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Strategic Water Management in the Great Lakes: Integrating Network Models and Optimization

Jingpeng Liu[1, *], Qingyun Chen[2], Yifan Lu[2]

[1]College of Informatics, Huazhong Agricultural University, Wuhan, China, 430070

[2]College of Public Administration, Huazhong Agricultural University, Wuhan, China, 430070

*Corresponding author: 15871975903@163.com

Abstract. The Great Lakes are the largest freshwater system in the world and have a significant impact on local social development and people's lives. To address the complex water level management challenges in the North American Great Lakes region, this study develops a network model and optimization algorithm for simulating the dynamics of the Great Lakes and their Atlantic tributaries. This study scientifically determines the optimal water level of the Great Lakes for each month of the year based on multi-objective planning theory, and uses an improved PID algorithm to regulate the dams to maintain the optimal water level, while considering the Great Lakes' significant economic, ecological, and social values in the context of climate change uncertainty and stakeholder conflict. The study strives to balance these aspects to provide a solid foundation for ecological conservation, economic growth, and climate resilience, as well as a viable strategy for Great Lakes water optimization issues.

Keywords: Great Lakes Water Level Management; Network Flow Modeling; Multi-objective optimization; PID control algorithm.

1. Introduction

The Great Lakes, spanning the US-Canada border, are the largest freshwater system globally. They cover 245,000 square kilometers, contain 22,700 cubic kilometers of water, and provide 21% of the world's surface freshwater. Managing their water levels is a complex challenge due to natural factors like rainfall, evaporation, and climate change, as well as human impacts. Effective management strategies, particularly for Lake Ontario, require collaboration across disciplines in meteorology, hydrology, environmental science, and socio-economics. Advanced technologies and models help anticipate water level variations and ensure sustainable limits for various needs.

Lake water level management is crucial for sustainability and conservation, requiring precise hydrological models and effective strategies. Models range from physical to conceptual, important for resource management as indicated by Singh et al.(2018) [1], with integrated management underscored by The World Bank et al.(2016). Optimizing control amidst uncertainties uses approaches like dynamic programming, highlighted by Tayfur et al.(2017) [2]. Bertram et al. (2019) present an integrated and optimal water resources management approach for multidisciplinary water resources management problems [3]. However, existing studies often overlook the integration of socio-economic factors with ecological impacts, a gap critical for holistic management. Enhancing models, strategies, and impact assessments is vital for addressing lake management challenges comprehensively.

To solve the above problems, we established a network model of the Great Lakes based on existing research and integrated various factors to determine the optimal water level of the Great Lakes. At the same time, we controlled the flow rate of each dam according to the PID algorithm to ensure the optimal water level.

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2. The basic fundamentals of the Great Lakes network

2.1. The structure of the Great Lakes network

We use theories related to operations research, such as graphs and networks, to model the Great Lakes and their surrounding rivers as a network [4]. In this network N, all lakes constitute the set of lakes V, $V = \{V_i\}$. Since the Lake Michigan River, Lake Huron, has essentially the same water level elevation, we treat it as one lake(V_2); A collection of all rivers: $A = \{a_{ij}\}, (i = 1,2, \ldots, 6)$, Each river is assigned a non-negative weight c_{ij}, constituting a capacity matrix $C = \{c_{ij}\}_{n\times n}$. Its elements are specified as:

$$c_{ij} = \begin{cases} 0\,, i = j \ or \ (V_i, V_j) \notin A \\ c(i,j)\,, i \neq j \ and \ (V_i, V_j) \in A \end{cases} \tag{1}$$

In this network, V_1 denotes the starting point which only associates outflow arcs; V_6 denotes the termination point which only associates inflow arcs. Since Lake Michigan, Lake Huron (V_2) , and Lake St. Clair (V_3) have similar water level heights, a_{23}, a_{34} can be viewed as two-way connecting arcs; the rest are one-way connectivity arcs. f_{ij} denotes the flow from lake i to lake j; $F = \{f_{ij}\}_{n\times n}$ denotes the traffic matrix consisting of all river traffic of the network, whose elements are specified as:

$$f_{ij} = \begin{cases} 0\,, i = j \ or \ (V_i, V_j) \notin A \\ f(i,j)\,, i \neq j \ and \ (V_i, V_j) \in A \end{cases} \tag{2}$$

For all rivers in the network structure N, the following constraints should be satisfied:

(1)River capacity constraints:

$$0 \leqslant f_{ij} \leqslant c_{ij}, \forall (V_i, V_j) \in A \tag{3}$$

(2)River flow asymmetry:

$$f_{ij} = -f_{ji}, \forall (V_i, V_j) \in A \tag{4}$$

(3)Lake flow balance conditions:

$$f_i^+ - f_i^- = \begin{cases} \mathrm{val}\ f, i = s \\ -\mathrm{val}\, f\,, i = t \\ 0, \forall i \in V/\{s,t\} \end{cases} \tag{5}$$

The network structure is shown in Figure 1.

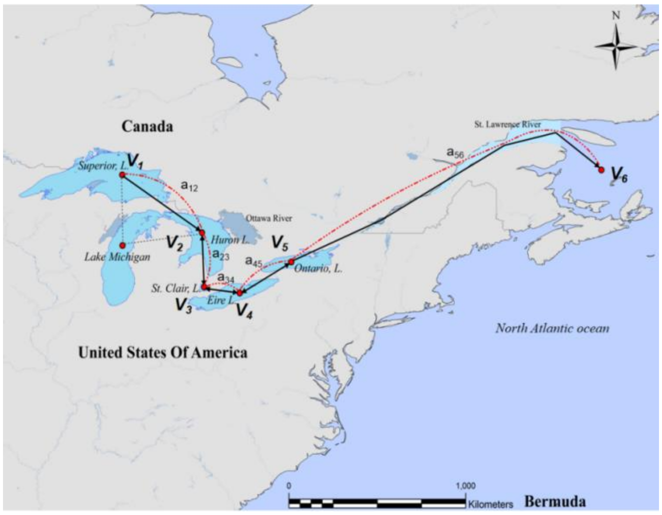


Figure 1: Structure of the Great Lakes network

2.2. Modeling water level dynamics using difference equations

Based on Figure 2, each lake can be approximated as an inverted cone, where the maximum depth of the lake denotes the height of the cone and the distance along the flow path denotes the diameter of the cone [5]. Based on the Great Lakes water level information, river flow information, and precipitation and snowfall provided by the U.S. Hydrologic Network, this study uses numerical simulation to calculate lake level changes. The process is described below:

Step1. Calculation of changes in water level due to river inflow and outflow

The lake structure is simulated as shown in Figure 2.

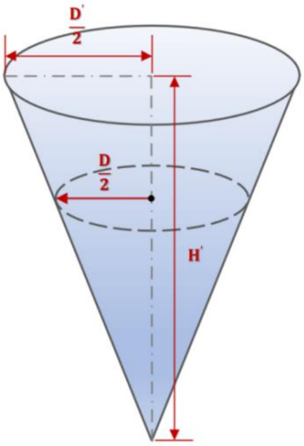


Figure 2: Lake structure simulation

According to the cone volume formula:

$$V = \frac{\pi}{3}\left(\frac{D}{2}\right)^2 H \tag{6}$$

Setting the angle of the cone pinch at θ, we have:

$$tan\frac{\theta}{2} = \frac{\frac{D}{2}}{H} = \frac{\frac{D'}{2}}{H'} = \frac{\frac{\Delta d}{2}}{\Delta h} \tag{7}$$

Let f_{jm} denote the flow from lake i to lake j, then the total volume of lake j is:

$$V' = V + \sum f_{ij} - \sum f_{jm} \tag{8}$$

Joining the above three equations yields the difference equation for h:

$$\frac{\pi}{3}\left(\frac{D}{2}\right)^2 H + \sum f_{ij} - \sum f_{jm} = \frac{\pi}{3}\left(\frac{D}{2} + \Delta h tan\frac{\theta}{2}\right)^2 (H + \Delta h) \tag{9}$$

It is possible to find the change in water level (Δh).

Step2. Calculation of evaporation

According to the Averjanov formula:

$$E_g = E_0\left(1 - \frac{\Delta}{\Delta_m}\right)^n \tag{10}$$

E_g denotes the submersible evapotranspiration;$E_0$is the evapotranspiration capacity; Δ, Δ_m and n are parameters.

Step3. Calculation of infiltration recharge from rainfall (snow)

Neglect volume changes due to snow melting into water. Since the infiltration recharge coefficient varies with rainfall:

$$a = \frac{dr_g}{dP} \tag{11}$$

r_g is infiltration recharge in m; P is rainfall in m.

By reviewing related information, we found that the infiltration recharge coefficients in the Great Lakes region of the U.S. varied within 1%, and in order to avoid overly complex model calculations, we assumed that the infiltration recharge coefficients, a , were constant values [6].

According to the initial value conditions:

$$r = 0, P = 0 \tag{12}$$

Get:

$$r_g = aP \tag{13}$$

In summary, the amount of water level change $\Delta h'$ is satisfied:

$$\frac{\pi}{3}\left(\frac{D}{2}\right)^2 H + \sum f_{ij} - \sum f_{jm} = \frac{\pi}{3}\left(\frac{D}{2} + \Delta h tan\frac{\theta}{2}\right)^2 (H + \Delta h) \tag{14}$$

$$\Delta h' = \Delta h + r_g - E_g \tag{15}$$

2.3. Multi-objective planning model for determining optimal water levels

Water level regulation in the North American Great Lakes involves numerous factors, and each lake has its own specific regulatory needs, adding complexity to the study. To tackle these intricate and uncertain challenges, we propose modeling water level regulation through a robust two-tier multi-objective planning approach, using Lake Ontario as a case study.

Since the water level regulation of the North American Great Lakes is a multi-objective, multi-benefit, and multi-contradiction system, the choice of the number of objectives must not be excessive, considering not to make the model scale too large [7]. We consider the three objectives of economic growth, ecological environment, and social benefits separately. The weighting values of these three objectives can be adjusted according to different scenarios to reflect the importance of different interest expectancies. Assume that the weight of economic benefits is α, the weight of environmental benefits is β, and the weight of social benefits is γ. In this way, we can construct the comprehensive benefit objective function as shown below:

$$\max F(x) = \alpha f_1(x) + \beta f_2(x) + \gamma f_3(x) \tag{16}$$

where $f_1(x), f_2(x), f_3(x)$ represent the desired water level change functions for economic growth indicators, ecological environment indicators, and social benefit indicators respectively

For each lake level W under a defined goal, assume that the change in expectation of the ith stakeholder under that goal for that lake level is Δh_i and the weight is E_i, then the combined change in expectation for that lake level can be expressed as:

$$E_j = \sum_{i=1}^{I} \Delta h_i \ E_i \tag{17}$$

2.4. Flow control system based on PID algorithm

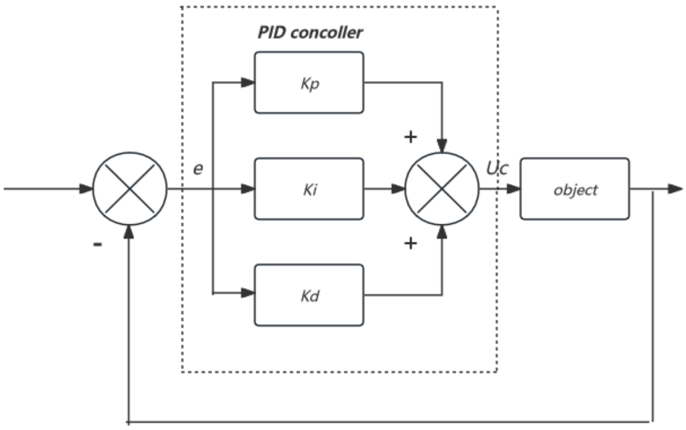


Figure 3: The structure of PID

The PID algorithm is a linear feedback control algorithm commonly used in industrial control for regulation. The PID controller adjusts its output based on the difference between the setpoint and the actual value using three components: proportional, integral, and derivative, aiming to achieve stable control of the system [8]. Its structure is shown in Figure 3.

The output relationship of the PID controller is:

$$U_c = K_p e + K_i \int_0^t edt + K_d \frac{de}{dt} \tag{18}$$

Discretize the above equation:

$$U_c = K_p e_i + K_i \sum_{i=1}^{N} e_i + K_d \frac{e_i - e_{i-1}}{\Delta t} \tag{19}$$

Let $K_d = \frac{K_d}{\Delta t}$,that is:

$$U_c = K_p e_i + K_i \sum_{i=1}^{N} e_i + K_d (e_i - e_{i-1}) \tag{20}$$

The input is X and the output is Y, Then Eq:

U_c denotes the controller output;

e denotes the error between the desired output and the actual output, that is:$e=X-Y$;

K_p, K_i, K_d are the proportionality coefficient, integration coefficient, and differentiation coefficient, respectively.

Compared to traditional closed-loop control systems, each lake needs to consider the influence of meteorological and environmental factors on water levels. Therefore, we have added a disturbance detector and a controller to the control system to eliminate errors caused by external factors, such as flow rate, as shown in Figure 4:

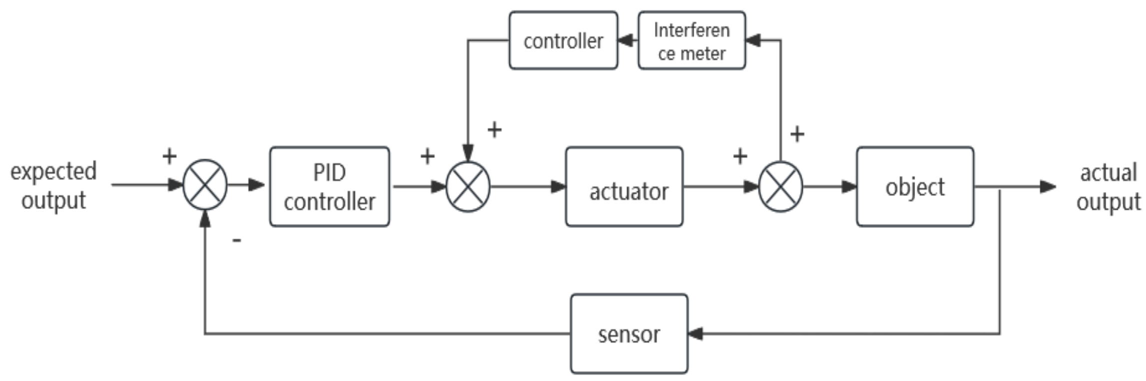


Figure 4: Feedforward-feedback composite control system for a single dam

3. Results

3.1. The establishment of the simulation model

This experimental model is implemented via Python and Matlab.

3.2. Determining Optimal Water Levels

Using Lake Ontario as an example, we can obtain the following expression for the optimal water level H that meets the overall expectations of all stakeholders:

$$maxH = h + \Delta h' + F(x) + \max(min\sigma) \tag{21}$$

And:

$$\max F(x) = 0.3f_1(x) + 0.2f_2(x) + 0.5f_3(x) \tag{22}$$

where $\max\ (min\sigma)$ is typically used to enhance the robustness of the model and to ensure that the resulting optimal water level takes into account the variability and uncertainty of the constraints.

In addition to the network flow modeling constraints we established earlier we have to ensure lake water level constraints:

$$W_{min} \le W_{(t)} \le W_{max} \tag{23}$$

And River inflow-outflow constraints:

$$Q_{min} \le Q_{(t)} \le Q_{max} \tag{24}$$

Since the Great Lakes water levels did not pass the normality test and did not conform to a normal distribution, we first performed a normal transformation. The transformed index X_i obeys a normal distribution: $X_i \sim N(\mu, \sigma^2)$, and the optimal water level range bandwidth is P_j.

Since we are more concerned with the impact of extreme values than the majority of the range of the data. Thus, based on the principle of minority, 1/3 of the index year X_i was taken as the safety interval for the water level, expressed as follows:

$$P = \{|X_i - \mu| < P_j\} = 1/3 \to P_j = 0.43\sigma \tag{25}$$

Then the optimal water level lies in the range $(\mu - 0.43\sigma, \mu + 0.43\sigma)$.

Final rankings were obtained for the best water scores for Lake Ontario and the rankings were processed:

$$W = \frac{T}{N} \times 100\%(\text{N: all intervals; T: optimal interval}) \tag{26}$$

We compared the solution results with the 2017 Lake Ontario lake levels and found that the upper boundary of the warning water level interval we modeled was significantly lower than the 2017 extreme levels. This justifies the optimal water level interval we established, as shown in Figure 5:

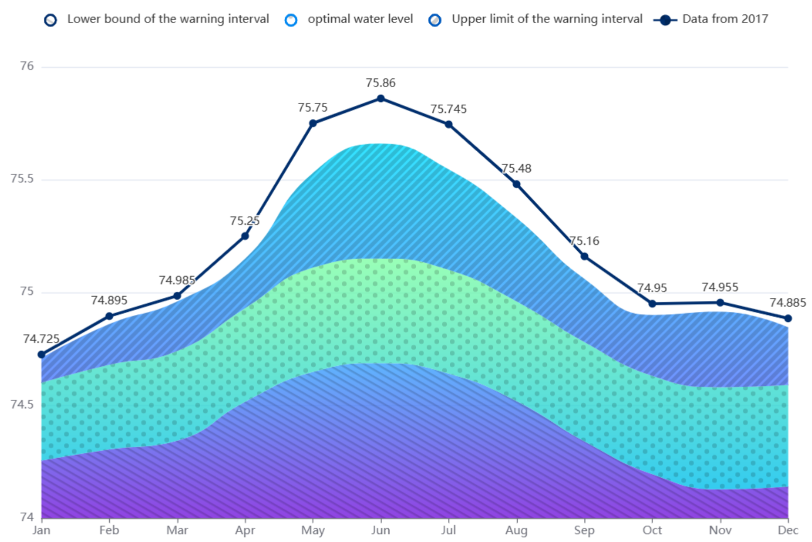


Figure 5: Optimum Lake Ontario water levels and their warning intervals

We have generalized the modeling of optimal water levels in Lake Ontario lakes that we have established and have determined optimal water levels for the Great Lakes throughout the year. The optimal water levels shown in Table 1 may not satisfy everyone, but they best meet the overall expectations of different stakeholders.

Table 1: Optimal water level of the Great Lakes

Date / *Lakes*	*Lake Superior*	*Lake Michigan and Lake Huron*	*Lake St. Clair*	*Lake Erie*	*Lake Ontario*
Jan	183.49	176.43	175.08	174.22	74.6
Feb	183.43	176.4	175.04	174.22	74.68
Mar	183.39	176.39	175.15	174.3	74.74
Apr	183.43	176.44	175.26	174.42	74.93
May	183.53	176.52	175.34	174.51	75.11
Jun	183.62	176.58	175.41	174.55	75.15
Jul	183.68	176.58	175.43	174.54	75.1
Aug	183.69	176.54	175.39	174.46	74.96
Sept	183.69	176.46	175.31	174.36	74.78
Oct	183.67	176.37	175.21	174.27	74.63
Nov	183.63	176.29	175.12	174.2	74.58
Dec	183.57	176.23	175.12	174.2	74.59

3.3. Simulation and Emulation

To verify the performance of the PID controller, simulation experiments of the controller are performed in the MATLAB 2020a environment:

We took Lake Superior and Lake Ontario as the study subjects in 2017 and initialized the parameters. The PID parameters and geographical parameters are shown in Table 2 and Table 3 respectively.

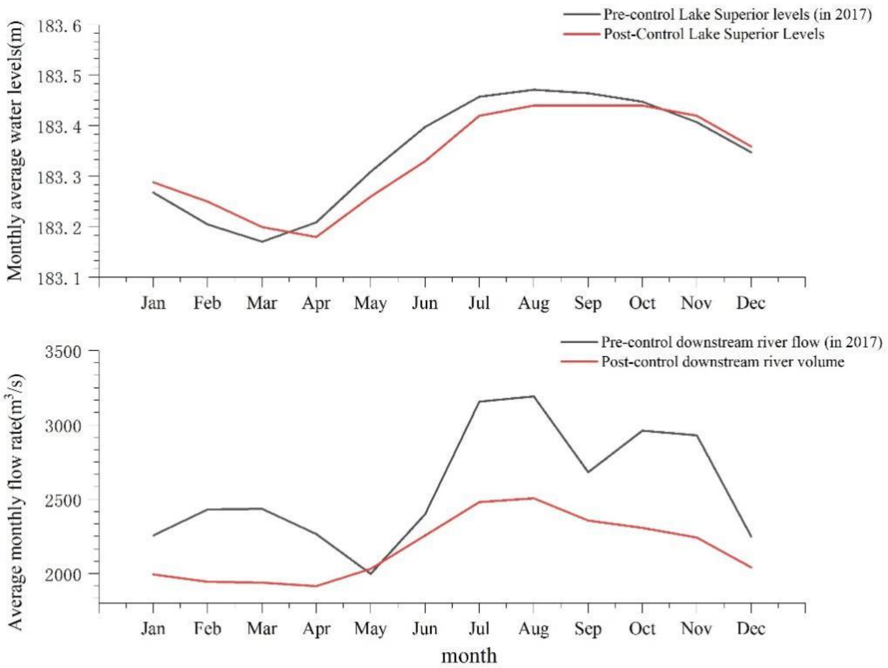
Table 2: PID parameters

PID parameters	value
K_p	0.36
K_i	0.025
K_d	0

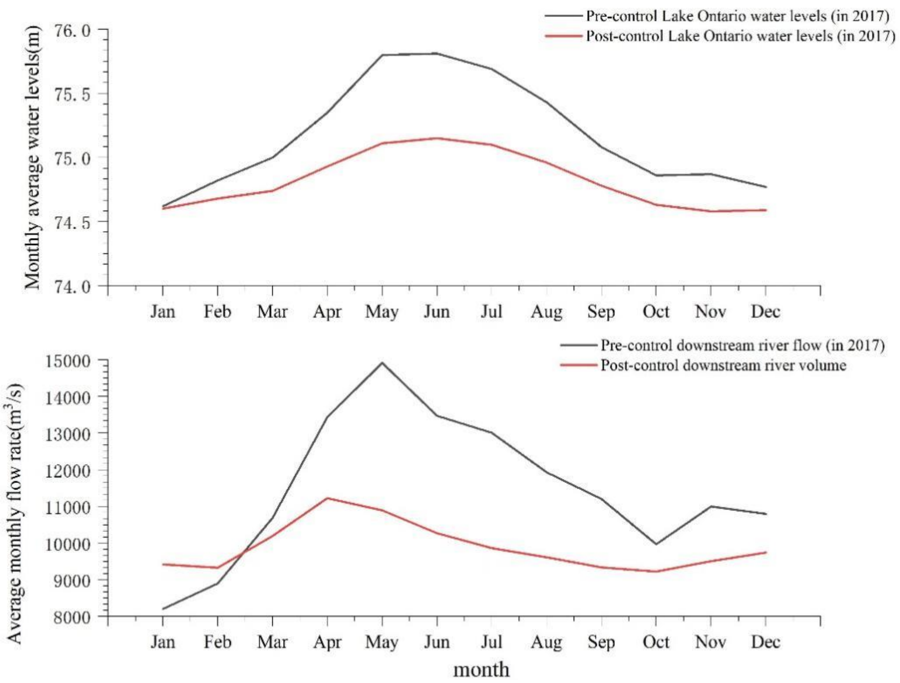
Table 3: geographical parameters

geographical parameters	value
H_a	244m
D_a	74m
H_s	406m
D_s	183m
a	7.5cm

Based on the 2017 river flow data we collected for the Great Lakes, we applied the PID algorithm to simulate and obtain flow data for the Great Lakes after control. The comparison of Great Lakes flows before and after control is shown in Figure 6.



(a) Changes before and after control of sluice gate compensation projects in lower Lake Superior



(b) Changes before and after control of the Moses Sanders Dam on lower Lake Ontario

Figure 6: Changes before and after control dam control

Observing the compensation projects at downstream of Lake Superior and the Moses-Saunders Dam at downstream of Lake Ontario, it is evident that algorithmic control has had a significant impact. In the case of Lake Superior, the water level, which generally exhibits a periodic variation resembling a cosine function throughout the year, has seen a noticeable reduction in amplitude and a delay in its fluctuations after algorithmic control. Additionally, the downstream river flow, subject to algorithmic control, no longer experiences abrupt surges and drops but instead follows a smoother trend, aligning its variations with the changes in the lake's water level [9].

For the Moses-Saunders Dam at Lake Ontario, the controlled water levels within the lake have been maintained within the desired range, meeting the requirements of all stakeholders and avoiding extreme situations like the high water levels observed in the spring and summer of 2017. Algorithmic control has also allowed the downstream river flow to remain stable, ensuring a consistent water supply to downstream areas and balancing the overall interests of all stakeholders [10].

4. Conclusions

In conclusion, this study provides a strategic framework for addressing the complexities of water level management in the North American Great Lakes, specifically through a detailed examination of Lake Ontario. Utilizing a network model combined with a two-tier multi-objective optimization approach, we propose a novel solution that effectively navigates the intricacies of balancing ecological, economic, and social interests related to water levels. Our approach prioritizes adaptability and precision in water level regulation, leveraging historical data and environmental variables to anticipate and respond to changing conditions. This methodology represents a significant step forward in the sustainable management of freshwater resources, offering a comprehensive model that could be adapted to similar environmental challenges globally.

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