Research On Water Level Control of The Great Lakes Based on Fuzzy Control Algorithm

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Abstract. Water level control plays a vital role in hydraulic engineering, because it helps to protect the environment and improve production efficiency. A well-designed control system is essential for regulating the flow through the sluice, managing water levels effectively, and meeting the diverse needs of stakeholders. Additionally, such a system must be capable of responding promptly to extreme weather events, such as floods, in order to minimize the risk of flood disasters. In order to realize the precise regulation of water level, a robust and flexible water level control system is constructed by using fuzzy control algorithm. This approach offers strong adaptability and resilience in varying conditions.

Keywords: Fuzzy control, Control model, Water level control, Simulation.

1. Introduction

With the increasing demand for water resource utilization in the 21st century, there has been a growing body of research on the control of water levels [1]. The significance of water level control is to ensure the effective management and utilization of water resources, while reducing the risk of flood disaster. By precisely controlling the opening and closing of the sluice, it is possible to adjust the water level and flow of the reservoir to meet various needs such as water supply, irrigation, and power generation.Additionally, reasonable water level control also helps maintain river ecological stability and promotes sustainable use of water resources.

In this study, a fuzzy control theory-based algorithm is employed to regulate the water level.The implementation of fuzzy control in mechatronics, as demonstrated by Emil PR and his colleagues, has yielded favorable outcomes [2]. Wang et al. developed a fuzzy observer to handle imprecise input and output signals in their study [3]. Han et al. applied fuzzy control to the cooling valve control of hydrogen energy vehicles, and the simulation results show that the fuel economy is improved by about 3.83% when fuzzy control is adopted [4]. Tejaswini ESS et al. utilized fuzzy control in the integrated supervision of a sewage biological treatment plant to enhance the overall performance of the plant [5]. Jiang et al. utilized fuzzy control in the multi-agent system to enable the agents to reach the convex hull generated by the leader signal from any initial position [6]. Mustafa employs active power factor correction using fuzzy control in its implementation [7]. Ozgur A proposed an iron making process and an automation system primarily controlled by logic rules and a PID controller [8]. Additionally, they suggested using fuzz-based gain regulation to enhance MRAC performance. Leilei Q conducted a study on the water level control system of natural circulation steam generators [9]. Xinyu W put forward an optimal operation method for parallel hydropower systems that integrates reservoir water level control and power distribution [10]. They also utilized a multi-objective simulation method to develop reservoir water level control rules.

By implementing a fuzzy controller, fuzzy input, fuzzy operation, fuzzy reasoning, and inverse fuzzification are utilized for variables that impact water levels. This process involves converting precise quantities into fuzzy quantities and making inferences based on fuzzy conditional statements. Ultimately, the fuzzy quantity is transformed back into a precise quantity to achieve the desired flow rate, maintain water levels, and effectively control the system. In summary, utilizing a fuzzy control approach proves to be an effective method for managing water levels.

2. Fuzzy Control of Great Lakes Water Levels

2.1. The Structure of Fuzzy Control System

Initially, it converts precise input quantities into fuzzy quantities and then carries out fuzzification based on the characteristics of the obtained fuzzy sets. Subsequently, a series of fuzzy conditional statements are formulated to describe the relationship between input fuzzy variables and output fuzzy variables. Following this, the fuzzy sets are determined through fuzzy logic calculations. Finally, the obtained fuzzy sets are converted back into precise quantities. The pivotal role of the fuzzy controller as the core component of the fuzzy control system, also known as the fuzzy logic controller, is to conduct fuzzification of inputs, perform various operations using fuzziness, engage in reasoning with fuzziness, and carry out inverse fuzzification. Figure 1 illustrates the block diagram outlining the components of the fuzzy controller. Figure 1 shows the schematic diagram of the fuzzy control system. Figure 2 shows the block diagram of the components of the fuzzy controller.

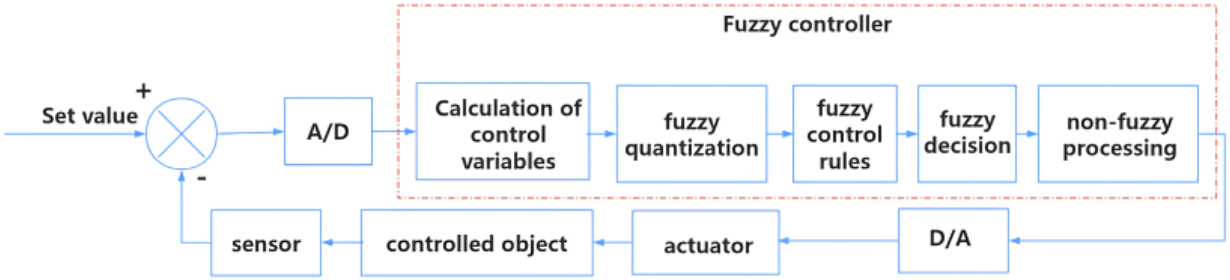


Figure 1. Principles of fuzzy control systems

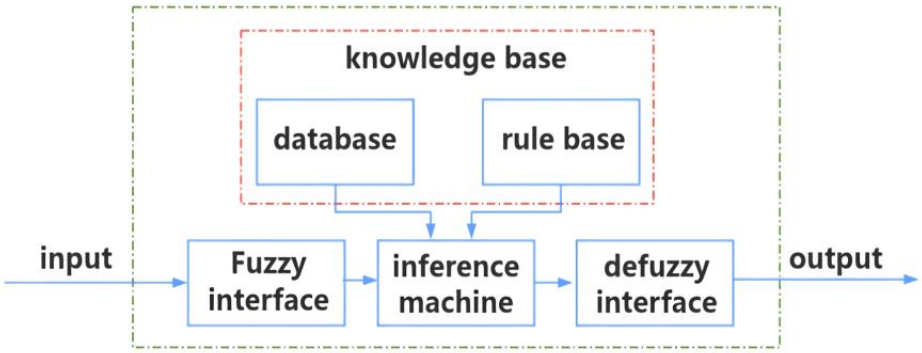


Figure 2. Block diagram of the components of the fuzzy controllerb

2.2. Control Systems for the Five Great Lakes Water Levels: Managing Inflow and Outflow

Lakes of the United States and Canada are the largest group of freshwater lakes in the world. There are several primary control mechanisms involved in the management of water flow within the Great Lakes system, including the use of dams and sluice gates. These mechanisms play a crucial role in regulating the movement and distribution of water throughout the interconnected lakes. We will utilize fuzzy control algorithms to adjust these devices to regulate the discharge of the sluice, thereby enabling the Great Lakes to maintain an optimal water level that meets the needs of all lake stakeholders.

To achieve stable control of water levels and ensure the reasonable allocation of resources, our team has developed an optimal water level maintenance algorithm for the five lakes. We have decided to close the devices when the current water level falls below the optimal range, taking into account operational costs. This approach will help us maintain a more efficient and effective management of water levels in the lakes. Conversely, if the water level exceeds the optimal range, we will open the devices until they return to within this range. The fuzzy controller is designed in a multi-input single-output mode. The inputs to the controller include water intake, river inflow per

unit time, snow cover, evaporation rate, ice content, and precipitation. The output of the controller is the dam outflow.

First, we must determine the range of input and output for the fuzzy controller. we introduce a new variable to characterize the impact of snow cover, evaporation rate, ice content, and precipitation on lake water levels. By substituting each value into formula (2), the resulting value is then inserted into formula (1) to determine the value of our newly defined variable.

$$CIFH = 0.4 \times P + 0.25 \times S - 0.2 \times E - 0.15 \times I \tag{1}$$

$$Score = \frac{\bar{x}}{\bar{x}_{\max} - \bar{x}_{\min}} \tag{2}$$

$$\begin{cases} P, S, E, I \in [0,1] \\ CIFH \in [-0.35, 0.65] \end{cases} \tag{3}$$

Where P represents the score of precipitation, S represents the score of snow cover, E represents the score of evaporation rate, I the score of ice content, and CIFH is the newly defined variable.

From Figure 3, we can determine the range of annual major river discharge flowing into each lake.

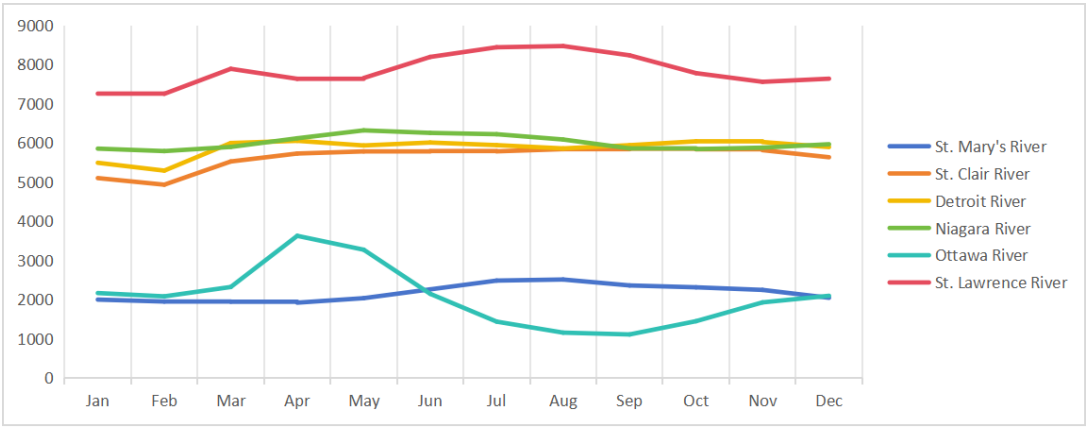


Figure 3. The major river flows into the five Great Lakes

The value range of dam water output is determined by the difference between lake water output, current water level, and optimal water level of the lake. By utilizing equation (4), we can derive the value range of lake outflow velocity.

$$\begin{cases} v_{\min_i} = \dfrac{\pi \times R^2{}_i \times \left(L_{present_i} - L_{best\,\max_i} \right)}{3 \times t} + w_{p_i} \times v_{i-1} \\ v_{\max_i} = \dfrac{\pi \times R^2{}_i \times \left(L_{present_i} - L_{best\,\min_i} \right)}{3 \times t} + w_{p_i} \times v_{i-1} \end{cases} \tag{4}$$

The entire lake is considered to be a cone, where R represents the estimated radius of the lake, L denotes the water level of the lake, and v indicates the discharge from the sluice.

Secondly, after careful consideration, our team has decided to define water intake, river inflow, and CIFH as "Low", "Medium", and "High". Figure 4 illustrates the membership function graph for each variable of the input and output.

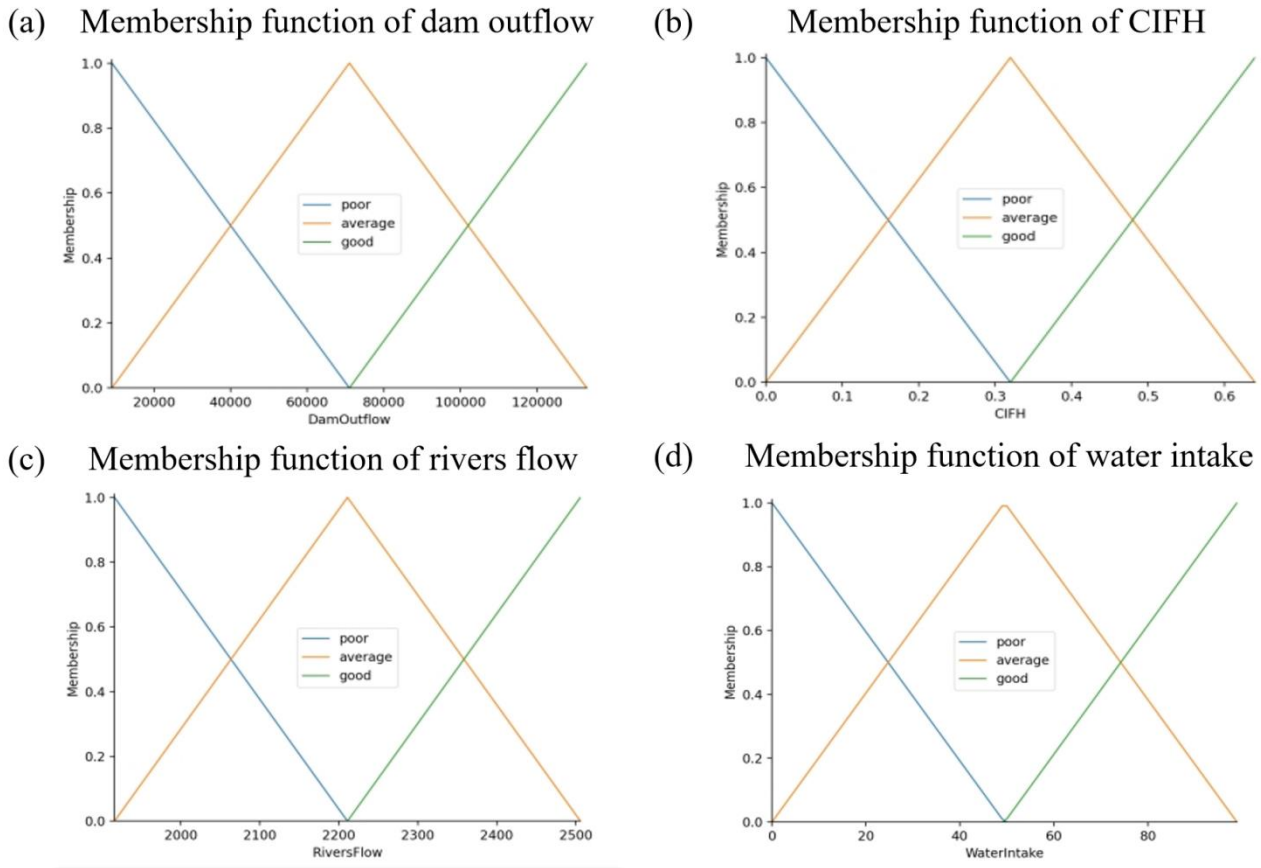


Figure 4. Demonstration of Lake Superior's Affiliations for Each Variable

Then, we employ the centroid method for conducting fuzzy reasoning, as fuzzy rules form the foundation of fuzzy control. Utilizing an IF-THEN conditional language, we categorize fuzzy rules into two cases based on input characteristics, with each case comprising 27 fuzzy control rules. The structure of a fuzzy rule is depicted in Figure 5.

CIFH is positive									
Water Intake	L	L	L	L	L	L	L	L	L
Rivers Flow	L	L	L	M	M	M	H	H	H
CIFH	L	M	H	L	M	H	L	M	H
CIFH is positive/negative	P	P	P	P	P	P	P	P	P
Fuzzy language variables	L	L	L	L	L	M	M	M	H
Water Intake	M	M	M	M	M	M	M	M	M
Rivers Flow	L	L	L	M	M	M	H	H	H
CIFH	L	M	H	L	M	H	L	M	H
CIFH is positive/negative	P	P	P	P	P	P	P	P	P
Fuzzy language variables	L	L	M	M	M	H	H	H	H
Water Intake	H	H	H	H	H	H	H	H	H
Rivers Flow	L	L	L	M	M	M	H	H	H
CIFH	L	M	H	L	M	H	L	M	H
CIFH is positive/negative	P	P	P	P	P	P	P	P	P
Fuzzy language variables	M	M	M	H	H	H	H	H	H
Water Intake	L	L	L	L	L	L	L	L	L
Rivers Flow	L	L	L	M	M	M	H	H	H
CIFH	L	M	H	L	M	H	L	M	H
CIFH is positive/negative	N	N	N	N	N	N	N	N	N
Fuzzy language variables	L	L	L	L	L	L	M	M	M
Water Intake	M	M	M	M	M	M	M	M	M
Rivers Flow	L	L	L	M	M	M	H	H	H
CIFH	L	M	H	L	M	H	L	M	H
CIFH is positive/negative	N	N	N	N	N	N	N	N	N
Fuzzy language variables	L	L	L	M	M	M	H	H	H
Water Intake	H	H	H	H	H	H	H	H	H
Rivers Flow	L	L	L	M	M	M	H	H	H
CIFH	L	M	H	L	M	H	L	M	H
CIFH is positive/negative	N	N	N	N	N	N	N	N	N
Fuzzy language variables	M	M	M	H	H	H	H	H	H

Figure 5. Fuzzy control rules

Finally, the fuzzy set is determined using fuzzy logic, and the precise quantity is the outflow quantity of the sluice.

3. Results and discussion

3.1. The establishment of the simulation model

Based on the relevant data from 2017, We have chosen two features and the lake water level as the objects of observation. Part of the simulation results of Lake Superior are shown in Figure 6.

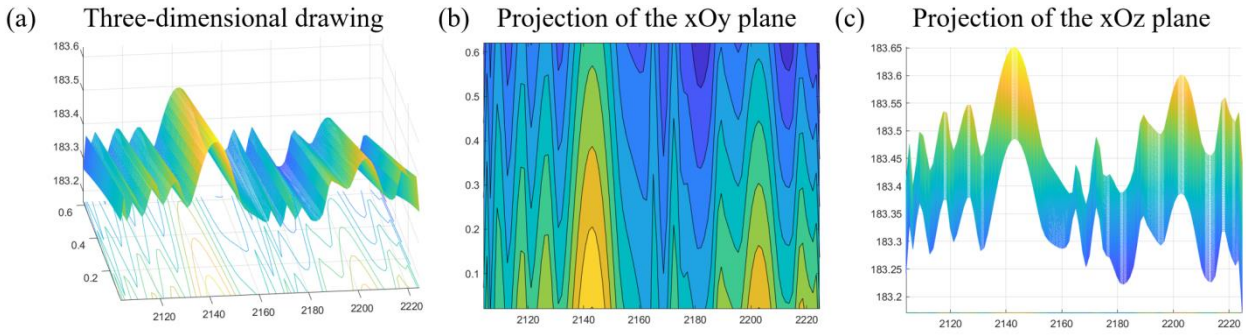


Figure 6. Simulation results of the changes of lake water level caused by CIFH and river inflow

The simulation results of the Great Lakes water level control system using the fuzzy control algorithm are depicted in Figure 7.

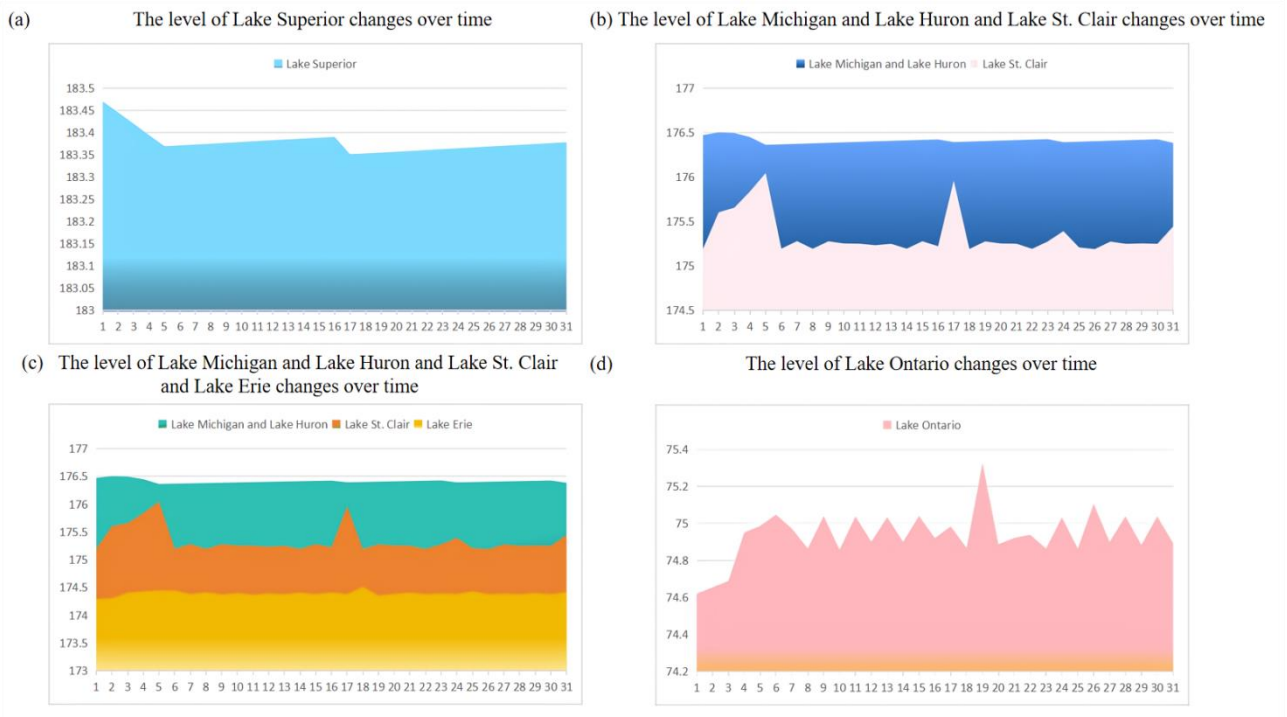


Figure 7. Comparative map of water level changes in the Great Lakes

3.2. Sensitivity analysis

Formulas 5 and 6 are utilized for the analysis of the sensitivity of the Great Lakes water level control algorithm during severe weather conditions.

$$x_i = x_0 \times (1 + i \times 0.01) \tag{5}$$

$$\sigma_i = \frac{y_i - y_0}{y_0} \tag{6}$$

The findings are presented in Figure 8.

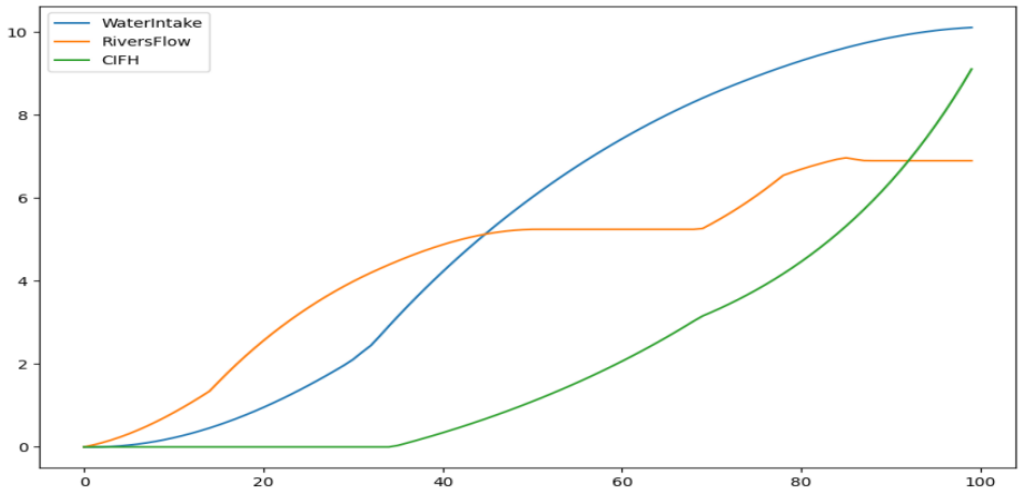


Figure 7. Lake Superior water level variation with input variables

The analysis reveals that when the change in CIFH is small, i.e., when CIFH tends towards a smaller value, there is minimal impact on the model. Conversely, when the change in CIFH is large, i.e., when CIFH tends towards a larger value, there is a significant effect on the model. This aligns with real-world scenarios as CIFH is influenced by seasonal variations, climate, and other natural factors. During abnormal climates, CIFH tends to increase significantly, leading to a greater impact on the model output. Consequently, the model becomes more sensitive to abnormal climates and better equipped to withstand their effects.

As depicted in the figure, the sensitivity of the model improves as two other input variables change within different ranges. These changes also affect dam outflow control differently and are beneficial for maintaining optimal water levels in controlling lake levels.

Overall，the findings suggest that understanding how changes in CIFH influence models can help mitigate potential impacts from abnormal climates and improve overall system performance.

4. Conclusions

Based on the principles of fuzzy control theory, an algorithm for water level control is proposed. This algorithm takes into consideration the actual operational costs and other related factors. Furthermore, it fully accounts for the impact of environmental changes on the model. By incorporating historical data to simulate the model, our results demonstrate that the model is capable of promptly adjusting water levels to reach optimal levels. This design not only enhances the intelligence level of dam management but also effectively reduces operating costs. As such, it holds significant implications for improving water resource management efficiency and addressing environmental changes. In addition, the sensitivity test has revealed that the fuzzy control algorithm is capable of effectively adapting to factors that lead to rapid changes in water levels, such as heavy rain. The testing has demonstrated that the fuzzy control algorithm exhibits high adaptability and can effectively handle various uncertain and constantly changing environments. By adjusting the fuzzy rules and membership functions, the fuzzy controller can autonomously learn and adjust, thereby facilitating the processing of diverse variables. Furthermore, the outstanding fault tolerance of the fuzzy control algorithm enhances its reliability and stability when dealing with complex systems like water level control.

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