

Optimization of water level management in the Great Lakes based on simulated annealing and Kalman filtering

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Abstract. This paper focuses on the water level management problems in the Great Lakes, and addresses the challenges of optimal water level regulation in the Great Lakes through methods such as simulated annealing multi-objective optimization algorithm and Kalman filter hydrological model. First, the simulated annealing algorithm was used to analyze the influence of each interest factor on the water level, and the interest balance point was established as the optimization objective function to obtain the optimal water level in the Great Lakes. Second, a Kalman filter hydrological model was introduced to keep the water level of the lakes fluctuating around the optimal level by monitoring and adjusting the inflow and outflow data of the lakes in real time to adapt to the effects of climate change and anthropogenic factors. Finally, a hierarchical analysis was applied to assess the importance of each stakeholder for water level management and to verify the robustness and reliability of the algorithm in case of conflicting interests. This study can provide scientific decision support for water resource management in the Great Lakes region.

Keywords: Water level management optimization, simulated annealing, Kalman filtering.

1. Introduction

In water resource management, optimizing water level management is essential to maintain ecological balance and meet human needs^[1-2]. The aim of this study is to propose a multi-objective optimization algorithm based on simulated annealing and Kalman filtering to solve the complex problems in water level management of the Great Lakes. First, the influence of each interest factor is analyzed by the simulated annealing algorithm, and the interest balance point is established as the objective function to satisfy the interests of all parties. Second, a Kalman filter model was used to dynamically adjust hydrologic data to cope with the effects of climate change and anthropogenic factors. The study aims to provide a scientific basis for lake water level management, protect the ecological environment and improve the efficiency of water resources utilization^[3-4].

2. Multi-objective Optimization Algorithm Based on Simulated Annealing

In the thinking of problem one, this paper analyzes the problem and establishes the interest balance point as the objective function by simulated annealing multi-objective optimization algorithm under the influence of various interest factors. The influence of rainfall, evaporation, natural inflow and outflow, industrial water consumption, and cost budget are selected to obtain the optimal water level as the constraint condition to solve the optimal water level problem of the five lakes^[5-6].

Through analysis, we adopt the total evaluation function $S(X)$ of the interests of all parties in the Great Lakes block as the main function of the simulated annealing multi-objective optimization problem in the Great Lakes block.

objective function:

$$\min \sum_{j=1}^n \omega_j \cdot f_j(V) \quad (1)$$

$$D_i = a_i \cdot (h_i - b_i)^2 + c_i \quad (2)$$

$$O_i = \sum_i (Cost_i \cdot Inflow_i + Benefit_i \cdot Demand_i) \quad (3)$$

$$O_i = \sum_i (Benefit_i \cdot Demand_i - Cost_i \cdot Inflow_i) \quad (4)$$

$$\text{minimize } J(h, E, U) = \alpha \int (h - h_{\text{target}})^2 dt - \beta \int E(t) dt - \gamma \int U(t) dt \quad (5)$$

The main constraints We select a variety of factors as constraints, such as rainfall, evaporation, natural water intake and water output, industrial water consumption, cost budget, and so on^[7].

The results show that the optimal water levels of the five lakes obtained by finite iterations are shown in table 1.

Table 1 the optimal water levels of the five lakes

	Name	Water level
0	St. Mary's River	1520.74
1	St. Clair River	4784.54
2	Detroit River	5399.02
3	Niagara River	6569.00
4	Ottawa River	1880.00
5	St. Lawrence River	7559.59
6	Lake Superior	182.09
7	Lake Michigan and Lake Huron	175.04
8	Lake St. Clair	174.08
9	Lake Erie	173.40
10	Lake Ontario	73.62

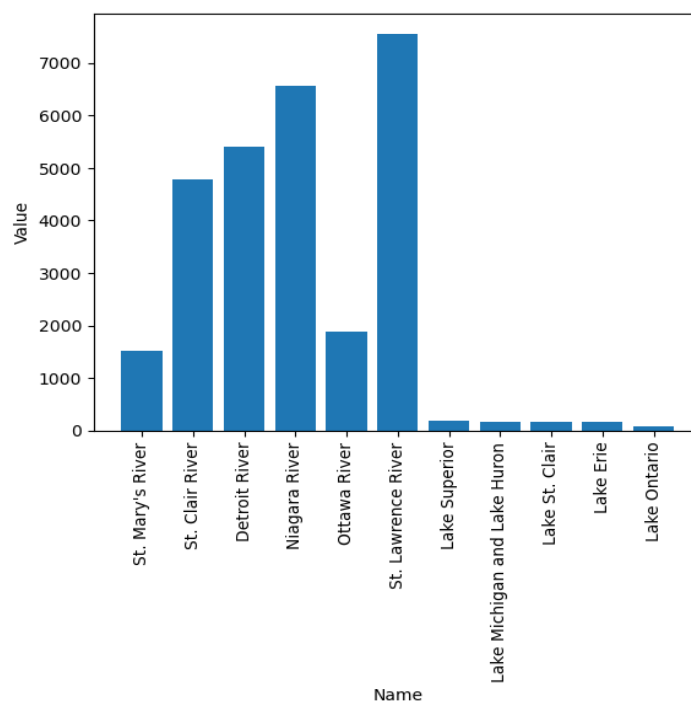


Figure 1 Data on lakes and rivers

Data on lakes and rivers is shown in figure 1.

Historical data analysis and real-time monitoring and adjustment:

$$J_{\text{hist}}(h, E, U) = \alpha \int (h - h_{\text{target}})^2 dt - \beta \int E(t) dt - \gamma \int U(t) dt \quad (6)$$

$$J_{\text{real-time}}(h, E, U) = \alpha \int (h - h_{\text{target}})^2 dt - \beta \int E(t) dt - \gamma \int U(t) dt \quad (7)$$

3. Kalman Filter Water Hydrology Model

In the second question, the algorithm must prioritize dynamic adjustments to address the combined impacts of climate change and human factors. Consequently, this study examines the natural recharge and human intervention aspects of the lake, and develops a Kalman filter-type hydrological model using the lake's inflow and outflow data. The model operates on a monthly time unit to regulate the water level of the five main lake sections in real time, aiming to closely maintain the optimal water level determined in the first question of this study. Establish a water balance model for the Great Lakes, incorporating current water volume, inflow and outflow, rainfall, evaporation, and manual intervention flow through monthly data, to sustain the Great Lakes at their optimal water level^[8-9].

Based on the subject, we can devise a water flow control algorithm for two water control dams to manage the water level of the five lakes and uphold the optimal water level with respect to manual intervention flow.

Initially, the parameters of the Kalman filter are defined, as well as the target water level data. The

$$X_1(n) = X^{(n+1|y(1), \dots, y(n))} = \sum_{k=1}^n W_1(k) \alpha(k) \quad (8)$$

According to the principle of orthogonality, the estimation error of the optimal prediction,

$$e(n+1, n) = x(n+1) - x_1(n+1) \quad (9)$$

should be orthogonal to the known value, so there is,

$$E\{e(n+1, n) \alpha^H(k)\} = E\{[x_1(n+1) - x(n+1)] \alpha^H(k_1)\} \quad (10)$$

$$\frac{dV_i}{dt} = Q_{in,i} - Q_{out,i} + P_i - E_i - I_i, i = 1, 2, \dots, 5 \quad (11)$$

$$S_i = k_2 \cdot (h_{\text{target}i} - h_i) \quad (12)$$

simulation time is set on a monthly basis. Following 12 rounds of observation control and simulation adjustment, the water level of the Five Great Lakes is maintained at the optimal water level^[10].

The initial water level state value for each initial cycle section of the five lakes is set to 0. For each water flow adjustment, the current target water level is first monitored and obtained, and then the participating month for water flow control in the cycle is input. Finally, the water level control and Kalman filter are simulated, the prediction steps of the Kalman filter are executed, and the real-time change curve of the water level is plotted in figure 2.

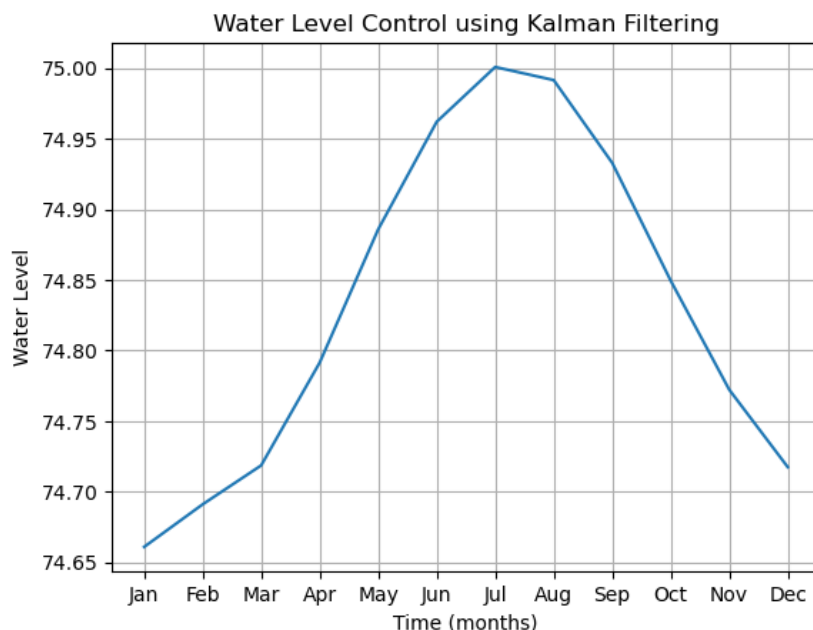


Figure 2 Water Level Control using Kalman Filtering

4. The Analytic Hierarchy Process

It can be seen from the question that through the sensitivity analysis of the data in 2017, the performance of the new algorithm in the situation of conflicts of interest among various stakeholders is evaluated, and the performance of the algorithm in balancing the interests of various stakeholders is discussed through comparison and sensitivity analysis. We carried out the analytic hierarchy process (AHP) on each stakeholder, and obtained different weight values to prove the rationality and reliability of the analysis of the five major lake water level control algorithm model in this paper. The application in practice can provide support for the final optimal water level maintenance decision.

For the stakeholders who pay attention to the water level management of the Great Lakes, we rank the importance according to their nature, give them corresponding weights according to their importance, and visualize the data. Then, according to the corresponding scale value of each stakeholder's satisfaction with the water level, the scoring matrix is constructed. Compared with the actual recorded water level data, the comparison matrix passes the consistency test, and the weight values of each stakeholder are obtained respectively. Then calculate the comprehensive weight of stakeholders to get the total score.

Finally, the sensitivity analysis of the AHP results is carried out to test the sensitivity of the model to the change of weight, which proves that the optimal water level control model of the five lakes in this paper is robust.

5. Kalman Filter Model

Kalman filter: A linear filter for estimating the state of a dynamic system that optimizes the estimation of the state of the system by minimizing the square of the error.

Through the interpretation of the fourth problem, this paper digitizes the environmental emergencies through the Kalman filter controller, visualizes the output of the data with the month as the time unit, and draws the real-time change curve of the water level under different environmental conditions, as shown in figure 3.

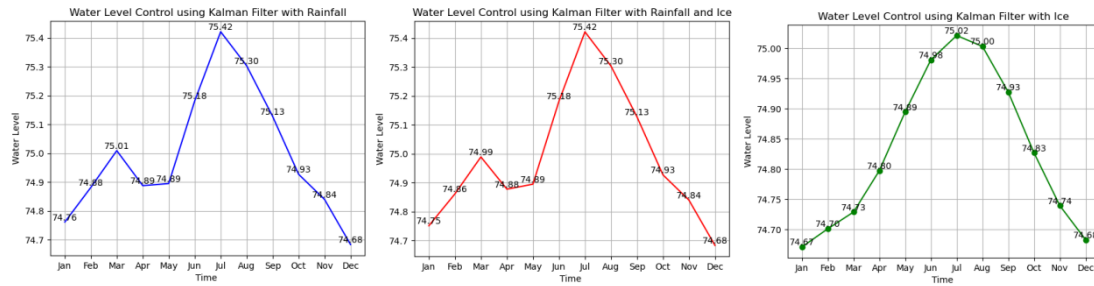


Figure 3 the water level under different environmental conditions.

6. Conclusions

This paper presents a multi-objective optimization approach based on simulated annealing for determining the optimal water levels of the Five Great Lakes. It formulates an objective function, considering various factors such as rainfall, evaporation, natural inflow and outflow, industrial water consumption, and cost budget, while maintaining the interest balance among stakeholders. Through finite iterations, the optimal water levels for each lake are obtained, ensuring an equilibrium among diverse interests.

Additionally, a Kalman Filter Water Hydrology Model is developed to dynamically adjust water levels considering both natural recharge and human interventions, particularly in response to climate change. This model operates on a monthly basis to regulate the water level in real-time, aligning it with the optimal levels determined previously.

Moreover, the Analytic Hierarchy Process (AHP) is employed to evaluate the performance and robustness of the proposed algorithms in managing conflicts of interest among stakeholders. Weight values are assigned to stakeholders based on their importance, and sensitivity analysis is conducted to assess the model's resilience to changes in weight, demonstrating the effectiveness and reliability of the proposed water level control algorithms for the Five Great Lakes.

In conclusion, this study provides a comprehensive framework for optimizing water levels in the Five Great Lakes, integrating simulated annealing, Kalman filtering, and AHP methodologies to address the complex interplay of environmental and human factors while ensuring stakeholder satisfaction and environmental sustainability..

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