International Journal of GEOMATE
(Geotechnique, Construction Materials and Environment)
ISSN: 2186-2982 (P), 2186-2990 (O), Japan
Vol. 31, Issue 144, August, 2026, pp.51-60; DOI: 10.21660/2026.144.5480

# FORECAST-INFORMED EARLY RELEASE FOR FLOOD CONTROL AT THE BERINGIN SILA DAM, INDONESIA

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**ABSTRACT:** Early release (pre-event reservoir drawdown) is an operational measure for flood mitigation, especially for dams with ungated spillways where flow regulation during flood peaks is limited. However, uncertainty in short-term rainfall forecasts often leads to operational hesitation and suboptimal use of flood-control storage. This study develops and tests a forecast-informed early-release framework for the multipurpose Beringin Sila Dam while respecting the Annual Reservoir Operation Plan (RTOW) constraints. Short-lead (1-7 day) rainfall forecasts from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) and The Weather Channel were transformed into inflow estimates using a rainfall-runoff model and then applied in reservoir operation simulations. Model calibration and verification yielded Nash-Sutcliffe Efficiency (NSE) values of 0.466 and 0.451, respectively, indicating moderate but adequate skill for operational decision support under data-limited conditions. Relative to conventional operation without early release, the forecast-informed strategy reduced peak outflow by approximately 15-25 %, lowered maximum reservoir water level by up to 0.8 m, and delayed downstream peak timing. These changes increased effective flood-control storage prior to flood arrival and reduced downstream flood risk, especially during the initial impounding stage. The proposed framework explicitly links real-time rainfall forecasts, inflow estimation, and RTOW-based operational rules for ungated spillway systems, providing a practical decision-support tool for improving flood management in similar multipurpose reservoirs.

*Keywords: Early Release, Real-Time Weather Forecast, Ungated Spillway, Flood-Control Storage, Reservoir Operation*

## 1. INTRODUCTION

A dam is a hydraulic structure designed to store water by forming a reservoir, with the primary objective of retaining surplus water during the wet season and supplying water during the dry season [1-2]. In practice, many dams are multipurpose infrastructures that support irrigation, raw-water supply, flood control, hydropower generation, and broader socio-economic development [3-5].

Indonesia implemented an accelerated dam development program during 2014-2024 to strengthen national food, water, and energy security [6-8]. The Beringin Sila Dam, located in Sumbawa Regency, West Nusa Tenggara Province, is part of this program and is classified as a National Strategic Project. Initial impounding commenced on 30 September 2022 when embankment construction had reached approximately 92%. Conducting initial filling while construction activities were still ongoing and coinciding with the onset of the rainy season significantly increased operational risk, thereby necessitating reliable hydrological analysis, conservative reservoir operation, and intensive monitoring [9-11].

As a flood-control infrastructure, the effectiveness of a dam is strongly influenced by several hydraulic and operational constraints, including (i) limited available storage relative to incoming flood volumes, (ii) the presence of an ungated spillway, and (iii) the adequacy of rule curves in defining allowable water surface elevation (WSE) throughout the year [12-14]. In ungated spillway systems, flood discharge cannot be actively regulated once the reservoir water level exceeds the spillway crest, making pre-event storage management critical [15-17]. Consequently, insufficient drawdown prior to extreme rainfall may lead to uncontrolled spilling, reduced attenuation of flood peaks, and increased downstream flood risk, particularly in fast-responding catchments [18-20].

In operational practice, reservoir operators are often required to decide whether to evacuate storage in advance of a forecasted rainfall event [21-23]. However, uncertainty in rainfall information often causes hesitation, which may lead to insufficient pre-event storage and elevated spill-related downstream flooding [24-27]. This challenge is especially pronounced during initial impounding stages, when operational experience is limited and safety margins are narrow.

Recent studies increasingly emphasize the need to incorporate forecast uncertainty into reservoir flood control operations. A review of recent studies and operational research suggests a transition from conventional deterministic rule curves to adaptive, risk-based, and forecast-driven strategies. Existing studies demonstrate the value of pre-release rules, robust multi-objective optimization, and uncertainty-aware flood control operations, but most focus on gated reservoirs, large systems, or long-standing operations. Relatively limited attention has been paid to gateless spillway reservoirs during the initial filling phase, particularly in tropical watersheds with short response times under data-limited conditions [12, 18, 21-27].

Compared to previous studies, the present research addresses several critical gaps. Most existing studies on reservoir flood operation focus on gated spillway systems, long-established reservoirs, or large-scale basins with relatively stable operational histories. In contrast, this study specifically targets ungated spillway systems during the initial impounding phase, where operational uncertainty and safety risks are significantly higher. Furthermore, previous approaches often rely on historical hydrological data or deterministic rule curves, whereas this study integrates short-lead rainfall forecasts into a dynamic operational framework under RTOW constraints. This distinction highlights the contribution of the proposed approach in bridging the gap between conventional reservoir operation and adaptive, forecast-informed decision-making in data-limited tropical catchments.

Accordingly, this study proposes a forecast-based early-release framework that converts short-lead rainfall forecasts into inflow estimates and integrates them with RTOW constraints to support proactive reservoir operation. The novelty of this study lies in: (i) explicitly linking rainfall forecasts from multiple sources to rainfall-runoff transformation for operational inflow estimation; (ii) applying the framework to an ungated spillway system during the critical initial impounding phase; and (iii) quantitatively comparing reservoir performance with and without early-release operation in terms of water level control and flood mitigation effectiveness.

## 2. RESEARCH SIGNIFICANCE

This study advances reservoir flood management by demonstrating a practical forecast-based early-release framework for ungated spillway systems under real-time operational constraints. By explicitly integrating short-lead rainfall forecasts with rainfall-runoff modeling and RTOW-based decision rules, the proposed approach bridges the gap between hydrological forecasting and operational reservoir management. The results provide quantitative evidence that anticipatory release can significantly enhance flood-control effectiveness during critical initial impounding stages. This framework offers a transferable decision-support tool for improving flood resilience in data-limited, multipurpose reservoirs.

## 3. MATERIALS AND METHODS

### 3.1 Study Location

The Beringin Sila Dam is located in Tengah Village, Utan District, Sumbawa Regency, geographically at approximately 8°27'18.85"S and 117°07'37.36"E, or at coordinates X=513,984.24 m; Y=9,065,372.25 m. The main characteristics of the dam are a dam height of 70.5 m, a crest length of 787.58 m, a crest width of 12 m, the reservoir area of approximately 126 ha, and a total storage capacity of 27.46 million m$^3$ [28]. Fig. 1 shows the location of the Beringin Sila Dam.

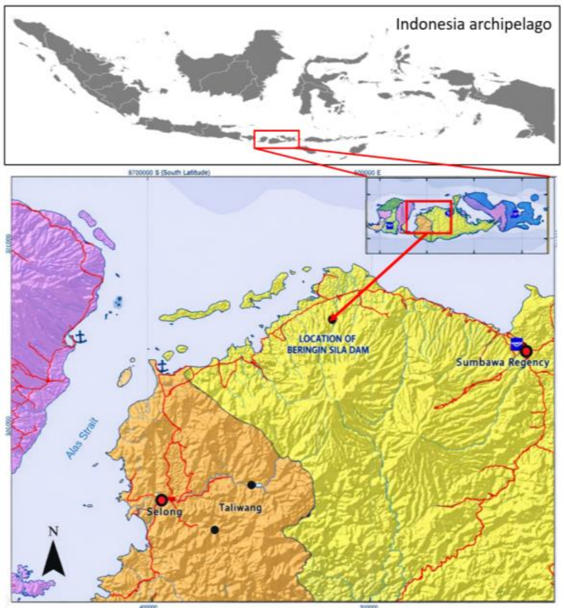


Fig. 1 Location of the Beringin Sila Dam

### 3.2 Data

The hydrological methods were selected based on the availability, temporal resolution, and reliability of observed and forecast data for the Beringin Sila watershed. The data sets used in this study are shown in Table 1.

Table 1. Data source and specification

| Data | Data Period | Temporal Resolution | Data Sources |
|---|---|---|---|
| Rainfall data | 2003-2022 (observed); event-based (forecast) | Daily and hourly | BMKG; The Weather Channel (TWC) |
| River discharge | 2003-2008 (calibration); independent period for verification | Daily | River gauging station (local water resources authority) |
| Reservoir water level (WSE) | 2022-2023 | Daily (sub-daily during events) | Reservoir operation records |
| Elevation-storage-area relationship | Static (design data) | - | Reservoir design documents |
| Evaporation and water-demand data | 2003-2022 | Monthly | BMKG; reservoir operation agency |

The data used in this study represent a combination of long-term historical records (2003–2022) and event-based forecast scenarios, allowing the analysis to capture both seasonal variability and extreme hydrological conditions. Therefore, the results presented in this study are not limited to maximum loading scenarios but reflect a range of hydrological responses under different seasonal conditions, including wet-season peak flows and transitional periods.

(Fig. 2) presents the reservoir storage allocation, distinguishing dead storage, effective (active) storage, and flood-control storage across defined water surface elevations. These storage zones establish operational boundaries for reservoir management, spillway activation, flood routing, and the implementation of forecast-based early-release strategies. (Fig. 3) illustrates the reservoir operating pattern, including upper and lower rule curves, normal and minimum operating levels, and seasonal operational zones. These boundaries define allowable water surface elevations under dry, normal, and wet conditions and serve as operational constraints for flood control and forecast-based early-release decisions.

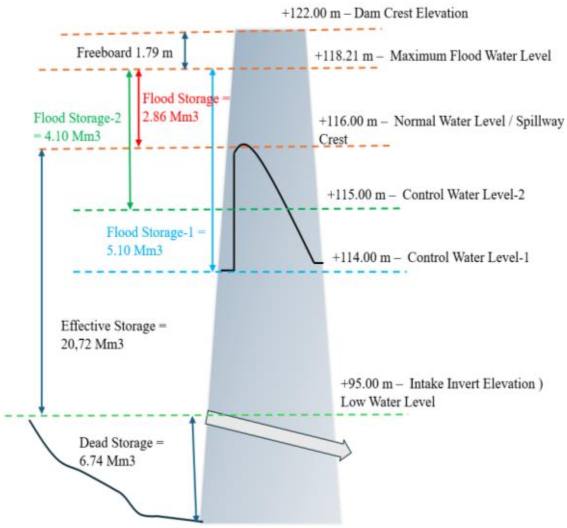


Fig. 2 Reservoir storage allocation

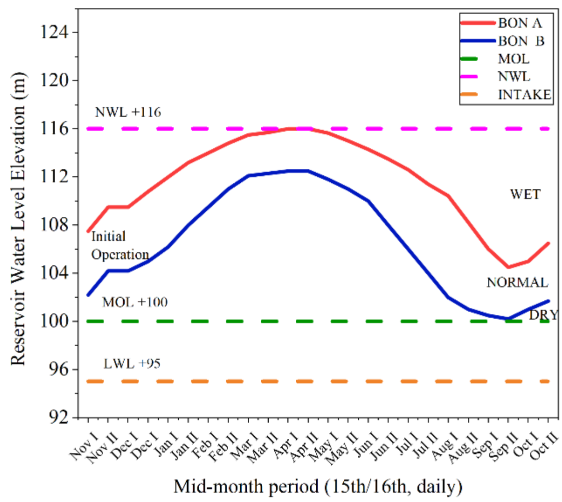


Fig. 3 Reservoir operation pattern

### 3.3 Methodological Workflow

The overall methodological framework consists of the following steps: (a) hydrological data compilation and quality screening; (b) design rainfall and forecast rainfall scenario analysis; (c) rainfall-runoff transformation; (d) event-based flood modeling and continuous water availability simulation; (e) model calibration and verification; (f) reservoir flood routing; (g) early release operation analysis; and (h) integration with RTOW constraints (Fig. 4).

Hydrological data were compiled from observed and forecast sources, including rainfall, river discharge, reservoir water level, evaporation, and water-demand data. Quality screening involved consistency checks, outlier detection, and missing data assessment using statistical screening and double mass curve analysis. Short data gaps were filled using standard interpolation, while longer gaps were excluded from calibration.

Design rainfall was derived from the Annual Maximum Daily Rainfall series following SNI 2415:2016 and disaggregated into temporal patterns due to limited hourly records. Forecast rainfall scenarios were obtained from short-lead (1-7 days) BMKG and The Weather Channel forecasts, processed as basin-average inputs and treated as decision-support information acknowledging inherent uncertainty.

Early-release operation analysis evaluated the effectiveness of pre-event reservoir drawdown in increasing flood-control storage. Forecast rainfall was transformed into inflow estimates to simulate anticipatory releases prior to flood arrival. Performance indicators included reductions in peak outflow and maximum water surface elevation, as well as delays in downstream peak timing compared to conventional operations.

All operational simulations were constrained by RTOW limits defining allowable reservoir elevations across operational zones. Early-release actions were permitted only within these limits, ensuring operational feasibility. The framework functions as a decision-support system, enabling adaptive reservoir operation under forecast uncertainty while maintaining compliance with established management rules.

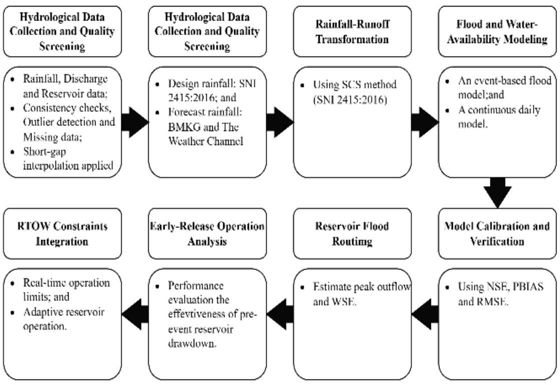


Fig. 4 Methodological workflow

### 3.4 Rainfall-Runoff Modeling

Rainfall-runoff transformation was conducted using the Soil Conservation Service (SCS) method, as recommended by Indonesian National Standards 2415:2016 [29], due to its suitability for watersheds with limited observed flood hydrographs and its extensive application in Indonesian catchments.

An alternative configuration based on Green-Ampt loss and Snyder unit hydrograph was also tested for comparison. Both approaches produced comparable hydrograph characteristics; therefore, the SCS-based model was selected due to its parameter stability, lower data requirements, and suitability for data-limited operational applications.

The main advantages of the chosen SCS-based approach are its modest data requirements, easy parameterization, and the practicality of converting rainfall estimates into operational inflow estimates. These characteristics make it well-suited for reservoir decision-making in tropical basins where dense real-time rainfall and discharge monitoring networks are not yet available. However, this approach also has limitations. It is less effective at reproducing very short-duration peak variability when the temporal resolution of rainfall is coarse, and it oversimplifies some watershed processes that may vary spatially during extreme storms. Therefore, this model is used here as an operationally robust estimate rather than as a high-resolution, physically based flood predictor.

### 3.5 Event-Based Flood Model and Continuous Simulation

The modeling framework consisted of two complementary components [30]:

a) an event-based flood model used to simulate extreme rainfall events, peak discharge, and spillway routing; and
b) a continuous daily model used to represent long-term water availability and reservoir dynamics.

The continuous model was calibrated using daily discharge data for the period 2003-2008, while an independent period was employed for verification to assess the temporal robustness of model parameters.

The operational mechanisms during filling and flood conditions can be summarized as follows. First, rainfall forecasts are collected from BMKG and The Weather Channel for a short timeframe of 1-7 days. Second, rainfall is converted into inflow estimates using a rainfall-runoff model. Third, the reservoir's current WSE is checked against the RTOW control level and available flood control storage. Fourth, if the inflow forecast indicates a risk of spillway activation or unacceptable downstream release, controlled early releases are initiated within the permitted operational zone. Finally, post-event recovery is conducted so the reservoir returns to its target operating level after the flood has passed. This sequence describes how the framework supports early filling and flood preparedness.

### 3.6 Calibration, Verification and Sensitivity Considerations

Model calibration aimed to ensure that hydrological parameters adequately represent watershed characteristics and hydrological response [31-32]. Model performance was evaluated using the Nash-Sutcliffe Efficiency (NSE), PBIAS, and Root Mean Square Error (RMSE) [33]. Verification was conducted using an independent dataset to assess the stability and transferability of calibrated parameters [34-36]. To address parameter uncertainty, a qualitative sensitivity analysis was performed by systematically varying key parameters, namely Curve Number (CN), initial abstraction, and baseflow recession constant within physically reasonable ranges derived from literature and calibration results [37-39]. The analysis indicated that peak discharge and runoff volume were most sensitive to CN variations, while baseflow parameters primarily influenced recession behavior in the continuous simulations.

### 3.7 Reservoir Flood Routing and Early-Release Analysis

Reservoir flood routing was conducted to estimate peak outflow discharge and maximum water surface elevation (WSE) above the spillway crest under different rainfall scenarios [40].

The early release analysis followed four main steps:

a) Flood prediction is based on forecast rainfall from BMKG and TWC.
b) Evaluation of available flood-control storage considering current WSE and rule-curve constraints (RTOW).
c) Assessment of spillway capacity and downstream channel conveyance; and
d) Post-event reservoir level recovery to restore operational conditions.

### 3.8 Assumptions, Scope, and Transferability

This study focuses on operational flood control analysis rather than structural safety analysis. Therefore, the modeling framework does not explicitly simulate erosion, sedimentation, seismic loading, geotechnical deformation, or other structural damage processes. The reservoir is assumed to operate under normal structural conditions, and the analysis is limited to estimating hydrological inflows, storage-release interactions, spillway routing, and RTOW-constrained operation. Therefore, the results should be interpreted as decision-support output for reservoir operation and not as a substitute for structural safety assessment.

The proposed framework was developed for the hydrological and operational context of the Beringin Sila River Basin in Indonesia, which is characterized by relatively short response times, limited real-time hydrometeorological data, and a gateless spillway system operated under RTOW constraints. While this approach is in principle transferable to other multipurpose reservoirs with similar characteristics, its practical application in other countries or hydroclimatic regions will require local calibration, estimation verification, institutional adaptation, and revision of operational thresholds. Therefore, this study should be considered a case-based operational framework with broader relevance than a universally applicable rule without contextual adjustments.

For practical implementation, a forecast-based early release framework requires at least the following inputs and institutional conditions: (i) short-term rainfall forecasts, (ii) current WSE and reservoir storage information, (iii) elevation-storage-area relationships, (iv) RTOW operational rule curves or equivalent, (v) downstream channel capacity estimates, and (vi) clear operator decision protocols for release approval and post-event recovery. These requirements should be interpreted in light of local economic and environmental conditions before applying this framework to other countries.

Although direct benchmarking against commercial hydrological software (such as HEC-HMS or MIKE Hydro) was not conducted in this study, the modeling framework follows widely accepted hydrological principles and standard methods (e.g., SCS-CN and unit hydrograph approaches) that are commonly implemented in such software. The agreement between simulated and observed discharge during calibration and verification provides indirect validation of the model structure. Future studies are recommended to perform cross-platform validation to further strengthen confidence in model performance.

## 4. RESULTS AND DISCUSSION

### 4.1 Hydrological Model Performance

Calibration of the continuous hydrological model resulted in an NSE of 0.466, while verification yielded an NSE of 0.451. These values indicate moderate model performance, which is commonly considered acceptable for operational decision-support applications, particularly in data-limited tropical catchments. The results suggest that while the model may not fully capture short-duration peak variability, it adequately represents overall flow dynamics relevant to reservoir operation.

PBIAS values of -19.10% during calibration and -14.45% during verification indicate a moderate tendency toward flow underestimation. From an operational perspective, this conservative bias is preferable to overestimation, as it reduces the risk of premature or excessive early release. RMSE values of approximately 0.73-0.74 $m^3/s$ further highlight the model's limitations in reproducing extreme fluctuations, which are primarily attributed to limited rainfall temporal resolution and the absence of dense upstream rainfall observations.

Figures 5 and 6 indicate that the model captures the seasonal trends and event magnitude of the watershed response quite well, while the discrepancies during the sharp peaks are due to a combination of the rapid concentration times, the intense spatial variability of rainfall, and the daily time step used in the continuous simulations. In other words, the discrepancies during peak events reflect hydrological constraints and data resolution, not a complete failure of the model. Overall, the model performance is adequate for scenario-based evaluation of early release strategies but is not intended for precise real-time flood prediction.

Although the model does not explicitly incorporate real-time discharge prediction as a separate forecasting module, its reliability is ensured through calibration and verification against observed discharge data, as well as the use of established hydrological performance metrics (NSE, PBIAS, and RMSE). The model is designed as a scenario-based decision-support tool rather than a deterministic real-time forecasting system. Therefore, the emphasis is placed on relative performance comparison between operational scenarios (with and without early release), which remains robust despite inherent uncertainties in discharge estimation.

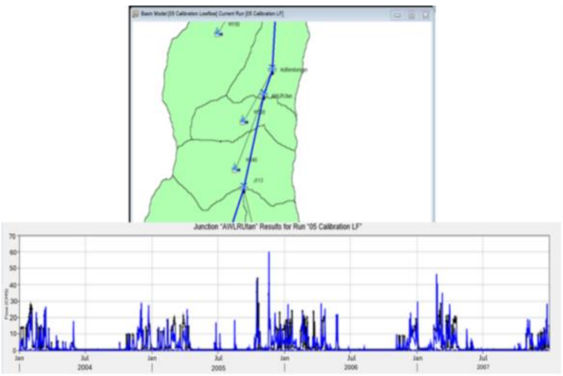

Fig. 5 Calibration results

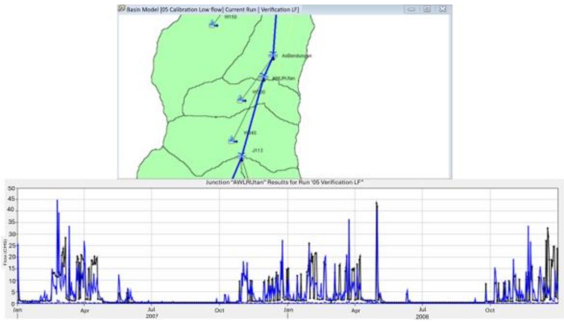

Fig. 6 Verification results

### 4.2 Extreme Rainfall Characteristics and Flood Response

Rainfall in the study area is strongly seasonal, with peak intensities occurring during the wet season (November-April), particularly in January. The watershed exhibits a short time of concentration, estimated using the Kirpich method, resulting in rapid runoff response following intense rainfall. As summarized in (Table 2), the estimated time of concentration ranges from 3.82 to 6.75 hours, depending on catchment scale. This short lag time underscores the importance of forecast-based operational preparedness, as reactive reservoir operation alone may be insufficient to mitigate flood peaks. Although extreme rainfall return periods were not explicitly derived due to data constraints, the analyzed events correspond to high-intensity rainfall commonly associated with 10-25-year recurrence intervals in comparable regional studies. The rapid hydrological response observed supports the need for proactive storage management prior to flood arrival [41].

### 4.3 Reservoir Operation Simulation: Without vs. With Early Release

The effectiveness of early-release operation was evaluated by comparing two scenarios:

Table 2. Estimated time of concentration for the Beringin Sila watershed

| Location | Catchment area (km²) | Time of concentration (hours) |
| --- | --- | --- |
| Beringin Sila Reservoir | 61.0 | 3.82 |
| Stowebrang Village | 65.0 | 4.35 |
| Estuary | 72.3 | 6.75 |

a) conventional operation without early release, and
b) forecast-based early-release operation.

In the no-early-release scenario, the simulated water surface elevation (WSE) approached the upper operational limit, increasing the probability of uncontrolled spilling and elevated downstream flood risk [42]. In contrast, early release reduced the initial WSE prior to flood arrival, thereby increasing available flood-control storage. Quantitatively, early-release operation resulted in a reduction in peak outflow, a delay in downstream peak timing, and a lower maximum WSE compared to the conventional operation. These improvements demonstrate the operational benefit of anticipatory releases, particularly under short lead-time flood conditions.

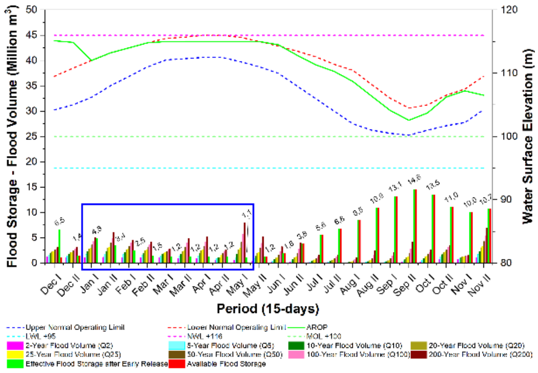


Fig. 7 Flood-operation guidance with early release

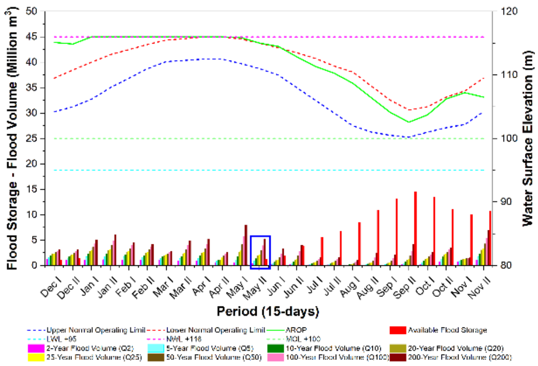


Fig. 8 Flood-operation guidance without early release

### 4.4 Integrating Weather Forecasts into Reservoir Operation

The integration of rainfall forecasts from BMKG and The Weather Channel significantly enhanced operational readiness, particularly during the reservoir's initial impounding stage. Short-term forecasts (1-7 days) provided actionable lead time to initiate controlled releases while remaining compliant with RTOW constraints.

Operational decisions were triggered when forecast rainfall exceeded predefined thresholds indicative of potential flood inflow, with release volumes adjusted dynamically based on updated forecasts and observed rainfall. While forecast accuracy varied spatially, the combined use of multiple forecast sources reduced reliance on a single deterministic prediction.

Nevertheless, spatial resolution differences between forecast grids and watershed scale introduce uncertainty, particularly for localized extreme rainfall. As such, forecast-based operation should be implemented as a dynamic and adaptive process, continuously updated as new observations become available. The application of forecast rainfall and inflow data during the initial impounding stage, comparing predicted and observed discharge with planned and actual reservoir water levels (Fig. 9). The integration of forecast information supports proactive operational adjustments, enabling controlled filling while maintaining water levels within operational limits and enhancing flood preparedness.

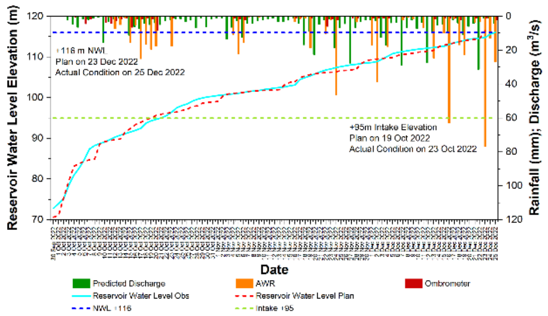


Fig. 9 Application of forecast data during initial impounding

### 4.5 Forecast Limitations and Operational Implications

Forecast uncertainty may lead to two primary operational risks: over-release, when predicted rainfall does not materialize, and under-release, when rainfall intensity exceeds forecasts. Over-release may temporarily reduce water availability, whereas under-release may compromise flood safety. In this study, hypothetical forecast error scenarios indicate that moderate overestimation of rainfall could lead to unnecessary early release but remains operationally manageable within RTOW limits. Conversely, significant underestimation poses a higher risk, as insufficient pre-release reduces available flood-control storage. These findings highlight the importance of treating forecasts as decision-support tools rather than deterministic inputs. Future implementations should incorporate ensemble or probabilistic forecasting approaches to quantify uncertainty and assess the robustness of early-release thresholds under varying forecast reliability [43]. Laboratory-scale experiments were not conducted in this study due to the large-scale nature of reservoir systems and the focus on operational hydrological modeling. Physical modeling of reservoir flood dynamics would require complex scaling and infrastructure that may not fully represent real-world watershed conditions. Therefore, this study prioritizes numerical simulation and field data analysis as a more practical approach. Future research may incorporate physical or hybrid modeling to complement and validate the findings presented here.

## 5. CONCLUSION

This study investigates the application of a forecast-informed early-release strategy for improving flood control performance in a multipurpose reservoir with an ungated spillway under data-limited conditions.

Early water release based on weather forecasts is a promising operational strategy to improve flood control performance in multipurpose reservoirs, particularly in areas with ungated spillways and limited storage capacity, which makes pre-event water level reduction crucial. In this study, the developed hydrological and operational framework demonstrated adequate performance for scenario-based decision-making under data-limited conditions.

The findings confirm that forecast-based early release can effectively increase available flood-control storage prior to flood arrival and reduce peak outflow relative to existing operation, thereby enhancing downstream flood mitigation under RTOW constraints. Short-lead rainfall forecasts (1-7 days) are shown to be operationally relevant, if decisions are updated dynamically and interpreted as decision-support rather than deterministic inputs. To mitigate identified limitations, future implementations should prioritize the acquisition of higher-resolution rainfall and discharge data through expanded rain-gauge networks, weather radar integration, or satellite-based products, and operate the model at an hourly time step where feasible. In addition, the use of ensemble or probabilistic rainfall forecasts is recommended to explicitly quantify forecast uncertainty and assess the robustness of early-release thresholds under over- and under-prediction scenarios. Collectively, these results support the practical implementation of the proposed framework as a decision-support tool for adaptive reservoir operation, while highlighting the importance of uncertainty-aware operation and pilot-scale testing prior to full-scale deployment. The proposed framework demonstrates strong potential for implementation in similar reservoirs, particularly in developing regions where data limitations and operational uncertainties remain key challenges.

## 6. ACKNOWLEDGMENTS

Authors would like to express our gratitude to all parties who provided data, shared knowledge, and trusted us to participate in the Beringin Sila Dam construction team. We are especially grateful for their cooperation, especially with the Nusa Tenggara 1 River Basin Center, the Dam Safety Commission Technical Team, PT Indra Karya, and the Beringin Sila Dam Supervision Team.

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