Numerical simulation on temperature of water released from multi-level intake of reservoir

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Abstract. In order to reduce the negative effect of lower water temperature released from the intake to the salmon in the downstream of the river, a multi-level intake was adopted in Glen Canyon Dam. Based on three-dimensional numerical model EFDC, this article simulated the water temperature under different discharge and open combination, obtained the effect law of discharge and open combination on temperature of water released. The results show that the temperature released increases slightly with the increase of the single diversion flow rate. The effect on the temperature released is very small when the intake opens in different combinations.

1. Preface
The construction of high dam and large reservoir has obviously promoted the development of social economy, but also inevitably brought a series of negative effects [1]. Large reservoirs exhibit seasonal temperature stratification in the water depth direction. The low temperature water produced by the traditional bottom water abstraction method has low dissolved oxygen content and poor water quality, which will cause a series of downstream environmental problems [2-4]. Therefore, the problem of low temperature water discharged from the reservoir has been highly valued by all parties, and the research on the low temperature water discharged from the high dam reservoir has been continuously strengthened. Multi-level intake as an effective means can alleviate the negative impact of low temperature water discharge on the downstream ecological environment. At present, the Shasta Dam in the United States and the Jinping I Hydropower Station in China have adopted Multi-level intake measures to alleviate the problem of low temperature water discharge.

For the study of numerical simulation of water temperature, most of the predecessors focused on the distribution and variation of water temperature in the reservoir, while the numerical simulation study on the temperature of the reservoir discharge, especially the stratified discharge water temperature, is relatively small. Vermeyen[5] used the one-dimensional Select model developed by the US Army Corps of Engineers Waterway Test Station to study the water intake effect of the Hungry Horse hydropower station, but the model error is large for the case of large temperature difference. Ma Shengwei et al. [6] used the two-dimensional mathematical model CE-QUAL-W2 to simulate the reservoir water temperature distribution under different water intake schemes of Kouris Dam. Research suggests that deep water intake accelerates the heat transfer of the upper and lower water bodies and increases the depth of the thermocline. Anil Caliskan et al. [7] used the three-dimensional
mathematical model EFDC to simulate the velocity distribution and water temperature distribution under different inlets of the Thatali reservoir. It is believed that the bottom water abstraction method can accelerate the mixing of water bodies and effectively slow down the anaerobic state of deep water bodies. Deng Yun et al. [8] conducted a numerical simulation study on the cumulative effect of water temperature in cascade hydropower stations. Song Ce et al. [9] studied the influence of water temperature structure evolution of Longyangxia Reservoir on the water temperature of downstream rivers. Gao Xueping [10], Zhang Shaoxiong et al. [11] used the three-dimensional mathematical model EFDC to simulate the discharge water temperature of the overflow intake of the Nuozhadu Hydropower Station and the bottom water intake of the Glen Canyon Dam. The regulation effect of the layered water intake on the discharge temperature was verified, and the variation law of the discharge water temperature was analyzed, but the influence of the water intake flow rate and the opening combination on the discharge temperature was not involved. The regulation effect of the layered water intake on the discharge temperature was verified, and the variation law of the discharge water temperature was analyzed, but the influence of the water intake flow rate and the opening combination on the discharge temperature was not involved.

Before the construction of the Glen Canyon Dam, the annual temperature of the Colorado River fluctuated between 0 °C and 29 °C as the season changed. Since the dam was built, the deep water intake of the dam has kept the water temperature of the downstream Colorado River between 8 °C and 9 °C throughout the year. In the downstream channel near the dam, non-native aquatic organisms can adapt to the low temperature water that is discharged, but for local aquatic organisms salmon, the water temperature is lower than the optimal growth temperature. In summer, as the low-temperature water drains from the Colorado River to the lower reaches of the Grand Canyon, the water temperature can rise back to 15 °C, but the water temperature is still lower than the optimal breeding and growth temperature of the salmon. The US Environmental Protection Agency and the Fisheries and Wildlife Society have conducted research on the control measures for the discharge temperature of the Glen Canyon Dam. It is considered that the key factor to restore salmon ecological environment is to build Multi-level intake to control the water temperature of the dam. In this paper, the effect of the combination of diversion flow and opening on the discharge water temperature of the Multi-level intake water of Glen Canyon dam is studied by three-dimensional numerical simulation. That is to say, under the condition that the water temperature distribution in the reservoir area is known, change the combination of inlet water diversion flow and opening, study the change of discharge water temperature, and discuss the regulation effect of inlet water diversion flow and opening combination on discharge water temperature.

2. Glen Canyon Dam profile

2.1 The geographical position
Glen canyon dam, located on the Colorado river in north-central Arizona, 19.3km below the Arizona-Utah border, was completed in 1964. The Colorado river originates from the north-central part of Colorado in the United States. The main stream passes through Colorado, Utah, Arizona, Nevada and California, and finally flows into the gulf of California. The total length of the main stream is 2320 km, and the basin area is 637,000 km². The water area formed by the dam construction is called lake Powell, with a total reservoir capacity of 33.3 billion m³. When the water level is the normal storage level of 1128m, the corresponding reservoir capacity is 25.75 billion m³.

Glen canyon dam is a concrete gravity arch dam with a crest elevation of 1132m, a crest height of 216m and a crest length of 475m, making it the 4th highest dam in the United States. The dam has eight hydro-turbine units with a total installed capacity of 1320 MW. Eight diversion pipes with a diameter of 4.6m lead water from the front of the dam to the water turbine set behind the dam. Central elevation of intake is 1058m, and the minimum water level of power generation is 1064m.
The Glen Canyon Dam’s stratified water intake program plans to build on existing water intakes and add a new surface water intake. The center elevation of the reconstructed surface water intake is 1106m, and the height of the water intake is 12.8m. After the reconstruction of the project, a multi-layer water intake composed of surface water intake (1106m) and bottom water intake (1058m) will be formed. See Fig. 2 for the reconstructed multi-layer water inlet.

In order to facilitate the study of the variation law of discharge water temperature, in the regulations, the eight water inlet from the direction of the flow direction of the water flow shall be numbered 1#~8# from the right to the left. In order to verify the regulation effect of multi-layer water intake on the discharge water temperature, the US Environmental Protection Agency is planning to renovate the water intake at #4 and #6. If the actual operation can significantly improve the discharge water temperature, then complete the reconstruction of other water intake.

The water temperature structure of Lake Powell is a seasonal stratified reservoir. In September, the temperature difference at the bottom of the reservoir is the largest at 20.95 °C. In February, the temperature difference at the bottom of the reservoir is the smallest at 2.70 °C. The water temperature distribution is shown in Figure 3.
3. Mathematical model

3.1 EFDC numerical model
EFDC (ENVIRONMENTAL FLUID DYNAMICS CODE) is a three-dimensional calculation model developed by John M. Hamrick [12], which includes hydrodynamic modules, water quality modules, sediment and heavy metal modules. It can perform one-dimensional, two-dimensional and three-dimensional simulations of water flow, water temperature, sediment and water quality in different spatial scales such as rivers, lakes, bays, estuaries and wetlands. EFDC is currently the main research tool for water environment simulation and evaluation in the United States, with more than 100 applications in the United States.

3.2 Mesh Generation and Boundary Conditions
The calculation range includes the river channel within 5km of the Glen Canyon Dam. The calculation area is divided by a curved orthogonal grid, the grid size is 5~50m, and the total number of grids is 750. The calculation is divided into 40 layers in the vertical direction. The calculation area grid diagram is shown in Figure 1.

The upstream boundary gives the reservoir water level and water temperature vertical distribution for each month, and the outflow boundary gives the water intake flow.

3.3 Model verification
The mathematical model was verified by the measured water discharge temperature of the Glen Canyon Dam in 1994. The verification results are shown in Table 1. It can be seen from Table 1 that the calculated value agrees well with the measured value, and the maximum error is only 0.42 °C. The model can better simulate the topographic boundary of the reservoir before the inlet, fully consider the three-dimensional flow characteristics of the water flow, and can accurately simulate the discharge temperature of the multi-level intake.

Table 1 Discharged water temperature of computed and measured

| Month | Calculated (°C) | Measured value(°C) | Error (°C) |
|-------|----------------|-------------------|------------|
| 3     | 8.35           | 8.51              | -0.16      |
| 5     | 8.34           | 8.41              | -0.07      |
| 8     | 8.36           | 8.55              | -0.19      |
| 11    | 8.44           | 8.86              | -0.42      |

Figure 3 Temperature distribution of the reservoir
4. Simulation results and analysis of discharge water temperature

4.1 Influence of single port diversion flow rate on discharge water temperature

In order to explore the influence of single-port water diversion flow on the water discharge temperature of the multi-layer water intake, the single-port water diversion flow rate is set to 30m3/s, 70m3/s and 120m3/s respectively. The numerical simulation simulates the discharge temperature of the surface water taken in the 12 months when all the water intakes of 1#~8# are opened. Numerical simulation results are shown in Table 2 and Figure 4.

It can be seen from Table 2 and Figure 4 that the discharge water temperature slightly increases with the increase of the single port water diversion flow rate, and the increase rate is small. Because the multi-layer water intake used in the Glen Canyon Dam is to take water from the horizontal opening on the vertical wall, the flow state of the water flow is roughly symmetrical with the upper and lower symmetry of the center line of the water intake. After increasing the water intake flow, the range of water extracted is still in a symmetrical flow state, and the temperature of the discharge water is less increased.

![Figure 4 Discharged water temperature of different flow rate](image)

| Month | Open combination | Single port diversion flow (30m³/s) | Single port diversion flow (70m³/s) | Single port diversion flow (120m³/s) |
|-------|------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| 1     | 1#~8#            | 10.88                               | 10.88                               | 10.89                               |
| 2     | 1#~8#            | 9.25                                | 9.26                                | 9.27                                |
| 3     | 1#~8#            | 9.77                                | 9.78                                | 9.80                                |
| 4     | 1#~8#            | 11.68                               | 11.67                               | 11.67                               |
| 5     | 1#~8#            | 17.44                               | 17.44                               | 17.46                               |
| 6     | 1#~8#            | 19.38                               | 19.40                               | 19.43                               |
| 7     | 1#~8#            | 23.36                               | 23.53                               | 23.77                               |
| 8     | 1#~8#            | 26.70                               | 26.81                               | 26.95                               |
| 9     | 1#~8#            | 25.82                               | 25.83                               | 25.91                               |
| 10    | 1#~8#            | 20.29                               | 20.29                               | 20.29                               |
| 11    | 1#~8#            | 15.85                               | 15.85                               | 15.85                               |
| 12    | 1#~8#            | 11.65                               | 11.65                               | 11.66                               |

4.2 The effect of unit opening combination on the discharge temperature

In order to study the effect of the combination of the water intake opening on the temperature of the discharge water, the water temperature stratification is not obvious in March and the water
temperature stratification is obvious in August as the representative month. Numerical simulation of the discharge temperature of different combinations of water intake openings, numerical simulation results are shown in Table 3.

It can be seen from Table 3. In March, when 4# was turned on, the discharge water temperature was 9.69 °C; when 1#-8# was all turned on, the discharge water temperature was 9.77 °C, which was 0.08 °C higher than that when 4# was turned on. In August, when 4# was turned on, the discharge water temperature was 26.54 °C; when 1#-8# was all turned on, the discharge water temperature was 26.70 °C, which was 0.16 °C higher than that when 4# was turned on. It can be seen from the calculation results that when the flow rate of the single port is constant, the water intake of different combinations is opened, and the influence on the temperature of the discharge is small. The regulation of the discharge temperature can’t be achieved by opening different water intakes.

| Mouth | Single port diversion flow (m³/s) | Open combination | Discharge water temperature (°C) |
|-------|----------------------------------|------------------|----------------------------------|
| 3     | 30                               | 4#               | 9.69                             |
|       |                                  | 4# , 6#          | 9.69                             |
|       |                                  | 2# , 4# , 6#     | 9.70                             |
|       |                                  | 2# , 4# , 6# , 8#| 9.72                             |
|       |                                  | 1#–8# Open all   | 9.77                             |
|       |                                  | 4#               | 26.54                            |
|       |                                  | 4# , 6#          | 26.65                            |
| 8     | 30                               | 2# , 4# , 6#     | 26.63                            |
|       |                                  | 2# , 4# , 6# , 8#| 26.66                            |
|       |                                  | 1#–8# Open all   | 26.70                            |

5. Conclusion

For the multi-level intake of the Glen Canyon Dam, the numerical simulation of the different water diversion flow of the water intake and the combined discharge water temperature. The research obtained the regulation effect of the water intake flow rate and the opening combination on the discharge water temperature.

(1) In order to adapt to the complex topographical boundary of the front reservoir area of the water intake, a three-dimensional numerical model of the water discharge temperature of the multi-level water intake of the Glen Canyon Dam was established by using the σ coordinate system. The numerical simulation results are verified by the measured values. The calculated values are in good agreement with the measured values, indicating the validity and practicability of the numerical model.

(2) Under the condition that the water temperature distribution in the reservoir area and the opening combination of the water intake are unchanged, the numerical simulation of the discharge water temperature when the single port diversion flow changes. The simulation results show that the single-port diversion flow increases, and the discharge temperature slightly increases, but the increase is small.

(3) Under the condition that the water temperature distribution in the reservoir area and the single port diversion flow rate are constant, the numerical simulation of the discharge water temperature of the different opening combinations of the water intake is simulated. The simulation results show that when the single port diversion flow rate is constant and the water intake opening is different, the influence on the lower discharge water temperature is small. The regulation of the discharge temperature can't be achieved by opening different water intakes.

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