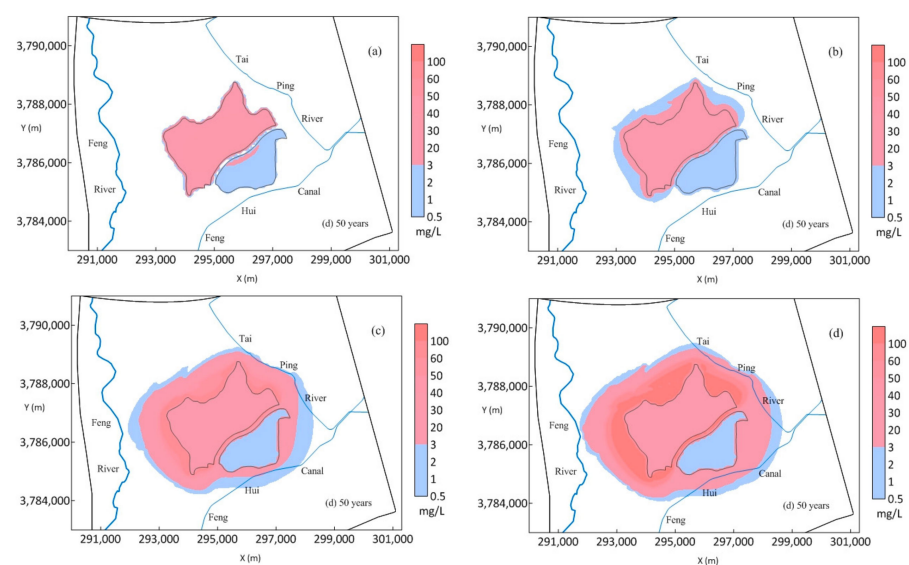


Figure 13. COD transport of (a) 3 years; (b) 10 years; (c) 20 years; (d) 50 years after water storage in DR.

The range of COD exceeding groundwater quality Class III standard after 3 years of storage in the reservoir will be 7.00 km^2 , the impact range will be 10.12 km^2 , and the

maximum transport distance will be 94 m. After 10 years of storage, the range of exceeding the standard will reach 8.27 km², the impact range will be 13.86 km², and the maximum transport distance will reach 439 m. After 20 years of impoundment, the exceeding range will reach 16.70 km², the impact range will reach 23.28 km², and the maximum transport distance will be 982 m. After 50 years of impoundment, the exceeding range will be 21.59 km², the impact range will be 27.28 km², and the maximum transport distance is 1267 m.

After the water storage of DR, the impact of NH₃-N is less than COD. However, in general, the impact of DR impoundment on the regional groundwater quality is mainly the pollution halo around North Lake. Therefore, in combination with the leakage results, two suggestions are put forward. One is to strengthen the control of the water quality of the Fenghe River, and control the water quality of Fenghe River to the class III surface water environmental quality standard or above. Secondly, it is recommended that all the North Lake can be used for seepage control, while the South Lake is used as a water supply source, and anti-seepage measures should be taken in the east of the south.

4. Conclusions

In this paper, the water level dynamics between the DRTS and the groundwater were discussed, and the water quality used by SFE and WQI method were analyzed. The integrated SW-GW model by using MODFLOW-NWT model and MT3DMS V.5.2 module was established to assess the hydrogeological effects of the DR, which aims to study the interaction between DR and groundwater during the initial and post-construction period and analyze the impact of reservoir leakage, water level variation, and surface water on groundwater quality. The main conclusions drawn are as follows:

- (1) The DRTS water level and groundwater level dynamics present a high degree of consistency and significant correlation. The cross-correlation coefficient is 0.85, and the lag time is about 7 days. There is a close hydraulic connection between them, and the change of groundwater level is mainly affected by the reservoir water level rather than precipitation.
- (2) In the same period, the groundwater quality is generally better than the DRTS water quality. The surface water quality deteriorates in the later stage, which is inferior to the diversion water quality. Briefly, DRTS water quality will not have a great impact on groundwater quality.
- (3) The average leakage rate of DRTS after impoundment is 6.86×10^3 m³/day, and the average leakage intensity is 1.5×10^{-2} m³/m². After 3 years of operation of the reservoir, the stable leakage will be 4.48×10^4 m³/day, the leakage intensity will be 4.3×10^{-3} m³/m², the annual leakage will be 16.35 million m³/day, and the storage capacity of DR will account for 0.32. The amount of surface water recharged is always 0.
- (4) After 3 years of operation of the reservoir, the groundwater level around the reservoir will rise obviously, and the groundwater at the bottom of the reservoir is directly hydraulically connected with the lake water. Within the simulation area (100 km²), the impact range of groundwater level variation greater than 0.5 m, 1 m, 2 m, 5 m will be 56.2 km², 38.4 km², 23.5 km², and 9.7 km². The most obvious rise of groundwater level is at the bottom of the reservoir area center, with a maximum of 8.5 m.
- (5) The range of NH₃-N exceeding groundwater quality Class III standard after 3, 10, 20, and 50 years of storage in the DR will be 6.14 km², 6.98 km², 13.01 km², and 18.18 km², respectively, and the range of COD exceeding groundwater quality Class III standard after 3, 10, 20, and 50 years of storage in the DR will be 7.00 km², 8.27 km², 16.70 km², 21.59 km², respectively. After the water storage of DR, the impact of NH₃-N is less than COD. In general, the impact of DR impoundment on the regional groundwater quality is mainly the pollution halo around North Lake.

Based on the above results, two suggestions are put forward. One is to strengthen the control of the water quality of the Fenghe River and control the water quality of

Fenghe River to the class III surface water environmental quality standard or above. Secondly, it is recommended that all the North Lake can be used for seepage control, while the South Lake is used as a water supply source, and anti-seepage measures should be taken in the east of the south. Horizontal bedding and drainage facilities are used to prevent continuous leakage of reservoir and groundwater environmental problems, such as reservoir immersion and salinization.

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