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Effects of Water-Level on Water Quality of Reservoir in Numerical Simulated Experiments

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There are many factors that affect the quality of reservoir water, one of the direct factor is water level of reservoirs. To quantitatively study the water quality in different water level of a source water reservoir, numerical simulation was carried out. Firstly, the reservoir hydrodynamic-water quality model was developed, and verified by the field data from reservoir administration. Then the models were used to predict the impact of water-level change on the water quality. The simulation results showed that at low water-level pollutants dispersal ability decreased, and increased at higher water-level. At low water-level, the contents of TN and TP were higher, compared with higher water-level condition, in water body of the reservoir. The simulation results have theoretical and practical significance for evaluating water quality impact of lowered water-level operation and water quality protection of reservoirs.

1. Introduction

Each year, lakes and reservoirs go through wet season, mean water season and dry season, due to the impact of rainfall and runoff, and the water-level of lakes and reservoirs appear the seasonal changes. Studies about the change of water quality and water temperature induced by this have been numerous reports (Wang et al., 2005). Water reservoirs always work under manual intervention. Before the flood season is coming, the water-level will be lower. Due to the reduction in runoff, at the dry season, in order to protect the water supply the discharge flow will stop (Xu, 2008). Reduce reservoir levels, on the one hand, flow velocity will increase and the migration of pollutants diffusion capacity enhancement; on the other hand, the amount of water reduced, and pollutants residence time is shortened in the reservoir, the amount of degradation is reduced, the amount of degradation of pollutants reduced too. If the pollution load inflow is content, the discharged water quality will change after lowering the reservoir level (Kourgialas et al., 2010).
Currently, the study on the effect of water quality of reservoir work with low water-level often adopts prototype observation method (Soon et al., 2010). The results of prototype observation are difficult to guide the development of water quality protection measures during the low water level. Prototype observation is usually conducted to select several representative cross-section, monitoring has a certain time interval, the distribution and variation of water quality of the reservoir cannot be revealed continuously and comprehensively.
The advantage of numerical simulation study are high efficiency, low cost, whit out Scale effect and can predict the water quality distribution and change law in detail (Du et al., 2015).

1.1 Overview of the study area

Reservoir catchment area are 460 $km^{2,}$ with a total capacity of 235 million m^3, the surface area are 14 km^2 (Figure 1), daily water supply capacity is 1 million m^3/day.
There are three main river empties into the reservoir, namely SJ river, WH river and WB river, reservoir inflow accounted for 75.4%, 13.3% and 4.5%, of the total respectively. Monthly distribution of water of the reservoir generally exhibit large, medium and small flood peak. Large peaks occur in June, because of plum rains, medium peak occurred in September, because of a typhoon, smaller peak occurred in March, because of spring rain. Dry season is between October to next February.

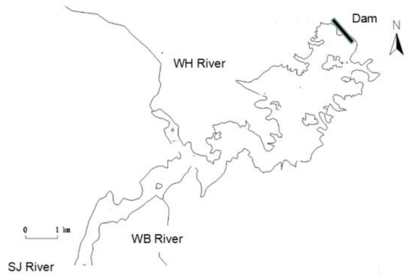


Figure 1: The planform of The reservoir

2. Section headings

2.1 Hydrodynamic equations

The hydrodynamic model of MIKE 21 follows the Navier-Stokes equations. Respect two-dimensional models, which mainly consider that the change of hydraulic parameters in the planar direction is much larger than the vertical change, so the three-dimensional depth of the water body integral equations to obtain two-dimensional shallow water power equations. Thus, the three-dimensional depth of the water body integral equations to obtain two-dimensional hydrodynamic equations equations (Ye et al., 2013).
The HD module is composed of control equations of conservation of mass and momentum equations.
Mass conservation equation:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=\frac{\partial d}{\partial t} \tag{1}$$

x- momentum equation:

$$\begin{aligned}&\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial x}+\frac{gp\sqrt{p^2+q^2}}{C^2\cdot h^2}\\&-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}\left(h\tau_{xx}\right)+\frac{\partial}{\partial y}\left(h\tau_{xy}\right)\right]-\Omega\cdot q-f\left(V\right)\cdot V\cdot V_x+\frac{h}{\rho_w}\frac{\partial}{\partial x}\left(p_a\right)=0\end{aligned} \tag{2}$$

y-momentum equation:

$$\begin{aligned}&\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+gh\frac{\partial \zeta}{\partial y}+\frac{gq\sqrt{p^2+q^2}}{C^2\cdot h^2}\\&-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}\left(h\tau_{xy}\right)+\frac{\partial}{\partial y}\left(h\tau_{yy}\right)\right]+\Omega\cdot p-f\left(V\right)\cdot V\cdot V_y+\frac{h}{\rho_w}\frac{\partial}{\partial y}\left(p_a\right)=0\end{aligned} \tag{3}$$

Where *x* and *y* are spatial coordinates(m); p_a is atmospheric pressure(Pa); ρ_w is the density of water(kg/m^3); *t* is time(s); *C(x,y)* is Chezy coefficient(m$^{1/2}$/s); *g* is gravity (m^2/s); *ζ(x,y,t)* is water level(m); *Ω(x,y)* is Coriolis oefficient, according to the latitude (s-1);*h(x,y,t)* is water deep(m), the value is equal to ζ minus *d*; *d* is water deep(m), which changes over time; *p,q(x,y,t)* is respectively unit width discharge *x, y* direction; and *p=u·h*, *q=v·h*; *u* is the average velocity of the vertical direction *x*; *v* is the average velocity of the vertical direction *y.f(V)* is wind friction coefficient; *V, Vx, Vy* are wind sped and its components in the *x, y* direction; $\tau_{xx},\tau_{xy},\tau_{vv}$ are Component of the effective shear stress in all directions.

2.2 Convection diffusion equation

MIKE 21 convection diffusion module to be applicable to simulation of suspended matter and soluble substances in the water convection diffusion process, also can set a constant attenuation coefficient to simulate the non-conservative matter of constant attenuation process can be used in simple water function division and water environment capacity calculation.
The model does not include the atmospheric oxygen process and the heat radiation calculation. The model is based on the hydrodynamic model, and the convection diffusion equation is used to simulate the calculation.
Model equation:

$$\frac{\partial\left(h\bar{C}\right)}{\partial t}+\frac{\partial\left(hv\bar{C}\right)}{\partial x}+\frac{\partial\left(hv\bar{C}\right)}{\partial y}=\frac{\partial}{\partial x}\left(hD_x\frac{\partial \bar{C}}{\partial x}\right)+\frac{\partial}{\partial y}\left(hD_y\frac{\partial \bar{C}}{\partial y}\right)-hk_p\bar{C}+hC_sS \tag{4}$$

Where c is the average concentration of pollutants in the vertical direction(mg/L); Dx, Dy is diffusion coefficients for X and Y directions, respectively(m/s^2); u and v are the flow velocity component along the X, Y direction, respectively; h is water deep(m); Cs is the source/sink((g/m^2/s); Kp is Biochemical reaction term.
For the attenuation of the equation, it is generally based on the attenuation characteristics of the concrete simulation material (Zhao et al., 2002). Many pollutants in water quality simulation can be considered to be in accordance with the first order kinetic reaction law.

$$C = C_0 \exp(-k_c t) \tag{5}$$

Where C_0 is Concentration of pollutants in the water at the initial time(mg/L); K_C is degradation coefficient of pollutant(d^{-1}); t is reaction time(d); C is concentration of pollutant in water in t time.

2.3 Grids division

According to the on-the-spot measured maps(1:5000), a digital map of the reservoir is obtained. There are few measured elevation data in reservoir area. In order to obtain the original terrain data in the reservoir area, in the study, based on the known point elevation data crick interpolation was adopted to generate more detailed reservoir height data. Finally, the data of scatter plots and boundary maps are produced for unstructured terrain file.

3. Model calibration and verification

3.1 Hydrodynamic model calibration and verification

The model parameters are according to the dam water level data of 2010, preliminary determination bed roughness and eddy viscosity coefficient, model validation by the dam water level data of 2011. analog and measured water level of hydrodynamic module rate in calibrated period and verification period was shown in Figure 2 and Figure 3.

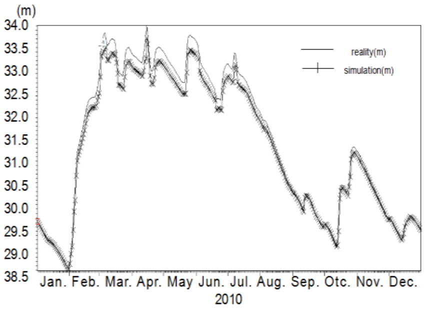


Figure 2: The measured and simulation water level in Calibration period

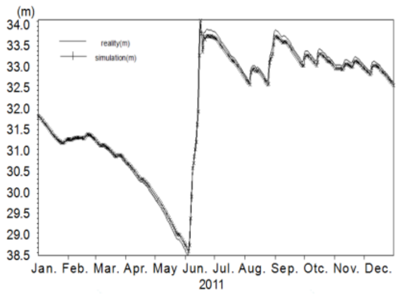


Figure 3: The measured and simulation water level in verification period

As shown above the chart that the calibration and validation results of model are better, and the measured data and simulation results of pool level has a good consistency. Analysis of the relative error in the range of 2.78% -0.09%. The linear regression equation of analog value and the measured value: y = 1.078x-2.299, where the correlation coefficient is 0.989, overall well fitted to meet the requirements of model calculations. Causes of error may be: (1) there is no wind farm in the model, ignoring the effect of wind on the surface of the water reservoir; (2) capacity error caused by the error of the terrain. Thus the difference between the measured value and analog value is large at the specific times. But the overall trend consistent, and the result can accurately reflect the interannual variability of reservoir water level. The results of calibration and verification show that the hydrodynamic model has high reliability, and the simulation results can reflect the hydrodynamic characteristics of the Reservoir.

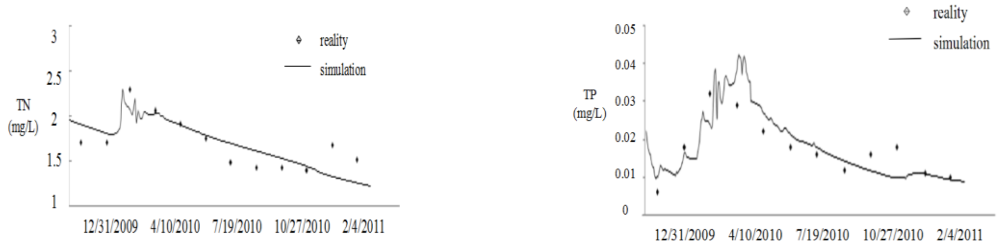
3.2 Hydrodynamic- water quality model calibration and verification

Water quality model calibration using the dam daily water quality data of 2009-2011, including the content daily of water nitrogen and total phosphorus, the reservoir management agency provide the data. Running the water quality model and verify it after Calibrating the main parameters of the model (Table 1).

Table 1: Water quality model parameter calibration results

parameter	diffusion coefficient in x direction (m2/s)	diffusion coefficient in y direction (m^2/s)	TN attenuation coefficient(1/d)	TP attenuation coefficient(1/d)
Value	1.0	1.0	0.01728	0.07776

Model validation results showed that the analog value is close to the actual value of TN and TP,basically meet the requirements of the model, meaning the selection of the parameters is right. Verification results shown in figure 4.



a: TN validation results

b: TP validation results

Figure 4: model validation results

Verification results show that the relative error of the content of simulated and measured values of total nitrogen in the water is in the range of 13.3% to 3%, and the average error is 8.7%; total phosphorus content of simulated and measured values of the relative error in the range of 14.9% to 5%, and the average error is 10.9%. This shows that the choice of parameters is reasonable, meetting the needs of the model calculations.

3.3 Simulation conditions set

Historical Statistics of hydrological data show that it is middle year in 2010 for the reservoir, and the reservoir hydrological characteristics can representative of normal hydrological characteristics, so choose the low, middle, and high water level in the reservoir of this year to study and simulate the distribution of pollutants carried by rivers in the reservoir area. The average content of choice during the spring flood in May that year is selected as the contaminants of pollutants from in flowing according to water quality monitoring data. The contaminants of pollutants in WH Creek are: TN,1.81 mg/L, TP, 0.019 mg/L; And the contaminants of pollutants in SJ Creek are: TN,1.94 mg/L, TP, 0.04 mg/L. The analog last for 1 month. Water level and in / out flow of the reservoirs select the actual data of the year (Table 2).

Table 2: Three running conditions

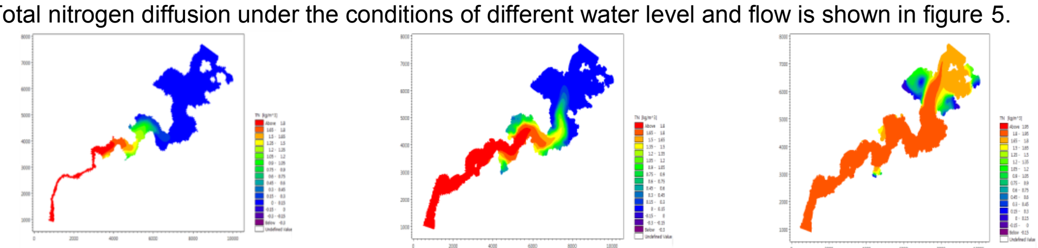
Water level	Inflow(m^3/s)	Outflow(m^3/s)	Water level (m)
Low Water level	2.12	10.69	24
Middle Water level	25.89	7.93	28.52
High Water level	185.4	173.7	33.5

4. Results and discussion

4.1 Results analysis

4.1.1 TN diffusion under different water level conditions

Total nitrogen diffusion under the conditions of different water level and flow is shown in figure 5.



a: Low water level

b: Middle water level

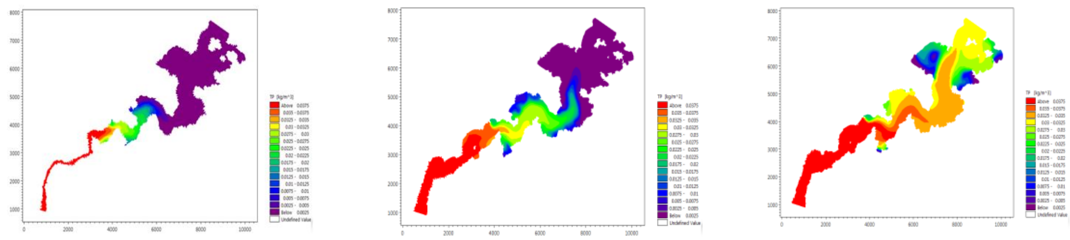
c: High water level

Figure 5: Distribution of TN diffusion under different water level

The simulation results show that the diffusion scale of the total nitrogen in water in the reservoir is different because of the difference of running water level and flow. When the reservoir is running in low water level, Both the flow and flow rate are small, so the area of the total nitrogen diffusion is only in a small place concentrated in the reservoir head. The content of total nitrogen in river and reservoir head is higher than that in the main reservoir area and front of the dam where not been affected. While during the period of high water level running, the flow is bigger and all of the flow rate, the speed of water-exchange, and total nitrogen diffusion are faster, total nitrogen had diffusion to the front of the main reservoir and dam location, even the content of total nitrogen in water has increased except the the wing of the main reservoir where affected littled by the total nitrogen diffusion due to the restrict of hydraulic conditions (figure 5-c). And during the middle water level running period, total nitrogen diffusion is heavier than than during the low water level, the diffusion has just entered the main reservoir and the water in the front of the dam are affected is still very small. Overall, the diffusion condition is between that in low and high water level.

4.1.2 TP diffusion under different water level conditions

Total phosphorus diffusion under the conditions of different water level and flow is shown in figure 6.



a: Low water level b: Middle water level c: High water level

Figure 6: Distribution of TP diffusion under different water level

The characteristic of the total phosphorus diffusion is similar to the total nitrogen in the water, which the diffusion scale is the smallest during low water level, i.e only occurred in the late in the reservoir head; The diffusion scope expanded to the middle of the reservoir during the middle water level, and spread into the main reservoir, influentting the location before dam during the high water level.

So, the rule of diffusion such as nitrogen and phosphorus pollutants was equal under different conditions of water level and flow. Pollutants came into the reservoir from the SJ /WH stream, constantly elapsed from the southwest to northeast with the flow, and the pollutant concentration gradually reduced along with the development of the diffusion. The pollutant diffusion is slow and influence scope is small when the reservoirs in the low water level operation. The pollutant could not spread into the main reservoirs when in low and middle water level. While during the high water level period the polluent will spread into the front of the dam due to the large flow, but there is local circulation area in the main reservoir because of the reservoir area of the terrain to make cross-sectional wide on both sides which made the contents of nitrogen and phosphorus small on both sides of the main reservoir.

4.2 Discussion

According to the diffusion of pollutants mentioned above, it can be found that with different water level and operation conditions, pollutants came into reservoir from WH River and SH River, and then began to migrate and spread. Pollutant dispersion trends is all along with the direction of the water flow to the main reservoir area before the dam. The diffusion range expanded. In this process, due to dilution and degradation, the concentration of pollutants decreased continuously. The result of diffusion distance and influence scale of the pollutants, after a month simulation, under different water level and operation conditions, is shown in table 3.

From the analysis, migration and transformation of pollutants in the reservoir is not only related with the water level but also related with the operation of reservoir. In the high water level, because of the larger flow, faster flow velocity and stronger water turbulence, which one hand help to dilute and degradate the pollutants, on the other there is not enough time for the pollutants to break down because of the faster flow rates, but quickly reach the dam water intake and thus threat the water security. When the low water level in the reservoir is running, inbound and outbound traffic is small, the water flow rate decreases and slower diffusion of pollutants, so there is plenty of time for pollutants to self-purification degradation, thus the water quality in reservoir and source would not be impacted heavily. However, the long residence time and slow water flow rate during low water level is conducive to blooms of algae, which increases the risk of water bloom. When the middle water level, although diffusion of pollutants range has increased, but the pollutants also be partially diluted and degraded when during it’s migration and diffusion process, which had little effect on water quality, and water safety can be guaranteed. Therefore, the reservoir running in middle level is most safe and reasonable.

Table 3: Diffusion range of pollutants

Working condition		Migration distance(m)	Scope of Influence(km^2)	Intake contaminants(mg/L)
Low water level	TN	5000	1	0
	TP	6000	1.2	0
Middle water level	TN	8000	3.2	0
	TP	9600	3.5	0
High water level	TN	12000	14	1.65
	TP	12000	14	0.031

5. Conclusion

Hydrodynamic model and water quality model of a Drinking water reservoir based on MIKE 21 software are established. The model is calibrated and validated with the data of hydrology and water quality of the reservoir. The simulation results are consistent with the actual data. It shows that the model can be applied to the simulation of the diffusion of pollutants in the reservoir.

The model was used to study the migration and diffusion of the total nitrogen and total phosphorus in the water flow under different water levels and the inflow / outflow. It found that, in the low water level and the corresponding to the inflow / outflow, the diffusion range of total nitrogen and total phosphorus is the least. In the higher water level, total nitrogen and total phosphorus diffusion reached the maximum. In the ordinary water level, the diffusion range is between the above two. In order to ensure the safety of water supply, and makes full use of the reservoir, the optimal selection is that reservoir works in the ordinary water level.

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