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Automatic scheduling and control technology of pump gate clusters of regional water conservancy project

Aijun Sun[a,*], Donghui Hu[a], Chengju Shan[b], Jun Wang[b]

[a]*Yuyao Water Resources Bureau, Yuyao City, Ningbo 315470, China, email: sunaijun188@outlook.com (A. Sun)*
[b]*Zhejiang University of Water Resources and Electric Power, Hangzhou 310018, China*

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ABSTRACT

With the frequent regional flood disasters in recent years, the study of automatic scheduling and control technology of pump gate clusters has become crucial in related academic circles. Here, an automatic flood control and scheduling model for pump and gate clusters of water conservancy projects is constructed by combining hormone regulation and particle swarm algorithm. The model can regulate the maximum discharge flow and maximum water level of reservoirs according to the actual situation in order to achieve flood prevention and consumption prevention. The model is validated using two reservoirs in city A as an example. The results show that the maximum discharge flow of the two reservoirs after the model treatment is 1,996.16 and 16,738.28 m^3/s, which reduces the incidence of flooding in city A. In addition, after the optimal flood control scheduling, the maximum water levels of the once-in-a-century flood and once-in-two-centuries flood in city A become 80.41 and 81.66 m, respectively, which are in the safe water level range. The study is of great significance for the reduction of flooding.

Keywords: Regional water conservancy project; Pump gate clusters; Hormone regulation; Particle swarm optimization algorithm; Scheduling and control

1. Introduction

To realize the deep integration of information technology and traditional industries, and to create a new development model, it is needed to make full use of Internet Technology. “Information Technology + Pump Gate Clusters Management” can apply Internet Technology in Water Conservancy Projects, and is essential for intelligent scheduling and control of pump gate clusters [1,2]. Pump gate clusters are used for several important activities such as flood control, and they play an important role in stabilizing regional economic and social development [3,4]. Therefore, to control the amount of water in the basin and reduce flood losses, intelligent design of pump gate clusters of water conservancy projects is needed to realize automate flood scheduling and control [5,6]. At present, the automatic control technology of pump and gate groups in China’s water conservancy projects is still relatively backward, and many hydropower stations still use traditional relay control, lacking intelligent information regulation and control means. As a result, many pump gate clusters are inefficiently managed. Therefore, this study combines endocrine hormone regulation and particle swarm optimization algorithm to realize the automatic scheduling and control of pump gate clusters to improve the efficiency of flood control.

2. Related works

Floods are a natural hazard that is faced in a large number of regions of the world and this hazard has both sudden and periodic characteristics. Proper flood control measures can reduce the damage of floods to a great extent and a large number of researchers worldwide have conducted studies in this area [7]. Huddiankuwera et al. [8] calculated

* Corresponding author.

the planned flood flow of Makanuai River. The results showed that the maximum flood level in the area during the 50-y recurrence period has exceeded the river capacity and therefore effective flood resilience facilities need to be constructed to prevent flooding problems. Zhang et al. [9] to develop a stochastic model of flood inflows from the Three Gorges project and designed a regulation model of the river based on its dynamic capacity. According to their calculations, for large scale flood events current flood control measures in the region are not effective in protecting the nearby economy and life safety. The study provides a feasible solution for the joint flood control scheduling of the upstream terrace reservoirs in the region. It can be seen that most of the current studies on flood control measures focus on a specific region or time, and there are fewer studies with generalization. In addition, the degree of automation of flood control scheduling calculations is still very low.

Particle swarm optimization algorithm is one of the most popular types of optimization algorithms and have been used in optimization problems in various industries [10]. Abood et al. [11] used accelerated particle swarm optimization algorithm to configure the installation location of wind turbines in a power generation system. The algorithm considers the minimization of power losses and the optimal matching of the number of iterations, time and memory capacity. The algorithm was analyzed using MATLAB and found to be more effective compared to the current configuration method [12]. Deng and Lin [13] modeled investor preferences using a normalized weighted evaluation function based on an improved particle swarm optimization algorithm. They proposed a model including six constraints, including investment ratio synthesis, non-negative ratio, etc. The test results show that the algorithm is better able to optimize the analysis of investor behavior. The study of the field of flood control and the application area of particle swarm optimization algorithm reveals that the current particle swarm algorithm has mature applications in the field of optimization problems, but it is less applied in the field of flood control configuration. The generality and automation of current research in the field of flood control is relatively lacking. Therefore, this study applies the particle swarm optimization algorithm to the application of flood prevention pump gate clusters, hoping to bring practical research to the field.

3. Hormone regulation of endocrine system

Endocrine glands are capable of secreting different types of hormones that act on specific target cells and tissues, thus inhibiting or promoting their function in order to stabilize the internal and external environment of the biological organism. The reason for the rapid stabilization of various types of glandular hormones in the organism is the law of endocrine hormone regulation. The endocrine hormone regulation function $F(G)$ plays an important role in the endocrine regulation law, which has monotonicity and non-negativity. These two characteristics can be decomposed into the rising functions $F_{\text{up}}(G)$ and falling functions $F_{\text{down}}(G)$ in the Hill regulation law, and the corresponding model is shown in Eq. (1).

$$
\begin{aligned}
F_{\text{up}}(G) &= \frac{G^n}{T^n + G^n} \\
F_{\text{down}}(G) &= 1 - \frac{G^n}{T^n + G^n}
\end{aligned}
\tag{1}
$$

where T indicates the concentration threshold of the endocrine hormone, which satisfies $T > 0$, and the corresponding variable in the process of hormone secretion is represented by G. n indicates the regulatory factor, and $n \geq 1$. The Hill adjustment function has three characteristics, including $F(G)_{T-G} = 1/2$; $F_{\text{down}}(G) = 1-F_{\text{up}}(G)$; $0 \leq F(G) \leq 1$, where $F(G)$ can represent both the rising function and the falling function. The parameter n in the Hill regulation function is set as 1, 2, 3, respectively, and the change curve as shown in Fig. 1 is obtained.

Assuming that when endocrine control is on, hormone y controls hormone x, so the model of the effect of hormone y on the secretion rate $V_{\text{up(down)}}$ of hormone x in a concentration environment of C_y is shown in Eq. (2).

$$
V_{\text{up(down)}} = aF\left(C_y\right) + V_{x0} \tag{2}
$$

Eq. (2), a indicates a constant. The initial secretion rate of hormone x is V_{x0}. Substitute Eq. (1) into Eq. (2) to obtain Eq. (3).

$$
\begin{aligned}
S_{\text{up}} &= a\frac{C_y^n}{T^n + C_y^n} + S_{x0} = S_{x0}\left(1 + \frac{a}{S_{x0}} \cdot \frac{C_y^n}{T^n + C_y^n}\right) \\
S_{\text{down}} &= a\frac{T^n}{T^n + C_y^n} + S_{x0} = S_{x0}\left[1 - \left(\frac{a}{S_{x0}} \cdot \frac{C_y^n}{T^n + C_y^n}\right)\right] + a
\end{aligned}
\tag{3}
$$

Inspired by the hormone regulation mechanism, this study mimics Eq. (2) and adds hormone factors in the process of updating the particle swarm algorithm to improve the searchability and the convergence speed of the particle swarm algorithm to obtain the optimal scheduling sequence of the pump gate clusters for water conservancy projects.

4. Automatic flood control and scheduling model construction for pump gate clusters

4.1. Water balance optimization model

Excessive rainfall often occurs in summer, and many basins are at risk of flooding. This study analyzes how

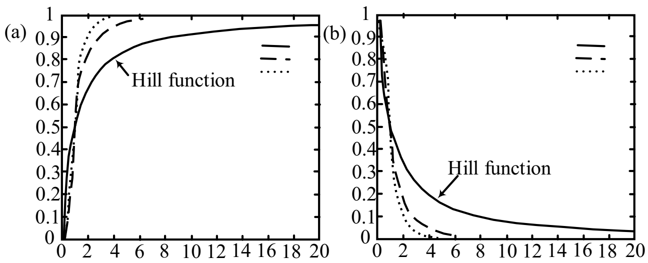

Fig. 1. Effect of parameter n on Hill function.

to effectively maintain the dynamic balance of water in a basin under excessive rainfall and ensure that the water in the basin does not exceed the storage capacity of large rivers during the scheduling cycle, and to achieve automated optimal scheduling control of the pump gate cluster of the basin. In general the amount of precipitation in a rainfall period is fixed, hence it is necessary to divide the whole rainfall cycle into several rainfall periods [14]. The premise of automated scheduling control is to predict the water intake of each rainfall period and set corresponding optimization objectives, so as to construct a mathematical calculation model. The objective function of the model is shown in Eqs. (4) and (5).

$$\min(F)=\sum_{t=1}^{T}\left(Q_{\text{out}}(t)-Q_{\text{in}}(t)\right)^2 \quad (4)$$

$$Q_{\text{out}}(t)=\sum_{i=1}^{N}\sum_{j=1}^{M}\left(Q_{ij}(t)\times X_{ij}\right) \quad (5)$$

where F in the above equation indicates the target function corresponding to the time when the basin water reaches dynamic equilibrium. $Q_{\text{out}}(t)$ indicates the amount of drainage outside the basin per unit time. $Q_{ij}(t)$ indicates the amount of drainage outside the pump. $Q_{\text{in}}(t)$ indicates the amount of inflow into the basin per unit time. X_{ij} indicates the state amount indicating the pump is on or off. i indicates the number of sequences corresponding to the pump and gate sites in the basin. j indicates the number of sequences corresponding to the flood pumps set up in the pump and gate sites. The constraints of the model are shown in Eq. (6).

$$Z_{\min}<Z_i(t)<Z_{\max} \quad (6)$$

where $Z_i(t)$ in the Eq. (6) indicates the river level in the basin. $Z_{\max}$ indicates the highest control level of the river in the basin, while $Z_{\min}$ indicates the lowest control level of it. The state volume constraint model of the water pump is shown in Eq. (7), and there are only two states of the pump, which are off and on, where 1 indicates on and 0 indicates off, and the corresponding state volume constraint is shown in Eq. (7).

$$X_{ij}=\{0,1\} \quad (7)$$

To ensure the service life of the pump unit, it is necessary to ensure the fixed switching of the unit. The frequency constrained model of the water pump unit is shown in Eq. (8).

$$\begin{aligned}&X_{11}^{n}-X_{11}^{n-1}>0 \text{ and } X_{12}^{n}-X_{12}^{n-1}<0 \quad (a)\\&X_{11}^{n}-X_{11}^{n-1}<0 \text{ and } X_{12}^{n}-X_{12}^{n-1}>0 \quad (b)\end{aligned} \quad (8)$$

Both (a), (b) assume that there are two pumps gates, each with the number 1, 2, respectively. The previous state of pump gate 1 in the (a) model is off and the preset state is on. At this time, pump gate 1 needs to be open, pump gate 2 is continuous operating. In the (b) model, it is necessary to let pump gate 2 on and the pump gate 1 run continuously.

4.2. Composition design for flooded areas

Based on the basin reservoir distribution, reservoir flood control systems can be classified into three types, namely, single reservoir flood control systems, tandem ladder flood control systems, and parallel ladder reservoir flood control systems [15–17]. Taking into account the actual situation of the basin in the country, this study focuses on analyzing the flood area composition of the flood control systems of two types of cascade reservoirs. To facilitate the flood frequency analysis, the corresponding regional composition is designed as shown in Fig. 2, using the dry and tributary floods as the design basis, while ignoring the role of upstream reservoir storage.

A in Fig. 2 represents the upstream cascade reservoir, and the natural water inflow is represented by X. The basin interval is represented by B, and the natural water inflow is represented by Y. The expression factor of downstream cascade reservoirs is C, and the natural inflow of reservoirs is expressed in Z. There is $Z = X + Y$. To conform to the relationship of each division, the frequency flood hydrograph of each division is calculated by using the independent sample calculation frequency curve of each division. The distribution model corresponding to the frequency curve is P–III, which has the density function shown in Eq. (9).

$$f(x)=\frac{\beta^{\alpha}}{\Gamma(\alpha)}\left(x-a_0\right)^{\alpha-1}e^{-\beta(x-a_0)} \quad (9)$$

The parameters a_0, α, β in the Eq. (9), respectively represent the location, shape and scale of P–III distribution where $\alpha > 0$, $\beta > 0$. $\Gamma(\alpha)$ stands for α gamma function. In addition, there is a relationship between relevant parameters of P–III distribution and total statistical parameters as shown in Eq. (10).

$$\alpha=\frac{4}{C_s^2};\ \beta=\frac{2}{\bar{X}C_vC_s};\ a_o=\bar{X}\left(1-\frac{2C_v}{C_s}\right) \quad (10)$$

The same frequency area composition means that the lower end of the sub-districts flood volume is designed to be of the same frequency, and this method is applied on the premise that it meets the actual needs of flood control. The remaining sub-districts calculate their respective flood volumes according to the water balance optimization model described above, and the flood peaks are distributed among the regions according to typical composition ratios. The

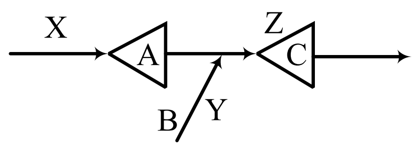

Fig. 2. Flood area composition design of the cascade reservoir.

two cascade reservoir models that are consistent with this study have two combinations of forms, as detailed below. When the design frequency of downstream reservoir section C is consistent with the frequency P of flood z_p, the same frequency P will occur for the y_p flood of sub-district B. At this time, the flood occurring in the upstream reservoir section satisfies $x = z_p - y_p$. Whether the upstream and downstream interzone floods in the composition of the same frequency area have the same frequency flood needs to be calculated by combining the spatial extent of the flood and the historical typical flood frequency.

4.3. Flood control and scheduling model based on hormone regulation particle swarm optimization algorithm

The solution principle of particle swarm algorithms is to guide the particles towards the optimal solution by continuously updating the particle velocity [18]. This principle is similar to biological hormone regulation, which continuously improves the adaptive capacity of the organism by continuously adapting to the internal and external environment. Therefore, this study applies the particle swarm optimization algorithm (IAPSO) based on hormone regulation to flood scheduling, taking full advantage of the PSO algorithm. The particle swarm optimization algorithm has higher efficiency and performance. In the particle swarm optimization algorithm, all types of initial solutions of particles are randomly and uniformly distributed over the interval [min, max] [19,20]. In order to improve the performance of the algorithm, after generating the random initial solution, the parameter ω, rand(), rand() needs to be selected and designed, and its model is shown in Eq. (11).

$$\text{rand}_i(k+1) = 4 \times \text{rand}_i(k) \times (1 - \text{rand}_i(k)),\quad \text{randi}(k) \in (0,1), i = 1,2 \tag{11}$$

The parameter ω usually has certain impact on the search accuracy of the algorithm, so the inertia factor ω is usually set scientifically to reduce the number of particle optimization iterations and thus improving the search accuracy. The adaptive adjustment model of the inertia factor ω is shown in Eq. (12).

$$\omega(k) = \omega_{\max} - (\omega_{\max} - \omega_{\min}) \times \frac{k}{k_{\max}} \tag{12}$$

where k in the Eq. (12) represents the current number of evolved particles, while the threshold of algorithm evolution is represented by $k_{\max}$. $\omega_{\max}$, $\omega_{\min}$ representing the extreme value of the range of inertia factor values. In the traditional particle swarm algorithm, the position of the previous moment determines the optimal position of the particle. However, in the actual motion of particles, the surrounding particles will have an impact on the current particle motion, so inspired by hormone regulation, a hormone factor is added to the particle swarm algorithm to enhance the local search characteristics of the particles, and the corresponding update equation is shown in Eq. (13).

$$\begin{cases} V_i(k+1) = \omega \times V_i(k) + C1 \times \text{rand1}(\ ) \times (\text{Xpbesti}(k) - X_i(k)) \\ +C2 \times \text{rand1}(\ ) \times (\text{Xpbesti}(k) - X_i(k)) \\ X_i(k+1) = V_i(k+1) + X_i(k) + \text{HF} \end{cases} \tag{13}$$

The main determinants of particle motion include three aspects, which are the initial position $X_i(k)$, the velocity $V_i(k+1)$ determined by the optimal position of the particle and the global optimal position, and the regulation factor HF. The corresponding particle motion is show in Fig. 3.

5. Analysis of optimal scheduling results for automatic flood control

To test the effectiveness of the above flood control model of the pump gate clusters, the study adopts the optimal flood control scheduling dealing with once-in-a-century flood and once-in-two-centuries flood. Taking city A as an example, the optimal flood control scheduling results are obtained as shown in Table 1. When a once-in-a-century flood occurs in city A, the maximum discharge flow of reservoir B is 1,996.16 m^3/s after automatic optimal scheduling of the pump gate clusters, and the maximum discharge volume of reservoir C is reduced to 16,738.28 m^3/s after the optimization of step scheduling, which reduces the risk of flooding in city A. When a once-in-a-century flood occurs in city A, the maximum discharge flow of reservoir B is 3,378.38 m^3/s after optimized scheduling, while the maximum discharge flow of reservoir C reaches 18,340.88 m^3/s after optimized scheduling. In conclusion, no matter facing which kind of flood, the maximum water levels of reservoirs B and C are controlled under their respective flood control water lines, thus improving the flood control efficiency and resource utilization rate of the two reservoirs and ensuring the safety of people near the two reservoirs.

According to the "City A Flood Control Planning Report", the flood control facilities in city A that do not meet the 50-y-period standard, regardless of whether they are key protection areas or ordinary protection areas, should be constructed to meet the standard by the end of 2020. At present, city A has already met the relevant dike construction requirements, and the overall flood control construction has met the 50-y-period standard. Combined with the report of dike construction in city A, the water surface

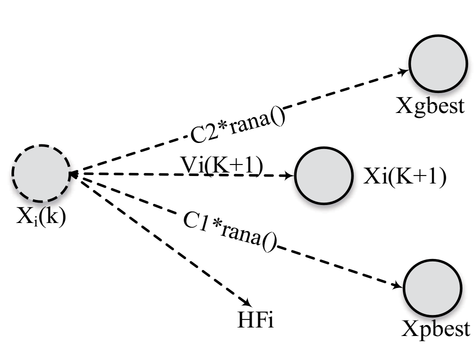

Fig. 3. Schematic of particle motion of particle swarm optimization algorithm based on hormone regulation.

Table 1
Flood control optimization results of city A

Recurrence period (y)	Reservoir B			Reservoir C			
	Peak clipping rate (%)	Maximum discharge flow ($m^3·s^{-1}$)	Highest water level (m)	Peak clipping rate (%)	Maximum discharge flow ($m^3·s^{-1}$)	Highest water level (m)	Peak clipping rate (%)
100.00	74.52	1,996.16	229.00	15.57	19,823.17	16,738.28	84.14
200.00	72.77	3,378.38	229.00	18.05	22,379.05	18,340.88	84.14
200 (original setting)	38.11	7,300.01	229.00	14.82	21,600.01	18,400.01	84.21

Table 2
Relationship between water level and flow in the river of city A

Z (m)	59.80	62.00	63.00	64.00	65.00	66.00	67.00	68.00	68.20
Q ($m^3·s^{-1}$)	0.00	191.00	561.00	1,081.00	1,681.00	2,341.00	3,071.00	3,831.00	4,601.00
Z (m)	69.20	70.20	71.16	72.16	73.21	74.21	75.31	76.56	77.94
Q ($m^3·s^{-1}$)	5,401.00	6,201.00	7,051.00	7,901.00	8,801.00	9,801.00	10,901.00	12,101.00	13,501.00
Z (m)	79.10	80.13	81.16	81.71	81.89	81.89	81.89	\	\
Q ($m^3·s^{-1}$)	14,901.00	16,351.00	17,801.00	18,401.00	19,301.00	20,751.00	24,301.00	\	\

calculation model is used to calculate the water flow relationship in the basin for the middle and high water level sections. The water level flow relationship after the construction of dike in city A is shown in Table 2.

According to Table 2, when the water level is higher, the river flow is higher. In addition, because reservoir C is located in the suburban area of city A, which is slightly remote, and also the basin has almost no intersection with the urban basin, the tampering deformation caused by the discharge of reservoir C to city A is not considered. The discharge from reservoir C was simulated as the discharge from city A, and the process of water level change under differentiated frequency was calculated as shown in Fig. 4.

From Fig. 4, when the time amount is [0,8], the water level change rate corresponding to P = 1% is faster. When the time amount is [8,18], the water level change rate corresponding to P = 0.5% is faster. When the time amount is [18,28], the water level changes under the two frequencies are consistent and both are in a constant state. When the time amount is [28,30], the water level change rate under the condition of P = 1% is first decreased and then increased, which is generally in an inverted U-shape. When the time amount is [30,55], the water level changes corresponding to the two frequencies are almost synchronous. When the time amount is [55,60], the water level drops faster when P = 1%. In order to further analyze the impact of the automatic optimal operation model of this study on the basin security, the river flow after optimal operation is discussed, and the corresponding results are shown in Fig. 5

From Fig. 5, after the processing of the flood control optimization operation model, the maximum frequency peak value of the once-in-a-century flood in city A is 16,738.28 m³/s, and the maximum frequency peak value of the once-in-two-centuries flood is 18,340.88 m³/s, and the respective highest water levels are 80.41 and 81.66 m, respectively, both of which are lower than the actual overtopping water level of the embankment in city A, namely 1.49 and 0.24 m. They are all within the safe flood control water level range of city A, thus the safety of people's lives and property in city A effectively ensured. In order to further verify the effectiveness of optimal scheduling technology, the calculation results of optimal scheduling are compared with those of conventional scheduling, and the results are shown in Table 3.

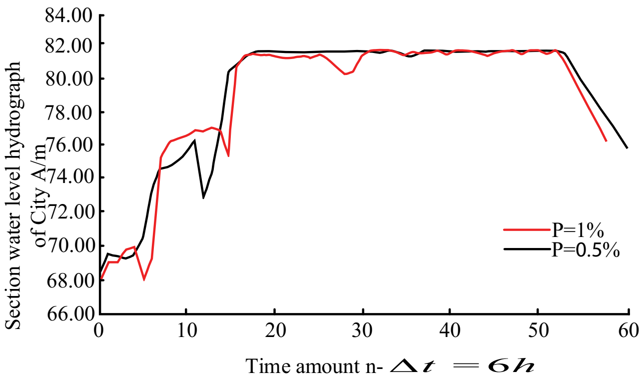

Fig. 4. Water level change process of city A section.

Table 3 shows the scheduling results of five basins in a region. Z_{max} is the highest operating water level, and T is the time length when the water level exceeds the flood control high water level. After optimized operation, the highest water level of the five basins has decreased, of which the drop of basin 3 is the largest, reaching 0.26 m. In terms of T, T of basins 1 and 4 after optimized scheduling is lower than that before optimization, and only T of basin 2 after optimization is higher than that before optimization.

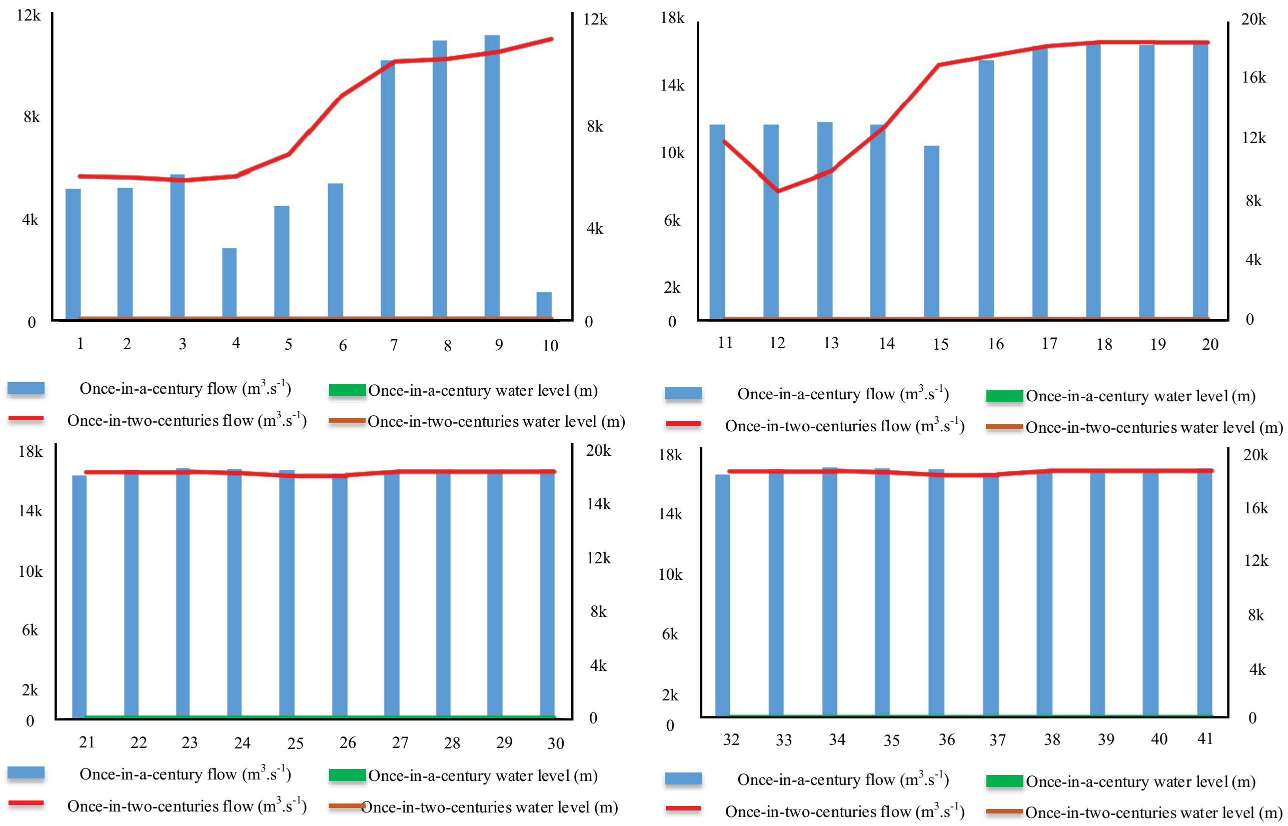

Fig. 5. River flow of city A after optimization and scheduling.

Table 3
Comparison results of optimized scheduling and conventional scheduling

Indicators	Regular scheduling		Optimized scheduling		Difference	
	Z_{max} (m)	T (h)	Z_{max} (m)	T (h)	Z_{max} (m)	T (h)
Basin 1	20.23	27.0	20.03	24.3	0.2	2.7
Basin 2	19.65	15.6	19.57	20.6	0.08	–5
Basin 3	18.77	\	18.51	\	0.26	\
Basin 4	19.31	41.9	19.29	38.4	0.02	3.5
Basin 5	18.86	\	18.81	\	0.05	\

6. Conclusion

In the research of automatic scheduling control technology for pump gate clusters in regional water conservancy projects, selecting an appropriate optimal scheduling algorithm is one of the most critical steps. This research takes hormone regulation and particle swarm optimization algorithm to construct the automatic optimal operation model for flood control of pump gate clusters. This model can regulate the maximum discharge flow and the highest water level according to the storage capacity of the reservoir, so as to achieve effective prevention of flood disasters. In order to verify the applicability of the model, B and C reservoirs in A city are taken as experimental objects to carry out research. The results show that the maximum discharge flow after automatic optimal operation of pump gate clusters is 1,996.16 m^3/s, and the maximum discharge flow of reservoir C after cascade operation optimization is reduced to 16,738.28, reducing the risk of flood in city A. In addition, the peak water level adjustment results suggest that after the processing of the proposed model, the highest water levels of the once-in-a-century flood and the once-in-two-centuries flood in city A are 80.41 and 81.66 m, respectively. Both water levels are lower than the overtopping water level of the levee in city A, and both are in a safe position, which is significant for the reduction of flood disasters in city A. Although this study has certain significance for the research on automatic flood control and scheduling of pump gate clusters in regional water conservancy projects, there is still a problem of less sample data selection in the experiment, which needs to be further improved in the future.

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