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Study on the Hydraulic Characteristics of Cascade Pumping Station on the East Route of South-to-North Water Diversion Project

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Abstract. Aiming at the hydraulic problems existing in the operation of the two lakes in the east route of the South-to-North Water Diversion Project, a one-dimensional hydraulic equation and a pump station performance equation were coupled. Based on the Fortran language, a simulation model for water delivery scheduling of the two-lake cascade pumping stations was developed and combined with the actual measurement from 2013 to 2017. The data has been calibrated for the model, which can simulate the hydraulics of different water transport conditions. Based on the hydraulics method, the hydraulic loss under normal water conveyance conditions between channels was analyzed, calculated and studied. In view of the aquatic problem, Changgou-Denglou section was selected as the research object, and the model was combined based on the measured data. The hydraulic loss under the plugging condition of the aquatic plant was analyzed and calculated and the law was studied. Based on the water balance method, the water loss in the two lakes was analyzed and calculated. The research results can provide reference for the operation of the two lakes in the east route of the South-to-North Water Diversion Project.

1. Introduction
The two-lake scheme of the East Route of the South-to-North Water Diversion Project is an important part of the East Route of the South-to-North Water Diversion Project and involves two rivers and three pumping stations. The project of the two lakes from the upper lake of Nansi Lake will enter Dongping Lake through the Liangji Canal, the Liuchang River and Changgou Pumping Station, the Denglou Pumping Station, and the Baliwan Pumping Station. The total length of the line is 108.227km and the water diversion volume is 100m³/s.

Through the practice of diverting water from the two-lake scheme of the East Route of the South-to-North Water Diversion Project from 2013 to 2017, it was found that there are many hydraulic problems affecting the safe operation of the section during the dispatching operation. On the one hand, the two lakes on the east route of the South-to-North Water Diversion project use existing river channels to transport water, and different lining forms are adopted along the rivers. The roughness varies greatly along the route and the water level varies greatly under different water transport conditions. The model has not achieved dynamic simulation of the water delivery process yet. On the other hand, in front of the pumping station, the trash racks were set up and when encountered special
conditions such as aquatic, the water level was high and severely affected the operation of the pumping station. Due to leakage, evaporation and other factors, the water loss of the river section is large and it is currently impossible to measure effectively.

The basic equations describing the water movement is the Saint-Venant equations, including continuity equations and dynamic equations [1]. River network hydraulic calculations can be attributed to the solution of the one-dimensional Saint-Venant equations [2]. With the gradual maturity of computer technology, The use of mathematical models to simulate actual problems has become the main method for studying problems in engineering operations [3]. In the hydrodynamic model, Zhang Cheng[4] established a one-dimensional unsteady flow mathematical model for long-distance open channels and realized continuous continuous simulation of open channels; Lei Yan[5] used a feasible turbulence model to simulate the three-dimensional turbulent flow of the layered intake; Huang Huiyong [6] established the hydraulics calculation model for the main canal of the Middle Route of the South-to-North Water Diversion Project to simulate the dynamic transition process of the operation and dispatch of the main canal. In the study of water loss, Hu Zhouhan [7] combined the characteristics of the first-phase water transfer of the East Route of South-to-North Water Diversion Project, studied the calculation method of leakage and evaporation, and constructed the water loss calculation model for water conveyance projects; Yu Weili [8] described the relationship between the measured water loss and the designed water loss in the two situations.

In summary, there are few researches related to the hydraulic characteristics of cascade water conveyance, and there is also less concern about water loss from the aquatic and water loss from the water transport. For the above problem, the hydraulic characteristics of the two-lake scheme were studied, and a scheduling simulation model was established by coupling the one-dimensional hydraulics model with the pumping station nodes. The model was calibrated based on actual operational data from 2013 to 2017. As well as the hydraulic loss with aquatic, and it provides a reference for dispatching operations.

2. Establishment of Hydraulic Dispatch Simulation Model for Cascade Pumping Stations

2.1. Research area
The Two Lake scheme of east route of the South-to-North Water Diversion Project includes two reservoir lakes (Dongping Lake and Nansi Lake) and two waterways (Liangji Canal and Liuchang River) and three pump stations (Changgou Pump Station, Denglou Pump Station and Buliwan Pump Station). This model used the design data and section data of the Liuchang River and Liangji Canal, dredging design data in the Nansi Lake waterway, and the basic data of pump station characteristic curves as the modeling basis.

The two lakes scheduling data for 2013-2017 includes the water level and flow data of the pump stations and the water level data of Nansi Lake and Dongping Lake.

2.2. One-dimensional hydrodynamic model
(1) Dynamic equation
The basic equation for the motion law of one-dimensional unsteady flow is the Saint-Venant equations. Its mathematical expression is:

Continuous equation:

\[ \frac{\partial Q}{\partial x} + b \frac{\partial h}{\partial t} = q \] (1)

Motion equation:
In the formula: \( x \) is the distance coordinate; \( t \) is the time coordinate; \( Q \) is the section flows; \( h \) is the section water level; \( A \) is the cross-section area; \( R \) is the hydraulic radius of the cross section; \( C \) is the Chezy coefficient; \( g \) is the acceleration of gravity; \( q \) is the lateral flow of the unit river; \( \alpha \) is the vertical velocity distribution coefficient.

(2) The solution of the equation

The Saint-Venant equation belongs to the first-order quasi-linear hyperbolic partial differential equations and in general, its universal analytical solution cannot be found. The commonly used solution method is to use some kind of calculation method to discretize the equations, transform them into a set of algebraic equations, and program to solve these algebraic equations according to the initial and boundary conditions of the problem. These numerical discrete methods include direct difference method, finite element method, and the like. The discrete format under Godunov framework has the ability to simulate large gradient flows and automatically capture shock waves. This method has good stability and high computational accuracy. Therefore, this study adopts the Godunov format finite volume method for discrete calculation.

The finite volume method is based on a conservative integral equation. The discrete equation is constructed by integrating the discrete subregions of fluid motion.

The vector form of the Saint-Venant equation is as follows:

\[
D \frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} = S
\]

(3)

\[
D = \begin{bmatrix} B & 0 \\ 0 & 1 \end{bmatrix}, \quad U = \begin{bmatrix} Z \\ Q \end{bmatrix}, \quad F = \begin{bmatrix} Q \\ Q^2 \\ A \end{bmatrix}, \quad S = \begin{bmatrix} q \\ -gA(S_0 - S_t) \end{bmatrix}
\]

(4)

Where, \( S_0 = -\frac{\partial z}{\partial x} \) represents the slope of the river bed, \( S_t = \frac{n^3 |Q|}{A^4 g^2 R} \) is resistance loss along the way, \( n \) is the Manning coefficient. In the formula: \( q \) is the side inflow; \( Q, A, B, Z, R \) respectively represent the section flow, the area of the river, the river width, the water level, and the wet period.

Write the above equation as a conservative type integral control equation:

\[
D_i \frac{\partial}{\partial t} \int_{\Delta t_i} U dx + \int_{\Delta t_i} \frac{\partial F}{\partial x} dx = \int_{\Delta t_i} S dx
\]

(5)

This formula can use the Green formula to perform the integral transformation. In the Godunov framework, the updated Euler method is used to update the variables of the n time layer, and the following discrete equation is obtained:

\[
U_j^{n+1} = U_j^n + \frac{1}{2} \Delta t D_i^{-1}(E_i(U^n) + E_i(\bar{U}))
\]

(6)

In the formula,

\[
\bar{U}_i = U_i^n + \Delta t D_i^{-1} E_i(U^n)
\]

(7)
\[ E_i = -\frac{F_{i+1/2} - F_{i-1/2}}{\Delta x_i} + S_i \]  

(8)

Where, the superscript \( n \) indicates the time layer; Subscript \( i \) represents the grid index; \( \Delta t \) and \( \Delta x \) correspond respectively to the time step and grid size of the i-th grid; \( D_i^{-1} \) represents the inverse matrix of the coefficient matrix \( D_i \) corresponding to grid \( i \); \( \bar{U} \) represents intermediate variables; \( E_i \) is the Euler coefficient; \( \bar{F_i} + \bar{F_{i+1/2}} \) and \( \bar{F_i} - \bar{F_{i-1/2}} \) correspond respectively to the Riemann fluxes passing through the right and left boundaries of grid \( i \).

(3) Boundary Condition Processing

Pumping stations, inverted siphons, culverts and other buildings are important over-water structures in the water distribution channels. The building involved in the model is pumping station. The correct simulation of the pump station is the key to building the Water Transfer Scheduling Simulation Model for Cascade Pumping Stations on the East Route of the South-to-North Water Diversion Project.

The pump station is the most important internal boundary as a water lift. By pressurizing the water flow, the water flow is transported from a low water level to a high-water level, and the pumping station plays a connecting role to the hydraulic relationship between the water intake side section and the water discharge side section of the pumping station. The treatment of the pump station mainly considers two conditions:

① Continuous equation

\[ Q(i,j) = Q(i,j-1) \]  

(9)

Where, \( Q(i,j) \), \( Q(i,j-1) \) indicate the flow rate at the outlet side and inlet side of the i-stage pump station.

② Head and flow relationship of Pump station

\[ h(i) = h(i,j) - h(i,j-1) = aq(i,j)^2 + bq(i,j) + c \]  

(10)

Where, \( h(i) \) is the pump lift of the i-th pump station; \( h(i,j) \), \( h(i,j-1) \) indicate respectively the water level at the outlet side and inlet side of the i-th pump station; \( q(i,j) \) is the flow rate of a single pump in the i-th pump station; \( a, b, c \) is the pump head flow relationship coefficient.

2.3. Model constraints and parameter calibration

(1) The upstream upper boundary and downstream boundary of the model are the flow process of the Nansi Lake and the water level process of the Dongping Lake. The water level constraint conditions are Liujiang River water level, Liangji Canal water level, and pump station water level. The flow constraint conditions are unit flow restriction, head-flow relationship curve, and pump station flow restriction.

(2) From January 14 to January 29, 2016, the measured water level and flow data at Changgou, Denglou and Baliwan Pump Stations were selected to determine the roughness values of different channels. The roughness values are: the roughness along the channel is 0.022, and the roughness of the inlet channel, forebay and outflow canal of three pumping stations is 0.015. Fig. 1 show the comparison of simulated values and measured values of the lower water level of Denglou pump.
station. It can be seen from the figure that the simulated water level and measured water level of the pumping stations are not much different. The overall error is within 0.05m and the model reliability is high.

Table 1. Constraint table of water level of pump station.

| Parameters of pumping station | Changgou Before pumps h1 | After pumps h2 | Denglou Before pumps h3 | After pumps h4 | Baliwan Before pumps h5 | After pumps h6 |
|-------------------------------|--------------------------|---------------|--------------------------|---------------|--------------------------|---------------|
| Characteristic water level    | highest 32.60            | 35.37         | 34.92                    | 37.39         | 37.00                    | 41.40         |
|                               | lowest 31.51             | 33.16         | 33.82                    | 36.49         | 35.62                    | 38.90         |

Figure 1. Comparison of simulated and measured values at Denglou.

3. Analysis of Hydraulic Characteristics
Based on the simulation of the dispatching simulation model, the different initial and boundary conditions were set to simulate different operating conditions, and the hydraulic and water losses under different operating conditions were calculated. Therefore, the law of hydraulic and water loss can be studied.

3.1. Analysis of hydraulic loss

3.1.1. Balanced condition. It is assumed that the system is in a state of balance. By setting different water flow and initial water level, the water surface profile is simulated, and the hydraulic loss under different water transport conditions is calculated. On the basis of this, the change law are analyzed.

Figure 2 shows the change along the river of water level through simulating different flow conditions. The result shows: ①There is a positive correlation between hydraulic loss and flow. Taking Changgou-Denglou section as an example, the hydraulic losses were 0.91m, 0.81m, and 0.77m under three different flow conditions. ②Hydraulic loss is positively correlated with mileage. The distances from lake outlet of Nansi lake to Changgou, Changgou to Denglou and Denglou to Baliliwan in the two-lake scheme are 25.92km, 32.21km, and 21.47km. The hydraulic loss is 0.73m, 0.91m and 0.565m at the flow of 98.73 m$^3$/s.

The model has simulated the relationship between upstream water level and flow and hydraulic loss from the lake outlet of Nansi Lake to the Changgou (Figure 3). It can be seen that when the upstream water level is constant, the greater the water flow, the greater the hydraulic loss between the canal sections. When the flow is the same, the upstream water level is negatively correlated with the
hydraulic loss between the canal sections. That is, the higher the upstream water level, the smaller the hydraulic loss between the sections.

![Figure 2. Simulated value of water level variation.](image2)

![Figure 3. Flow and hydraulic loss curves at different upstream water levels.](image3)

3.1.2. **Aquatic condition.** During the period of April and May 2016, a large amount of aquatic plants appeared in lake outlet to Changgou, Changgou-Denglou Canal, floating on the river, with a thickness of 0.35m, which was causing a large blockage of the trash rack. Meanwhile, the water level in the inlet pool rapidly dropped, aquatic caused multiple pump station shutdowns. The plants in the two-lake scheme are mainly Potamogeton crispus, which was born in lakes, paddy fields, ponds, rivers, and other fresh water bodies. It is a typical submerged plant that germinates in autumn, grows in winter and spring, and disappears in early summer. The growth of the Potamogeton crispus was related to the depth of water, and the water depth was negatively correlated with the growth of the Potamogeton crispus[9]. Under the condition of aquatic plants, on the one hand, large areas of aquatic plants are suspended in the water body, causing increased head loss along the way. On the other hand, due to the gradual accumulation of water grasses in front of the trash rack, the blockage of the trash racks caused a sharp increase in the loss of local water heads.

According to the actual measured water level flow data from April 15 to 29 in Changgou-Denglou section, combined with the distribution of aquatic in the field and the hydraulic model, the water-blocking effect of aquatic plants is generalized with the roughness value, and the different types of hydroplaners are calculated. The relationship between water distribution and roughness was initially analyzed. Table 2 shows the statistical status of the surface lines of water plugs.
Table 2. Water surface line statistics of Changgou-Denglou with aquatic.

| Degree of clogging of aquatic | Floating aquatic on the surface of the water | Part hydraulic loss at the trash rack | Roughness |
|-------------------------------|---------------------------------------------|--------------------------------------|-----------|
| without aquatic               | without aquatic                             | between 0.05m-0.1m                    | 0.022     |
| slight                        | cover the river 100-300m                    | between 0.1m-0.7m                     | 0.022-0.025|
| general                       | cover the river 300-400m                    | between 0.7m-1.2m                     | 0.025-0.027|
| serious                       | cover the river 400-500m                    | between 1.2m-1.5m, maximum reach 1.5m| 0.027-0.029|

The model is simulated for different overflowing conditions of aquatic. The upper and lower boundary conditions are the water level of the Changgou pumping station and the Denglou pumping station, respectively.

Among them, and the roughness value of the trash rack to intake is about 0.022.

Figure 4 shows the difference between the hydraulic loss and the local hydraulic loss caused by different levels of aquatic cover under the conditions of equivalent flow. When the effect of flow can be ignored, the hydraulic loss of the trash rack of the Changgou pumping station to the Denglou pumping station is 0.27m, 0.31m and 0.36m under the 3 different aquatic conditions (slight, normal, and severe), respectively. The part hydraulic loss at the trash rack were 0.36m, 0.76m and 1.40m respectively. Thus, hydraulic loss is positively correlated with the degree of aquatic overflowing.

3.2. Analysis of Water Loss Based on Total Balance

The East Route of the South-to-North Water Diversion Project is of large scale and long distance of water conveyance. Due to factors such as leakage and evaporation, water loss is unavoidable in the process of water transfer. In order to effectively control the water diversion in the two-lake scheme of the East Route of the South-to-North Water Diversion Project, it is necessary to make a reasonable calculation and analysis of the water loss in the two-lake scheme of the East Route of the South-to-North Water Diversion Project.

3.2.1. Empirical formula method. In the past water loss calculation of water conveyance projects, empirical formula method is usually adopted. By analysing the composition of the water loss, calculate the leakage and evaporation losses to calculate the total loss. Water loss mainly includes leakage loss and evaporation loss.

(1) Leakage loss

The leakage loss is calculated according to the lining form of the river courses along the river.
The leakage loss of the river section in the unlined river section is as follows:

\[ S = 0.0116k[b + 2\gamma_1(\bar{z} - z_o)\sqrt{1 + m^2}] \]  

(11)

Where \( S \) is the free leakage per kilometer of the channel, m³/(s*km); \( k \) is the bed permeability coefficient, m/d; \( b \) is the bottom of the river, m; \( \bar{z} \) is the mean water level of the river, m; \( z_o \) is the average river bottom elevation of the river, m; \( m \) is the slope coefficient of the river; \( \gamma_1 \) is the correction coefficient of slope lateral capillary soaking, Generally, 1.1 is used for sand, 1.2 for sub-sand, 1.3 for sub-clay, and 1.4 for clay.

Lining sections are usually treated with concrete cover, bituminous material cover, slurry masonry lining and plastic film seepage control. Lining leakage loss formula is:

\[ S_F = \beta S \]  

(12)

Where \( S_F \) is the amount of water seepage per kilometer channel after taking anti-seepage measures, m³/s; \( \beta \) is the reduction factor of leakage after adopting anti-seepage lining measures.

(2) Evaporation loss

Evaporation loss is the product of measured water surface evaporation depth and water surface area:

\[ E = VA = V[\bar{b} + 2(\bar{z} - z_o)m] \]  

(13)

Where \( E \) is the total evaporation loss, mm; \( v \) is the evaporation depth on the surface, mm; \( \bar{A} \) is the surface area of the river, m²; \( I \) is the length of the river, km.

3.2.2. Analysis of Water Loss Based on Total Balance.

It is known that the flow of the three pumping stations of Changgou, Denglou and Baliwan. Considering the variation of storage capacity between canal sections, a formula for calculating water loss between channels is proposed:

\[ W = \bar{I} \Delta t - \bar{O} \Delta t - \Delta W \]  

(14)

Where \( W \) is the loss of water in period \( \Delta t \), m³; \( \bar{I} \) and \( \bar{O} \) are the average discharge of incoming and discharging water in time \( \Delta t \), m³/s; \( \Delta W \) is the amount of water added or reduced during period \( \Delta t \), m³.

During the period from January to June in 2016, the average single-phase flow of Changgou Pump Station was 31.1 m³/s, and the average single-machine flow of Denglou Pump Station was 30.06 m³/s. The average single-machine flow of the Baliwan Pump Station was 29.87 m³/s. The above water loss calculation formula can be used to obtain the monthly water loss from Changgou to Baliwan Pump Station.

| Month | Changgou-Denglou | Denglou-Baliwan | Changgou-Baliwan |
|-------|------------------|-----------------|------------------|
| 1     | 157.2            | 154.8           | 312              |
| 3     | 183.5            | 234.2           | 417.7            |
| 4     | 625.2            | -221.4          | 403.8            |
| 5-6   | 246.4            | 373.5           | 619.9            |
| Total | 1212.3           | 541.1           | 1753.4           |

Table 3, Calculation of water loss in the two-lake scheme.
In this water transfer, the 401.5351 million m³ was transferred from the of Nansi Lake, and 388.5749 million m³ was transferred into Dongping Lake. The total amount of water lost was 17.6802 million m³, accounting for 4% of the adjusted amount of water. Combined with the water transfer data, the amount of water loss resulting from the use of the water balance formula based on the total balance was 17.534 million m³, which was not much different from the loss of 17.6802 million m³ in the water transfer results.

The result shows: In January 2016, the water loss was small, and maybe it was in winter; the total water loss from Changgou to Baliwan in March and April is not much different, but there is a big difference in water loss from Changgou to Denglou and Denglou to Baliwan. The reasons for this phenomenon are not clear. The water loss in May-June is relatively large, which is about 50% more than the losses in March and April, mainly due to weather and irrigation.

4. Conclusion
(1) This paper used the basic theory of unsteady flow to establish the simulation model of unsteady flow in the water delivery system of cascade pumping stations. Through the numerical simulation of normal working conditions and aquatic, the values of the roughness interval and partial head loss under different working conditions were obtained, and the rationality of the model was verified.

(2) By simulating the flow at different flow, the water level changes along different flow were plotted, and it was concluded that there was a positive correlation between hydraulic loss and flow and distance; by simulating the water transport process at different upstream levels, it is concluded that the hydraulic loss is negatively related to the upstream water level; by simulating the water transport process under the condition of aquatic, it is concluded the hydraulic loss and the part hydraulic loss increased with the increase of the number of aquatic under such working conditions.

(3) In this paper, the water loss situation of the two lakes is preliminarily analyzed, and the water loss during different water transport periods is calculated. It is concluded that the water loss in winter is small. The overall losses in March and April were comparable to those in winter. Due to weather, irrigation and other reasons, the water loss in May and June is relatively large. These laws provide the basis for the study of the law of water loss in the later period.

(4) In view of the dispatching control of the East Route of the South-to-North Water Diversion Project, it is necessary to further analyze the unsteady flow hydraulic phenomena that may occur in the water transfer project in the future.

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