Hindawi
Geofluids
Volume 2018, Article ID 9720970, 11 pages
https://doi.org/10.1155/2018/9720970

Research Article

Evaluation of the Influence of Jiangxiang Reservoir Immersion on Corp and Residential Areas

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Received 30 October 2017; Revised 1 March 2018; Accepted 14 March 2018; Published 18 April 2018

Academic Editor: Stefano Lo Russo

Reservoir immersion is an environmental geological issue. Jiangxiang reservoir was taken as an example, where both analytical and numerical methods were employed to calculate the banked-up water level after reservoir impoundment, based on the hydrological, meteorological, geological, and hydrogeological conditions. The capillary rise height of soils in the reservoir area was determined through in situ measurement and laboratory analysis. The depth of foundation and crop roots in residential areas can be obtained by field investigation. The critical depth to groundwater was calculated according to the height of capillary rise and land elevation. Furthermore, the influence of reservoir immersion was evaluated, which provides a scientific basis for the relocation of people in reservoir areas, planting of crops, and project investment.

1. Introduction

Swampiness and salinisation of farmlands can be generated by the rise in capillary water in soils, which weakens foundations in residential areas [1, 2]. When water levels, after reservoir impoundment, are higher than those of the original groundwater level in a plain area, this will cause the rise of groundwater levels in the surrounding areas. Despite the causes of rising groundwater level, the phenomenon can cause deterioration of the environment in terms of agriculture and building structures as seen in many places around the world [3]. Thus, immersion issues after reservoir impoundment are worth investigating and, in particular, in plain areas [4]. Future influences of reservoir immersion need to be evaluated with respect to the critical positioning of the groundwater depth, that is, immersed groundwater depth. The immersion values of residential area and crops are the sum of the height of capillary rise and the depth of crop roots. Thus immersion will happen if the groundwater level reaches a critical depth after reservoir impoundment. For a sandy soil, the capillary rise height was calculated according to the provisions in the Engineering Geological Manual [5]; but the predicted values are greater than those of clay soils; thus the initial hydraulic gradient should be considered for clay sediments.

In addition, groundwater levels are also an important variable. Most methods used to model and predict changes in groundwater level should also consider dynamic changes that are linked to future urban development and expansion or contraction of agricultural land use. The normal forecasting methods used for groundwater dynamic changes include neural network methods, genetic algorithms, wavelet analysis, grey-Markov models, and time-series methods (Jin et al. 2011; [6–9]). With the development of computer technology, the numerical method has become the main method of calculating groundwater levels [10–12]. Also, the regression equations and a three-dimensional unsteady flow system numerical model of groundwater have been established for China's Three Gorges Project. The immersion scope and extent were obtained using a 3D numerical modelling method to calculate rising groundwater levels [13].

Here, based on the geological and hydrological conditions, an integrated analytical and numerical method was employed to calculate the groundwater level for residential and farming areas. A comparison has been conducted between the two methods. The numerical results matched analytical values and the determination of capillary rise height considered the effect of the initial hydraulic gradient of soil clay, which makes the range of immersion values more accurate.

2. Study Area

2.1. Location of the Reservoir. Jiangxiang reservoir is located in the north of the Jianghuai River watershed, about 30 km northeast of Hefei City, China (Figure 1). The main function of Jiangxiang reservoir is to supply water for irrigation and flood control. The total volume of the reservoir is 0.122 billion m^3 and the normal storage level of reservoir is 43.0 m. The reservoir contains a barrage, spillway, flood discharge culvert, and an irrigation culvert. The top elevation of the reservoir dam is 46.7 m and the maximum height of the dam is 16.03 m.

The average rainfall for many years in Jiangxiang reservoir and the surrounding region has been 934 mm, the maximum annual precipitation is 1561 mm (1991), and the minimum annual precipitation is 499 mm (1978). The annual average temperature is 15°C with the extreme highest temperature in summer being 40.3°C, the extreme lowest temperature being −18.6°C, and the annual average evaporation from the water surface being 798 mm y^{-1}.

2.2. Geological Setting

2.2.1. Lithologic Units. The geologic setting of the reservoir and residential area is relatively simple. The whole region is covered by upper Pleistocene deposits (Q_3^{al}) except for the old river pathway area and beach land, which are covered by Holocene deposits (Q_4^{al}), while the underlying bedrock is the Upper Cretaceous system of the Zhangqiao formation (K_{2z}). The 15 to 30 m thick soil cover is composed of mainly silty loam and silty clay. The stratigraphic distribution across the study area is illustrated in Table 1 and Figure 2.

2.2.2. Hydrogeological Conditions. The hydrogeological conditions of the Jiangxiang reservoir are controlled by the recharge from rainfall and groundwater. Rainfall is the main source of recharge of groundwater in the study area and it is then discharged to the reservoir. The groundwater level in the Jiangxiang reservoir is higher than the local river level. Groundwater types consist of pore water and fractured water. Fractured water in the study area is affected by the porosity and permeability conditions of the aquifers. It is found in the bedrocks within the red shale and sandstone units (Table 1). Pore water from Pleistocene and Holocene sediments is controlled by heavy silty and silty clay with a relatively low permeability. Groundwater has limited storage volume with most recharge arising from precipitation and discharge being through artificial exploitation and lateral runoff to gullies. This aquifer represents, however, the main water resource with relatively good quality water for local residents. Data from some wells, such as JM1, JM5, JM11, and JM14, indicated water yields per unit to be below 10 m^3/d and the type of groundwater is HCO_3-Ca·Na and HCO_3·Cl-Ca·Na with total dissolved solids of 0.3–0.7 g/L.

Figure 1: Location of Jiangxiang reservoir.

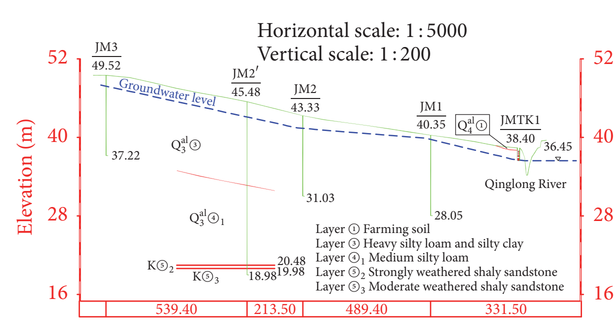


Figure 2: Geological profile of Jiangxiang reservoir showing location of test boreholes, groundwater levels, lithologic types, and distances between boreholes. The elevation was based on the Yellow Sea level. The numbers are the distances between two boreholes (m).

The pore water is distributed within the unconfined aquifer and the soil in the aquifers is silty. The water-bearing capacity of the aquifer varies with its soil properties. The fractures and voids develop in surface soil due to weathering

Table 1: Strata in the study area: key data.

Sequence number	Soil property	Age	Bottom elevation (m)	Thickness (m)	Soil property characteristics	Distribution
	Modern soil	Q^{ml}	39.1~49.9	0.3~0.7	Yellow, grey, and soft containing plant rhizomes	Surface of farmland
②	Silty loam	Q_3^{al}	24.0~45.3	0.5~14.7	Greyish yellow, containing Fe and Mn concretion.	Project area
③	Silty loam and silty clay		23.1~40.3	2.3~20.4	Brown yellow, grey white clay minerals	Dam abutment and local dunes
④$_1$	Medium silty loam		19.9~37.5	0.7~7.8	Greyish yellow containing Fe and Mn concretions	Discontinuous
④$_2$	Medium silty loam including sandy loam, silty-fine sand		19.9~27.2	0.7~6.0	Greyish yellow, with gravel particles	Discontinuous
⑤$_1$	Fully weathered shale and sandstone	K_2z	19.0~29.8	0.3~1.5	Reddish, brown red soft rock, and fully weathered containing clay	Project area
⑤$_2$	Strongly weathered shale and sandstone		18.6~28.4	0.5~1.4	Brick red, purple red soft rock	Project area
⑤$_3$	Moderate weathered shale and sandstone		22.1~26.1	2.3~2.9	Purple red soft rock	project area
⑤$_4$	Weak weathered shale and sandstone		17.1	6.3	Purple red soft rock	Project area

and they have good transmissibility. The underlying layer is of the low permeability as a result of the compacted soil structure. The groundwater is recharged by precipitation and discharged mainly by evaporation due to the small volume of runoff, and only a small amount of water is supplied to the underlying fractured water. Water yields of single well are below 5 m^3/d and the water quality indicates HCO_3-Ca·Na or HCO_3·Cl-Ca·Na with total dissolved solids of 0.5 g/L.

Groundwater dynamic monitoring data showed that the depth of groundwater below the surface was from 1.3 m to 4.6 m. Groundwater levels varied greatly with surface fluctuation, generally from 35.6 m to 40.8 m, which was mainly affected by rainfall, surface water, and the permeability of the soil layers.

3. Methods and Analyses

3.1. Field Work. Ten exploration pits were formed, 1.5 m to 2.0 m higher than the river water level, near the Chenji River, the Chucheng River, and the Qinglong River, and the depth of each exploration pit was extended to 0.5 m below groundwater level. Meanwhile, two exploration pits were excavated in the Jiangxiang, Yanshou, and Caiqiao reservoirs, where a comparison was conducted between Jiangxiang and the completed reservoirs. The exploration pits have been protected by plastic film or asbestos with ditches to prevent rainfall from entering the pits. The undisturbed soils were sampled below the surface of each exploration pit in a vertical direction at 0.15 m intervals. Each soil sample was accurately recorded, stored, and sent to the laboratory for measurement of soil water content and saturation ratio.

Field investigation showed that the soil depth for wheat root and rice in study area ranges generally from 0.15 m to 0.20 m and from 0.20 m to 0.30 m, respectively. Soil water content has little impact on rice because it grows in paddy fields all year round except when it is ripe and needs to be dried. The nonflood season of Jiangxiang reservoir ranges from October to April in the following year and the minimum water level is 42.4 m. The maximum water level of Jiangxiang reservoir is 43.0 m in the flood season (from May to September).

3.2. Calculating Capillary Rise Height. Capillary rise height in clay size materials was studied by Zhang and Zhao [14] and the relationship between capillary force and capillary rise height is given as follows:

$$h_c = \frac{p_c}{(I_0 + 1)} = \frac{2\alpha^2}{(I_0 + 1) D} \cdot \frac{1}{1000}, \qquad (1)$$

where h_c is the height of capillary rise (m), p_c is the capillary force expressed by the height of the water column (m), I_0 is the initial hydraulic gradient in a clay soil when bound water flows (dimensionless), D denotes the diameter of the soil particle fraction (mm), and α is a constant related to the temperature; if the temperature is 15°C, α is equal to 15 mm; if the temperature is 0°C, α is equal to 15.4 mm. Equation (1) is not only suitable to clayey, but also to sandy soils. The relationship between capillary rise height and grain size according to the theoretical, empirical, and field-measured capillary rise height in different soil layers is shown in Figure 3 [14].

Figure 3 illustrates that the theoretical value of capillary rise height for different soil types is increasing irrespective of grain size, while the field monitoring value of capillary rise height does not show the same trend, increasing first and then decreasing. This can be explained by (1): the larger the sand grain size, the smaller the capillary force. To overcome the

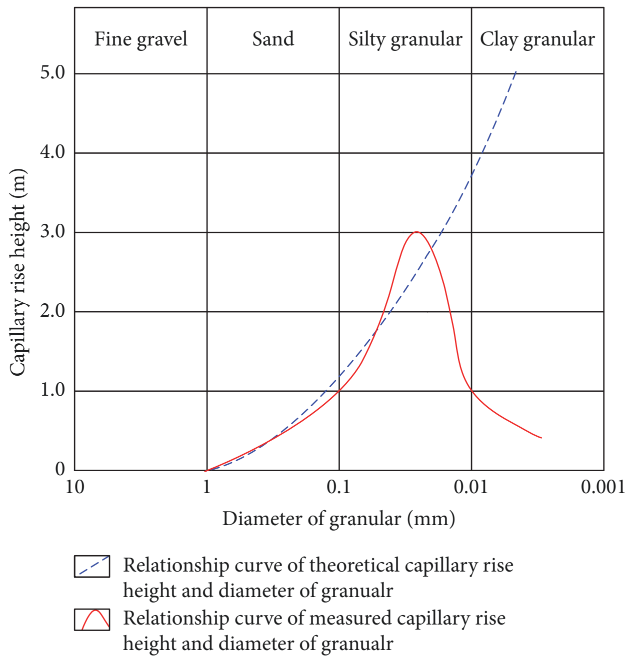


Figure 3: Relationship between capillary rise height and grain size.

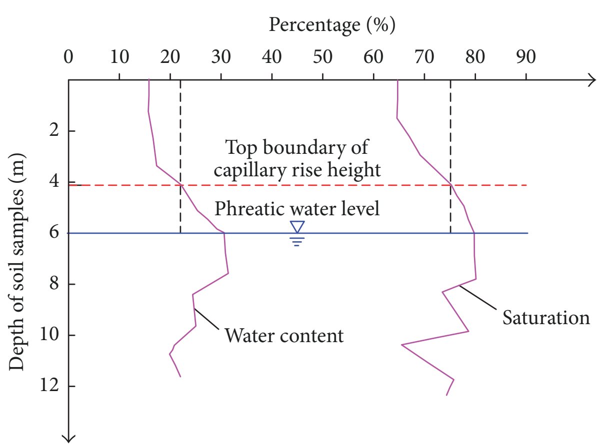


Figure 4: Soil moisture content and saturation ratio versus soil sample depth.

viscous force of bound water during capillary rise, that is, if $I_0 = 0$, $h_c = p_c$ with small capillary rise heights, the grain size is a controlling factor. With the small grain size of silty clay, p_c is large and I_0 is small or equal to zero, so the capillary force and capillary rise heights are greater. Clay sized soils are similar to silty clay: the grain size is small, so p_c and I_0 are larger and h_c decreases.

The capillary rise height can be defined as the distance from an obvious wet surface under the surface to the phreatic water level (Figure 4). Parameter, h_c, can be determined by measuring the water content in the field for cohesive soils or sorted soils. The upper boundary of the capillary zone can be set close to saturation ($S_w = 75\%$). The upper boundary is defined as maximum water content of hanging capillary water when using the natural water content curve. The given

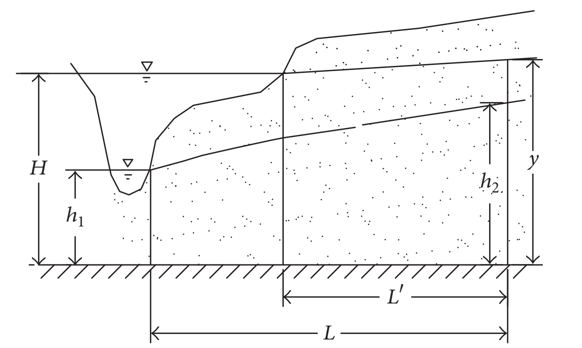


Figure 5: Groundwater level variation before and after reservoir impoundment.

phreatic water level was adopted to determine h_c using the water content of soil (its value is defined as $\theta = nS_w$). The capillary rise height was determined using measured soil water content and the saturation ratio (Figure 4). As shown in Figure 4, for a certain position, the depth of corresponding soil sample on the top surface is 4.2 m. The phreatic water surface is 6.0 m and the capillary rise height is 1.8 m.

3.3. *Calculating Critical Groundwater Depth.*

Critical groundwater depth is the required shallowest buried depth of groundwater that will not cause the salinisation of the ploughed soil layer. The critical buried depth of groundwater level in the immersion area should be determined by specific hydrogeological conditions, or by using the formula given in the Code for Geological Survey of Water Resources and Hydropower Engineering (GB50487-2008) as given in

$$H_{cr} = H_k + \Delta H, \tag{2}$$

where H_{cr} is the critical buried depth of groundwater in immersion area, H_k represents the capillary rise height of soil above groundwater level, and ΔH is the safety margin (design value).

3.4. *Solution Methods for Groundwater Banked-Up Level*

3.4.1. *Analytical Solution Method.*

Due to the approximately horizontal direction of underlying aquitard in the study area, the groundwater flow is assumed to be steady flow before and after reservoir impoundment according to Darcy's law. A conceptual model for the rise of groundwater level is shown in Figure 5. The empirical formula can be expressed as

$$y = \sqrt{\frac{L'\left(h_2^2 - h_1^2\right)}{L} + H^2}, \tag{3}$$

where y is the banked-up groundwater level after reservoir impoundment, L' is the distance between the river water boundary and the borehole after reservoir impoundment, L refers to the distance between the river water boundary and the borehole before reservoir impoundment, h_1 is the height difference from the river level to the aquitard, h_2 is the height difference from groundwater level to the aquitard, and

Table 2: Calculation results of capillary rise height in each exploration pit profile.

Pit number	Water content (%)	Saturation ratio (%)	Depth of soil sample (m)	Buried depth of groundwater (m)	Capillary rise height (m)
JMTK01	25.7	87	0.95	1.70	0.75
JMTK02	22.8	80	0.55	1.20	0.65
JMTK03	23.4	76	0.90	1.45	0.55
JMTK04	22.5	85	0.25	0.73	0.48
JMTK05	22.3	87	0.45	0.93	0.48
JMTK06	23.8	79	0.45	0.89	0.44
JMTK07	24.8	86	0.85	1.20	0.35
JMTK08	25.2	84	0.80	1.20	0.40
JMTK11	26.1	86	0.55	1.15	0.60
JMTK09	NA	NA	NA	Dry hole	NA

H is the height from the normal impoundment level to the aquitard.

3.4.2. Numerical Solution Method. The study area was assumed to be a heterogeneous isotropic medium, so the mathematical model for 3D groundwater unsteady flow can be expressed as

$$\begin{gathered}\mu\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left(K\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial H}{\partial y}\right)\\ +\frac{\partial}{\partial z}\left(K\frac{\partial H}{\partial z}\right)+\varepsilon,\\ x,y,z\in\Omega,\ t\geq 0,\\ H\left(x,y,z,t\right)\big|_{t=0}=H_0,\quad x,y,z\in\Omega,\ t\geq 0,\\ K_n\frac{\partial H}{\partial\vec{n}}\bigg|_{\Gamma_1}=q\left(x,y,z,t\right),\quad x,y,z\in\Gamma_1,\ t\geq 0,\end{gathered}\tag{4}$$

where Ω is the seepage area (m^3), H is the groundwater level aquifer (m), K denotes the hydraulic conductivity (m/d), μ is the specific yield (dimensionless), ε is the source and sink term of the aquifer (m/d), H_0 is the distribution of initial water level of the aquifer (m), Γ_1 is the second boundary of the seepage area (m^3), including the second impermeable boundary of the confined aquifer and lateral flow or impermeable boundary of the seepage area, n represents the normal direction of the boundary surface, K_n is the permeability normal to the boundary surface (m/d), q is per unit flow volume of the second boundary (m/d), inflow is positive, outflow is negative, and impermeable layer flow is zero. Equation (4) was discretised and calculated by Feflow Software, which was developed by WASY Institute for Water Resources Planning and Systems Research, Germany. It is an interactive finite-element simulation system for modelling 3D and 2D steady and transient flows and mass and heat transport processes in groundwater and the unsaturated zone.

4. Results and Interpretations

4.1. Determination of Capillary Rise Height and Critical Groundwater Depth. The capillary rise height for each exploration pit was calculated using measured soil water content and saturation ratio. Table 2 displays the capillary rise height being 0.35~0.75 m in the reservoir region and the mean value being 0.53 m. Capillary rise heights of less than, or equal to, 0.55 m account for 70% of all measured data. Consequently, the capillary rise height was set at 0.53 m under comprehensive consideration of the real conditions prevailing in the reservoir area.

Groundwater rise is insignificant in the flood season and has little effect on wheat. The water level of Jiangxiang reservoir in nonflood seasons varies between 41 m and 43 m and has little impact on rice. The safety margin was suggested to be 0.25 m for crop areas. The critical value of groundwater depth is 0.78 m (2) considering the capillary rise height of 0.53 m.

In the residential area, the foundation depths of houses range from 0.2 m to 0.7 m. Two-storey houses have used foundations buried at 0.8 m to 1.5 m in recent years. Actually, the burial depth of the foundations is about 1.0 m below groundwater level in the reservoir area, but there is no significant settlement of houses and no reduction in foundation strength. This indicates that the impact of groundwater on residential foundation strength is insignificant. Consequently, the burial depth of residential foundation was suggested to be 0.67 m considering the general conditions in the residential area. The capillary rise height is 0.53 m, leading to a critical burial depth below groundwater level of 1.2 m in residential areas.

4.2. Results of Groundwater Banked-Up Level

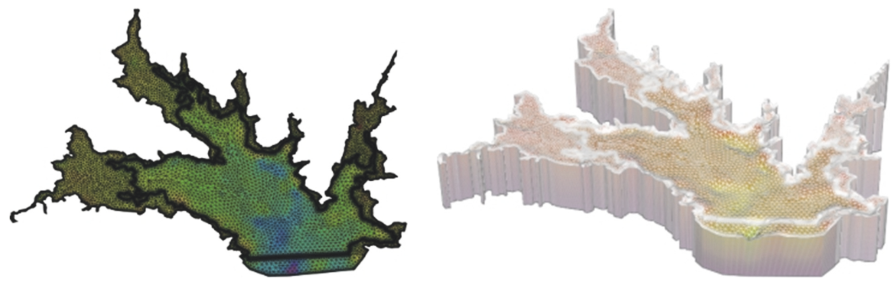
4.2.1. Analytical Solution Results. The lithology of the reservoir area is relatively simple with clay soil predominating. It can be regarded as an aquitard because the underlying bedrock permeability is negligible and the clay bed is nearly horizontal. The groundwater banked-up level of each

Table 3: Calculation of groundwater banked-up levels at different positions on the bank slope after reservoir impoundment (normal water level: 42.5 m).

Name of profile	Distance from reservoir water level 42.5 (m)	Ground elevation (m)	Ground elevation before storage (m)	Ground elevation after storage (m)	Groundwater banked-up level (m)
Guoxiaowei	0.00	42.50	41.00	42.50	1.50
	50.00	42.80	41.15	42.70	1.55
	100.00	43.16	41.31	42.75	1.44
	150.89	43.61	41.53	42.83	1.30
	200.00	44.02	41.95	42.99	1.04
	213.26	44.23	42.16	43.035	0.879
	384.60	45.81	43.56	43.56	0.00
Mengyan (left bank)	0.00	42.50	42.03	42.50	0.48
	50.00	43.19	42.25	42.76	0.51
	80.00	43.60	42.39	42.86	0.48
	83.40	43.68	42.41	42.901	0.795
	168.88	44.21	42.98	43.014	0.036
	180.68	44.28	43.15	43.15	0.00
Mengyan (right bank)	0.00	42.50	41.88	42.50	0.62
	50.00	43.05	42.07	42.65	0.58
	98.91	43.58	42.21	42.80	0.59
	100.00	43.59	42.26	42.81	0.55
	150.66	44.13	42.36	42.9593	0.579
	150.00	44.14	42.35	42.94	0.59
	282.78	44.78	43.21	43.21	0.00
Dongfangcao	0.00	42.50	42.27	42.50	0.23
	50.00	42.79	42.41	42.69	0.28
	70.00	42.90	42.46	42.76	0.30
	209.08	43.55	42.82	42.82	0.00
	277.08	43.78	42.94	42.94	0.00
	334.01	44.29	43.07	43.07	0.00
Qigang	0.00	42.50	42.08	42.50	0.42
	20.00	42.74	42.31	42.71	0.40
	36.75	42.95	42.50	42.88	0.38
	80.65	43.49	43.00	43.00	0.00
Xiaomiaochen	0.00	42.50	42.33	42.50	0.17
	30.00	42.57	42.42	42.56	0.14
	50.00	42.63	42.45	42.60	0.15
	57.83	42.65	42.50	42.62	0.12
	121.07	43.09	42.76	42.76	0.00

borehole could be calculated using (3). Table 3 shows the calculated groundwater banked-up level according to the measured water level before and after reservoir impoundment at each investigation profile in the reservoir area. The data indicates that groundwater banked-up levels in the Guoxiaowei, Mengyan (left river), Mengyan (right river), Dongfangcao, Qigang, and Xiaomiaochen are 0~1.55 m, 0~0.51 m, 0~0.62 m, 0~0.3 m, 0~0.42 m, and 0~0.17 m, respectively. Compared to the normal water level of 42.5 m in the study area, the maximum rises in groundwater are 1.06 m, 0.65 m, 0.71 m, 0.31 m, 0.5 m, and 0.12 m, respectively.

4.2.2. Numerical Calculation Results. The coordinate origin for area calculation was set at the central position of the project area. The positive direction of the y-axis is northwards, the positive direction of the x-axis is eastwards, and the positive direction of the z-axis is upwards. As shown by Figure 6, the study area was discretised into 51,001 nodes and



(a) Plan view (b) Three-dimensional view

Figure 6: Meshing graph of study area based on a numerical method.

Figure 7: Groundwater contours with a reservoir water level of 42.5 m.

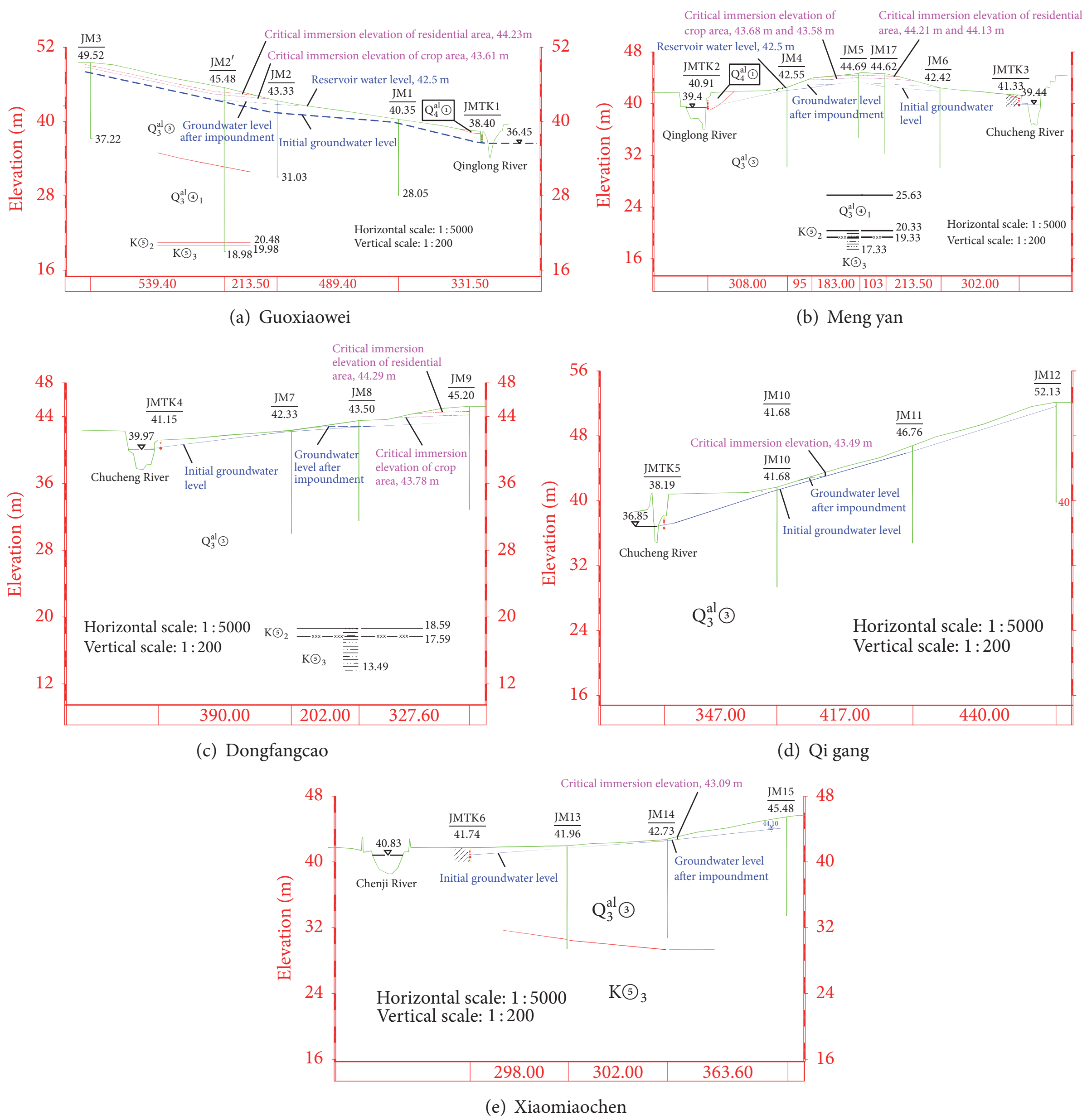
57,860 elements considering one layer in the vertical direction. It is a relatively independent hydrogeological element in the study area. The groundwater flows from the surrounding area to the reservoir area. The hydraulic head boundary is the external boundary derived from interpolation of measured groundwater levels. The normal water level is 42.5 m and was set as an internal boundary. The upper boundary is a rainfall infiltration and evaporation boundary while the bottom is an impermeable boundary at bedrock. The contour of groundwater level, with the reservoir water level at 42.5 m, is shown in Figure 7.

The numerical results show that the groundwater banked-up level is 0.09~1.53 m compared with the initial groundwater level. Groundwater levels are 0.32~0.56 m higher than normal groundwater levels in surrounding areas with a mean value of 0.41 m. Compared with analytical results, the relative errors in the numerical method for five chosen profiles are 1.4%, 2.8%, 4.6%, 2.2%, and 5.1% respectively. The numerical results match the analytical values. It is noticed that the analytical method based on (3) has not considered the effect of soil permeability; however, the numerical method based on (4) involves the hydraulic conductivity. The analytical formula assumed that groundwater will fill the zone between present reservoir water levels and those after reservoir impoundment; therefore, calculated groundwater levels from the analytical formula are a little greater than those obtained numerically. The analytical values are the maximum calculated groundwater level. Finally, the range of immersion influence was determined by the analytical values with the reservoir water level at 42.5 m.

4.3. Determination of Immersion Influence Scope in the Reservoir Area. Three factors, groundwater banked-up level after reservoir storage, capillary rise height of soil, and safety margins for crops and residential areas, were taken into consideration to determine the range of immersion influence on the reservoir area. The capillary rise height of soil, safety margin for crops, and residential areas have been discussed, and the critical value of groundwater level depth was also determined, that is, 0.78 m for cropped areas and 1.2 m for residential areas. Consequently, the range of the immersion zone was determined in conjunction with the banked-up level of groundwater (Figures 8 and 9).

The initial groundwater level, groundwater level with a reservoir normal water level of 42.5 m, critical groundwater immersion level in cropped areas, critical groundwater immersion level in residential areas, and ground elevation line are illustrated in Figure 8. A normal water level of 42.5 m, normal reservoir storage water level of 43 m, the reservoir scope line, farmland line 43.5 m, and resettlement line 44 m are included in Figure 9.

The immersion elevation in crop and residential area can be obtained according to the intersection point of two lines of stable groundwater level in Figure 8 and critical groundwater depth in cropped and residential areas (Table 3). For profiles at Qigang and Xiaomiaochen, the measured burial depth of groundwater level is small. There was already some immersion before considering reservoir storage. The field investigation also indicated that, due to the low permeability of the soil, it was easy to cause obvious capillarity in residential areas through the accumulated water after rainfall (Figure 10). Thus, the zone of immersion influence for these two profiles was ground elevation at the position where there was no obvious groundwater banked-up. It is the same approximation that was made in cropped and residential areas (Table 3). Although there is some immersion under natural conditions, groundwater levels rise to some extent after reservoir impoundment. As shown in Figure 3, immersion influence elevations in cropped areas (farmland) range from 43.09 m to 43.78 m and the mean value is 43.54 m. In residential areas, it is 43.09 m~44.29 m with a mean value of 43.91 m. Immersion influence elevation in cropped areas



(a) Guoxiaowei (b) Meng yan (c) Dongfangcao (d) Qi gang (e) Xiaomiaochen

Figure 8: Profiles of zone of immersion influence at a normal water level of 42.5 m.

and residential areas is slightly higher than the farmland line (43.5 m) and resettlement line (44.0 m).

The zone of immersion influence in the reservoir area could be calculated according to the immersion elevation (Figures 8 and 9), which is the horizontal distance to reservoir normal water level, 42.5 m: in cropped and residential areas it is 80.65 m~277.08 m and 80.65 m~334.01 m, respectively (Table 4).

Immersion elevations in reservoir areas are shown in Table 4. The distances from the immersion zone to contours at 43.5 m and 44.0 m were calculated based on different resettlement lines at 43.5 m and 44.0 m in cropped and residential areas, respectively (Table 5). Distances to Guoxiaowei, Mengyan, and Dongfangcao districts are beyond the contour lines of 43.5 m and 44.0 m, but distances to profiles at Qigang and Xiaomiaochen are within the 43.5 m and 44.0 m contours. The signs "−" and "+" are used to represent the distance within and beyond the 43.5 m and 44.0 m lines, respectively. Consequently, the immersion elevation of cropped and residential areas is slightly higher than that of farmland (43.5 m) and residential resettlement (44.0 m).

5. Conclusions

According to geological and hydrogeological conditions, the zone of immersion of a reservoir was determined using an analytical equation and a numerical method. The capillary rise height was calculated by a modified equation, which

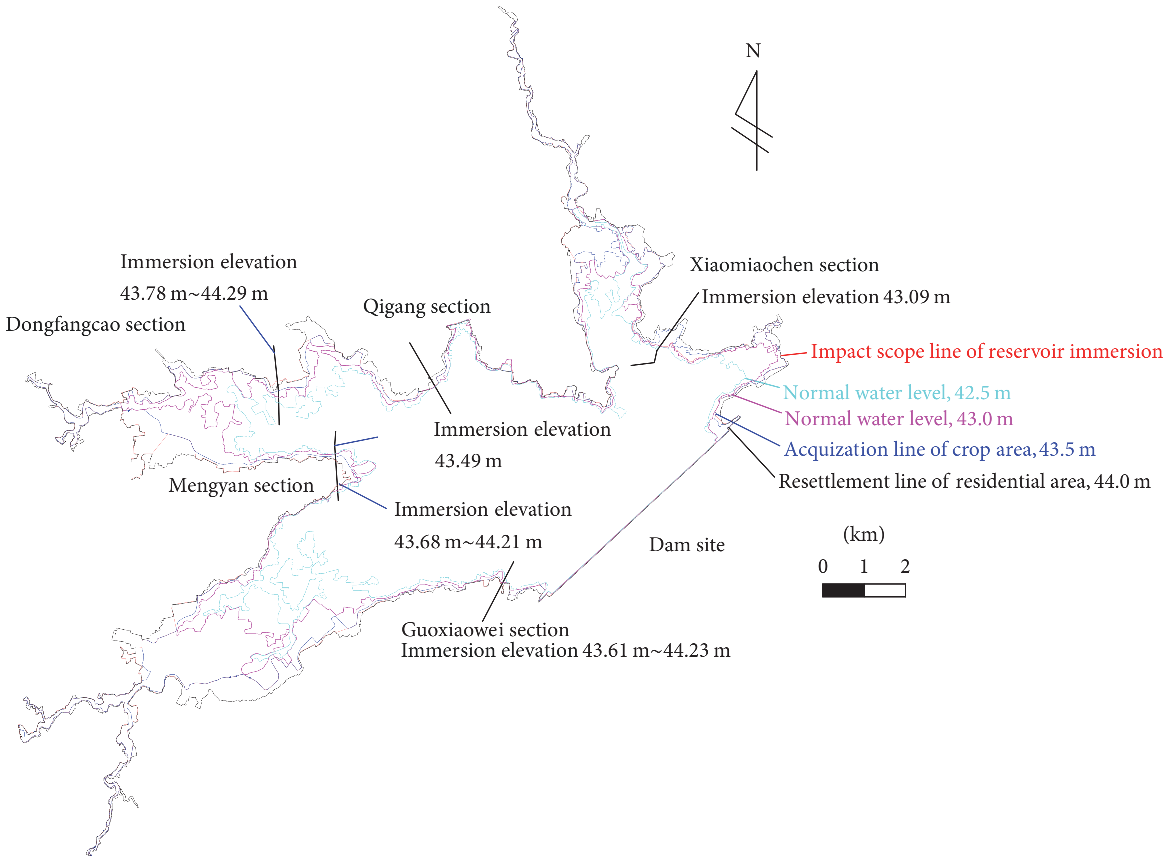


FIGURE 9: Plan view of range of immersion influence at a normal water level of 42.5 m.

TABLE 4: Immersion zone and corresponding maximum elevation after reservoir storage.

Name of profile	Study object	Impact scope (m)	Maximum of elevation (m)	Groundwater level before storage (m)	Groundwater level after storage (m)	Groundwater level banked-up value (m)
Guoxiaoyu	Crop area	150.89	43.61	41.53	42.83	1.30
	Residential area	213.26	44.23	42.16	43.03	0.87
Mengyan (left bank)	Crop area	83.40	43.68	42.41	42.90	0.49
	Residential area	168.88	44.21	42.98	43.01	0.03
Mengyan (right bank)	Crop area	98.91	43.58	42.21	42.80	0.59
	Residential area	150.66	44.13	42.36	42.93	0.57
Dongfangcao	Crop area	277.08	43.78	42.94	42.94	0.00
	Residential area	334.01	44.29	43.07	43.07	0.00
Qigang	Crop area	80.65	43.49	43.00	43.00	0.00
	Residential area	80.65	43.49	43.00	43.00	0.00
Xiaomiaochen	Crop area	121.07	43.09	42.76	42.76	0.00
	Residential area	121.07	43.09	42.76	42.76	0.00

considered the initial hydraulic gradient for clay. It is more reasonable than the formula from the Engineering Geology Manual for sandy soils. Groundwater level was calculated using the analytical and numerical methods after reservoir impoundment. The numerical results matched the analytical values. Calculated groundwater levels for analytical formula are little higher than that for numerical solution. The analytical values are the maximum calculated groundwater levels. For security, groundwater levels calculated by the analytical method were selected to determine the immersion zone.

Figure 10: Photos showing immersion of residential buildings in the Qigang and Xiaomiaochen.

Table 5: The distance between the immersion zone and the 43.5 m and 44.0 m contours.

Immersion position	Guoxiaowei	Mengyan (left bank)	Mengyan (right bank)	Dongfangcao section	Qigang section	Xiaomiaochen section
Distance to 43.5 m contour line (cropped area)	+12.08	+11.03	+7.73	+20.47	−0.5	−44.51
Distance to 44.0 m contour line (residential area)	+24.81	+59.19	+13.90	+35.23	−41.05	−125.09

The results indicated that immersion elevations in cropped areas (farmland) range from 43.09 to 43.78 m with a mean value of 43.54 m. Immersion elevations in residential areas range from 43.09 to 44.29 m with a mean value of 43.91 m. Thus, immersion elevations in cropped and residential areas are slightly higher than the farmland line (43.5 m) and residential resettlement line (44.0 m). The size of the immersion-affected zone, in the horizontal direction, for cropped and residential areas could be obtained according to the immersion elevation in the reservoir area, and it ranges from 80.65 to 277.08 m and from 80.65 to 334.01 m, respectively. This work can provide a scientific basis for the relocation of people in reservoir areas, the planting of crops, and project investment decisions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was financially sponsored through a Qing Lan Project of Jiangsu Province (Grant no. 2016B16073).

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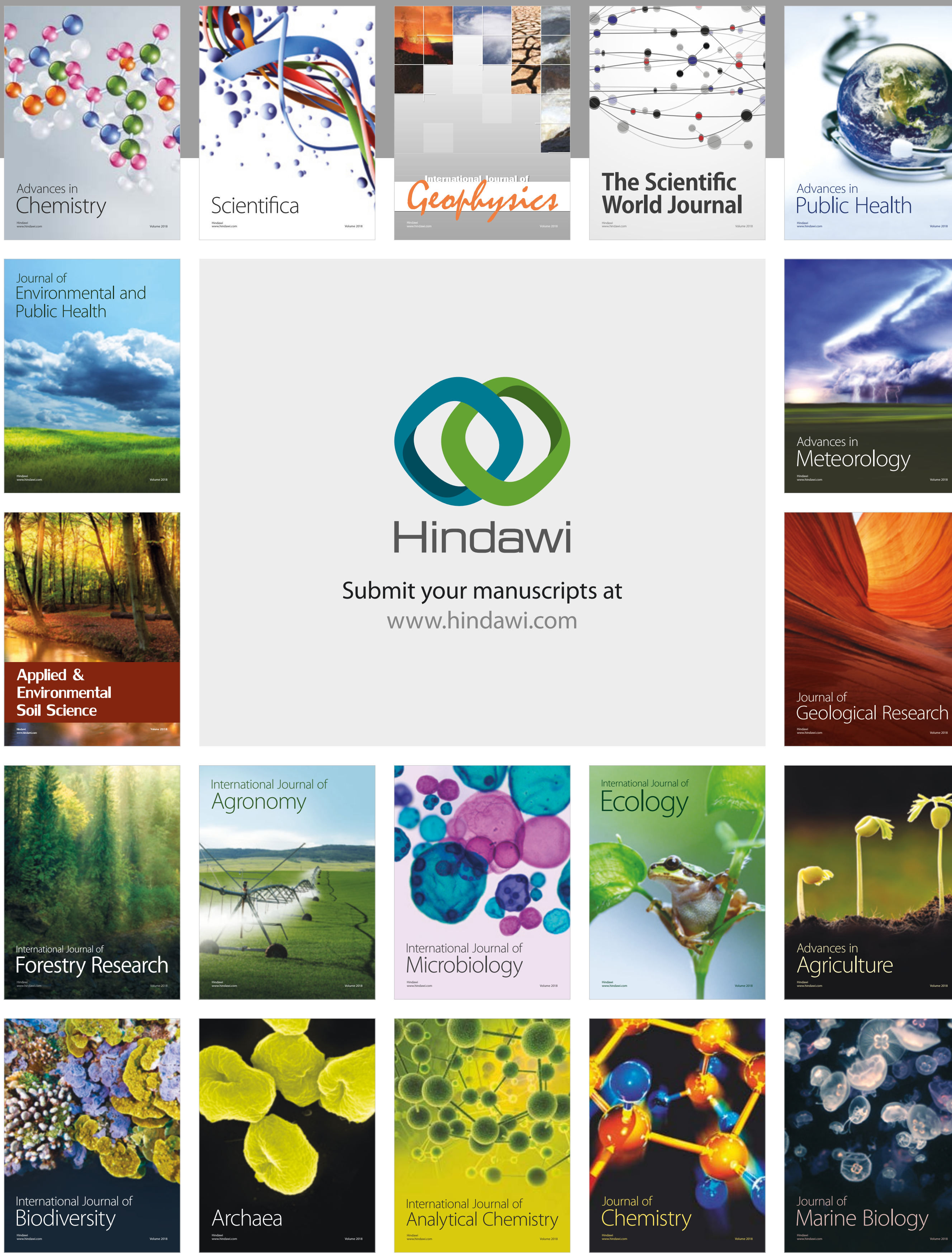
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