Analysis of the impact of Shifosi Reservoir water level on underground water
B. Yan, Y. Xie, C. J. Guo and C. S. Zhao

ABSTRACT

Shifosi Reservoir is a plain reservoir. High groundwater level in the nearby area caused by impoundment of the reservoir has not only submerged the nearby farmland and village, but also reduced production and affected farmers’ living. To analyze the influence of reservoir impoundment on surrounding groundwater level, Visual MODFLOW software was used to simulate the groundwater in Zhujiapu and Chenpingpu areas on the right auxiliary dam of Shifosi Reservoir. Results show that with the rise of the reservoir water level from 45.5 m to 46.2 m and 46.5 m, the area under the critical groundwater table (45 m) in the study area decreased in turn. In 2008, when the reservoir water level was 46.2 m and 46.5 m, the area under the critical groundwater level was reduced by 0.64 km² and 0.84 km², respectively, compared with the case of reservoir water level of 45.5 m, and would decrease by 0.38 km² and 0.45 km², respectively, by 2022. This indicates that the impact of reservoir impoundment on groundwater level is great. Therefore, relief wells or drainage ditches should be arranged along the auxiliary dam axis to effectively lower the groundwater level, and improve the surrounding ecological environment of the reservoir.

Key words | groundwater, numerical simulation, Shifosi Reservoir, water storage level

INTRODUCTION

The population of the plain area is densely populated, the economy is developed, and the large infrastructure is numerous, thus in order to ease the contradiction of regional water shortages, plain reservoirs are often built. The construction of reservoirs can not only adjust the uneven distribution of water resources in time, but also make full use of surface water resources and ensure the water demand for industrial and agricultural production. However, most of the plain reservoirs are located at the front of an alluvial-proluvial fan and the surrounding terrain is flat. Reservoir impoundment easily leads to high groundwater level on the reservoir’s bank, causing problems to the ecological environment such as soil salinization around the reservoir area. Seeboonruang (2012) studied the effects of reservoir impoundment on the saline soil in Thailand by monitoring the changes of reservoir and groundwater levels in salty-alkaline fields in northeastern Thailand. The results showed that there was a significant correlation between the reservoir storage elevation and the groundwater level. When the local groundwater rose to the surface soil, the dissolved salt was transported to the ground, resulting in soil salinization. Zhou (2015) utilized the dynamic change of water level in the Second Fenhe Reservoir and surrounding groundwater level to discuss the change relationship of recharge of surface water to Jinci spring and Lancun spring by using correlation analysis when the reservoir was impounded to the normal water level. It was found that the impact on groundwater was the most obvious when the reservoirs were impounding to the normal water level. Zhang (2015) analyzed the plain reservoir’s engineering characteristics, hydrogeological characteristics, and ecological characteristics by means of numerical simulation. Based on treating Boxing Reservoir as a typical plain reservoir, it concluded that reservoir leakage caused groundwater
level to rise around the reservoir during the operation of the reservoir. Overall it showed the groundwater level rose higher and higher near to the reservoir. Korytowski & Waligórski (2017) described the impact of the Przebedowo catchment on groundwater in the surrounding area and found that there was a close relationship between reservoir impoundment and groundwater. According to the data from 2015, the correlation coefficient between reservoir water storage level and groundwater level was 0.87.

Shifosi Reservoir is located in the middle reaches of Liaohe River in Shenyang Xinchengzi District and Yiniupu County of Faku County, about 40 km away from Shenyang. Shifosi Reservoir is the only one with a flood control, industrial and agricultural water supply and other functions of large-scale controlled water conservancy project on the Liaohe River. The left bank of the dam is located in Huangjia Township, Shenbei New District, Shenyang City, and the right bank is located in Yiniupu Township, Faku County, Shenyang City. The total reservoir capacity is 185 million m³, detention flood storage capacity is 160 million m³, and it is a typical river plain reservoir. Since the trial operation of the reservoir in 2006, the reservoir began to be impounded. When the water level reached 46.5 m during the impoundment, serious seepage occurred outside the reservoir, resulting in immersion. Ecological operation was scheduled in 2009, to control the reservoir water level at 46.2 m, but the immersion problem has not yet eased.

In order to understand the influence of reservoir impoundment on the surrounding groundwater level, Visual MODFLOW software was used to simulate the groundwater in Zhujiapu and Chenpingpu auxiliary dam areas on the right bank of Shifosi Reservoir. The changes of groundwater level around the reservoir at 45.5 m, 46.2 m, and 46.5 m were calculated, respectively. The influence of reservoir impoundment on the surrounding groundwater table was determined by comparing the areas below the critical groundwater table (45 m).

HYDROGEOLOGICAL CONDITIONS

The research area is located at the downstream of Zhujiapu and Chenpingpu on the right auxiliary dam of Shifosi Reservoir, and the length is about 3.44 km. The upstream embankment connects with the foot of the west slope of South Hill, and the downstream connects with the Shijia wasteland. Tuan Mountain and the mountain behind Shijia wasteland are denuded residual hill topography, with an elevation of 70–96 m and relative elevation of 30–50 m. The research area is located on the floodplain formed by alluvial-proluvial deposits on the right bank of the Liaohe River. The terrain is flat and the surface elevation is between 44 m and 48 m. The geological layer belongs to the Quaternary sedimentary layer, mainly distributed with clay and sand. The ground elevation of the piedmont clino-plain near Chenpingpu is more than 50 m, the terrain is fluctuating, and the front edge is tilted.

The research area is an alluvial plain of the lower Liaohe River. According to comprehensive survey data, the main aquifer lithology is coarse sand, gravelly sand, and round gravel. There is a close hydraulic connection between Liaohe River water and groundwater: during the dry season, groundwater is discharged to the Liaohe River and the western part of downstream; Liaohe River water is used to invert groundwater on both banks when the flood season or upstream reservoir discharges water. The aquifer lithology is fine sand and gravel sand with a thickness of only 5 to 10 m. The loess-like silty clay distributed in the sloping plains in the front of the mountain and mound zone is generally thicker than 10 m. There is groundwater in contact with the underlying bedrock, but the amount of water is small.

GROUNDWATER MODEL ESTABLISHMENT

Range of simulation area

Based on the scope of investigation, the range of simulation calculation considers the impact of reservoir immersion on surrounding agriculture (village). From the perspective of sustainable development, the scope of the simulation calculation is determined at the downstream of the Zhujiapu and Chenpingpu auxiliary dam in Shifosi Reservoir. The southeast of the simulation area is bounded by the roads of Zhujiapu and Chenpingpu Auxiliary Dam, the northwest of the area is bounded by a stable zone of groundwater at a distance of 1,800 m from the dam, the northeast of the area is bounded by MingShen Highway, and the area is...
about 2.5 km². The location of the study area is shown in Figure 1.

**Generalization aquifer**

According to the hydrogeological conditions in the reservoir area, it is determined that the aquifer is an unconfined aquifer. Based on the Shifosi Geological Prospecting Report and the General Arrangement of Shifosi Project, the data of 26 observation holes in the study area were used to establish a 3D geological model. For the convenience of simulation, the coordinate system of observation holes position adopted Beijing 54 coordinate system. The positions of the 26 observation holes are shown in Table 1. This simulation considers the aquifer as the target layer and generalizes the aquifer in the study area into six formations of silty clay, silt, fine sand, medium sand, medium coarse sand, and gravel sand. The 3D geological model in the study area is shown in Figure 2.

**Source-sink term**

The recharge modes of groundwater system in the region are infiltration and atmospheric precipitation, seepage supply of river and channels, and supply of groundwater lateral runoff. The groundwater runoff in the area is mainly seeping from southeast to northwest, and the hydraulic gradient is 0.2–1‰. Due to the depth of groundwater being mostly less than 4.5 m, there is some evaporation. Recharge of precipitation infiltration mainly reflects the strength of recharge of groundwater, which is determined by rainfall multiplied by rainfall infiltration recharge coefficient. The phreatic evaporation is distributed to each calculation unit according to the evaporation intensity. The limit evaporation depth is considered according to 4.5 m measured by Shenyang Equilibrium Experimental Station of Liaoning Province Environmental Geological Station. The average annual rainfall of Shifosi Reservoir is 1,059 mm, infiltration coefficient 0.2, and the average annual evaporation is 1,000 mm. The

**Table 1 | Positions of observation holes**

<table>
<thead>
<tr>
<th>Observation holes</th>
<th>X coordinates</th>
<th>Y coordinates</th>
<th>Observation holes</th>
<th>X coordinates</th>
<th>Y coordinates</th>
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</table>

Figure 1 | Study area location.

Figure 2 | 3D geological model.
reservoir seepage supply is mainly reflected in the reservoir recharge groundwater, along the right auxiliary dam of Shifosi Reservoir to establish the river boundary. Taking 45.5 m, 46.2 m, and 46.5 m as the river water level respectively, the bottom elevation of the river bed is 41 m, the thickness of the riverbed is taken as 2 m. The vertical conductivity \( (K_z) \) of the silty sand layer in the reservoir area is obtained by field water seepage test and determined as 0.0495 m/d.

Boundary conditions in simulation area and selection of calculation parameters

The selection of the boundary conditions directly affects the correctness and rationality of the simulation results (Zhu & Wang 2006). The southern and southeastern part of the study area is the reservoir water level, and its change directly affects the riparian groundwater (Huang & Ruan 2006). Therefore, the reservoir water level after the impoundment can be defined as the upstream constant head boundary. According to the observation holes’ data and the geological profiles, the groundwater level at 1,800 m from the right bank auxiliary dam is 43.81 m long term. Therefore, the northwestern side of the study area about 1,800 m from the auxiliary dam is defined as the downstream constant head boundary, and the downstream water level is 43.81 m. It can be seen from the engineering geological profiles in the study area that the bottom of the phreatic aquifer is granite and migmatite, which is defined as impervious boundary. The study area is mainly affected by the water storage elevation. Therefore, the groundwater seeps mainly in the direction perpendicular to the axis of the dam, so the other boundary is set as the streamline boundary.

According to the on-site testing, drilling, sampling, and geophysical data analysis, it is found that the main lithology in the study area is silty clay, silt, sand, and bedrock. Based on the impoundment immersion geological survey and impact assessment report of Shifosi Reservoir, the water storage coefficient is 0.18. The permeability coefficients of the main soil layers are listed in Table 2.

Generalization of groundwater seepage

According to the aquifer type, lithology, thickness, water conductivity and so on, the model is generalized as a inhomogeneous anisotropic aquifer. The groundwater in the calculation area is affected by the dry flood season, and the water flow is unstable. The water flow conforms to Darcy’s law and generalizes to the unsteady three-dimensional flow.

Groundwater system model set-up

According to the hydrogeological conditions in the simulated area, input aquifer parameters, initial conditions, and boundary conditions, a 30 x 30 x 6 layer conceptual model was established in Visual MODFLOW software, and 5,400
effective meshes were divided. Taking January 1, 2007 as the starting simulation time, the flow field on January 1, 2007 was set as the initial flow field to simulate the changes of groundwater under different water levels.

The mathematical model is defined as:

\[
\begin{aligned}
\frac{\partial}{\partial x} \left[ K_x (h - B) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_y (h - B) \frac{\partial h}{\partial y} \right] \\
+ \frac{\partial}{\partial z} \left[ K_z (h - B) \frac{\partial h}{\partial z} \right] + \epsilon_1(x, y, z, t) - \epsilon_1(x, y, z, t) \\
= \mu \frac{\partial h}{\partial t}, (x, y, z) \in \Omega, t \geq 0 \\
h(x, y, z, t)_{t=0} = h_0(x, y, z), (x, y, z) \in \Omega \\
h(x, y, z, t)|_{S_1} = f(x, y, z, t), (x, y, z) \in S_1, t \geq 0 \\
K \frac{\partial h}{\partial t} |_{S_2} = q(x, y, z, t), (x, y, z) \in S_2, t \geq 0
\end{aligned}
\]  (1)

In the formula, \( h \) and \( B \) are water level and bottom elevation (m) of aquifers, respectively; \( \epsilon_1(x, y, z, t) \), \( \epsilon_2(x, y, z, t) \) are the recharge and evaporation intensities of the aquifer (m/d); \( (x, y, z) \) is the node coordinate (m); \( K_x, K_y, K_z \) are the conductivity values (m/d) in the x, y, and z directions, respectively; \( \mu \) is specific yield in phreatic aquifer; \( h_0(x, y, z) \) is the initial head (m); \( f(x, y, z, t) \) is water level (m) under the first kind of boundary condition; \( q(x, y, z, t) \) is boundary single-wide flow (m²/T); \( S_1 \) is head of the flow curve; \( S_2 \) is flow calculation boundary; \( n \) is the outer normal of \( S_2 \); \( \Omega \) is the calculation area range.

Model identification and verification

This simulation used the flow field on January 1, 2007 as the initial flow field, and that on December 31, 2007 as the end of the identification period, totaling 365 days. The boundary conditions, initial conditions, and source-sink terms were input into the model. The observation wells GC1 and GC6 were selected as the typical observation wells. The fitting degree of the calculated water levels and the observed water levels were analyzed. The fitting curves of the observation wells GC1 and GC6 are shown in Figures 3 and 4. The fitting results show that the calculated water level fits well with the actual water level. At the same time, the flow field on September 9, 2010 was selected as the calibration flow field, and the calculated flow field was compared with the actual flow field using the observation hole data of September 9, 2010 in the study area. The calibration curve is shown in Figure 5.

It can be seen from Figure 5 that the last-minute flow field in the model correction period can reflect the seepage state of groundwater in the calculated area, and the variation trend between the calculated flow field and the measured flow field is basically consistent. In summary, the hydrogeological parameters used in the model can reflect the actual hydrogeological conditions in the study area, and the model can be used to simulate and predict future groundwater changes.

![Figure 3](https://iwaponline.com/jwcc/article-pdf/9/2/367/244310/jwc0090367.pdf)

**Figure 3** | Fitting curves of the observation well GC1.
SIMULATION RESULTS

In order to reflect the influence of reservoir impoundment on groundwater level, the change of groundwater level during the impoundment of 45.5 m, 46.2 m, and 46.5 m, respectively, was simulated. Most of the surface elevation in the study area is between 44 m and 48 m with an average elevation of 46.3 m. Due to the fact that the upper soil layer in the study area is silty clay and the thickness is generally larger than 15 m, the combined experience shows that the capillary water level of silty clay in the surrounding area of Shifosi Reservoir increases by 1.2 m. The root length of crops in the study area was determined to be 0.5 m, so the safe groundwater depth was 1.2–1.7 m. Therefore, we simulated a 45 m critical groundwater level line and analyzed the influence degree of different water storage elevation on the groundwater level according to the area under the critical groundwater level line.

When the water storage elevation is 45.5 m, the simulation area of groundwater level in the study area from 2008 to 2022 is shown in Figure 6(a)–6(o). As can be seen from the simulation results, due to the impoundment of reservoir, the groundwater level rises year by year with the changing of time; the groundwater level is between 42 and 45.3 m, decreasing gradually from southeast to northwest. Up to 2008, the area of groundwater level below 45 m is about 1.6 km², accounting for 64% of the total area of the study area. In 2015, the area of groundwater level below 45 m is about 1.23 km², accounting for 49% of the total area of the study area. By 2022, the area of the water table below 45 m is about 0.66 km², accounting for only 26% of the study area.

When the water storage elevation is 46.2 m, the simulation area of groundwater level in the study area from 2008 to 2022 is shown in Figure 7(a)–7(o). It can be seen from the simulation results that when the water storage elevation is 46.2 m, the groundwater level is between 42 and 46 m. Up to 2008, the area of groundwater level below 45 m is about 1.23 km², accounting for 49% of the total area of the study area. In 2015, the area of groundwater level below 45 m is about 0.66 km², accounting for only 26% of the study area. By 2022, the area of
Figure 6 | Groundwater variations under 45.5 m reservoir water level during different periods. (a) 2008. (b) 2009. (c) 2010. (d) 2011. (e) 2012. (f) 2013. (g) 2014. (h) 2015. (i) 2016. (j) 2017. (k) 2018. (l) 2019. (m) 2020. (n) 2021. (o) 2022. (Continued.)
Figure 6 | Continued.
groundwater below 45 m is about 0.28 km², accounting for only 11% of the total area of the study area.

When the water storage elevation is 46.5 m, the simulation area of groundwater level in the study area from 2008 to 2022 is shown in Figure 8(a)–8(o). It can be seen from the simulation results that when the reservoir water level is 46.5 m, the groundwater level is between 42 and 46.3 m. Up to 2008, the area of groundwater table below 45 m is about 0.76 km², accounting for 31% of the total area of the study area. In 2015, the area of groundwater table below 45 m is about 0.45 km², accounting for 18% of the total area of the study area. By 2022, the area of groundwater below 45 m is about 0.21 km², accounting for only 8% of the total area of the study area.

Figure 6 | Continued.

Under different reservoir water levels and operating times, the proportion of the area with groundwater below 45 m in the study area is shown in Table 3. As can be seen from Table 3, the groundwater level not only varies with time under the same reservoir water level, but also shows a significant difference during the same period when the water level is different. Under the same water level, the groundwater level gradually increases with the lengthening of water storage time. Under the same storage time, the groundwater level rises with the increase of the water storage elevation. In 2008, when the water level was 46.2 m and 46.5 m, the area under the critical groundwater level was reduced by 0.64 km² and 0.84 km², respectively, compared with the case of 45.5 m, and decreased by 0.38 km².
Figure 7 | Groundwater variations under 46.2 m reservoir water level during different periods. (a) 2008. (b) 2009. (c) 2010. (d) 2011. (e) 2012. (f) 2013. (g) 2014. (h) 2015. (i) 2016. (j) 2017. (k) 2018. (l) 2019. (m) 2020. (n) 2021. (o) 2022. (Continued.)
Figure 7 | Continued.
and 0.45 km², respectively, in 2022. Thus, the water storage elevation has a great influence on the groundwater level downstream of the auxiliary dam. The higher the water storage elevation, the smaller the area under the critical groundwater level. Therefore, the adverse effects of groundwater level rise can be reduced by properly controlling the reservoir water level.

**IMMERSION TREATMENT MEASURE**

In order to reduce the unfavorable influence of reservoir impoundment on the agriculture and residential life on the shore of the reservoir, appropriate measures should be taken to reduce the phreatic water level inside the seepage prevention wall and to reduce the thickness of the capillary saturation zone and the recharge amount of rainfall infiltration in order to achieve effective protection (Zhang et al. 2015). According to different geological conditions and topography, reservoir treatment measures vary from place to place (Lan et al. 1999). For plain reservoirs, the effect of suspended vertical anti-seepage measure is poor (Xue 2011). Full cut vertical anti-seepage can easily break the original nature exchange of groundwater laws, causing a deterioration in the water environment. Therefore, a vertical anti-seepage program...
Figure 8 | Groundwater variations under 46.5 m reservoir water level during different periods. (a) 2008. (b) 2009. (c) 2010. (d) 2011. (e) 2012. (f) 2013. (g) 2014. (h) 2015. (i) 2016. (j) 2017. (k) 2018. (l) 2019. (m) 2020. (n) 2021. (o) 2022. (Continued.)
Figure 8 | Continued.
is not a good policy (Yu & Huang 2008). For the dualistic structure stratum, drainage ditches or relief wells can be used not far away from the dike and can greatly reduce the water table and reduce the pressure head at the bottom of the impermeable layer for the purpose of immersion control (Zhang et al. 2008). Therefore, aiming at the phenomenon that the water storage of Shifosi Reservoir leads to high groundwater level on the right bank of the reservoir, it is suggested to arrange relief wells or discharge drainage ditches along the axis of the auxiliary dam to alleviate the immersion of the reservoir bank and improve the ecological environment around the Shifosi Reservoir.

**CONCLUSIONS**

Aiming to deal with the problem of groundwater level rise around the reservoir caused by reservoir impoundment, a three-dimensional groundwater model was established for the downstream area of Zhujiapu and Chenpingpu auxiliary dams on the right bank of Shifosi Reservoir and groundwater numerical simulation was carried out. The simulation results show that under the same water level, the groundwater level increases with the extension of water storage time. Under the same water storage time, the groundwater level rises with the increase of the water storage elevation. In 2008, when the water level was 46.2 m
and 46.5 m, the area under the critical groundwater level decreased by 0.64 km² and 0.84 km², respectively, compared with the case of 45.5 m and reduced by 0.38 km² and 0.45 km² by 2022, respectively. Therefore, under the condition of ensuring the ecological operation of the reservoir, it is possible to alleviate the high groundwater level in the surrounding areas of the reservoir by minimizing the reservoir impoundment height. In addition, in view of the immersion problem that has been caused so far, measures such as relief wells or drainage ditches should be arranged along the axis of the auxiliary dams to effectively reduce the groundwater level and to improve the ecological environment around the Shifosi Reservoir.

### REFERENCES


First received 8 February 2018; accepted in revised form 28 February 2018. Available online 29 March 2018

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**Table 3** | Area and proportion of regions with groundwater level below 45 m in the study area

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| 2022                | 0.66  | 26              | 0.28  | 11              | 0.21  | 8