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Influence of Reservoir on Groundwater Environment in the Ecologically Fragile Area, Northwest of China

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Abstract

As the research proposed reservoirs after impact on the surrounding ecological fragile areas of groundwater level and scope, through the proposed reservoir area and its surrounding data collecting, hydrogeology survey and related test, for Modflow system simulation platform, through to the boundary conditions, initial conditions and source sink term and related hydrogeological parameters, the model identification and verification, The model of hydrogeological parameters in the study area is constructed. The simulation results show that the groundwater depth near the reservoir area will be higher than the critical value (1.8 m) of secondary salinization of soil. At the same time, according to the investigation and experiment, if the reservoir does not do seepage treatment, the water infiltration in the reservoir will aggravate the environmental hydrogeological problems in the ecologically fragile area.

Keywords

Ecologically Fragile Area, Reservoir Construction, Groundwater, Numerical Simulation, Environmental Influence

1. Introduction

Tahe Industrial Park in Manas County is located about 10 km east of Manas County. According to the "Environmental impact tracking evaluation Report of the master planning of Tahe Industrial Park in Manas County", the sewage of the park has been treated to meet the second level of "Comprehensive Sewage Discharge Standard" (GB8978-1996). Part of it meets the supplementary water demand of circulating water for enterprises after in-depth treatment, and part of it meets the requirements of "Urban Waste Water Quality of Municipal Sewage Recycling and Utilization" (GB/T18920-2002). It is prescribed that in spring, summer and autumn, it is used as park greening water and road scouring water. The remaining or winter intermediate water is intended to be discharged to the desert intermediate water reservoir in the north to be used as greening water in non-freezing period. In order to adjust the utilization of water resources in the park and study whether the construction of reclaimed water reservoir will cause unnatural fluctuation of the groundwater level in the construction area and its surrounding areas, it is decided to build reclaimed water reservoir in the desert. It is estimated that the amount of water discharged into the desert reservoir is about 4.5 million m^3/a, and the water resources in Tahe Industrial Park can be fully utilized through reservoir regulation and storage. However, the proposed Zhongshui reservoir is located in the hinterland of Gurbantunggut Desert, and the ecological environment is relatively fragile.

China has the largest number of reservoirs in the world. At present, more than 97,000 reservoirs have been built nationwide, with a total storage capacity of 0.8 trillion m^3. These reservoirs have played an important role in flood control and silt reduction, water supply and power generation, and have produced huge economic benefits, effectively promoting industrial and agricultural economic development and people's living needs. However, the construction of reservoirs (especially large reservoirs) has changed the natural, social and other environmental conditions around the reservoir, bringing adverse effects or damages to the environment around the reservoir [1]. Winter *et al.* (1976, 1999) a scholar from the United States Geological Survey, comprehensively considered hydrogeological parameter anisotropy, groundwater flow field, surface water level, source and sink characteristics and other factors, and analyzed the influence of reservoir water seepage on groundwater system by using mathematical model as the main research method [2] [3]. Through calculation and analysis of reservoir leakage, Unal B. *et al.* (2007) revealed the relationship between groundwater flow field changes and reservoir water level [4]. Lei Chunrong *et al.* (2018) studied and analyzed the characteristic effects of groundwater environment after impoundment of Dongzhuang Reservoir in Jinghe River by establishing a three-dimensional seepage numerical model. Under the recommended anti-seepage scheme, the impounding of the reservoir will cause the rise of the groundwater level near the reservoir area and dam site, but will not change the overall direction of groundwater runoff [5]. Chang Y.W. *et al.* (2016) adopted groundwater numerical simulation technology to assess the environmental impact of groundwater in Zhuangli Reservoir. According to the simulation results, the groundwater level of Yangzhuang, Xishilou and Houshiwan all increased, and the minimum average annual elevation was 0.9 m [6]. Zeng M. *et al.* (2022) analyzed the influence of the construction of Xiongdu Reservoir in Yidu City, Hubei Province on groundwater level through data collection, field investigation and sampling analysis. The groundwater level in the near-surface area around the reservoir rises about 45 m, and the groundwater hydraulic gradient changes greatly [7]. Liu X.G. *et al.* (2020) studied the flooding problem of Jiangxiang Reservoir, established a three-dimensional numerical model of groundwater flow with Modflow software, generalized the water level of the reservoir into a stepped periodic variation, and predicted the variation law of the groundwater level. It is recognized that the lag of groundwater level change on the bank of storage is mainly related to the distance, permeability coefficient, feed water degree and other factors, and that precipitation evaporation has little effect on the lag of groundwater level [8]. Siyal A.A. *et al.* (2019) used remote sensing and geospatial tools to study Chotiari Reservoir in Pakistan, and about 2578 ha of fertile farmland became unproductive salinized land [9]. Wang Q.J. (2017) took Xinji Wa Reservoir, a supporting project of the South-to-North Water Diversion project, as an example to build a prediction model of the impact of reservoir water leakage on groundwater level [10]. In the case of failure of anti-leakage measures, reservoir construction projects will greatly affect groundwater level, especially if the reservoir is stored for more than one year, which will not only increase groundwater level, but also cause soil secondary salinization [11] [12].

Therefore, for the proposed intermediate water reservoir, it is necessary to start from the perspective of groundwater environmental protection and build a groundwater simulation model to analyze the scope and degree of influence of reservoir impoundment on groundwater environment, so as to provide a scientific basis for the construction of the reservoir.

2. Study Area Profile

The proposed Zhongshui reservoir is located in the northwest of Beiwucha Town, Manasi County, Xinjiang Province, on the Laogu Gully at the tail of the Taxi River. It is a natural gully with relatively flat terrain (**Figure 1**).

Beiwucha Town, where the proposed reservoir is located, is located in the northern Tianshan Mountains of Xinjiang Province. It is located in the hinterland of Eurasia continent, far away from the ocean. It has a dry climate and scarce rainfall, which is a typical mid-temperate continental arid desert semi-desert climate. Winter is long and severe, summer is short and hot, and the temperature difference between day and night is large. The annual evaporation (1713.8 mm/a) is much larger than the precipitation (192.7 mm/a) (**Figure 2**).

The proposed reservoir is formed by surrounding the dam on three sides with natural gullies and depressions. The gullies are distributed nearly to the north and south, and the shape is extremely irregular. The bank slope is alternately convex and concave, with twists and turns. The vegetation in the reservoir area is developed and the soil salinization is serious. Reeds grow thickly along part of the bank and the bank, forming a marsh wetland landform. The surrounding terrain of the bank is relatively flat and open, and the overall terrain is high in the southeast and low in the northwest. The current situation is mostly farmland

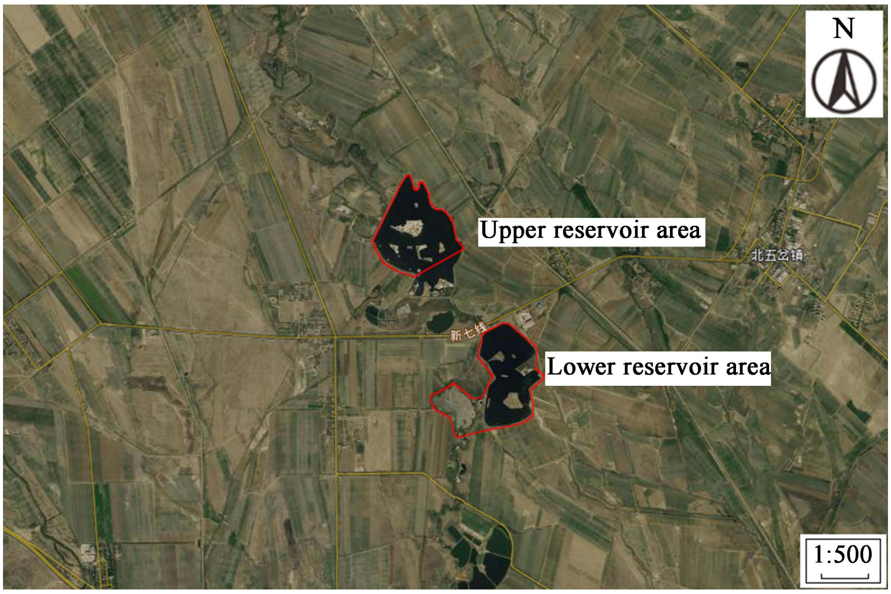

Figure 1. Geomorphic map of the study area.

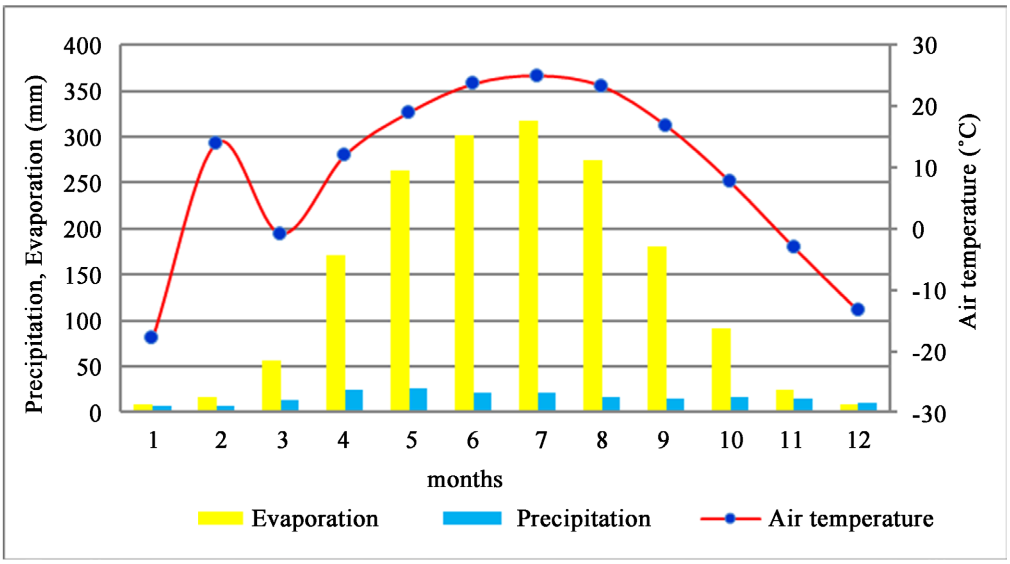

Figure 2. Precipitation, evaporation and temperature of the study area.

and cultivated land (**Figure 3**).

Due to the drainage of the upstream flood drainage channel, surface water of a certain water collection area is collected in the reservoir basin at the north end of the reservoir area (near the main dam). The outcropping beds in the reservoir area are mainly alluvial-diluvium and silt deposits of the Quaternary Holocene Series. The lithology is mainly alluvial-diluvium low liquid limit silt soil, low liquid limit clay and silty silt and clay. The groundwater is mainly composed of Quaternary pore-water and pore-microconfined water aquifers. The lithology is silty sand, low liquid limit silt and sandy silty soil layer. The groundwater depth varies greatly with different topography, ranging from 0 to 8.1 m, with an average depth of 4.3 m. There are groundwater overflows in the low-lying areas of

Figure 3. Site of the proposed recycled water Reservoir.

reservoir area. The flow of groundwater is basically the same as that of surface water, about 330˚ NW. The pH value of groundwater is 7.03 - 7.42, the groundwater type is SO_4·Cl-Na type, and the concentration of SO_4^{2+} is 62.2 - 5630 mg/L, with an average of 1086.6 mg/L. The concentration of Cl^- ranged from 22.3 to 4210 mg/L, with an average of 765.55 mg/L. Salinity 243 - 19200 mg/L, average 3664 mg/L.

When the reservoir is normally filled, the length of the reservoir is about 1.3 km from north to south, the maximum width from east to west is about 1.26 km, and the minimum width (main dam section) is about 65 m.

2. Acquisition of Simulation Model Parameters

2.1. Hydrogeological Drilling

According to the research needs, 11 hydrogeological boreholes were arranged in the reservoir area and its surrounding areas.

At a depth of 40 m, the borehole exposed a formation that can be roughly divided into five separate aquifers. 1) The upper 0 - 6.72 m is the aquifer, 2) 6.72 - 18.02 m is the relative aquifer, 3) 18.02 - 20.82 m is a relatively stable confined aquifer, 4) 20.82 - 30.21 m is the relative aquifer, 5) 30.21 - 36.82 m is a stable confined aquifer.

The K1, K5 and K9 drilling holes constructed in the upper reaches of the reservoir, the middle of the two reservoirs and the lower reaches at 40 - 80 m have been exposed. In the exposed borehole, it is a relatively stable water-proof layer with a thickness of about 25 m from 40 to 65 m. The lithology is dominated by silty soil and silty clay. At 55 m, there is about 2 m gray-black cement which have excellent water-proof effect.

By comparing the north-south strata of the proposed reservoir (**Figure 4**), it can be seen that the thickness of the two confined aquifers varies greatly from southeast to northwest, and it can be inferred that there may be lenticular body pinout in the middle of the aquifer. There is a relative water barrier between diving and confined water, and there is a certain local hydraulic connection.

2.2. Vertical Infiltration Coefficient of the Vadose Zone

The vertical permeability of the vadicle zone directly affects the atmospheric precipitation infiltration and natural anti-seepage performance around the reservoir. According to the distribution of strata and vadroic zones in the proposed reservoir area, four sets of double-ring seepage tests were arranged in combination with the rediameter and drainage conditions of groundwater (**Table 1**). The vertical infiltration coefficients of different soil vats in the study area vary to a certain extent, in the order of 10^{-4} - 10^{-5} cm/s, and the overall difference is small, with medium-weak permeability.

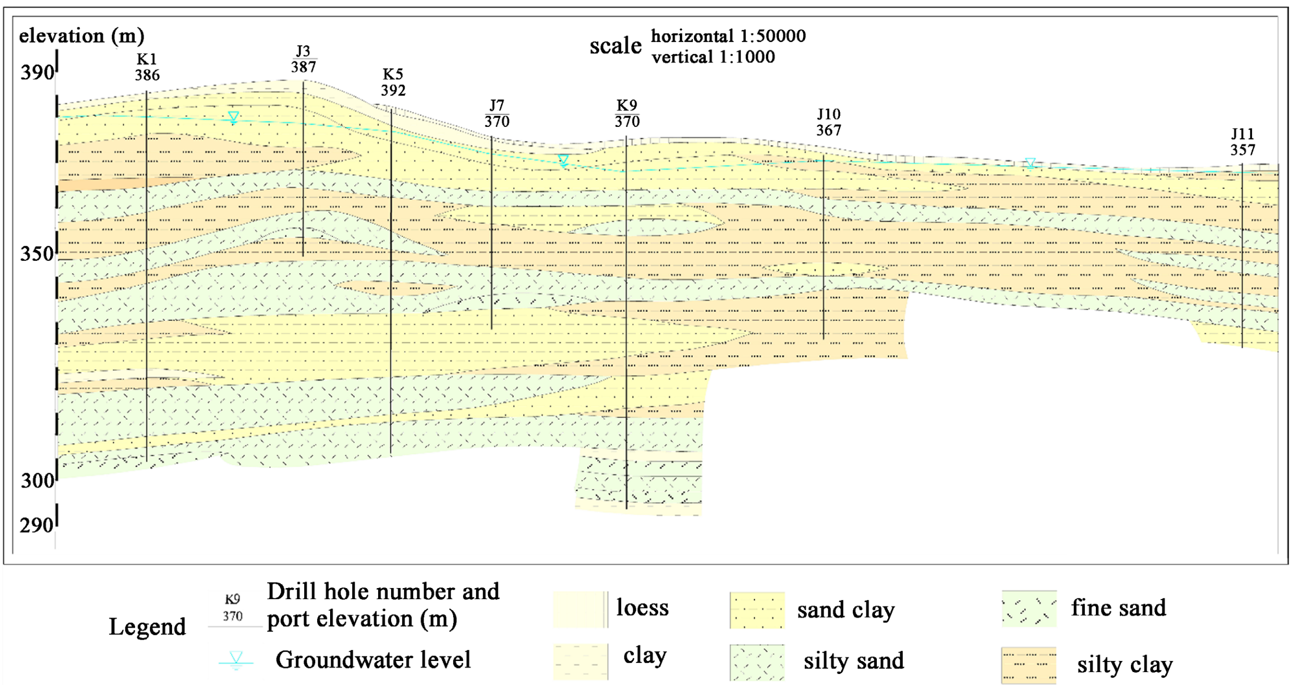

Figure 4. Stratigraphic correlation map of the proposed reservoir from north to south.

Table 1. Seepage test results.

Label position	Lithology of stratum in test place	Vertical infiltration coefficient of aeration zone K(cm/s)
Upstream of reservoir 1#	clay	0.0000340
Upper reservoir 2#	clay	0.0000722
Lower reservoir 3#	silty clay	0.0001764
Downstream of reservoir 4#	silty clay	0.0001613

2.3. Water Injection Test

In order to determine the permeability and water discharge capacity of the reservoir aquifer, three Wells were selected to carry out a water injection test (Table 2), and the mixed permeability coefficient of the aquifer was between 0.0575 and 0.1614 m/d.

3. Construction of Hydrogeological Model of Reservoir Area

3.1. Hydrogeological Generalization Model

The establishment of the conceptual model of hydrogeology is to generalize the actual internal structure, boundary properties, hydraulic characteristics, permeability, water content and replenishment and discharge conditions of aquifer and aquifer, so as to facilitate the numerical simulation of computers to calculate in the time dimension [13].

3.1.1. Simulate Scope

Since the alluvial plain of the lower reaches of Taxi River Basin is far away from the natural hydrogeological unit boundary, the principle of determination of the simulation range is as follows: the northwest boundary is bounded by about 5 km outside the reservoir boundary, the northeast boundary is bounded by about 2.5 km outside the reservoir boundary, and the southeast and southwest boundary is bounded by 1 - 2 km outside the reservoir boundary.

3.1.2. Simulate Target Aquifer

According to the understanding of hydrogeological conditions in the simulated area, such as analysis of previous data and field investigation, the aquifer most directly affected by reservoir impoundment is the shallow aquifer with a depth of 40 degrees. Due to the poor continuity of the clay layer in the simulation area, the phenomenon of pinching-out and bifurcation exists, and there are mixed mining Wells of upper and lower aquifers, the hydraulic relationship between confined aquifer and the submersible aquifer is close, and the trend and change of water level are consistent [14]. Therefore, the submersible and micro-confined aquifer with a buried depth of about 40 m is generalized into the same aquifer in this simulation.

3.1.3. Boundary Conditions

Plane boundary: When large-scale mining does not affect groundwater flow

Table 2. Results of water injection test.

Borehole number	Water level buried depth (m)	Water level elevation (m)	flow Q (m^3/d)	Drop depth S (m)	Permeability coefficient K (m/d)	Influence radius R (m)
K1	5.53	380.47	3.456	5.53	0.1159	18.83
K5	4.89	387.11	3.405	4.89	0.1614	19.64
K9	6.45	363.55	1.152	6.45	0.0575	15.47

direction, the southwest and northeast boundaries that are basically parallel to the iso-water line can be simplified to zero flow, while the northwest and southeast boundaries can be used as the boundary of lateral runoff [15]. The boundary setting can be set by the General Head module of Visual Modflow.

Vertical boundary: The submersible surface is the upper boundary of the simulation area, and the submersible boundary has the exchange of submersible evaporation, drainage and atmospheric precipitation infiltration [16]. According to the data of K1, K5 and K7 exploration holes, the average thickness from the bottom of the model to the clay and silty clay layer is about 20 m, the thickness is stable, the distribution is continuous, and the water insulation performance is good. Under natural conditions, the water exchange between the upper and lower aquifers is weak due to the existence of the thick aquifer, which can not be considered in this study. Therefore, the lower boundary of the model is taken to the clay and silty clay layers.

3.2. Establishment and Solution of Groundwater Model

3.2.1. Mathematical Model

According to the hydrogeological conceptual model, the mathematical model of groundwater flow in the simulation area is described by the following definite solution problem of three-dimensional partial differential equation:

$$\frac{\partial}{\partial x}\left(K\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \tag{1}$$

where: K - permeability coefficient (LT^{-1}); H - water head (L); W - vertical flow per unit volume (T^{-1}), used to represent source and sink items; S_s - elastic water release (storage) rate of porous media (L^{-1}); T - time (T)[1] (**Table 3**).

Equation (1), together with the corresponding initial and boundary conditions, forms a mathematical model to describe the groundwater flow movement. The definite solution condition can be expressed as:

Initial conditions:

$$H(x,y,z,0)=H_0(x,y,z) \tag{2}$$

The first type of boundary conditions:

$$H(x,y,z,t)\big|_{\Gamma_1}=H_1(x,y,z,t) \tag{3}$$

The second type of boundary conditions:

$$K\frac{\partial H(x,y,z,t)}{\partial n}\bigg|_{\Gamma_2}=q(x,y,z,t) \tag{4}$$

where, H_0 (x, y, z) is the initial water head value of the aquifer in the simulation area, H_1 (x, y, z, t) is the actual measured water head value on the first type boundary of each layer in the simulation area, and q (x, y, z, t) is the unit area flow on the second type boundary of each layer in the simulation area (**Table 3**).

[1]Guidelines for Environmental Impact Assessment technology-groundwater environment (2016).

Table 3. Summary of formula parameters.

symbol	explain
K	Permeability coefficient
H	Head of water
W	Vertical flow per unit volume
S_s	Elastic water release (storage) rate of porous media
T	Time
$H_0\,(x, y, z)$	The initial water head value of the aquifer in the simulation area
$H_1\,(x, y, z, t)$	The actual measured water head values at the first boundary of each layer in the simulation area
$q\,(x, y, z, t)$	The flow per unit area on the second boundary of each layer in the simulation area
ε	Phreatic evaporation intensity
ε_0	Evaporation of 20 mm diameter pan during the same period
β	surface evaporation conversion coefficient, 0.55
λ	Submersible evaporation coefficient

3.2.2. Initial Conditions

According to the data of groundwater level measured in the field survey, the Gaussian interpolation method is used to obtain the groundwater iso-water line, which is used as the initial water level of the model.

3.2.3. Source and Sink Items

The main sources of groundwater recharge in the simulated area and the surrounding area are lateral runoff recharge and atmospheric rainfall infiltration recharge. The main ways of groundwater discharge are lateral runoff discharge, artificial discharge and evaporation discharge to the surrounding strata. Rainfall infiltration recharge is simulated and budgeted by RCH subroutine package provided by Visual Modflow system, which is given in the form of water layer recharge rate. Lateral recharge and lateral discharge runoff were calculated by GHB subroutine package. The maximum rate and ultimate depth of submersible evaporation were determined according to the characteristics of the vats in the simulation area.

The simulated area belongs to arid and semi-arid continental climate. Combined with geomorphic type, shallow aquifer lithology and annual average rainfall, the infiltration coefficient of atmospheric precipitation is 0.18.

One of the most important ways to discharge water in the simulated area is evaporation. According to meteorological station data, the average annual evaporation in this area is about 1713.8 mm. The submersible depth of the simulation area is shallow. According to the research results of Changji groundwater equalization test site near the simulation area, formula (5) is used to calculate the evaporation intensity:

$$\varepsilon = \varepsilon_0 \cdot \beta \cdot \lambda \tag{5}$$

ε —phreatic evaporation intensity (mm);

ε_0 —Evaporation of 20 mm diameter pan at the same time (mm);

β —surface evaporation conversion coefficient, 0.55;

λ —coefficient of submersible evaporation (**Table 3**).

3.2.4. Selection of Permeability Coefficient

Reasonable hydrogeological parameters are the basis and key to reliable and high precision of numerical simulation results. The hydrogeological parameters of this model are obtained according to the actual exploration data of the initial reservoir and the field test. The initial permeability coefficient $K_x = K_y = 0.13$ m/d, $K_z = 0.013$ m/d and water supply $S_y = 0.2$ are taken.

3.2.5. Model Identification and Verification

Limited by the actual observed data, the identification period and verification period of the model were from July 13, 2015 to August 15, 2017, among which, the identification period of the model was from July 13, 2015 to July 31, 2016, and the verification period was from August 1, 2016 to August 15, 2017. According to the historical observation data, the preliminary model was fitted and identified. In this process, the preliminary hydrogeological parameters were appropriately adjusted until the variation trend of the simulated water level was basically consistent with that of the measured water level. The final water level fitting error ranges from 0.095 m to 1.243 m, with an average of 0.365 m (**Figure 5**). The three-dimensional hydrogeological model and numerical simulation constructed in this study can accurately draw the variation characteristics of underground flow field in the simulation area, which can meet the accuracy requirements of this numerical simulation. The hydrogeological parameters after model identification were adjusted as follows: $K_x = K_y = = 0.08$ m/d, $K_z = 0.008$ m/d, water supply $S_y = 0.18$.

4. Results and Discussion

4.1. Influence of Reservoir Storage on Groundwater Level

This simulation assumes that the dam of Zhongshui Reservoir is geomembrane inclined wall impervious homogeneous earth dam, the main impervious material is PE composite geomembrane, and the reservoir area is not impervious treatment. Therefore, vertical leakage will occur after reservoir impoundment. The hydrogeological model after identification and verification is used to simulate the future variation trend of groundwater level around the reservoir after normal impoundment, and the influence degree of impoundment on surrounding soil secondary salinization can be predicted according to the variation of water level and its range [17]. The simulation time was 10 years after the normal storage of the reservoir. The simulation results show that the reservoir leakage decreases gradually with time, and the average leakage is 2593.2 m^3/d (**Figure 6**).

The water table will rise as a result of leakage. The simulation results show

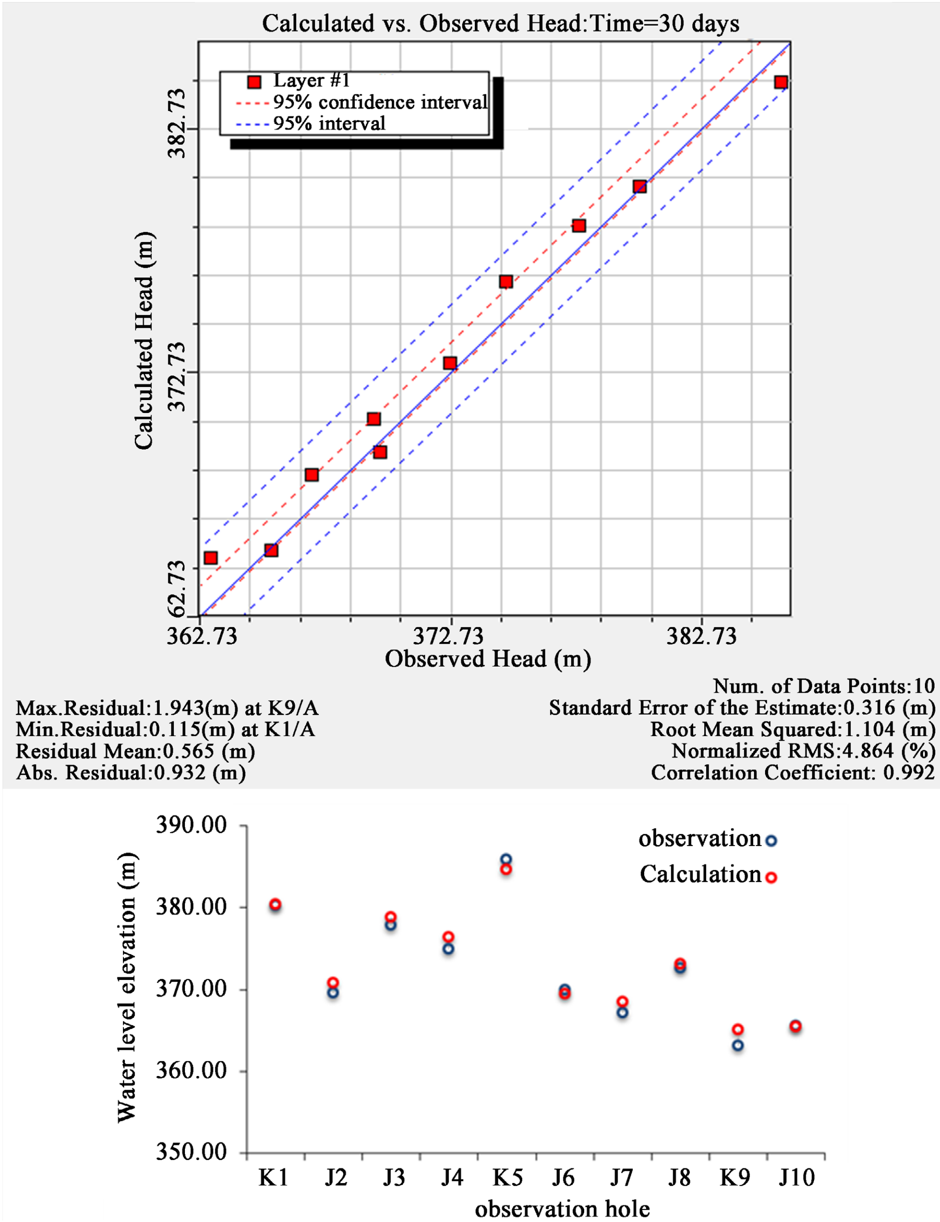

Figure 5. The model identifies the final observed water level and the calculated water level pair.

that, except for K5 and J10 observation holes, the water level of other observation holes will rise, with an increase of 1.2 - 7.5 m, and the influence range will gradually expand with the storage time (Figure 7 and Figure 8).

4.2. Influence of Reservoir Storage on Soil Salinization

Since the simulated area is located in the downstream of alluvial plain, the groundwater level around the reservoir will rise after the reservoir is impaled, resulting in salinization or swamping. According to the relevant data of reservoir area, the critical groundwater depth for preventing soil secondary salinization and suitable for crop growth is 1.8 m. Therefore, the groundwater depth of 1.8 m was taken as the critical value to evaluate the secondary salinization of soil

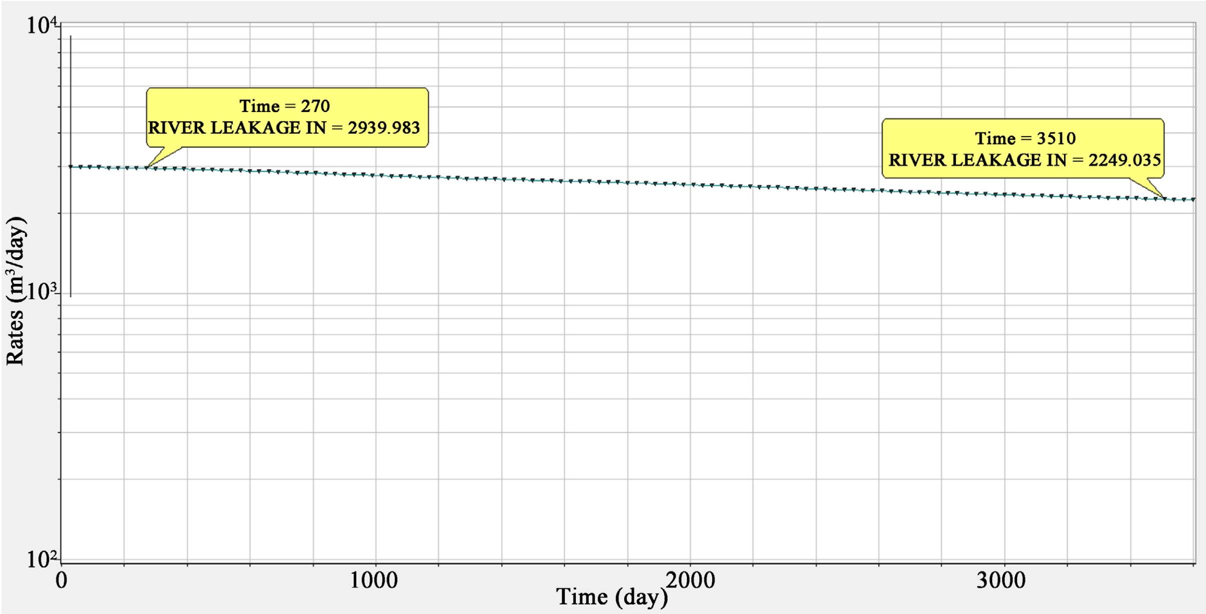

Figure 6. Variation curve of reservoir leakage rate.

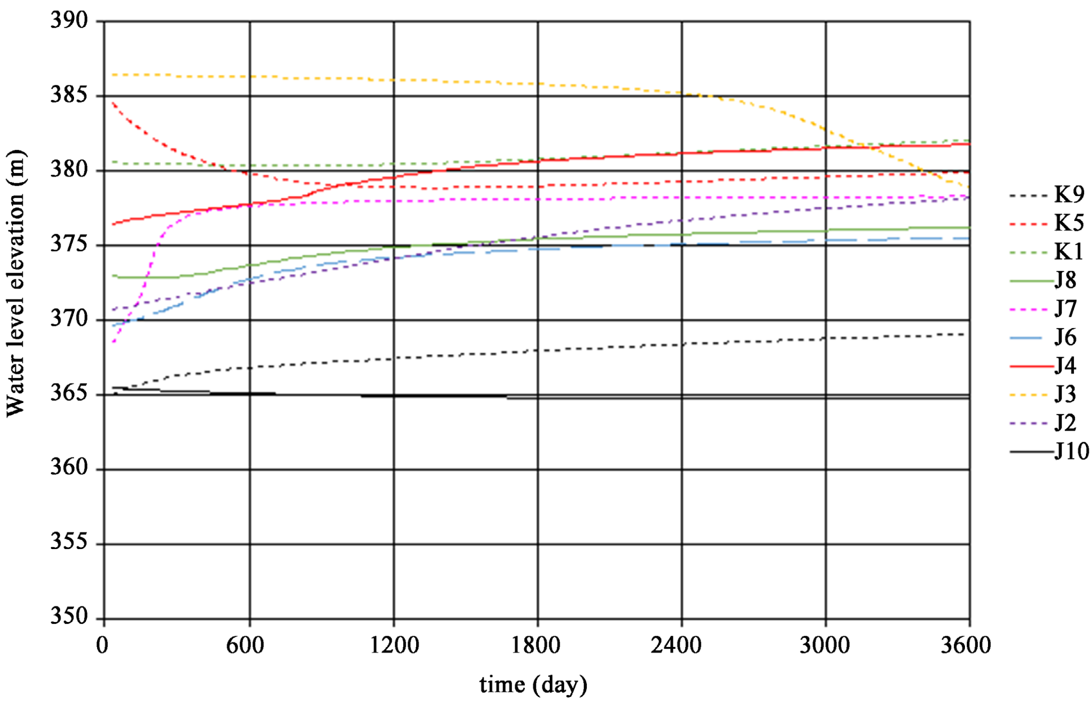

Figure 7. Variation of water level in water level observation hole during the simulation period.

caused by reservoir leakage. According to the numerical simulation results (Figure 8), after 0.5 years of normal storage of the reservoir, the buried depth of the groundwater level in the area near the reservoir will be higher than 1.8 m. With the passage of storage time, the affected area becomes larger and larger, and the range of 1.8 m water level (buried depth) expands continuously, which may aggravate the secondary salinization of soil around the reservoir area.

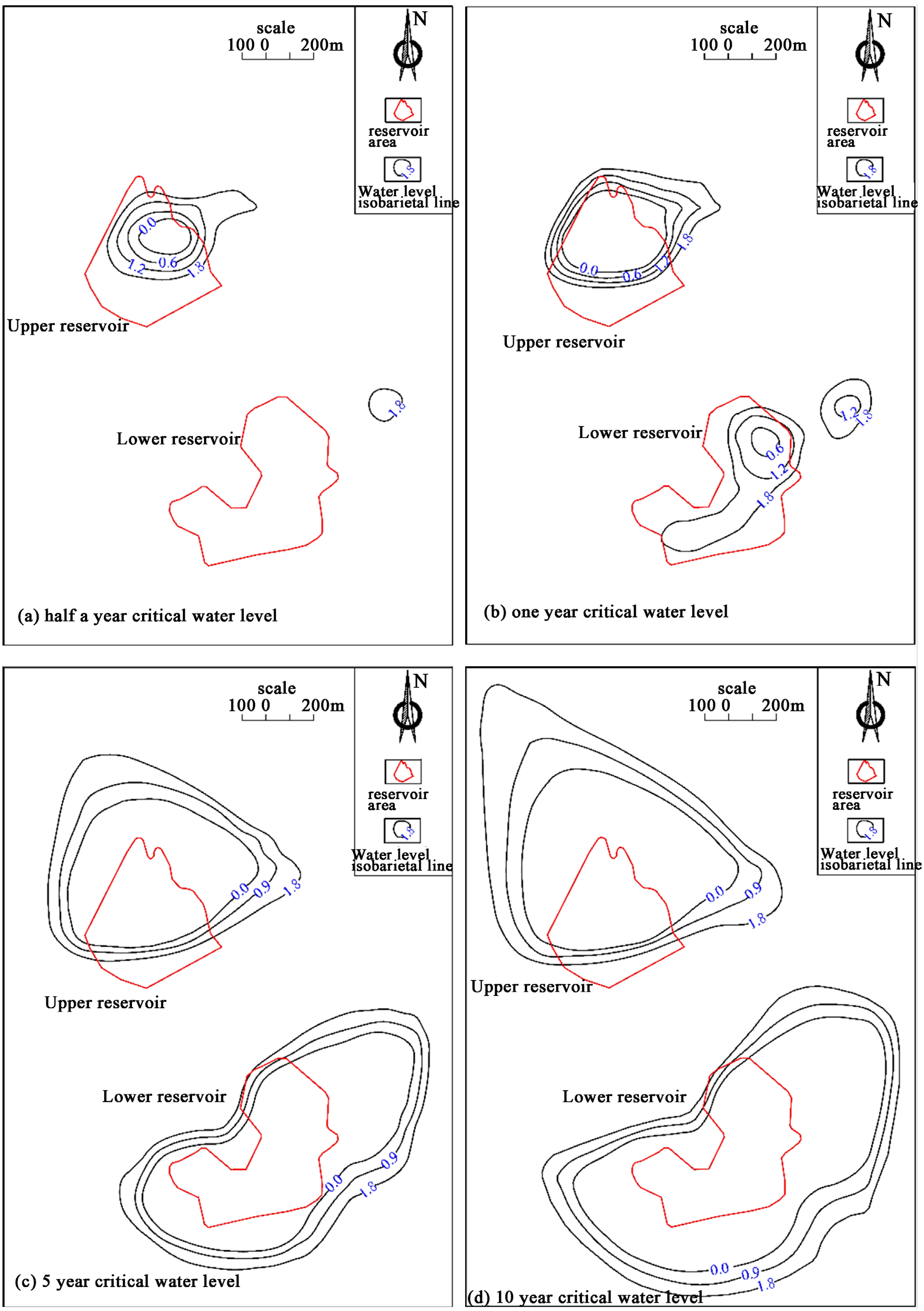

Figure 8. Range of critical water level (1.8m) of soil secondary salinization after reservoir water storage.

According to the numerical simulation prediction calculation, the range of secondary salinization around the reservoir area will reach 3383 m^2 in 10 years, including 1492 m^2 in the upper reservoir and 1891 m^2 in the lower reservoir. The salinization trend of upper and lower repositories in 10 years is shown in Figure 9. The salinization area expanded rapidly in the first two years of reservoir operation, but slowed down and tended to be stable after three years. The overall trend of secondary salinization expansion was in line with logarithmic function.

4.3. Discussion on the Control of Soil Secondary Salinization

The leakage of the reservoir in the arid plain will raise the groundwater level behind the dam, which often leads to secondary salinization of the soil, resulting in reduced production or even abandoned farmland, which endangers the healthy development of the ecological environment. Zhang Yunchang, first-class inspector of the Department of Three Gorges Project Management of the Ministry of Water Resources and deputy chairman of the Public Cognition and Public Relations Committee of Reservoir DAMS of China Dam Engineering Society, believes that the impact of reservoir construction on natural ecology and society should be correctly understood, long-term monitoring and research should be carried out, and the harmony between the dam, human and nature should be gradually enhanced [18].

Huang F. *et al.* (2020) adopted drainage ditches to regulate the groundwater

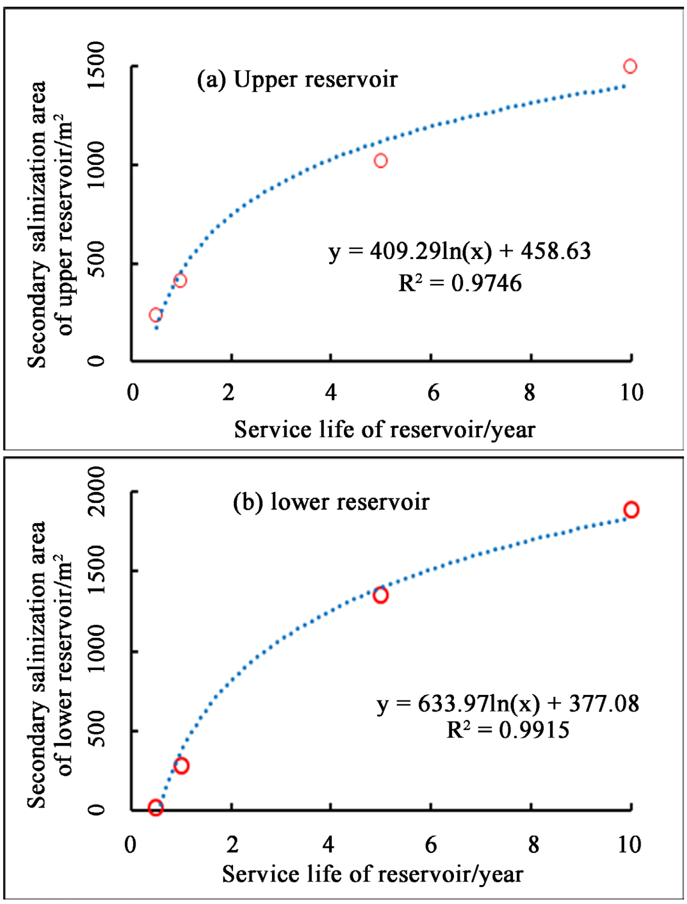

Figure 9. Relationship between secondary salinization area and reservoir operating life.

level of farmland behind the dam, and used HYDRUS to simulate the changes of soil water content and salt content under different groundwater levels and depths, and believed that setting drainage ditches was a better way to solve the salinization of farmland soil behind the dam [19].

Wang L. *et al.* (2020) took the buried depth of farmland groundwater level behind the dam of Chala Reservoir in Weili County, Bayingoleng Mongolian Autonomous Prefecture, Xinjiang as the research object, and adopted the numerical simulation method to study the influence of "anti-intercept-guide" seepage control of plain reservoir on the buried depth of groundwater behind the dam. Farmland groundwater level behind the dam can be effectively reduced and secondary salinization of soil can be prevented by means of "seepage prevention in the upstream and drainage cut in the downstream" [20].

It can be seen that in the design and construction process of reclaimed water reservoir, in addition to considering the seepage problem, it is necessary to strengthen the research and demonstration of drainage problems behind the dam, to ensure that the operation of reclaimed water reservoir will not aggravate the secondary salinization of soil around the reservoir.

This simulation only considers the reservoir without anti-seepage treatment and determines the maximum degree of the impact of the reclaimed water reservoir on the groundwater environment. The impact prediction with higher accuracy needs to be combined with the detailed design and construction results of intermediate water reservoir, and then the simulation calculation.

5. Conclusions

1) According to the field investigation and test, the structural characteristics and initial parameters of the simulation model were obtained, and on this basis, a 3D hydrogeological simulation model based on Visual Modflow was constructed.

2) After normal storage of the reservoir, without anti-seepage treatment, the average leakage is 2593.2 m^3/d, which will cause the rise of the groundwater level near the reservoir area, with an increase of 1.2 - 7.5 m.

3) Taking the underground water depth of 1.8 m as the standard for soil secondary salinization, the area of secondary salinization around the reservoir was 3383 m^2 after 10 years of normal storage.

4) The construction of intermediate water reservoirs in the ecologically fragile areas of northwest China can further improve the efficiency of water resource utilization, but the ecological environment issues must be taken into account as one of the important constraints, and the relationship between development and environment should be properly handled.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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