

A study of Great Lakes dam regulation based on water level and flow prediction models: application of particle swarm algorithm and LSTM neural network

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Abstract. This study aims to solve the problem of maintaining optimal water levels in the Great Lakes by proposing a dam regulation method based on a water level and flow prediction model. First, a river flow was derived using Manning's formula, and a water level and flow prediction model was developed by combining the effects of rainfall and evaporation on lake inflows and outflows. Secondly, the local optimal solution of the dam was determined using particle swarm algorithm to realize the reasonable regulation of water level. Finally, future rainfall and evaporation were predicted by LSTM neural network to further optimize the predictive ability of the model. The experimental results show that the method can accurately predict the water level changes of the Great Lakes and effectively regulate the dams to maintain the optimal level, which provides an important reference for lake management and protection.

Keywords: Water level prediction, Dam regulation, Neural networks.

1. Introduction

The Great Lakes are located in the most freshwater-rich region of the North American continent and are an important source of freshwater supply and a key component of the ecosystem. However, changes in the water levels of the Great Lakes continue to be of concern due to the effects of climate change and human activities [1-3]. Maintaining optimal levels of Great Lakes water levels is essential to protect the lakes' ecosystems and promote economic development in the surrounding areas. Therefore, it is crucial to develop an effective water level regulation method. Currently, traditional water level regulation methods mainly rely on empirical models and real-time monitoring data, which have problems such as low regulation accuracy and poor adaptability. To solve these problems, this study proposes a dam regulation method based on water level and flow prediction model [4-5]. The method combines the key technologies of river flow prediction, water level prediction and dam control, and utilizes particle swarm algorithm and LSTM neural network to predict and regulate the water level of the Great Lakes from different perspectives. The research focus of this paper is to propose a water level regulation method that integrates meteorological factors, hydrological factors and hydraulic engineering factors to realize accurate prediction and reasonable regulation of the water level of the Great Lakes. Through experimental verification, the method has high accuracy and feasibility, and is expected to provide important technical support and decision-making reference for water resources management and ecological protection in the Great Lakes region [6].

2. Water volume forecasting and dam control models

2.1. Model preparation

To solve the second problem, which is to maintain the optimal water level of the five lakes, it is necessary to control the opening time of the dams. For the opening of dams, it is necessary to predict the water level of each lake in the Great Lakes region at any given time, and it is necessary to consider the effect of rainfall and evaporation on the inflow and outflow of each lake. The overall treatment idea is as follows, Figure 1.

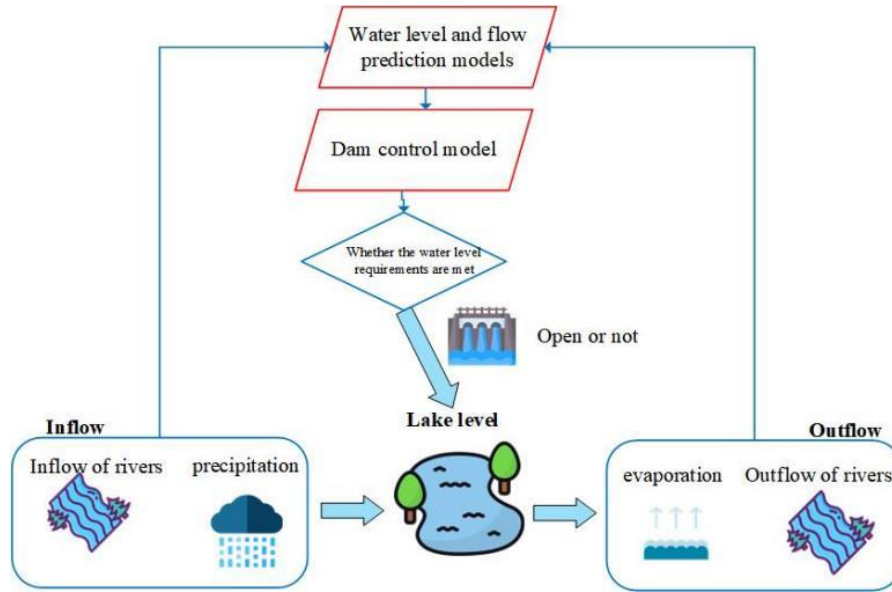


Figure 1. The process of dealing with question two

2.2. Model structure

2.2.1. Water level and flow predictive models

According to the Manning formula:

$$l = \frac{K}{N} D_h^{2/3} \times S^{1/2} \quad (1)$$

l is the velocity, D_h is the hydraulic radius, and S indicates the slope of the canal.

It can be inferred that l is proportional to the square of the height difference, and considering the influence of rainfall and evaporation on the river flow, the flow l can be expressed by the following formula:

$$l_i(t) = b_i \sqrt{\Delta h} + C_i (R_i(t) - E_i(t)) \quad (2)$$

b_i and C_i are constants, and Δh is the height difference.

For the amount of water in each lake, consider the factors that affect the inflow and outflow of the river, as well as the amount of rainfall and evaporation[7-8]. Based on the river flow obtained from the above equation, the volume change of each lake at any given moment can be calculated:

$$V_i(t+1) = V_i(t) + R_i(t) \times \Delta t - E_i(t) \times \Delta t + \alpha \times k_{i-1}(t) \times l_{i-1}(t) \times \Delta t - k_i(t) \times l_i(t) \times \Delta t \quad (3)$$

$$V_i(t) = h_i(t) \times S_i \quad (4)$$

The α is the percentage of loss when the river flows into the lake, and under normal circumstances, the water from each river does not flow completely into the current lake, so the α value is about 0.95, but the water from each lake flows out of the river completely.

k_i ($i=1, 2, 3, 4$) refers to whether the water in the river can flow, and the value of k_i ($i=1, 2, 3, 4$) is 0 or 1. $k_i=0$ indicates that there is no water flowing in the river due to the absence of a river or the closure of a dam, and vice versa. Special instructions, $k_0=0$.

The values of b_i and C_i are obtained by using the least squares method, and the judgment conditions used are as follows:

$$\min \sum_i \sum_t (\hat{h}_i(t) - h_i(t))^2 \quad (5)$$

2.2.2. Dam control model

After the water level of each lake and the flow of the river are predicted, the dam can be controlled according to the water level predicted by the model of the first question. Since $k_i=1$ indicates that the water is flowing, it can also indicate that the dam is opened.

$$\min \sum_i \sum_t (\hat{h}_i(t) - H_i)^2 \quad (6)$$

$$k_1 = \begin{cases} 1, S_1 \leq S_2 \\ 0, S_1 > S_2 \end{cases} \quad (7)$$

$$s_1 = r_1 (\hat{h}_{on1}(t+1) - H_1)^2 + r_2 (\hat{h}_{on2}(t+1) - H_2)^2 + r_3 (\hat{h}_{on3}(t+1) - H_3)^2 \quad (8)$$

$$s_2 = r_1 (\hat{h}_{off1}(t+1) - H_1)^2 + r_2 (\hat{h}_{off2}(t+1) - H_2)^2 + r_3 (\hat{h}_{off3}(t+1) - H_3)^2 \quad (9)$$

$$k_{2,3}(t) = \begin{cases} 1, h_i(t) \leq H'_i \\ 0, \text{others} \end{cases} \quad (10)$$

$$k_4(t) = \begin{cases} 1, h_4(t) > H_4 \\ 0, h_4(t) \leq H_4 \end{cases} \quad (11)$$

H_i is the optimal water level size for each lake calculated by the first question.

Here, the particle swarm optimization algorithm is used to obtain the local optimal solution of r_i ($i=1, 2, 3$).

2.2.3. Prediction model of precipitation and evaporation volume

Now, the model has been able to predict and analyze the existing water level data, but in order to make the model more universal and practical, that is, to predict and control the future water level, it must be able to predict the future precipitation and evaporation [9-10].

Here, LSTM neural network is selected for the time series characteristics of precipitation and evaporation. By learning the collected precipitation and evaporation data in the Great Lakes region from 2019 to 2023, the results are shown in the Figure 2.

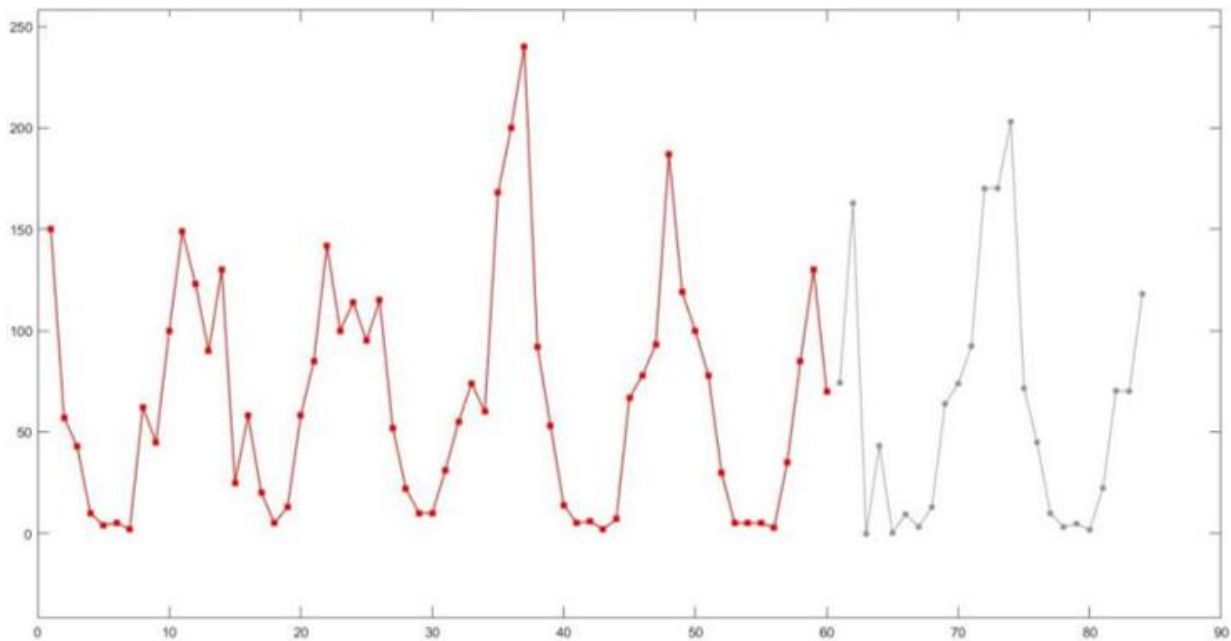


Figure 2. LSTM Neural network prediction results

2.3. Model prediction results

2.3.1. Lake water level prediction

In the case of Lake Michigan and Lake Huron, the horizon height of the two is essentially the same, and Lake Michigan is connected by no other river than the one connected to Lake Huron. Therefore, when predicting the water level, the two are considered as a whole.

The prediction effect of the water level of each lake is as shown in Figure 3.

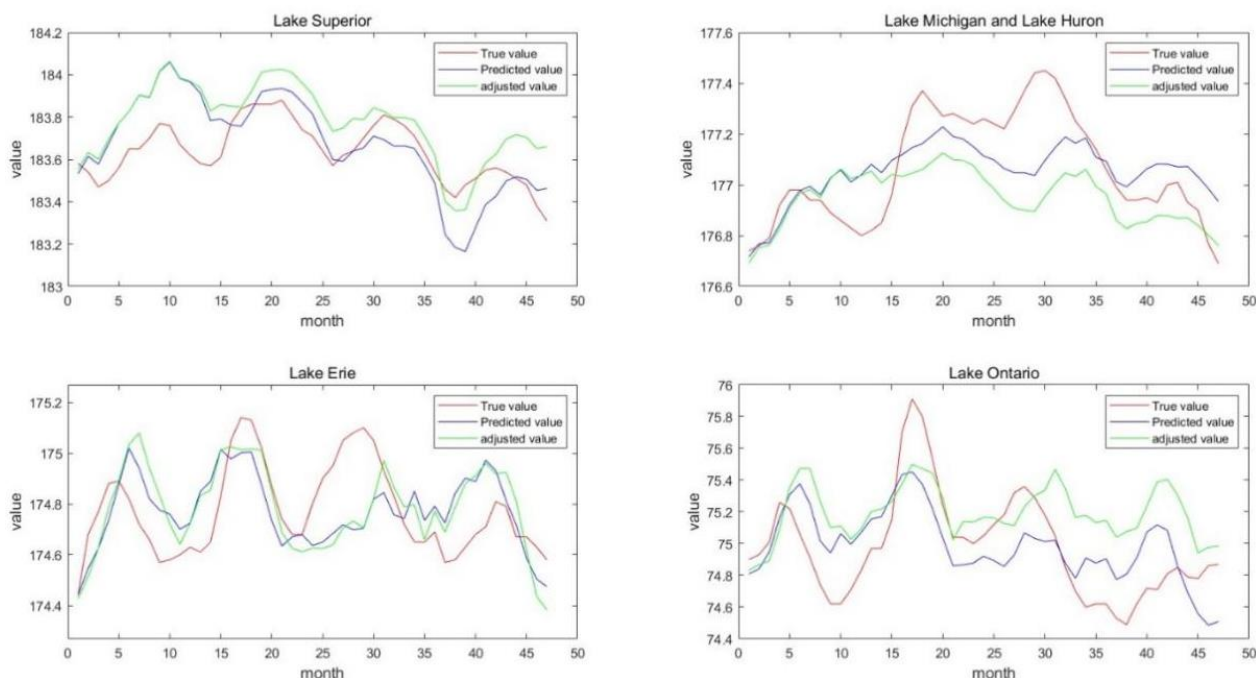


Figure 3. Water level forecast for each lake in 2019~2022(48 months)

In Figure 3, although the blue prediction curve and the red real data curve have a certain error, the error is small, the data are basically consistent and the water level tends to be the same, indicating that the prediction effect of the model is very good. The resulting error structure diagram is shown in Figure.4.

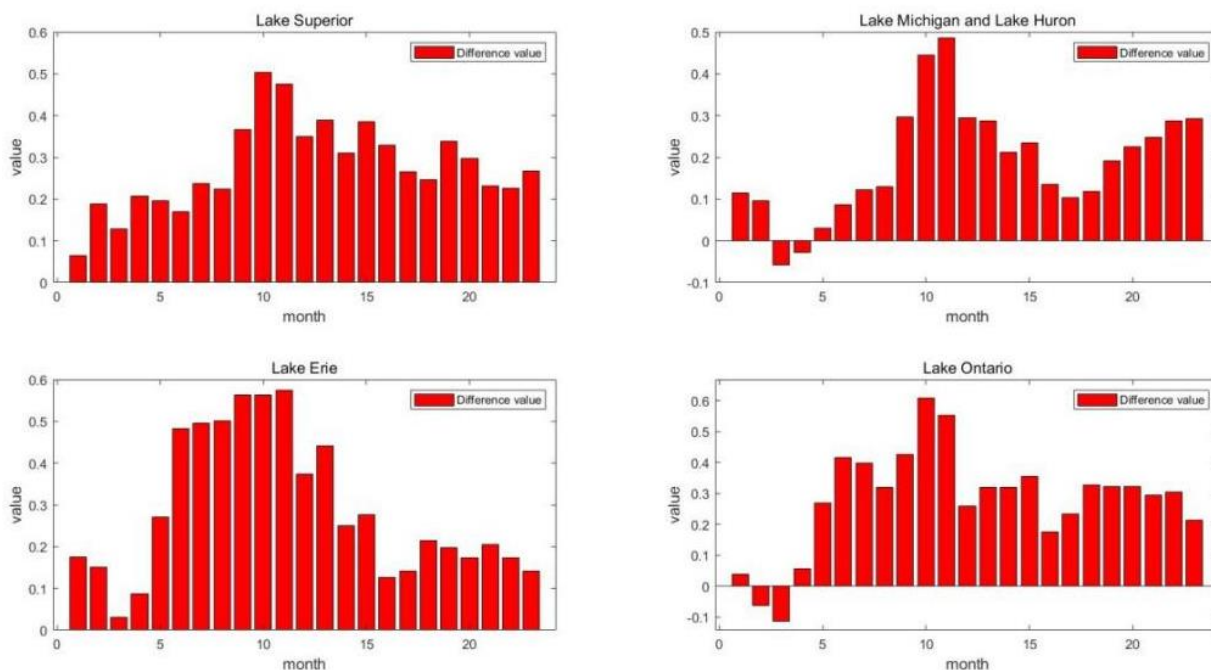


Figure 4. Error result graph

The maximum prediction error from the results is 0.66 meters, equivalent to 2.16 feet, but basically the prediction error is not more than 2 feet, which will not greatly affect some stakeholders.

2.3.2. Dam regulation prediction

Continuing the definition defined above, it is open when 1 is open and closed when it is 0. If we want to maintain the optimal water level for each lake each year, we need to follow the predicted opening or closing times of the dams, such as Figure.5 and Figure.6.

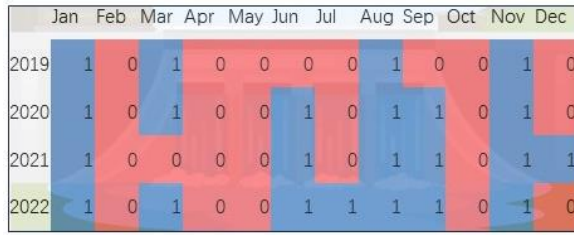


Figure 5. St. Marys Falls Dam

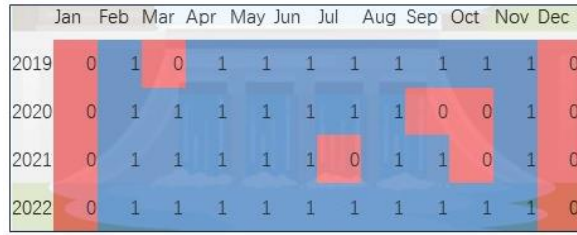


Figure 6. The Moses Saunders Dam

2.3.3. Forecast results for the next three years

The future precipitation data predicted by the LSTM network can be used to predict and manage future water levels, the result is shown in figure 7.

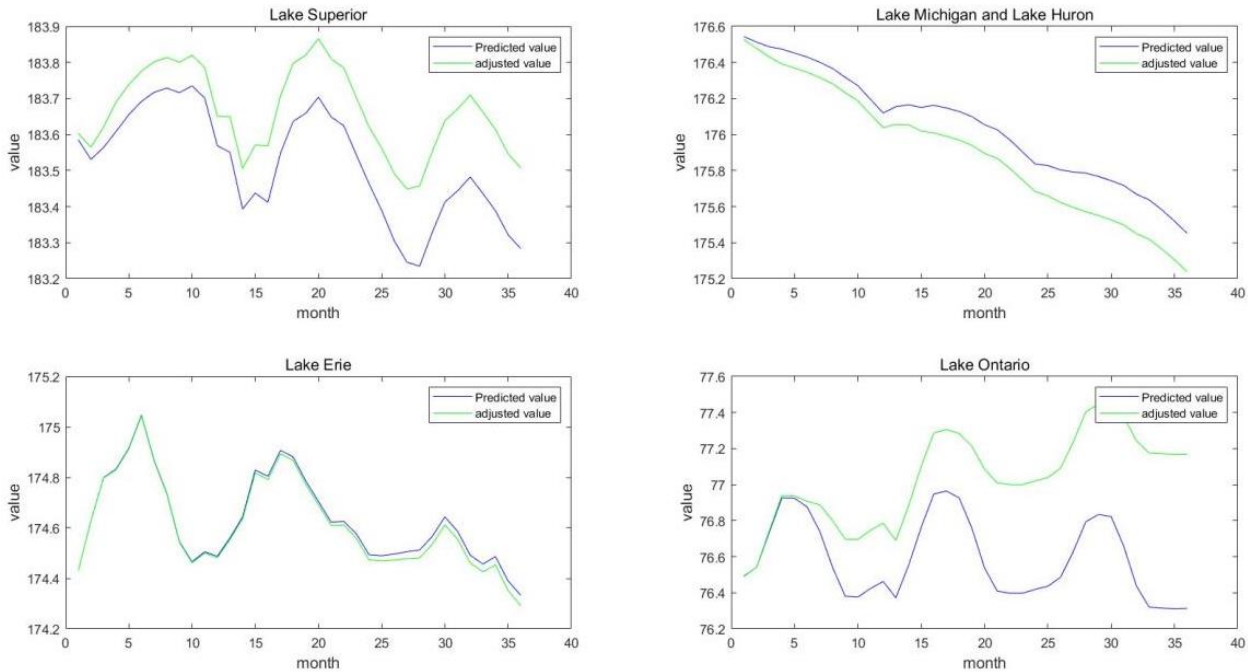


Figure 7. Future water level forecast

2.4. Model correction and optimization

In the previous model, it is assumed that the dam is in the state of on or off, but in practice, the dam still has a semi-open state, that is, its flow control should not be discrete but continuous, and this is helpful in the sensitivity results of the following analysis, so the definition of k_i in the previous paper is corrected a little bit. Here, the Sigmoid functions commonly used in neural networks are used to replace the previous RELU type function.

$$k_1 = 1/(1 + e^{-s_1}) \quad (12)$$

$$k_4 = 1/(1 + e^{-s_2}) \quad (13)$$

$$s_1 = r_1 \times (h_1(t) - H_1) - r_2 \times (h_2(t) - H_2) - r_3 \times (h_3(t) - H_3) \quad (14)$$

$$s_2 = r_4 \times (h_4(t) - H_4) \quad (15)$$

Similarly, the particle swarm algorithm is used to obtain the local optimal solution of the dam as figure 8:

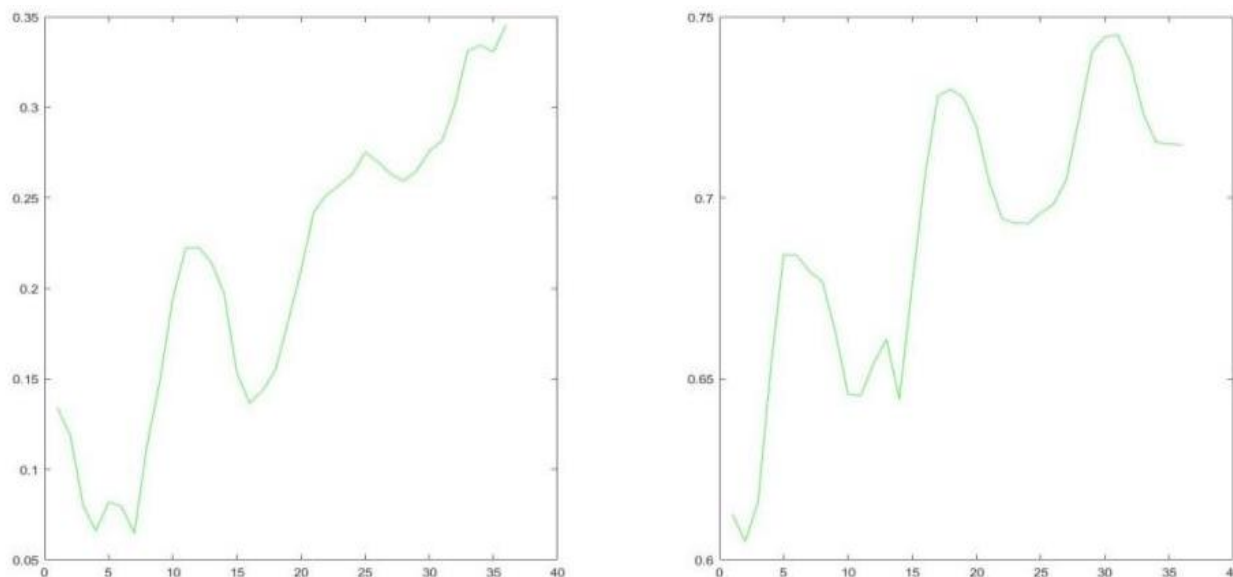


Figure 8. Dam opening

3. Conclusion

In this study, based on the water level and flow prediction model, a dam regulation method is proposed to address the problem of maintaining the optimal level of water level in the Great Lakes. Accurate prediction of the water level of the Great Lakes was realized by Manning's formula to derive river flow and LSTM neural network to predict rainfall and evaporation. The particle swarm algorithm is used to determine the local optimal solution of the dam and realize the reasonable regulation of water level. The experimental results show that the method has high accuracy and feasibility, and provides an effective means and important reference for water resource management and ecological protection in the Great Lakes region.

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