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Numerical Simulation Study on Water Quality of a Pumped Storage Reservoir in Arid Region

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Abstract: The reservoir is very important in the arid region for water supply. It is of great significance for reservoir management and local economic development that ensuring the water quality safety. To make a quantitative research on migration-diffusion rules of contaminant in the reservoir, a numerical simulation on water quality of a reservoir in the arid region was studied. Taking Yazidang Reservoir as an example, three-dimensional hydrodynalic and water quantity model were constructed. And the model was validated with monitoring data. Utilizing the model, a research on migration and diffusion of COD and ammonia nitrogen and the distribution of water concentration when the reservoir is at different operative conditions was carried out. The results show: the diffusion of COD and ammonia nitrogen in Yazidang Reservoir is depended on flow field. And the migration and diffusion of contaminants vary in area when the reservoir is filling with water, specifically, the farther away from the inlet the affection by filling is lag.The change of contaminant concentration is small and the contaminant has seen a decreasing trend when the reservoir is not filling with water. So it is very important to ensuring the water supply quality of Yazidang Reservoir and the time of filling water should be set in light of its conditions.

Keywords: *arid region, pumped storage reservoir, water quality, numerical simulation*

1. Introduction

Yazidang Reservoir is the water source project of the Ningdong Energy Resources and Heavy Chemical Industry Base in Ninxia, China, which provide production, living and ecological water for Ningdong area. It serves as a controlling project for water supply in Ningdong area. With little rainfall, the area has an average evaporation capacity of 2,000 mm. The main source of the reservoir water is the Yellow River. Ensuring the water quality of Yazidang Reservoir is a prerequisite for reaching the standard of quantity and quality of the water supply in Ningdong area.

There are a large number of researches, at home and abroad, on water quality of lakes and reservoirs. Now domestic researches on water quality simulation and its application mainly focus on six major lakes and three key reservoirs [1]. Zhu Yongchun [2] made a simulation on horizontal and vertical distribution of lake current in Meiliang Bay of Taihu Lake. Zhen Binghui [3] and Liu Yusheng [4] improved the ecological dynamic model of the Dianchi Lake, they made a simulation on variation of water quality indexes like TN and TP throughout a year. Tu yingqing [5] built Chaohu Lake's ecological model, which was used for simulation and forecast of changes in ecosystem health of the lake. Shen,Y.M,Wang,J.H. [6-7] made a simulation study on water quality and retention time of Dahuofang Reservoir, listed both the distribution of various indexes and sensitive factors that influence the water quality of the reservoir. They found that the water conveyance project has limited influence on reservoir water quality. There are few researches concerning water quality of the pumped storage reservoir in the arid region. Therefore, taking Yazidang Reservoir as an example, a simulation on water quality of the pumped storage reservoir in the arid region was studied. Indexes like COD and ammonia nitrogen were choosen to make the numerical simulation in such cases as the reservoir is filling with water and not so as to provide reference for the water quality protection and management.

2. Theoretical Methods

2.1 Model Building

Hydrodynamic model follows Navier-Stoke equation. Mathematical model equations include continuity equation, momentum equation, k equation, ε equation and the contaminant diffusion equation [8-9].

Continuity equation: $$\frac{\partial(\rho U_i)}{\partial x_i} = 0 \qquad (1\text{-}1)$$

Momentum equation:

$$\frac{\partial}{\partial x_i}\left(\rho U_i U_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\left(\mu + \mu_i\right)\left\{\frac{\partial(U_i)}{\partial x_j} + \frac{\partial(U_j)}{\partial x_i}\right\}\right] \qquad (1\text{-}2)$$

k equation:

$$\frac{\partial}{\partial x_i}\left(\rho U_i k\right) = \frac{\partial}{\partial x_i}\left[\left\{\mu + \frac{\mu_t}{\sigma_k}\right\}\frac{\partial k}{\partial x_i}\right] + G - \rho\varepsilon \qquad (1\text{-}3)$$

ε equation:

$$\frac{\partial}{\partial X_i}(\rho U_i \varepsilon) = \frac{\partial}{\partial X_i}\left[\left\{\mu + \frac{\mu_t}{\sigma_\varepsilon}\right\}\frac{\partial \varepsilon}{\partial X_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad (1\text{-}4)$$

Contaminant diffusion equation:

$$\frac{\partial}{\partial X_i}(\rho U_i \varphi) = \frac{\partial}{\partial X_i}\left[\left\{\mu + \frac{\mu_t}{\sigma_C}\right\}\frac{\partial \varphi}{\partial X_i}\right] + \rho S_\varphi \quad (1\text{-}5)$$

$$\mu_t = \rho C_\mu \rho \frac{\varepsilon^2}{\varepsilon}$$

$$G = \mu_t\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right)\frac{\partial U_i}{\partial X_j}$$

In above two equations, i refers to coordinate direction (i=1,2,3), ρ is water density (kg/m^3), U_i (m/s) is the water velocity in i direction, P is pressure, μ is dynamic viscosity coefficient, μ_t is the dispassion rate of turbulence kinetic energy, $\sigma_k, \sigma_\varepsilon, \sigma_C$ are turbulence kinetic energy, the dispassion rate of turbulence kinetic energy and Prandtl number of water quality factors respectively, and their corresponding values are 1.0, 1.3 and 1.0, φ is the mass concentration of water quality factors like DO, CODcr, $C_\mu, C_{1\varepsilon}$ and $C_{2\varepsilon}$ are model constants, their values are determined by the basic experiment, which are 0.09, 1.44 and 1.92 respectively, S_φ is the source item of contaminant diffusion equation.

The attenuation term in the equation is usually determined by the attenuation characteristic of the simulated contaminant. The degradation of many contaminants in the water quality simulation is in line with the first-order kinetics, namely,

$$C = C_0 \exp(-k_c t) \quad (1\text{-}6)$$

In the equation, C0 refers to the contaminant concentration of the water at the initial period, KC is the degradation coefficient of contaminants, t is response time, C is the contaminant concentration of the water at t moment.

The equation set is discretized by the cell-center finite volume method(FVM). The Roe's Riemann solution is used for avoiding numerical oscillation, and the second order TVD limiter is also used.

2.2 Model Configuration

The designed highest water level of Yazidang Reservoir is 1249.5 m. Because the water inflow is much higher than its outflow, the contour line of 1253 m was chosen as the border of the simulate area to avoid the water outflowing during the calculating process. Yazidang Reservoir is a small-size deep reservoir with a small area and an irregular shape. In the paper, the unstructured grid is used for better simulating a complex border of the reservoir, the Delaunay triangulation method is used for generating the triangle mesh in the simulate area[10], which has 11,146 nodes and 21,626 elements, as is shown in the Figure 1. vertically, the reservoir is divided into ten layers on average according to the depth of water, as shown in Figure 2. To better match the topographic change, the inverse distance weighted interpolation is applied to each mesh point and the grid near the reservoir border is densified. Then the topographic map is made as shown in Figure 3. The initial water level is taken as the approximation of the practical initial condition, which set as 1247 m.

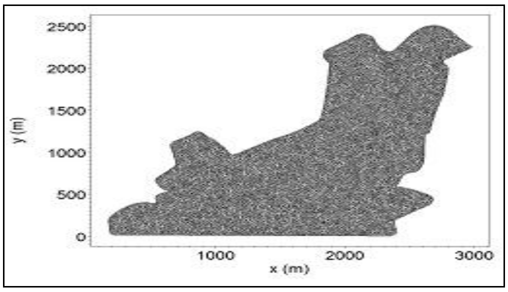


***Figure 1** The simulate section mesh of Yazidang Reservoir*

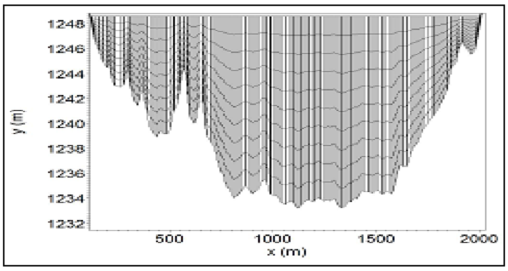


***Figure 2** The vertical mesh of Yazidang Reservoir*

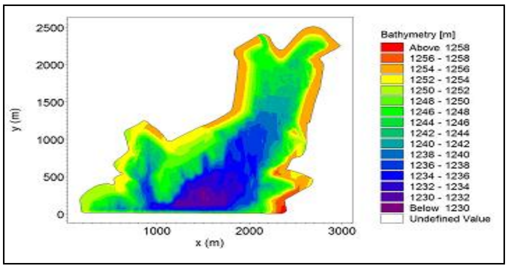
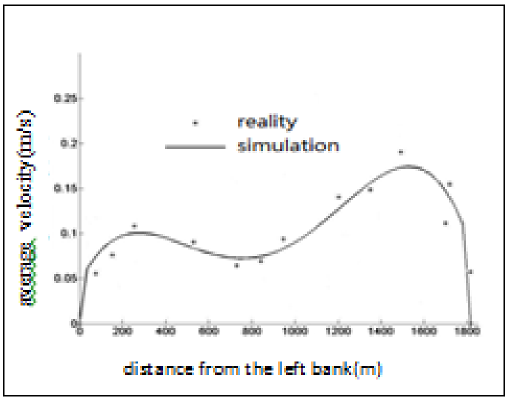
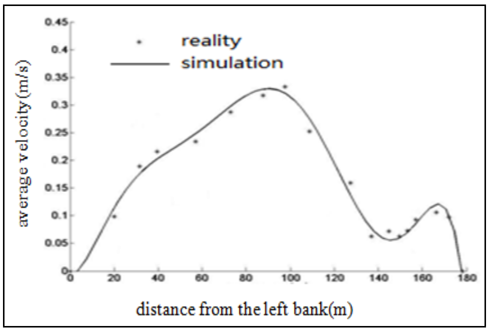


***Figure 3** The simulate topographic map of Yazidang Reservoir*



(4-a) near the water inlet



(4-b) near the water outlet

Figure 4 *The comparison between the measured data and the simulated data of the current velocity*

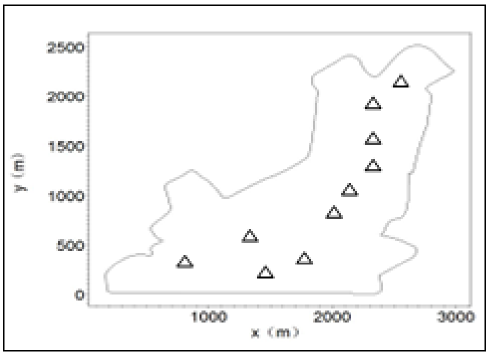


Figure 5 *The distribution of sampling points*

The water quality degradation coefficient of Yazidang Reservoir is acquired via calibration of references[11-12],namely K_{COD}=0.02d^{-1} and K_{NH3-N}=0.006 d^{-1}, and diffusion coefficent is 0.02 m^2/s.

In the simulation, the initial condition is hard to be given according to the measured data, especially the current velocity. Therefore, the water level at the initial moment and the outlet flow are initial conditions during the calculating process. The water level of the inlet is set as 1247 m, the initial current velocity of flow field is zero, which is equal to u, v, w. The outlet flow is 4.63 m^3/s.

The initial condition of water quality can be given by the measured data, and the initial value is acquired from interpolation of the first measured data.

2.3 Model Verification

The flow velocity at two chosen sections near the water inlet and outlet were measured. The verification resluts are shown in Figure 4, which indicate that the measured data is well matched with the simulated data. So model can be applied in Yazidang Reservoir.

There are ten water quality sampling points at Yazidang Reservoir, as is shown in Figure 5. And the main test indexes are COD and ammonia nitrogen. The model is verified according to the practical measured data in 2015. The comparison between the measured data and the simulated data of COD and ammonia nitrogen can be seen in Figure 6-a and Figure 6-b.

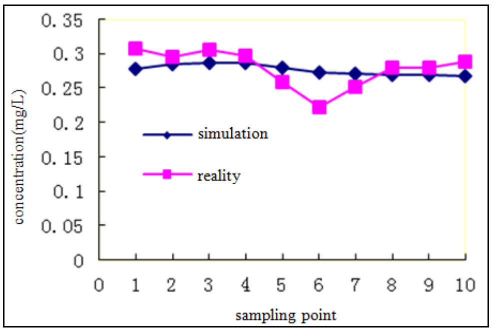


Figure 6-a *The comparison between measured data and simulated data of COD*

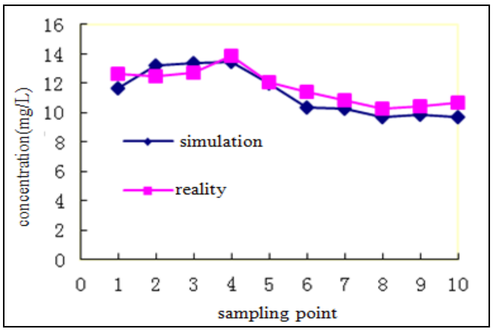


Figure 6-b *The comparison between measured data and simulated data of NH4-N*

Figure 6 shows the verification result of water quality on sampling points. It can be observed that the simulated data and the measured data of COD and ammonia nitrogen are well matched. The relative error range between simulated value and measured data of COD is 0.83% to 9.37%, the average error is 7.54%; and that of ammonia nitrogen are 22.52% to 3.37% and 7.54% respectively. In the result of ammonia nitrogen simulation, a big error of 22.52% is shown in the sixth sampling point. The reason is the sampling point close to the outlet of reservoir, and there is a great difference between the current velocity and the initial one. The error of other points is within 10%, which indicates that the chosen parameter is reasonable and can meet the need of model calculation.

2.4 The Simulation of Working Operative Model

Yazidang Reservoir supplies 400,000 m^3/d water to Ningdong Base, and the amount of filling water of Jinshuiyuan Pump Station can reach 600,000 m^3/d. In the research, the spatial-temporal distribution of flow field and water quality at two working operative models were simulated. When the reservoir is filling water from Jinshuiyuan Pump Station, the inflow of reservoir is 6.95 m^3/s, and the outflow is 4.63 m^3/s, the COD and NH_4-N concentration of inflow are 16 mg/L and 0.3 mg/L respectively. When the reservoir is not filling with water, the inflow of reservoir is 0 m^3/s, and the outflow is 4.63 m^3/s.

3. Results and Discussion

The flow field is the basis of contaminants simulation. The flow field feature at two working operative models in Yazidang Reservoir are shown in Figure 7-a and Figure 7-b.

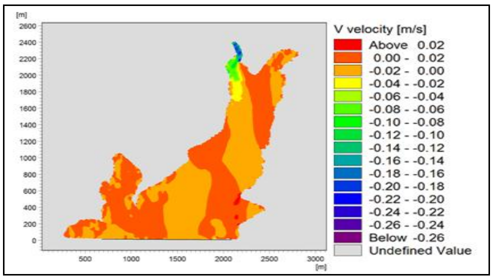


Figure 7-a *The flow field when the reservoir is filling with water*

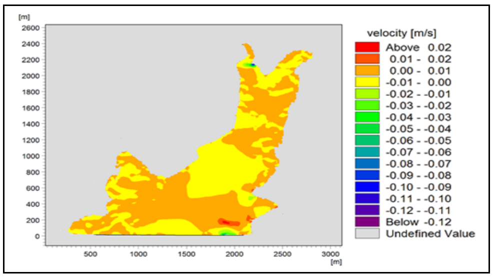


Figure 7-b *The flow field when the reservoir is not filling with water*

3.1 The Diffusion of Contaminants When the Reservoir is Filling with Water

To make a research on the distribution of contaminants in Yazidang Reservoir, point t1 to t5 were choosen to observe the change of water quality as seen in Figure 8.

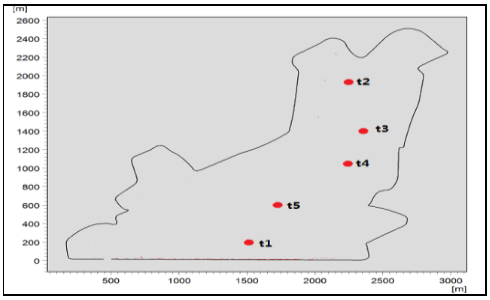


Figure 8 *The chosen points*

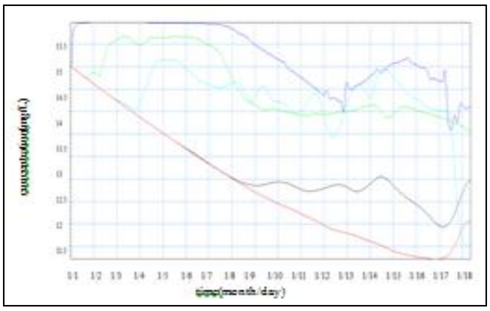


Figure 9 *The changing curve of COD concentration from point t1 to t5. (The terminal changing curves represent t2, t3, t1, t5, t4 respectively)*

It can be seen clearly from Figure 9 that the flow field depends on inflow-outflow current. Because the inlet is at the north of reservoir, Accordingly, the points influenced by the water inlet are t2, t3, t4, t5, t1 in order. The t1 is at the south of outlet, so it shows a decrease trend in the graph before the last part. The contaminant concentration at t5 is rather later influenced by the inflow. Unlike t1, t5 is close to the outlet. According to Figure 7-a, the large velocity in that place may directly influence the contaminant concentration there.

The variation trend of t2 to t4 is almost the same, and t1 and t5 are different from t2 to t4. If the simulation time is longer, the trend may be almost the same. The radical reason is that the main driving force of the reservoir is inflow-outflow current. It takes some time for the water enters the reservoir and then influences the sampling points. Meanwhile, the different velocity distribution in reservior result in the variation of contaminant concentration of different places at a certain time.

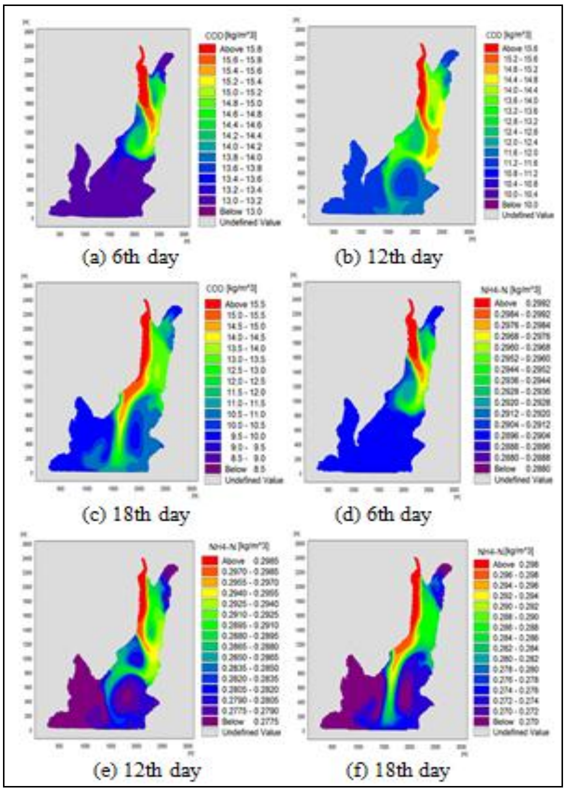


Figure 10 *The Difussion of COD and Ammonia Nitrogen When the Reservoir is Filling with Water*

Figure 10 shows the difussion of COD and ammonia nitrogen at different times. According to the simulation result, the migration and difussion scale of contaminants, including COD and ammonia nitrogen, is different in area of the reservoir, which depends on the water fill time. But as a whole, the difussion trend of COD is basically consistent with that of ammonia nitrogen. The farther away from the inlet, the shorter time for the contaminant is influenced. The velocity is the largest at the area near inlet, so the influence here is the most obvious. As is shown in the figure, there is a long strip depicts of the contaminant concentration between the inlet and outlet. In the southern of the outlet, the contaminant concentration spreads eastward, which is mainly because there is a circulation near the outlet. Radically, the difussion of contaminants is mainly controlled by the flow field of Yazidang Reservoir.

3.2. The Diffusion of Contaminants When the Reservoir is Not Filling with Water

Figure 11 shows the COD and ammonia nitrogen concentration at different times when the reservoir is not filling with water. According to the result, water velocity in reservoir is small because there is only outflow and no inflow. The velocity of area near the outlet is large. And the variation on contaminants concentration is not great at most area. In this working operative model, the distribution of COD and ammonia nitrogen is almost the same. At the last stage of the operation, with well mixed, the contaminant concentration has decreased, which is conducive to improve the water quality. But due to the fact that water level has decreased with time, it is important to consider that whether the health ecological environment can be maintained. Therefore, the lowest water level should be determined. When the reservoir is filling with water, the contaminant concentration will increase, which has a negative effect on the water environment. It is an important work need to be carried out that reasonably determine the time of filling water.

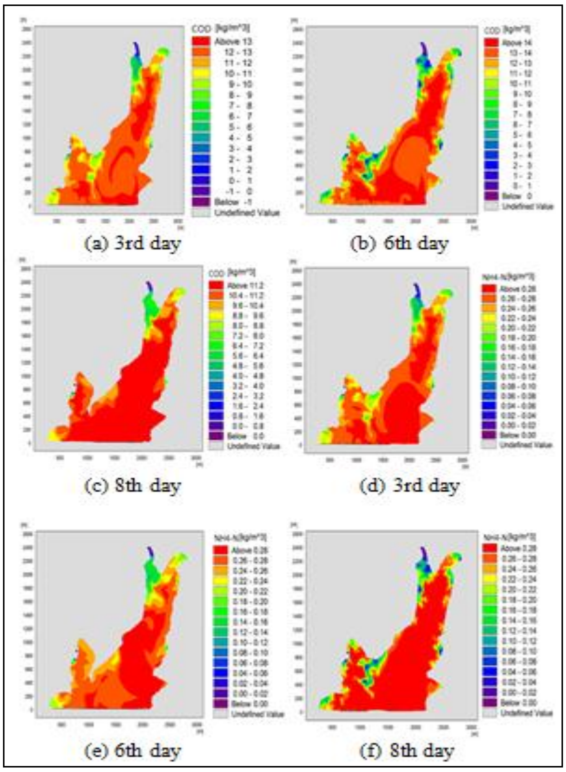


Figure 11 *The difussion of COD and ammonia nitrogen when the reservoir is not filling with water*

4. Conclusion

Three-dimensional hydrodynamic and water quality model is builded with the parameter calibration by measured data. The simulation result is relatively consistent with the practical data, which indicates that the model can be used in the research on migration and diffusion of the contaminant inYazidang Reservoir.

According to the research on migration and diffusion of COD and ammonia nitrogen at two different working operative models, namely the reservoir is filling with water and not, the most critical factor for contaminant migration and diffusion is the reservoir's flow field. The diffusion of COD and ammonia nitrogen is almost the same. When the reservoir is filling with water, the farther away from inlet the later contaminant is influenced. When the reservoir is not filling with water, there is little change in contaminant concentration. Therefore, it is very important for ensuring the water quality of Yazidang Reservoir,and the time of filling water should be set in light of its conditions.

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