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Original Article

Smart Flow Management: Mitigating Flood Risks through Effective Reservoir Operations

Aswathy Ananthan[1], Y Stalin Jose[2]

[1,2]*Department of Civil Engineering, Noorul Islam Centre for Higher Education, Kanyakumari, TamilNadu, India.*

[1]*Corresponding Author: AswathyAnanthan@outlook.com*

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Abstract *- Factors such as climate change, urbanization, poor infrastructure, and extreme weather events collectively increase the risk and severity of flooding. Efficient flood management is essential for mitigating risks caused by extreme weather incidents, especially in areas such as Idukki, Kerala, which has substantial monsoonal rainfall. The floods of 2018 and 2019 exposed the flaws of the Idukki multi-reservoir system, emphasizing the necessity for enhanced operational strategies. This study develops a comprehensive hydraulic model utilizing the MIKE 11 system to simulate the Idukki multi-reservoir's response to flood scenarios, necessitating the optimization of water flow strategies to improve flood management. The modeling framework incorporates a one-dimensional hydrodynamic model, calibrated and validated using historical flood data from 2013, applying conservation of mass principles to compute inflows and outflows within the reservoir system. The findings demonstrate a robust correlation between simulated and actual water levels, as indicated by calibration metrics such as the correlation coefficients, ranging from 0.90 to 0.96, and Nash-Sutcliffe coefficients, ranging from 0.95 to 0.98. In the 2018 floods, reservoir operations were strategically controlled, leading to effective pre-discharge procedures and optimized outflows to keep levels within safe limits. The model exhibited its predictive abilities during peak inflow situations, validating that effective control measures can substantially reduce downstream flooding risks. The results underscore the significance of adaptive management strategies in reservoir operations, demonstrating the model's effectiveness in real-time decision-making and enhancing the adaptability of flood management systems in susceptible areas like Idukki.*

Keywords *- Flood management, Multi-reservoir, Hydrodynamic model, Mike 11, Reservoir Operations.*

1. Introduction

Natural disasters like floods are among the most disastrous causes affecting people and their surroundings [1]. The magnitude of natural and man-made calamities is increasing day by day. Floods are predicted to become more frequent due to variations in climate change and weather patterns, making efficient flood flow management even more crucial. Urban areas experience significantly higher levels of destruction and damage from natural disasters than rural communities since they are shaped primarily by high population density, large vehicles on the road, and severe building construction regulations [2]. Due to urbanization, flood risks have increased, leading to significant losses in commercial and industrial infrastructure. Based on the study conducted by the Socio-Economic and Educational Development Society and the Centre for Research on the Epidemiology of Disasters, 77% of all disasters in India are caused by floods [3]. Floods have direct and indirect causes, including heavy rainfall, a growing human population, and global warming. These factors exhibit a wide range of consequences, from damage to property and ecosystems to the replacement of entire populations and even the death of human lives.

The underlying unpredictability of weather patterns like rain, snow, storms, and cloudbursts makes it impossible to generate reliable predictions of precipitations. There are five different types of landscapes with flooding behavior [4]. High mountain ranges were subjected to flash floods, while intense rainfall and snowmelt caused floods in foothill areas. In extensive floodplains, the flood is caused by the inability of the landscape to handle incoming flows. The inadequate sewage and drainage systems cause flooding in urban areas, whereas in coastal areas, the flooding is caused by cyclones and storm surges. Various structured and non-structured prevention measures should be prioritized to reduce the effect of floods [5]. The World Meteorological Organization (WMO) has inspired a transition to nonstructural measures such as real-time flood prediction and early warning systems to minimize the impact of the rise in urban floods.

The construction of reservoirs across rivers reduces the frequency and severity of floods by altering the stream flows of channels and rivers [6]. The reservoirs help in irrigation, hydropower generation, water supply, recreation, navigation, and downstream flood control. Several reservoirs operated simultaneously in a valley are termed a multi-reservoir system. Through proper planning and operation management, the reservoir system attains maximum benefits. Forecasting practices targeting optimal flow releases in a multi-reservoir system for flood management are proposed in this study. The main contributions of the study are listed below.

- To develop a methodology for developing optimal flow releases in a multi storage system for flood management.
- To control flood flows and levels to reduce the total damages during flood events.
- To maximize storage reliability while reducing occurrences of downstream flooding and emergency spillway releases.
- To assess the effectiveness of the forecasting model through calibration and validation.

The structure of the study is arranged as follows: Section 2 provides a literature review of existing multi-reservoir operations for sustainable flood management and explores the research gap that delves into the proposed model. Section 3 detailed the proposed method to forecast optimal flow release in a multi-reservoir system for flood control. Section 4 details the analysis of the results obtained. Section 5 provides concluding remarks.

2. Literature Review

Phankamolsil et al. [7] proposed a fuzzy logic application for multiple reservoir operations in a tropical region of Thailand. Using the data from 2008 to 2021, the Fuzzy Rule-Based Model (FRBM) controlled the upper stream reservoir operation. The model provided the details of available water storage and seven-day ahead predicted inflow as fuzzy inputs, and the fuzzy output was the release fraction derived from the three operational conditions. The results demonstrated that the FRBM scheme increased the total water storage in the Upper Mahanadi River Basin (UMRB) by 123.56 MCM/year for effective reservoir management and downstream flood prevention. The variability in hydrological variables and climatic data limited the study. Tantra [8] investigated the reliability of Tugu-Bagong multi-reservoir inflow. The model collected watershed parameters and rainfall data to evaluate the dependable discharge from the four-discharge condition. The outcomes showcased the ability of simulation modeling of the multi-reservoir. The model possessed challenges in the potential of infiltration and retention coefficients that vary due to local environmental conditions.

Xie et al. [9] developed a model utilizing a volume-based aggregation-decomposition technique for optimal flood control and dynamic operation of water levels for cascade reservoirs downstream of the Jinsha River in China. The outcomes indicated a consistent increase in the growth of pre-discharge water volume and enhanced annual power generation. However, the study was limited by the volume-based aggregation-decomposition technique, which is suitable for systems with small interbasin areas. Lu et al. [10] designed a framework to improve the dual functionality of the reservoirs by controlling floods. The model determined the maximum safe water levels to support the water supply. This approach converted single-purpose reservoirs into multipurpose reservoirs by increasing the water demands while ensuring adequate water supply and flood control. The less effectiveness of operations in regions with less historical inflow data limited the study.

Nakamura and Tebakari [11] developed a reservoir operation method based on dam inflow prediction in the Chi River Basin. The model formulated the relationship between the inflows and rainfall for 28 days and predicted the floods in 2010 and 2011. The results indicated the model's effectiveness by enabling maximum discharge in operation, and in 2011, the maximum inundation depth was reduced by 0.7 m in the lower basin. The study was limited by the inflow operation using two ground rainfall stations from the large dam catchment. Guo et al. [12] proposed a stochastic error-based cloud (SE-cloud) model for flood control operation in reservoirs utilizing an AI-based ensemble flood forecast model under uncertainty. To deal with the control issues, a Multi-objective Robust Optimization model (MRO) was integrated; in contrast, a Two-objective Stochastic Optimization model (TSO) was developed to reduce the expected highest reservoir level and peak release. The results demonstrated that the MRO outperformed the TSO with more inflow. The study relied more on the observed weather conditions than forecasts, leading to overestimating forecast quality.

Zhong et al. [13] suggested a flood regional composition (MUFRC) method for cascade reservoirs in the Yalong River basin to predict the design flood based on flood risk analysis. The results indicated that the downstream uncontrolled subbasin allocated a higher flood volume than the conventional FRC methods. However, the study possessed challenges in fitting the joint distribution of annual maximum flood volume data. Ning et al. [14] applied the Multi-Objective Ant Lion Algorithm (MOALO) in the Fuzhou River Basin for the optimal control of flooding in the reservoir. The advanced MOALO (AMOALO) model was employed to improve MOALO's search efficiency by using a power function to reconstruct the search distribution. The results revealed that AMOALO performed better in solving multi-objective reservoir operation problems. However, the effectiveness of large-scale basins posed challenges due to the implementation of the proposed model in a small river basin.

Liu et al. [15] proposed a hierarchical pre-release flood operation rule for real-time flood management. The study developed a many-objective optimization model with a region search evolutionary algorithm to control flood and power generation in cascade reservoirs. The results demonstrated increased average multi-year power generation by ensuring flood control. The limitation of the study was the computational complexity of the many-objective optimization model, which hampered its practical application in real-time decision-making scenarios for reservoir managers.

Zhou et al. [16] presented a flood water utilization model for flood risk control. The model provided a Flood Limited Water Level (FLWL) under different risks. The model raised the FLWL by 1 m above the current FLWL without flood risk. Global climate change remained a challenge for the study.

The studies reviewed reveal notable advancements in reservoir operation and flood management; however, several gaps remain. Many models, including fuzzy logic and stochastic approaches, face limitations due to reliance on local environmental conditions and insufficient historical data, which affects their general applicability. Additionally, the complexity of many-objective optimization models can hinder real-time decision-making, limiting their effectiveness for reservoir managers in urgent situations.

Furthermore, existing methodologies often do not adequately consider the impacts of climate change on hydrological variability, which is critical for long-term planning and flood risk mitigation. Addressing these gaps could significantly improve the effectiveness and adaptability of reservoir management strategies in the face of changing climatic conditions and increasing flood risks.

3. Materials and Methods

Predicting optimal flow release in a multi-storage system is essential to enhance the effectiveness of flood management systems. Smart decisions about water releases from reservoirs reduce flood risks, protect downstream communities, and maximize the potential of hydropower generation and irrigation. This study proposes modeling and simulating the river reservoir system using a 1D hydraulic model in the Idukki district, Kerala, for efficient flood control.

3.1. Study Area

The Idukki multi-reservoir, located in Kerala, India, is an important hydraulic infrastructure designed to effectively manage water resources while addressing the needs of irrigation, hydropower production and flood control. The Idukki multi-reservoir consists of the Idukki, Cheruthoni, and Kulamavu reservoirs. These three dams have generated an artificial lake of 60 km^2 in area and 649.3 km^2 in catchment area [17]. Table 1 summarizes the features of the Idukki reservoir. The reservoir gross storage is 1996 Mm^2. Figure 1 illustrates the layout of the Idukki reservoir. The Idukki region is defined by its mountainous terrain and heavy monsoonal rainfall, averaging over 3,000 mm annually. This heavy rainfall makes The area more susceptible to flooding, particularly from June to September. The major flood disasters in 2018 and 2019 caused heavy damage to the entire infrastructure.

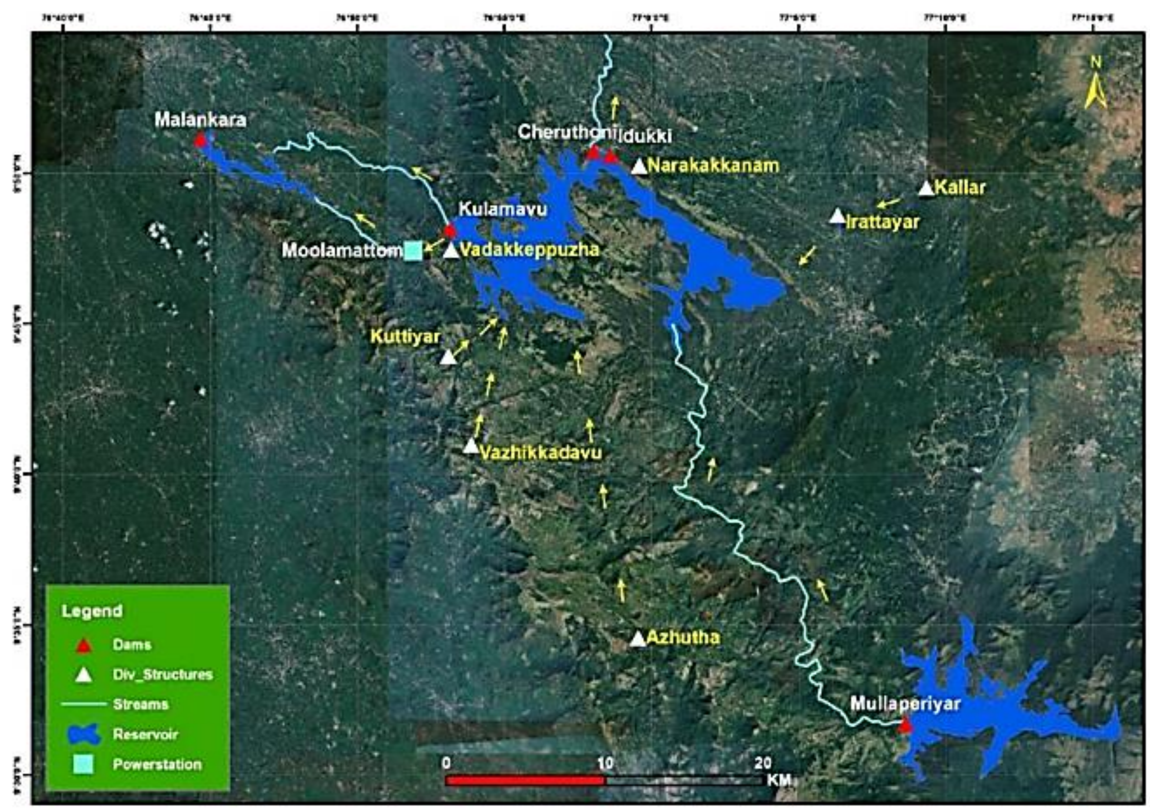


Fig. 1 Idukki reservoir layout

Table 1. Idukki reservoir-Salient feature

Feature	Details
Year of Impoundment	February 1973
Maximum Water Level (MWL)	2408.5 feet (734.1 m)
Full Reservoir Level (FRL)	2403 feet (732.43 m)
Latitude, Longitude	9.7885° N, 76.9747° E
Minimum Draw Down Level (MDDL)	2280 feet (694.94 m)
Dam Top Level	2415t (736.09 m)

3.2. Reservoir Equation

The river reservoir system consists of a reservoir operation model grounded on the mass conservation principle for a control volume [18]. Equation 1 illustrates the inflow to a reservoir, calculated using the available stream flows.

$$Inflow(T) = Storage(T) - Storage(T-1) + Outflow(T) \quad (1)$$

The mathematical expression of conservation of mass is given by Equation 2.

$$\frac{d}{dt}V = \sum Q_{in} - \sum Q_{out} \quad (2)$$

Where $\frac{d}{dt}V$ is the volume change in the reservoir, $\sum Q_{in}$ and $\sum Q_{out}$ represents the total volumetric inflow and outflow through the control structure, as shown in Figure 2.

The finite difference form of Equation 2, over a small-time step (ΔT) is given by Equation 3.

$$V_{T+1} - V_T = \left(\frac{Q_T^{in} + Q_{T+1}^{in}}{2}\right)\Delta T - \left(\frac{Q_T^{out} + Q_{T+1}^{out}}{2}\right)\Delta T \quad (3)$$

The discharge released from the reservoir is determined using various strategies in the reservoir operating model, including turbine and spillway gates.

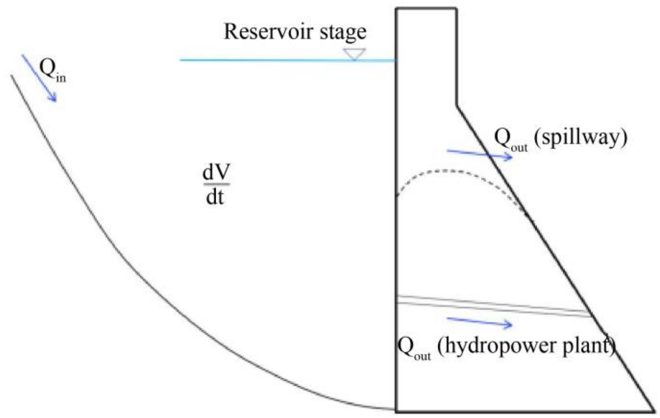


Fig. 2 Reservoir operation system

3.3. Proposed Modelling System

A Mike 11 model has been employed for the flow simulation in the Idukki multi-reservoir system. The Danish Hydraulic Institute (DHI, 2014) created the software program Mike 11 to simulate fully dynamic sediment transport, 1D flows, river water quality, and irrigation systems [19].

The Hydrodynamic (HD) module, the foundation of the Mike 11 system, can model inconsistent flows in an open channel network. Figure 3 shows the overall procedure for simulating the river-reservoir system.

The hydraulic model is the first part, which allows users to compute 1D unsteady flow for the Idukki River network. The multi-reservoir operation strategy is analyzed after the calibration and validation of the HD model. The second component is the Structure Operation (SO) module in the Mike 11 modeling system, used for the spillway gate operation. The model calculation for flood elevation and outflow in the reservoir system offers operation rules.

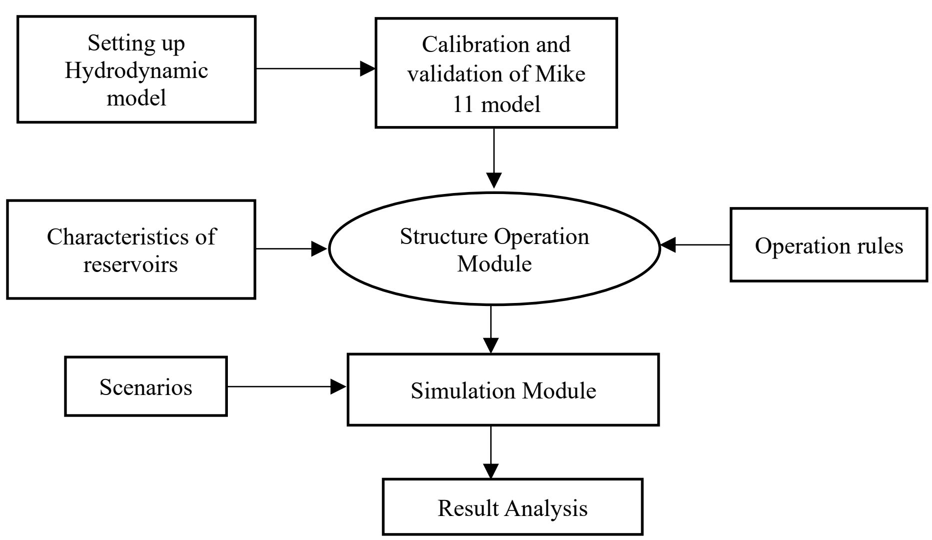


Fig. 3 Block representation of the proposed reservoir system operation modeling

3.3.1. Modeling of the Mike 11 System

The steady flow of rivers is calculated implicitly using the finite-difference model known as the Mike 11 hydrodynamic (HD) modeling system. Using a mathematical approach that adjusts to the local flow conditions, the modeling tool explains the subcritical and supercritical flow conditions. The dynamic ware description of Mike 11 HD is used to solve the Barré de Saint Venant equations, also known as the shallow water equations, which represent the equations for conservation of continuity and momentum. Equations 4 and 5 represent the equations that emerge from deriving the continuity and momentum equations used in Mike 11.

$$\frac{\partial Q}{\partial t} + \frac{\partial A}{\partial t} = q \tag{4}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(\alpha \frac{Q^2}{A}\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 AR} = 0 \tag{5}$$

Where Q is the discharge, and q is the lateral inflow. A is the cross-sectional area, h is the stage above the datum, R is the hydraulic or resistance radius, g is the gravitational acceleration, C is the Chezy resistance coefficient, ∝ is the momentum distribution coefficient, x and t are the distance and time, respectively. These momentum and continuity equations represent first-order, quasi-linear, simultaneous, partial differential equations of hyperbolic type. The six-point Abbott scheme represents the solution for the implicit finite difference model. After resolving the model, the water elevation, h, and velocity V in each cross-section of the simulated river systems were determined. Historical hydrographs are used to calibrate the hydrodynamic model for the Idukki catchment.

3.3.2. 1D Hydrodynamic Model for Idukki Multi-storage System

The multi-reservoir system operation in the Idukki catchment area is simulated by developing a 1D hydrodynamic model. Spillway gate operations are predicted using this model, particularly during the flood season. The simulator editor in the model helps integrate the river network and other components in Mike 11 editors. Other tributaries flow into the reservoir system of the Idukki River network, primarily made up of the Periyar River. The Periyar River and its tributaries, along with the channels that connect it to the reservoirs of Idukki, Cheruthoni, and Kulamavu, serve as the foundation for the model's development. Figure 4 represents the location of reservoirs within the Idukki catchment. During floods, the reservoirs incorporate spillway gates to initiate the simulation operations.

Cross-sections are used to depict the geometric data of the reservoirs and rivers. Over 500 cross-sections are used to describe the Periyar River and the three reservoirs. According to cross-sections, the river channel widens considerably as it gets closer to the Cheruthoni Dam, affecting the flood-carrying capacity during high inflow conditions. For the HD model, upstream and downstream conditions are included to accurately simulate the water flow and reservoir operations. The upstream boundary condition predominantly includes the inflow from the Periyar River into the Idukki Reservoir. The inflow was appr oximated using a rainfall-runoff model that integrates historical precipitation data, catchment attributes, and land utilization. The inflow at any time t is given by Equation 6.

$$Q_{in}(t) = C_r \times A_c \times P(t) \tag{6}$$

where C_r is the runoff coefficient, A_c is the catchment area, and $P(t)$ is the precipitation intensity.

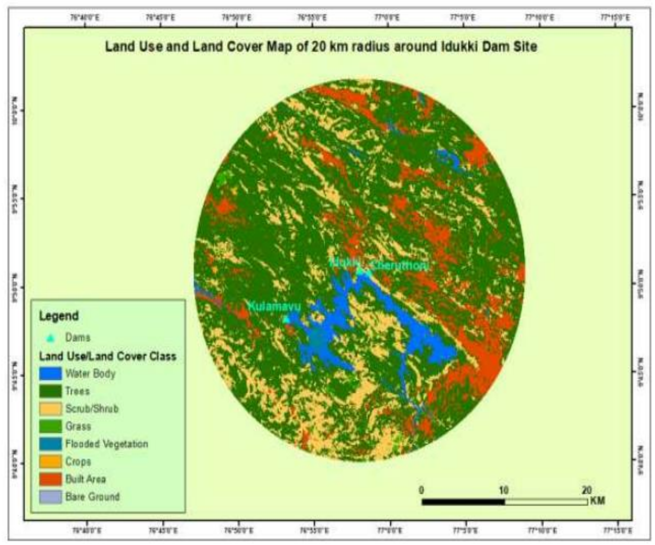


Fig. 4 Location of reservoirs within the Idukki catchment

The downstream boundary conditions encompass the water levels and discharges at the Cheruthoni and Kulamavu reservoirs. The functioning of spillway gates and power tunnels regulates water release during many scenarios, including flood management and power generation.

The weir flow equation and orifice flow equation, as given by Equations 7 and 8, are used to model the outflow of each reservoir for the spillways and power tunnels, respectively.

$$Q_{spill}(t) = C_w \times L_w \times \sqrt{2g \times (h(t) - h_c)} \tag{7}$$

where C_w represents the discharge coefficient of the weir, L_w is the length of the spillway crest, $h(t)$ is the upstream water level, and h_c is the elevation of the spillway crest.

$$Q_{tunnel}(t) = C_o \times A_o \times \sqrt{2g \times (h(t) - h_o)} \tag{8}$$

where C_o is the discharge coefficient for the orifice and h_o is the elevation of the tunnel outlet. The total outflow from each reservoir is given by Equation 9.

$$Q_{out}(t) = Q_{spill}(t) + Q_{tunnel}(t) \tag{9}$$

3.3.3. 1D HD Model Calibration and Validation

In real world conditions, model calibration is essential for developing hydrodynamic models [20]. Calibration ensures that the simulated flow dynamics closely match the observed data of the 1D HD model. Historical data from the Idukki reservoir and its river network, including the water levels, rainfall measurements, and discharge rates, was collected in 2013. The collected data was separated into two datasets for the calibration process. One is to determine the ideal values for the model's free coefficients, and another is to validate the calibration findings. With the use of two datasets, the model is made to be reliable and robust under a range of flow situations.

The inverse of Manning's roughness n, the Strickler roughness coefficient M, as given by Equation 10, is a crucial hydrodynamic parameter for calibration because it influences the flow resistance within the river channels and reservoirs. A trial-and-error method is employed to select the Strickler roughness values. Using some rough values from previous studies, the best value for the flow parameter is chosen by testing against the observed data. The values are adjusted according to specific channel conditions throughout the Idukki River network, like vegetation, sediment deposition, and channel geometry.

$$M = \frac{1}{n} \quad (10)$$

Equation 11 illustrates the relationship between V, R, and the roughness coefficient in terms of M.

$$V = M \cdot R^{2/3} S^{1/2} \quad (11)$$

Where S is the channel slope. The flow rate, Q, in an open channel is derived from Equation 12.

$$Q = A \cdot V \quad (12)$$

The water levels measured at downstream monitoring gauges like Idukki, Cheruthoni, and Neriamangalam have been compared with simulated water levels. Initially, a constant M value of 40 was given to the Mike 11 HD model. The local values of M were decreased because it led to an overestimation of water levels downstream.

From 1 June 2018 to 19 August 2018, Kerala experienced an abnormally high rainfall. As a result, thirteen out of fourteen districts experienced severe flooding. The calibrated HD model has been validated for using this flood data. The performance of the suggested model is assessed by comparing the observed water levels with the simulated water levels at downstream gauging stations.

3.3.4. Structure Operation Modeling

After the validation of the 1D unsteady flow hydraulic model, structure operation is used to specify the plan of operation for river network structures like sluice gates, pumps, radial gates, overflow gates, and reservoir releases. The control structures operate movable gates to regulate the flow. This model is regarded as a pump simulation. Using the SO module, the control structure is operated by selecting from various control methods. The flowchart of the SO module is given in Figure 5.

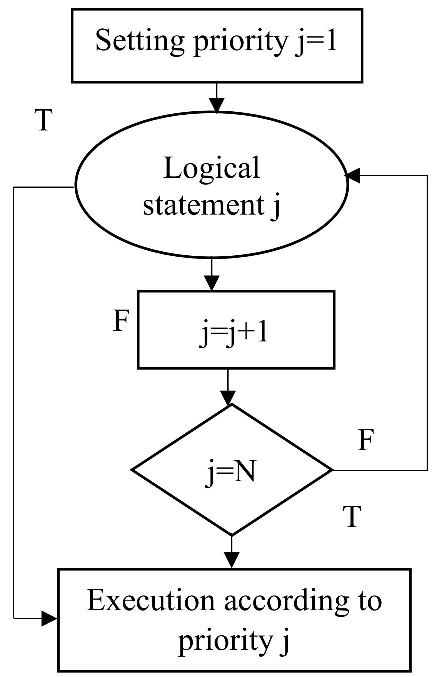


Fig. 5 SO module operation

The SO module implements a variety of control strategies for users. This option enables customized operations according to certain system requirements or conditions. The operational decisions based on real-time data and system state satisfy each control strategy with certain requirements. These conditions can be based on parameters such as water levels, inflows, and operational thresholds.

The gate operations are according to the selected control strategy. This computation determines the timing and method for opening or closing gates to sustain ideal flow conditions. The gate operation is based on the relationship between independent and dependent variables in the control strategy. The control strategy establishes an operational connection between an independent variable like upstream water level and a dependent variable like gate opening. This relationship describes the response of the gate level to variations in the independent variable. For instance, the gates are opened incrementally as the water level rises to maintain the safe operating range in the reservoir. The gate operation is automated based on a control in Equation 13.

$$h(t) \geq h_{set} \Rightarrow open\ gate\ by\ \Delta A \quad (13)$$

Where h_{set} is the setpoint water level at which the gate operation is triggered, and ΔA is the difference in gate opening area.

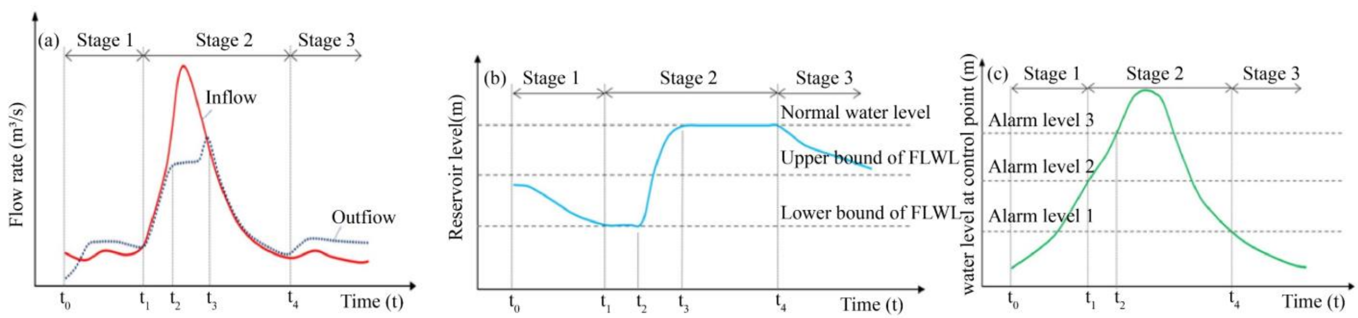


Fig. 6 Description of three flood stages

3.3.5. Modeling of Multi-Storage System in the Idukki Catchment

The modeling of multi-reservoir systems is mainly focused on regulating flood control, including the pre-discharge, flood management, and prefill events. The Idukki Reservoir's spillway gates open according to the reservoir stage, the inflow water level, and the season. The three flood stages are described and illustrated in Figure 6.

The first stage is the flood preparation phase. The time frame of flood arrival in this stage is selected as $[t_0, t_1]$. The main objective of this stage is to pre-release water from the reservoir to increase flood storage capacity. In order to lower the reservoir stage and increase storage space, a release should exceed inflow if the reservoir level is approaching the Full Reservoir Level (FRL) and downstream levels are below alert thresholds. The control condition for the first stage is given below.

Stage 1-Flood preparation phase

```
IF ReservoirLevel(t) ≥ (FRL - Threshold) THEN
  IF DownstreamLevel(t) < AlarmThreshold THEN
    AdjustedOutflow(t) = Inflow(t) + ExtraDischarge
    // Increase outflow to create additional flood storage
  ELSE
    AdjustedOutflow(t) = Inflow(t)
    // Maintain current outflow to keep reservoir level stable
  END IF
ELSE
  Adjusted Outflow(t) = Outflow(t)
  // No adjustment needed, continue monitoring
END IF
```

During the second stage, the flood management phase, the time frame is selected as $[t_1, t_4]$. This stage manages the reservoir levels to reduce the downstream flooding when a flood occurs. To keep the reservoir below the lower bound of the FLWL, balance the inflow and outflow during the manageable inflow phase. To prevent the reservoir from exceeding the FRL, adjust the outflows to nearly match the inflows as much as possible once the inflows rise significantly. Maximize the outflow during peak inflows while maintaining safe bounds to reduce the flood peak. The control condition for the second stage is given below.

Stage 2-Flood management phase

```
IF Inflow(t) ≤ Manageable Inflow THEN
  Adjusted Outflow(t) = Inflow(t)
  // Equalize inflow and outflow to stabilize reservoir level
ELSE IF Inflow(t) > Manageable Inflow AND Inflow(t) < Peak Inflow THEN
  Adjusted Outflow(t) = MIN(Inflow(t), SafeDischargeLimit)
  // Increase outflow to match inflow within safe limits
ELSE IF Inflow(t) ≥ Peak Inflow THEN
  Adjusted Outflow(t) = SafeDischargeLimit
  // Maximize outflow to prevent the reservoir from exceeding FRL
END IF
```

The final stage is the post-flood recovery phase. After the flood event, to ensure the area is prepared for future events or the dry season, lower the reservoir levels back to the upper bound of the FLWL. Water can be safely released to lower reservoir pressure by restoring storage capacity. The control condition for the final stage is given below.

Stage 3-Post-flood recovery phase

```
IF FloodPeakHasPassed THEN
  IF Reservoir Level(t) > UpperBoundFLWL THEN
    Adjusted Outflow(t) = SafeDischargeLowering
    // Safely lower reservoir level to restore capacity
  ELSE
    Adjusted Outflow(t) = Outflow(t)
    // Maintain current outflow reservoir at a safe level
  END IF
END IF
```

4. Result and Discussion

The results of Mike 11 modeling simulations are analyzed, focusing on the hydrological responses of the Idukki Reservoir during the 2018 flood. The evaluation metrics used for the evaluation of calibration and validation of the 1D HD model are given in Equations 14 to 17.

Correlation Coefficient (R),

$$\frac{\sum_{i=1}^{n}(H_{o,i}-\overline{H_o})(H_{s,i}-\overline{H_s})}{\sqrt{\sum_{i=1}^{n}(H_{o,i}-\overline{H_o})^2(H_{s,i}-\overline{H_s})^2}} \quad (14)$$

Root Means Squared Error (RMSE),

$$\sqrt{\frac{\sum_{i=1}^{n}(H_{o,i}-H_{s,i})^2}{n}} \quad (15)$$

Nash-Sutcliffe Coefficient (NSE),

$$1-\frac{\sum_{i=1}^{n}(H_{o,i}-H_{s,i})^2}{\sum_{i=1}^{n}(H_{o,i}-\overline{H_o})^2} \quad (16)$$

$$\Delta H_{max}\ (m) = max\left|H_{o,i} - H_{s,i}\right| \quad (17)$$

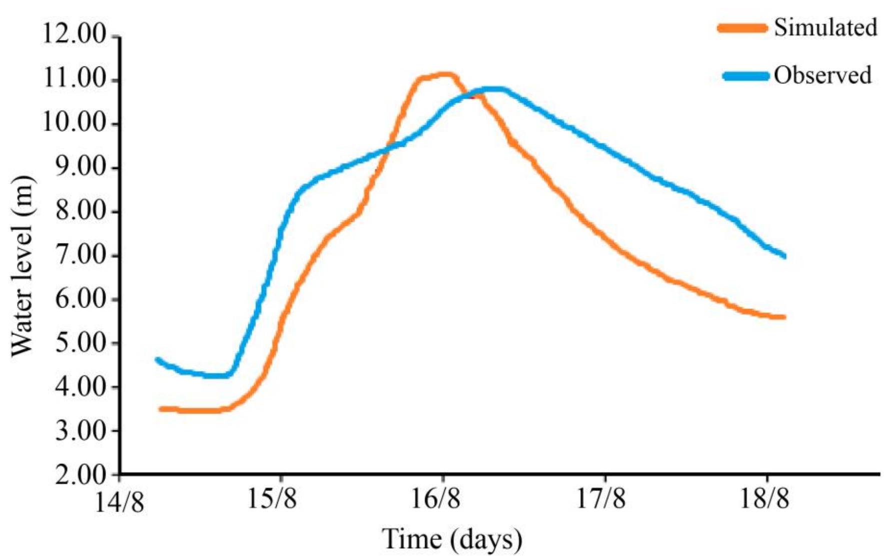
where $H_{o,i}$ and $H_{s,i}$ are observed and simulated water level values respectively at a time step I, $\overline{H_s}$ and $\overline{H_o}$ are the mean simulated and observed water levels. NSE quantifies how well the simulated data ($H_{s,i}$) matches the observed data ($H_{o,i}$) relative to the mean of the observed data. CC measures the strength and direction of the linear relationship between observed values ($H_{o,i}$) and simulated values ($H_{s,i}$).

The outcomes of calibration and validation of the simulation model at different gauging stations are given in Table 2.

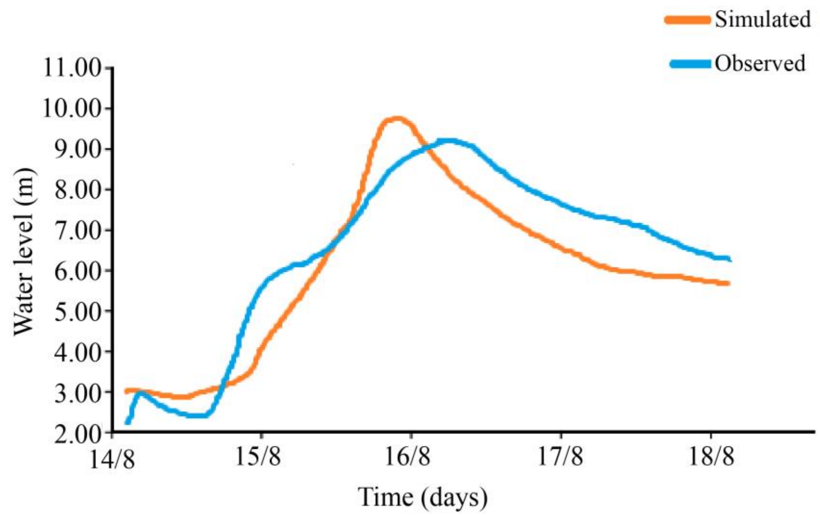
Table 2. Statistical evaluation of the simulation model at different gauging stations

Simulation	Performance Metrics	Gauging Stations		
		Gauge 1	Gauge 2	Gauge 3
Calibration	**R**	0.94	0.96	0.90
	NSE	0.97	0.98	0.95
	RMSE	0.99	0.72	0.83
	ΔH_{max}(m)	0.20	0.13	0.03
Validation	**R**	0.91	0.94	0.84
	NSE	0.97	0.98	0.93
	RMSE	1.22	1.05	0.99
	ΔH_{max}(m)	0.05	0.16	0.37

The simulation results reveal strong performance across all the gauge stations, with calibration metrics displaying strong R values between 0.90 and 0.96 and remarkable NSE values between 0.95 and 0.98. These findings suggest that the model accurately reflects the variability of the observed data. The model's dependability is further demonstrated by the low RMSE results, especially during calibration. The R and NSE values across validation demonstrate a predictive solid capacity. Gauge 2 has the most consistent and accurate performance across calibration and validation, with high correlation, low RMSE, high NSE, and relatively low maximum absolute error. Figure 7 and Figure 8 provide the hydrographs that show the variation of observed and simulated water levels at different gauges during calibration and validation, respectively, demonstrating the 1D HD model's ability to replicate the flooding procedure that occurs downstream of the Idukki reservoir system. Figure 9 illustrates the reservoir flow during 2018, whereas Figure 10 represents the reservoir flow during the flood in 2018.

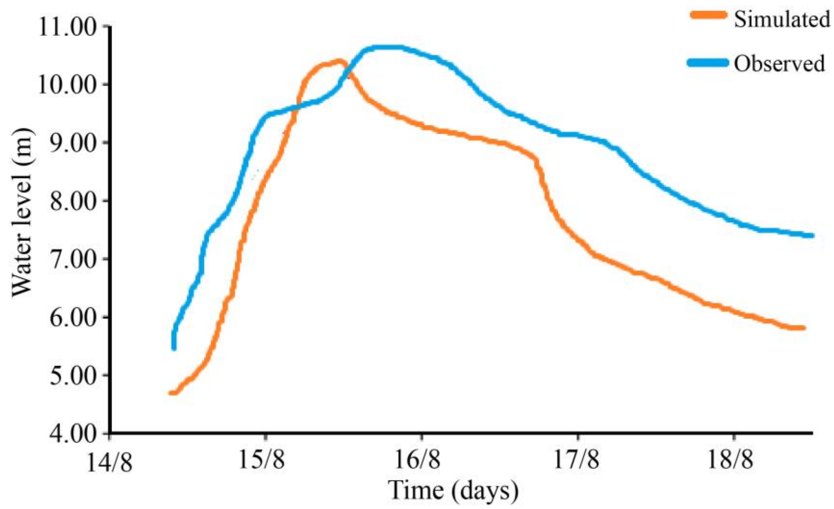


(a) Gauge 1

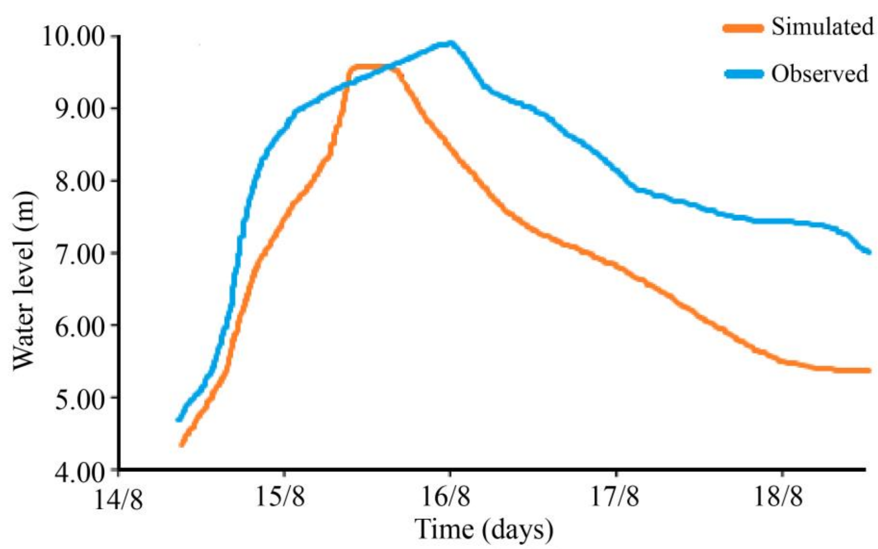


(b) Gauge 2

Fig. 7 Hydrographs showing the variation of simulated and observed water levels during the calibration process



(a) Gauge 1



(b) Gauge 2

Fig. 8 Hydrographs showing the variation of simulated and observed water levels during the validation process

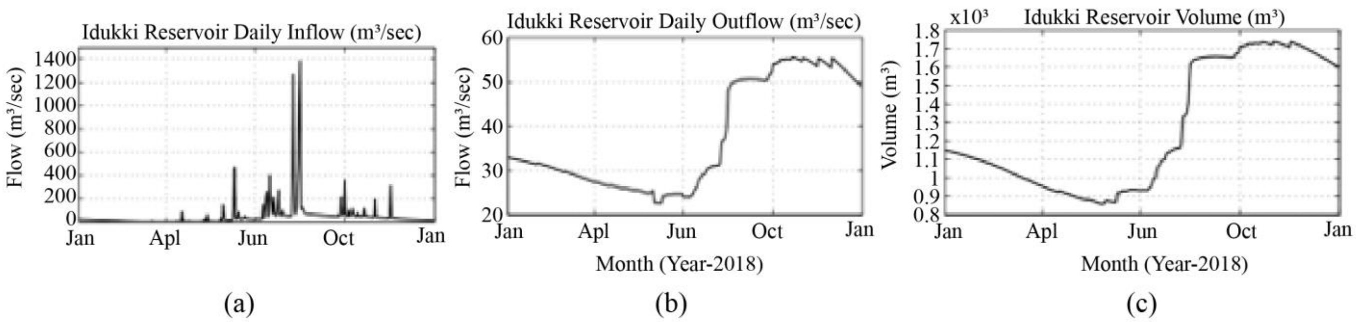


Fig. 9 Reservoir operation during 2018 (a) Inflow (b) Outflow (c) Volume

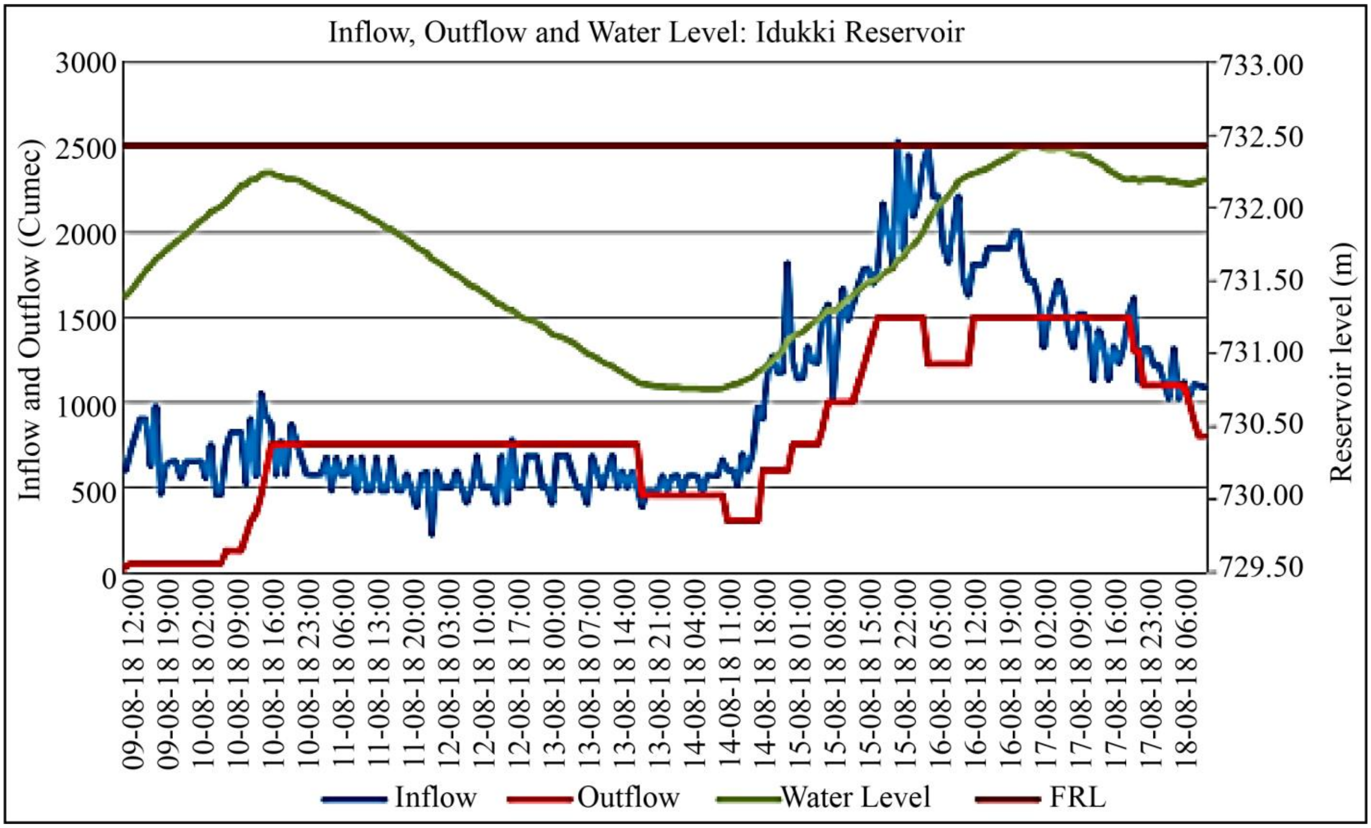


Fig. 10 Inflow, outflow and water level in idukki reservoir during flood

The reservoir defines the spillway's gate levels, which then releases discharge to the turbines. In the case of the Idukki flood 2018, as a discharge phase on 10th August 2018, the water level in the reservoir was 731.82 m, which is just 0.61 m below the FRL of 732.43 m. Only 40 MCM of flood cushion existed in the reservoir below FRL. At this point, the inflow was around 649 cumecs spilt, and an additional 115 cumecs were released via the powerhouse into the Muvattupuzha River. The release was more than the inflow, which lowered the reservoir stage and generated more storage space because the reservoir was near its FRL, and the downstream levels were below warning level 2. In order to keep the reservoir level inside the FRL, the spill was increased to 750 cumecs on August 10th.

In the flood management phase, releases were kept constant from August 10 to August 13 to increase flood storage capacity. By August 13, the reservoir was lowered to 730.80 meters, bringing the flood cushion up to 90 million cubic meters. The level was maintained close to the lower bound of FLWL by managing reservoir discharges to equalize inflow. In order to control the rising reservoir level, outflows were reduced to 1615 cumecs on August 15th due to increased inflows. During the peak inflow of 2532 cumecs on 15th August, outflows were held at 1614 cumecs to prevent exceeding the FRL. On August 17, the water level was gradually decreased to the upper bound of FLWL. Figure 11 illustrates the flood control procedure at Idukki during the 2018 floods.

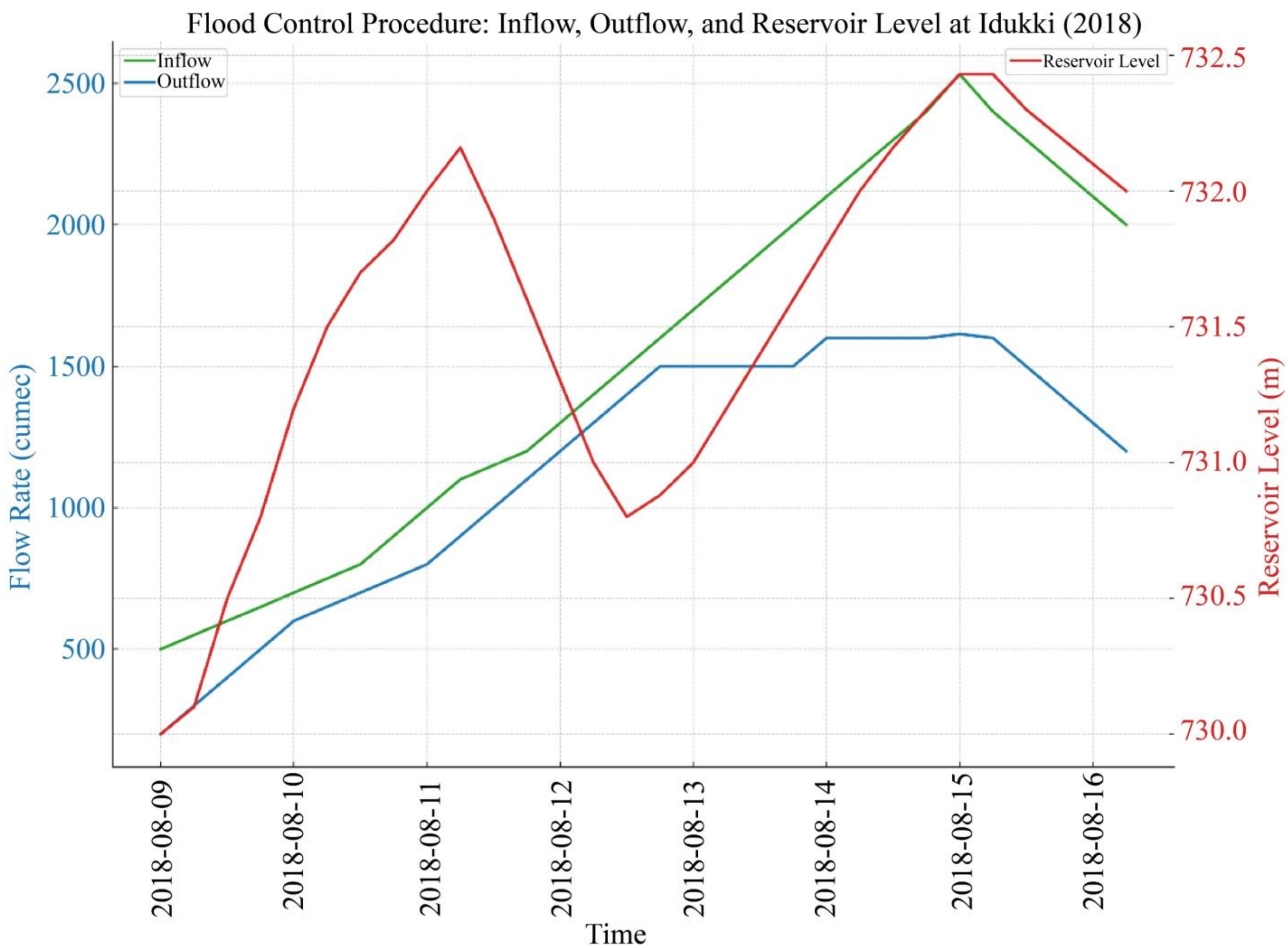


Fig. 11 Flood control phase for Idukki reservoir in the 2018 flood season

5. Conclusion

This study effectively illustrates the efficiency of Mike 11 modeling in enhancing reservoir operations for flood management in the Idukki multi-reservoir system. The calibration and validation of the 1D HD model with historical data demonstrated a robust correlation between simulated and observed water levels, indicating the model's reliability in predicting reservoir responses during flood occurrences. The study demonstrated that strategic water flow management through spillways and turbines can reduce flood risks, optimize hydropower generation, and facilitate efficient irrigation. The results from the 2018 flood underscored the model's ability to respond to variable input conditions, highlighting the significance of pre-release and flood management stages to maintain reservoir levels below safe limits. This research highlights the crucial role of advanced modeling techniques in facilitating real-time decision-making for flood management, ultimately improving the resilience of at-risk areas like Idukki. The findings from the study provide the development of comprehensive flood management strategies, enhancing sustainable water resource management while ensuring community safety.

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