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Predictive Rainfall–Runoff Modelling and Spillway Adequacy Assessment for Mindu Dam in Morogoro, Tanzania Using HEC-HMS

Revodius Bishanga Stanslaus[1,2*]; Edmund Mutayoba[1]; Livingstone Swilla[1]

[1] Department of Water Supply and Sanitation Engineering, Water Institute, P.O.BOX 35059, Dar es Salaam
[2] Lake Victoria Water Board; P.O.BOX 1342, Mwanza

Corresponding Authors: Revodius Bishanga Stanslaus*

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Abstract: Reliable forecasting of reservoir inflows and accurate prediction of flood events are crucial for ensuring dam safety and maintaining water supply reliability. This study assesses the adequacy of the spillway at Mindu Dam, located in Morogoro, Tanzania, by combining hydrological modelling with a performance-based assessment. A rainfall–runoff model was developed using the HEC-HMS platform. It was calibrated using basin-average precipitation from the Mondo, Hobwe and Mlali rainfall stations and observed discharge data from the Konga gauging station on the Ngerengere River. The model was validated from 2005 to 2019 to ensure it represents catchment hydrological processes well. Model performance was evaluated using statistical indicators, including the Nash–Sutcliffe Efficiency (NSE), the coefficient of determination (R^2), and Percent Bias (PBIAS). The results show model performance. During calibration, NSE was 0.72 and R^2 was 0.76, while during validation NSE was 0.68 and R^2 was 0.71. These values demonstrate agreement between simulated and observed flows, confirming the model's suitability for analysis in the study area. Simulated flood hydrographs were used to estimate peak inflows and to assess the spillway's capacity to safely convey flood events. The analysis reveals that the existing spillway performs under moderate flood conditions but may be insufficient during flood scenarios. This limitation introduces a risk of overtopping, particularly under conditions of increased variability and uncertainty. The findings highlight the importance of integrating modelling with hydraulic design and evaluation in dam safety assessments. In the context of climate change, which brings increasing rainfall intensity and event frequency, such integrated approaches are essential. They help develop infrastructure and inform adaptive water resources management strategies. The Mindu Dam spillway assessment shows that combining modelling with performance-based evaluation can identify potential risks and inform strategies to mitigate them, ensuring dam safety.

Keywords: *Rainfall–Runoff Modelling; HEC-HMS; Spillway Adequacy; Flood Hydrograph; Dam Safety; Peak Discharge.*

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I. INTRODUCTION

The spillway is an indispensable feature of a dam, as it ensures the safe release of surplus floodwater and thereby prevents the dam from overtopping, the second-most common cause of dam failure worldwide. In many developing countries, including Tanzania, the dikes were constructed based on scarce hydrological data, which has now raised concerns about their capacity to cope with severe flooding amid intensified climatic variability and human alteration of land cover (Mango et al., 2011).

The Mindu Dam reservoir is the watershed that supplies the Municipality of Morogoro with water. Therefore, whether the spillway can safely pass the peak inflow generated in the catchment largely determines the dam's safety and reliability. The Mindu watershed is highly variable in rainfall and experiences very rapid runoff, making it naturally prone to extreme runoff events.

Hydrological modelling provides a robust basis for inflow estimation to assess spillway capacity (Beven, 2012). However, if the only calibration data are the reservoir outflow data, there is always some uncertainty introduced by storage and regulation effects. This is why, in this study, we used the natural flow from the upstream Konga gauging station to minimise these uncertainties and make the model more realistic.

The primary goal of this work is to determine the Mindu Dam's spillway capacity to handle extreme flood events using a calibrated rainfall-runoff model.

II. MATERIALS AND METHODS

➢ *Introduction*

Hydrological modelling and rainfall data analytics were combined to estimate runoff volumes in the Mindu catchment and inflow quantities relevant to spillway curve analysis worldwide. The initial model was calibrated and validated using rainfall and runoff data streams, yielding high determination coefficients, as evidenced by the Nash-Sutcliffe efficiency index (NSE) values. It is well established that the dynamics of inflow events at any water supply reservoir are captured through hydrograph simulation. At the same time, peak discharge exceedance is extracted for surface hydrological calculations and related engineering analyses to determine spillway flow capacity.

➢ *Study Area*

Situated within the Uluguru Mountain ecosystem in the Morogoro Region, Tanzania, the Mindu catchment covers approximately 303 km^2. Rainfall is bimodal, with long rains (March–May) and short rains (October–December). The topography consists predominantly of steep to moderately steep slopes, which significantly increase the speed of runoff.

The land-use pattern mainly comprises forests, various agricultural activities, and residential areas, which play an important role in shaping infiltration and runoff dynamics (Mango et al., 2011). These landscape features are significant factors in rainfall-runoff modelling.

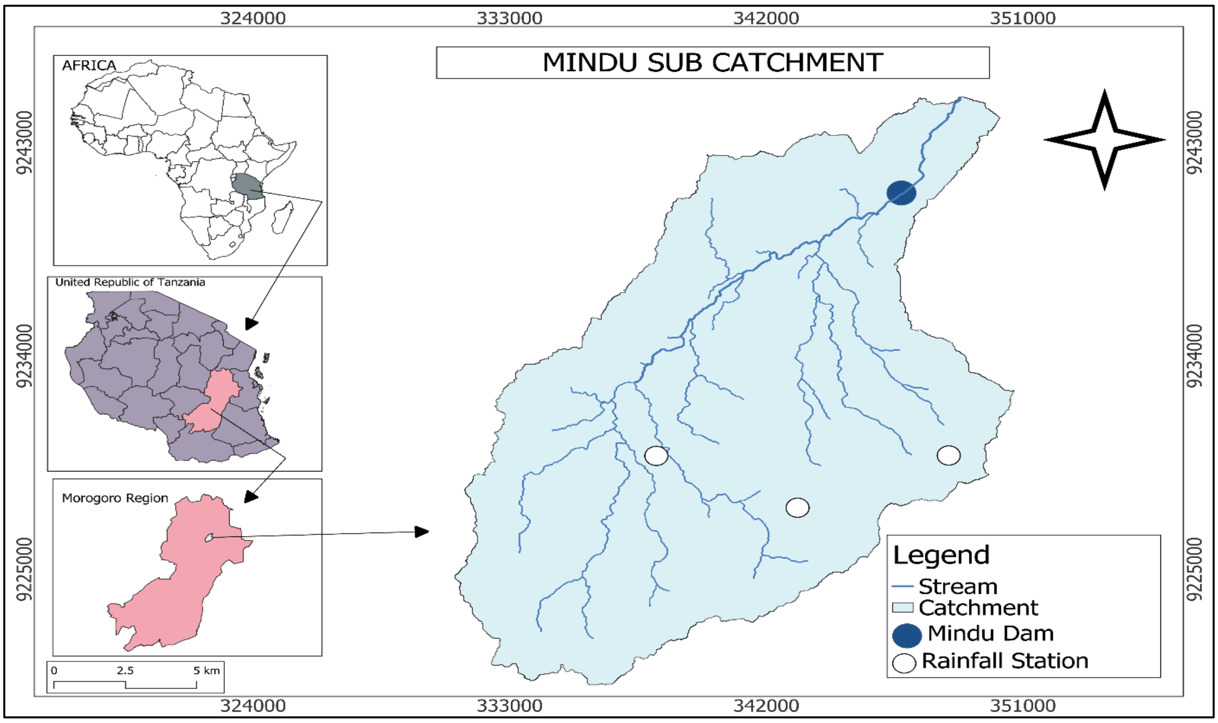

Fig 1 The Mindu Subcatchment

➢ *Data Collection and Processing*

Daily rainfall data (1990–2019) were obtained from three stations: Mondo, Hobwe, and Mlali. Basin-average rainfall was computed to capture spatial variability. Observed discharge data from the Konga station (2005–2019) were used to calibrate and validate the model.

Land-use characteristics influence runoff generation by affecting infiltration and evapotranspiration (Mango et al., 2011; Shaw, 1994).

Data preprocessing included consistency checks, outlier removal, temporal alignment, and gap filling. All datasets were standardized to a daily time step.

➢ *Hydrological Modelling (HEC-HMS)*

The rainfall-runoff model has been developed in HEC-HMS using standard hydrological modelling procedures (USACE, 2016; USACE, 2018). The SCS Curve Number method and the Unit Hydrograph approach are widely used for catchment-scale runoff simulations (Chow et al., 1988; Shaw, 1994).

- *A Rainfall–Runoff Model was Developed Using HEC-HMS with the Following Components:*

- ✓ Loss method: SCS Curve Number (CN ≈ 76)
- ✓ Transform method: SCS Unit Hydrograph (lag time ≈ 9.5 hours)
- ✓ Baseflow: exponential recession (constant ≈ 0.94)

- *Runoff Estimation Followed:*

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)}$$

Where

$$S = \frac{25400}{CN} - 254$$

➤ *Methodological Framework*

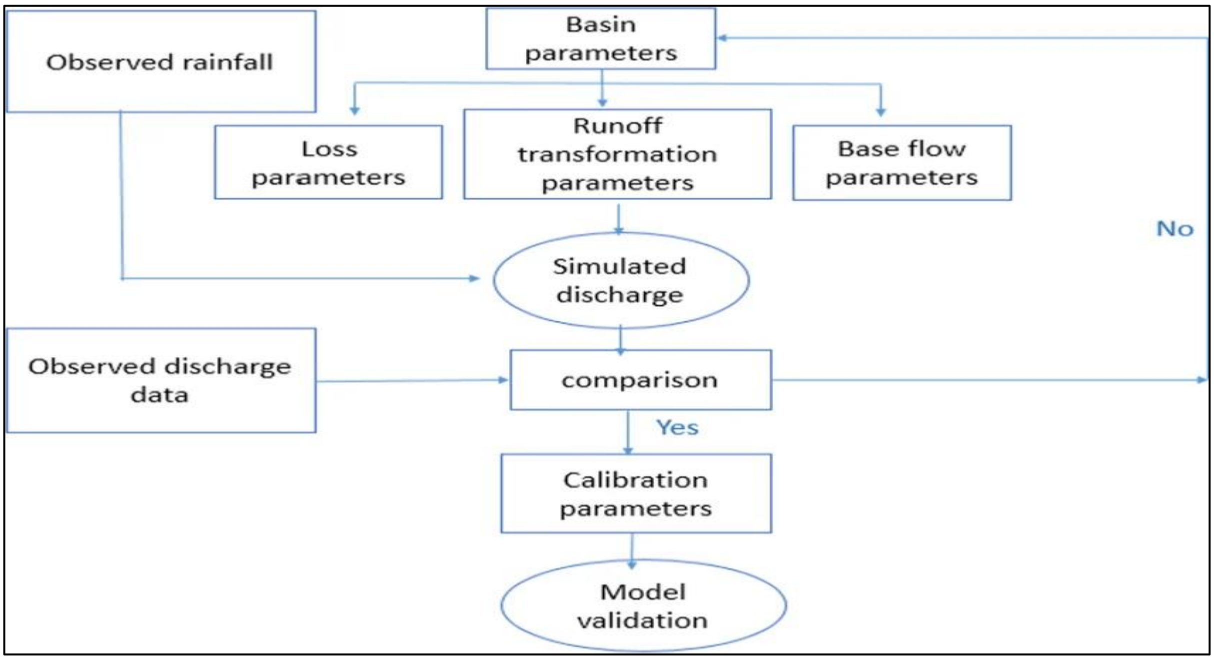

Fig 2 Methodological Framework for Rainfall–Runoff Modelling and Spillway Adequacy Assessment

The modelling framework begins with data collection and preprocessing; it then estimates basin rainfall and sets up the HEC-HMS model. Discharge at Konga station is used to calibrate the model; an independent dataset is used for validation; and the model is then used to simulate peak flood. The derived inflows are then compared with the spillway capacity to assess adequacy.

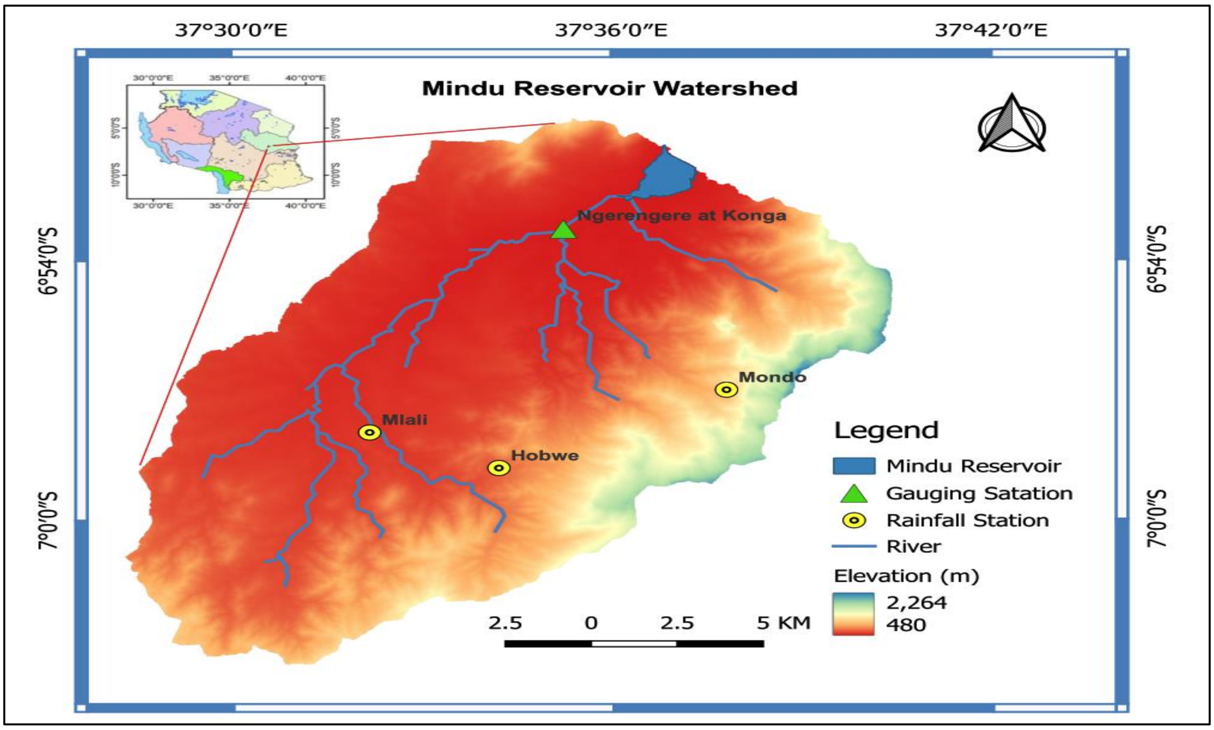

Fig 3 GIS-Based Representation of the Mindu Catchment Showing Topography, River Network, Rainfall Stations (Mondo, Hobwe, Mlali), and the Location of Mindu Dam.

The map illustrates the spatial distribution of rainfall stations and the drainage pattern within the catchment. The upstream high-elevation zones contribute significantly to runoff generation, while the river network converges toward the Mindu reservoir.

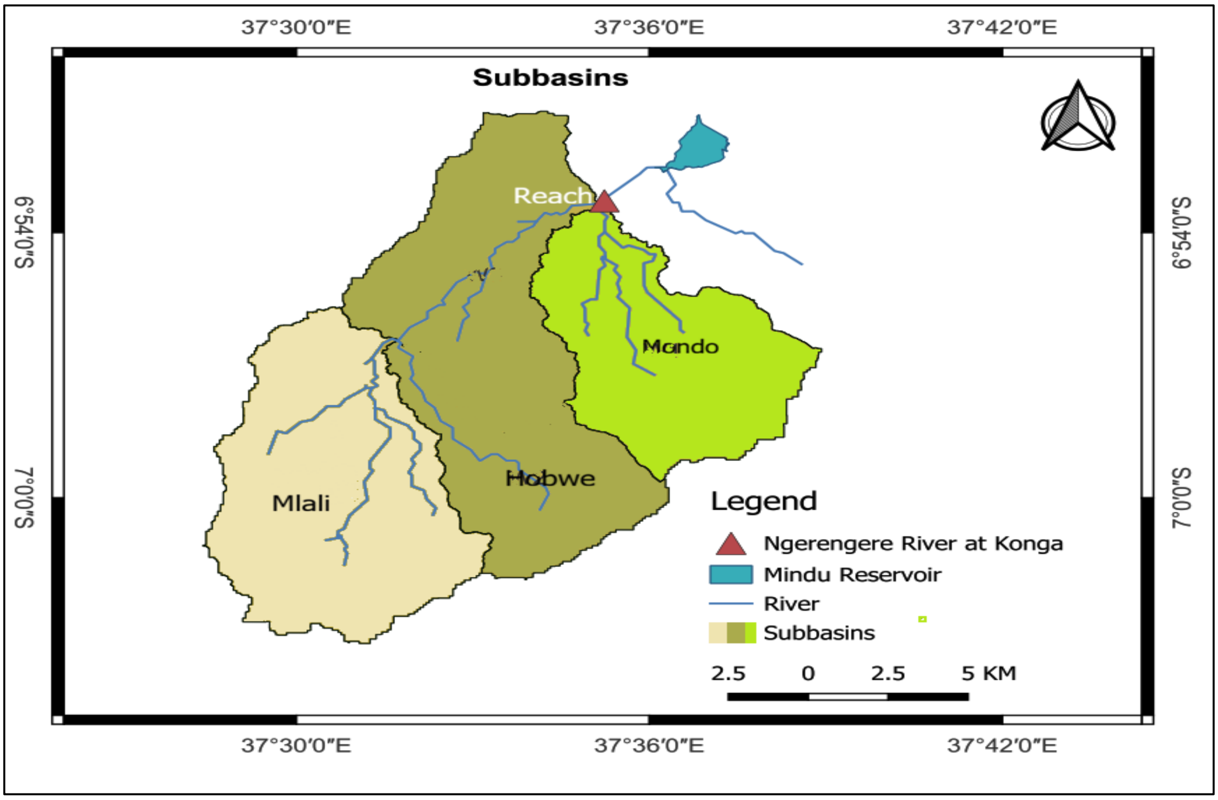

Fig 4 HEC-HMS Basin Schematic Showing Rainfall Inputs, Sub-Basin Transformation, Channel Routing, and Reservoir inflow at Mindu Dam.

The schematic represents the conceptual hydrological model structure used in HEC-HMS. Rainfall inputs from the three stations are aggregated into a sub-basin, transformed into runoff, routed through the channel system, and delivered to the reservoir.

➢ *Model Calibration and Validation*

Model performance was evaluated using NSE, R², and PBIAS, which are widely recommended for assessing hydrological models (Moriasi et al., 2007).

The model was calibrated using observed discharge data for the period 2005–2012 and validated for 2013–2019.

➢ *Performance Metrics*

Model performance was evaluated using:

- *Nash–Sutcliffe Efficiency (NSE):*

$$NSE = 1 - \frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - \bar{Q}_{obs})^2}$$

- *Coefficient of Determination (R²):*

$$R^2 = \frac{[\sum(Q_{obs} - \bar{Q}_{obs})(Q_{sim} - \bar{Q}_{sim})]^2}{\sum(Q_{obs} - \bar{Q}_{obs})^2 \sum(Q_{sim} - \bar{Q}_{sim})^2}$$

- *Percent Bias (PBIAS):*

$$PBIAS = 100 \times \frac{\sum(Q_{sim} - Q_{obs})}{\sum Q_{obs}}$$

These metrics are widely used in hydrological model evaluation (Moriasi et al., 2007).

➢ *Peak Flood Estimation*

Design flood estimation was based on simulated extreme events and established flood frequency principles (Pilgrim, 1987; WMO, 2009). Peak discharge (Q_{peak}) was obtained from simulated hydrographs under extreme rainfall conditions. Design flood scenarios were derived from historical extremes and model simulations.

➢ *Spillway Capacity Assessment*

Spillway discharge was evaluated using standard hydraulic relationships for ogee spillways (Chow et al., 1988; FAO, 2010), using the ogee spillway equation:

$$Q = CLH^{3/2}$$

Where:

Q=discharge (m³/s)

C=dischargecoefficient

L=crestlength (m)

H= head over crest (m)

The computed capacity was compared with the simulated peak inflow to assess adequacy.

III. RESULTS AND DISCUSSION

- *Hydrograph Analysis*

The observed underestimation of peak flows is consistent with known limitations of lumped hydrological models, particularly under conditions of high rainfall variability (Beven, 2012).

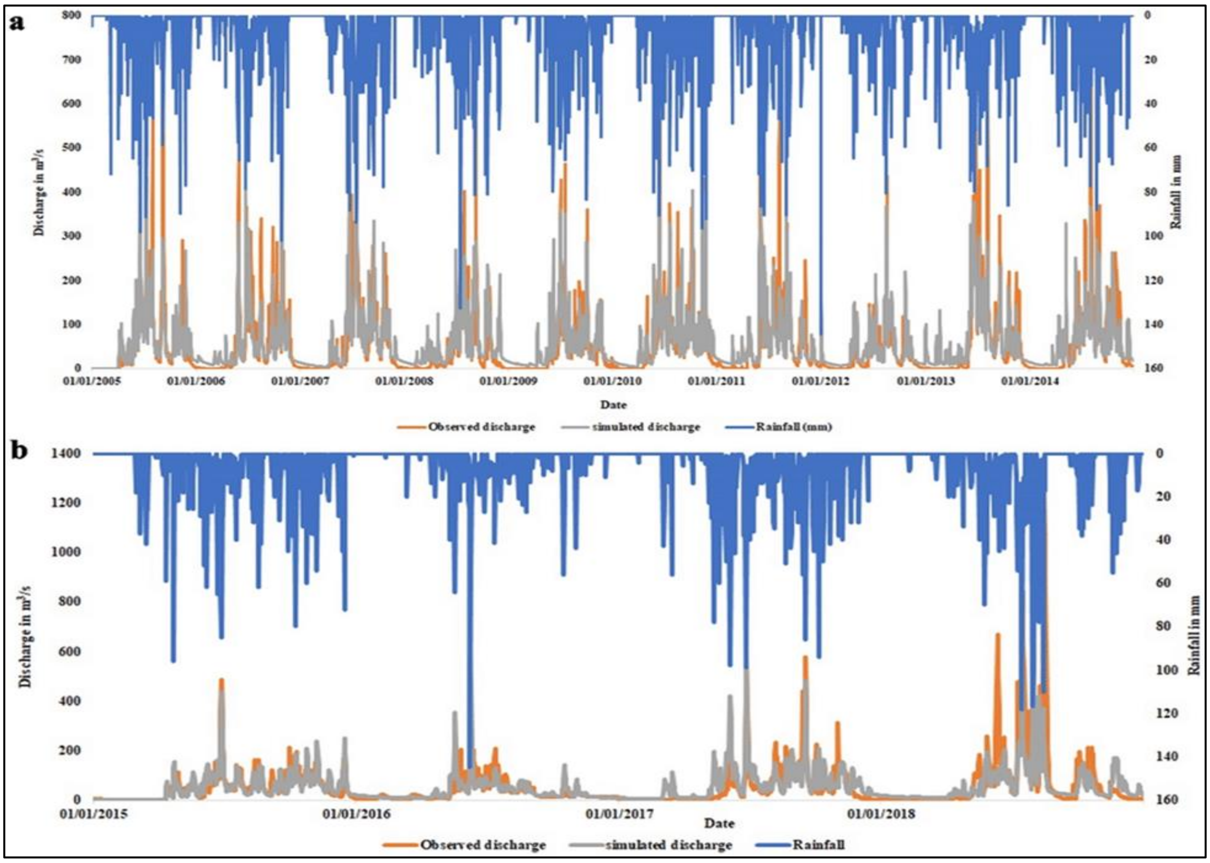

Fig 5 Observed vs Simulated Daily Discharge at Konga Station.

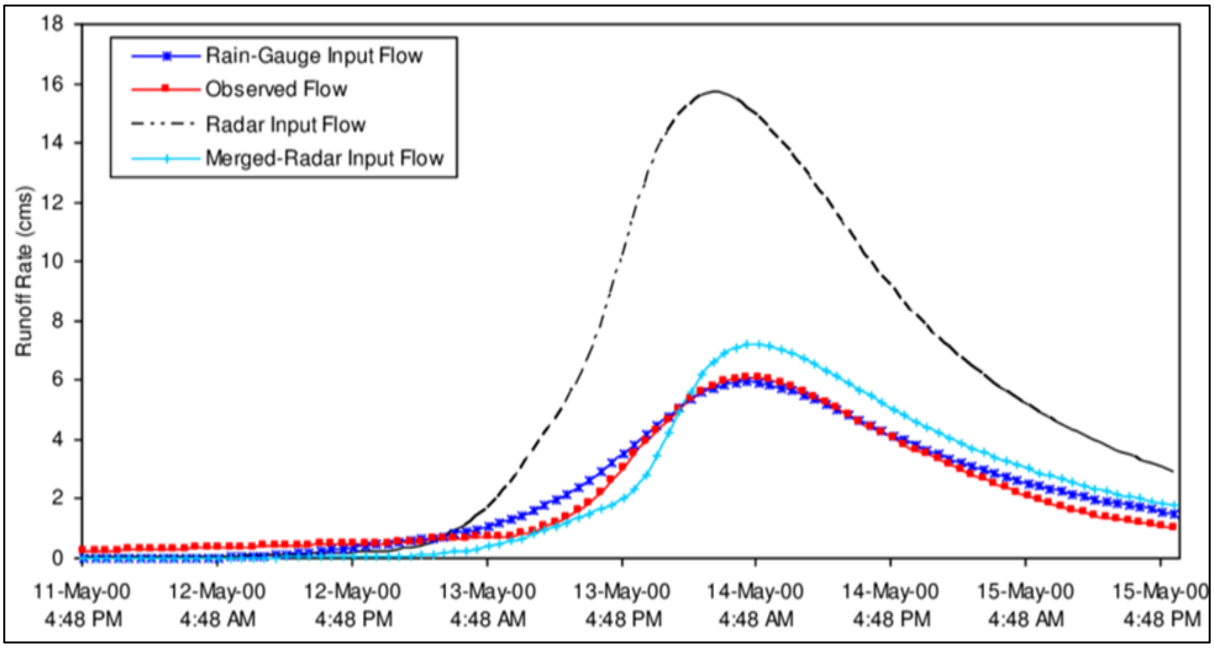

Fig 6 Observed vs Simulated Daily Discharge at Konga Station.

The model can reproduce seasonal changes and peak timing, although it slightly underestimates high flows.

The comparison of hydrographs from the observed and simulated data shows that the model accurately captures the seasonal variability of streamflow in the Mindu catchment area. In particular, the model correctly identifies the timing of peak flows during the main rainy season (March - May), indicating that the chosen parameters for lag time and runoff transformation are appropriate indicators of the catchment response.

On the other hand, there is always some degree of underprediction of the very high flow peaks. This is a characteristic of simplified rainfall-runoff models, and the reasons behind it may include the following:

- Not capturing the spatial variation of rainfall with only three stations
- Lack of sub-daily rainfall intensity disaggregation, which is essential for the generation of peak flows.
- Use of a simplified method such as the SCS Curve Number for infiltration modelling

Although the aforementioned issues exist, the model captures the recession limbs well, indicating that the baseflow processes are consistent with reality. This further indicates that the use of the recession constant captures groundwater contribution and storage dynamics.

➢ *Scatter Plot Analysis*

Reasonable questions can arise about the use of scatter plots in analysing observed versus simulated discharges, because this approach is at odds with the temporal nature of streamflow data and neglects issues related to model timing performance by failing to account for time lag. However, as a first approximation, scatter plots can be instructive for assessing model bias and the overall scatter of model estimates relative to the observations (Fotopoulos et al., 2010).

Recording and enumerating such deviations are common in tropical catchments, where rainfall exhibits very high spatial and temporal variability (Beven, 2012; Mango et al., 2011).

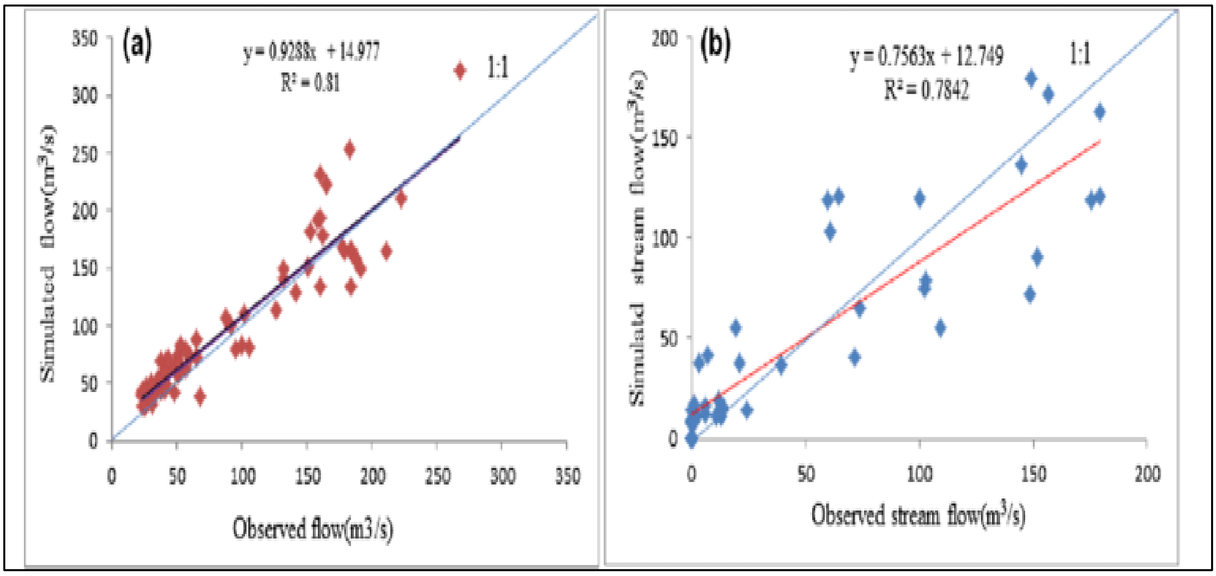

Fig 7 Observed vs Simulated Discharge.

The scatter plot shows that data points are concentrated near the 1:1 reference line, indicating a close match between observed and simulated discharge measurements. The coefficient of determination ($R^2 = 0.81$ during calibration) indicates that the model accounts for a substantial portion of the variation in observed flow.

Still, at higher discharge levels, there is noticeably greater scatter, indicating that the model is less reliable at predicting these kinds of events. Moreover, the slope of the regression line (less than 1) provides further evidence that the model consistently underestimates peak flows.

- *From a Hydrological Point of View, this Indicates:*

✓ That runoff at peak is directly affected by rainfall intensity and soil moisture conditions before the event.
✓ That changes in loss parameters, or the use of distributed rainfall inputs, would help improve the model.

These sorts of errors are very often encountered in tropical catchments, where convective storms produce very local and extremely heavy showers (Beven, 2012).

➢ *Monthly Rainfall, Runoff Relationship*

Runoff output does not vary linearly with rainfall due to catchment storage and evapotranspiration processes (Shaw, 1994).

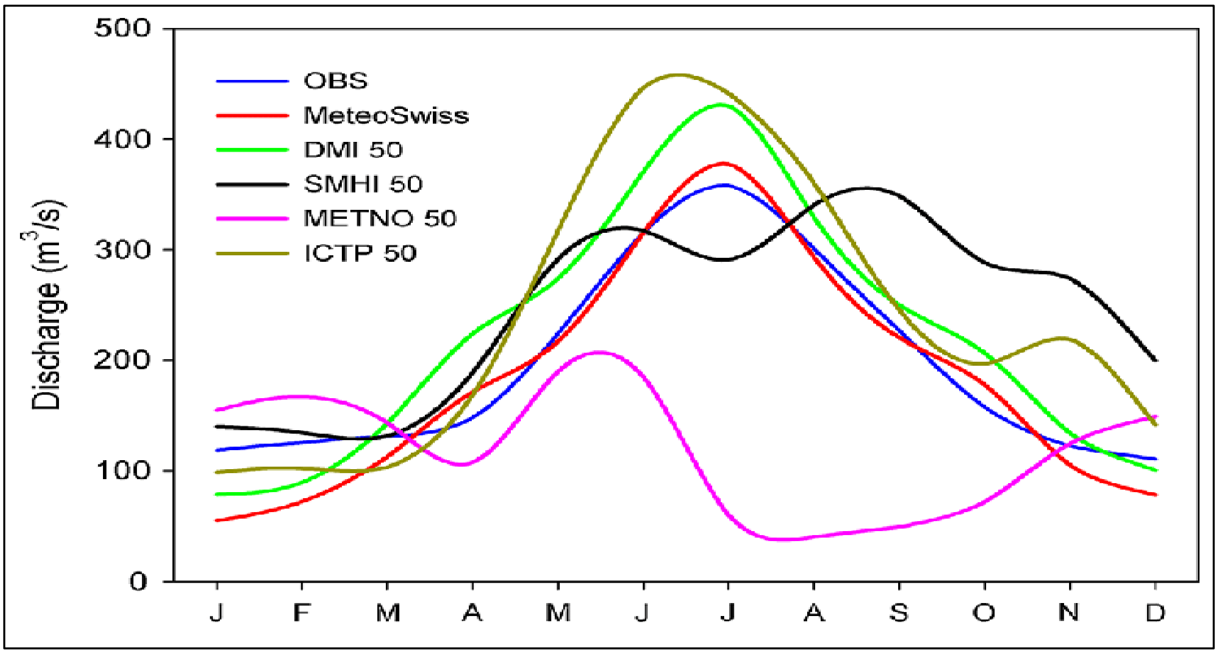

Fig 8 Monthly Rainfall and Discharge Relationship.

The monthly review indicates an extraordinarily strong positive link between rainfall amount and river discharge. In fact, runoff generation in the Mindu catchment appears to be largely controlled by rainfall. Highest river flow values happen at the same time as maximum rainfall, mainly in the long rainy season.

On the other hand, the connection is not a perfect one, showing that several hydrological elements besides rainfall affect the scenario, such as:

- Soil moisture content
- Evapotranspiration
- Groundwater supply

Moreover, the delay observed between a rain event and a peak in river discharge suggests the involvement of catchment storage and routing processes. This pattern is consistent with the SCS Unit Hydrograph method, which assumes a delayed runoff response.

➢ *Model Performance Evaluation*

The model performance parameters indicate that the HEC-HMS model satisfactorily represents catchment hydrology, in accordance with Moriasi et al. (2007).

- Calibration: NSE = 0.72, R^2 = 0.76, PBIAS = -6.8%
- Validation: NSE = 0.68, R^2 = 0.71, PBIAS = -9.5%

By measuring against a set of acknowledged model performance criteria (Moriasi et al., 2007):

- NSE > 0.65 is a marker of good model performance.
- PBIAS within ±10% means a low level of systematic bias.

The negative PBIAS in the output indicates marginal underestimation of discharge, which is consistent with the hydrograph and the scatter plot. The minor decrease in performance from the calibration to the validation stages indicates that the model is strong and reliable, given the minimal overfitting. Hence, this point is crucial for predictive purposes such as flood estimation and spillway design.

➢ *Spillway Adequacy*

A shortfall in the spillway safety margin, combined with underestimation of peak flows, suggests that the spillway could cause the dam to overtop even though it may be capable of handling moderate flood events.

Evidence from global dam safety records (ICOLD, 2011) indicates a limited safety margin for spillways and their vulnerability to extreme conditions.

➢ *Discussion*

The results clearly show that rainfall is the main factor driving runoff generation in the Mindu catchment. This finding matches the hydrological response characteristics of tropical catchments. In these areas, runoff mainly depends on rainfall intensity, duration, and distribution over time. The strong link between rainfall events and simulated discharge confirms that the catchment operates under a rainfall-driven regime, with limited ability to buffer during intense storms. However, the modeling results also showed a consistent underestimation of peak flows. Although the HEC-HMS model did well in replicating seasonal flow patterns and general discharge trends, it was less sensitive to extreme rainfall events. This introduces uncertainty in flood predictions. This issue is particularly important in dam safety assessment, where accurately estimating peak inflows is critical for spillway design and flood routing. Similar findings have been noted in studies of tropical and sub-humid catchments. In these regions, the high spatial and temporal variability of rainfall often complicates the capture of extreme hydrological responses. Short-duration, high-intensity storms can create disproportionately large runoff volumes, which are not always represented well in rainfall-runoff models. As a result, even well-calibrated models may show biases when simulating extreme events. The underestimation of peak flows creates uncertainty that cannot be overlooked in engineering applications. From a design viewpoint, this requires conservative assumptions to ensure structural safety. For spillway adequacy, conservative design may include using higher design floods, such as the Probable Maximum Flood, adding safety factors, or providing auxiliary spillways to manage possible exceedance flows. Therefore, incorporating hydrological modeling uncertainty into hydraulic design is essential. Instead of relying only on deterministic model outputs, a risk-informed approach should be used. This involves considering uncertainty bounds in spillway sizing and dam safety evaluation. This approach improves resilience by accounting for model limitations and the natural variability of tropical rainfall systems, thus reducing the risk of overtopping and potential dam failure.

IV. CONCLUSION

Hydraulic design and hydrological modelling are often treated as separate components in dam hazard assessment. However, their interaction can introduce inconsistencies if not properly addressed. The World Meteorological Organization (2009) and the International Commission on Large Dams (2011) emphasise that integrating hydrological models with hydraulic design frameworks is crucial for comprehensive dam safety evaluation, particularly under changing climate conditions and uncertainty. In this study, we used the HEC-HMS model to simulate rainfall-runoff processes in the Mindu catchment. The model performed well during both calibration and validation. It accurately captured seasonal flow patterns and showed strong agreement with observed discharge data. However, we observed a consistent bias, with the model slightly underestimating extreme peak flows. This shortcoming is significant in dam safety analysis because underestimating peak inflows can compromise the reliability of design flood estimates. The spillway adequacy assessment indicates that the current spillway can safely handle moderate flood events. However, under extreme hydrological conditions, such as probable maximum flood (PMF) scenarios, the spillway capacity appears inadequate. The narrow safety margin and uncertainty in peak flow estimates increase the risk of overtopping, a major cause of earth-fill dam failure worldwide. These findings underscore the importance of integrating hydrological modelling results with hydraulic design verification. The approach we used provides a useful decision-making framework for understanding inflow behaviour, identifying structural weaknesses, and guiding water resource management strategies. This integration is especially important in semi-arid and data-limited regions like Tanzania, where climate variability increases hydrological uncertainty and infrastructure risk.

RECOMMENDATIONS

From what was found in this study, the following are some of the recommendations that could be implemented to enable the safety and operational reliability of Mindu Dam:

- ➢ Detailed Spillway Capacity Reassessment. The existing spillway must be hydraulically evaluated against extreme floods, such as the Probable Maximum Flood (PMF) and high-return-period events (e.g., 100-year and 1000-year floods), to determine whether it meets modern dam safety standards under hydrological extremes.
- ➢ Spillway Upgrade and Auxiliary Structures. Work on structural enhancement from below:

- Lengthening or raising the spillway crest
- Getting rid of discharge inefficiencies
- Providing an emergency spillway so that excess flows can be safely passed during extreme events.

- ➢ Climate Change Modelled in Adjusted Floods. Projections of climate change, especially increasing rainfall intensity and frequency, have to be integrated into spillway design and reassessment. One way to do this is through rainfall factor adjustments or by using climate model outputs to revise storm design events.
- ➢ Improved Hydrological Monitoring Network. Model accuracy and precision should be promoted through:

- More rainfall stations in the catchment
- Real-time discharge monitoring systems
- Automated data logging and telemetry systems. Improved data availability will go a long way in decreasing uncertainty in peak flow estimation and model calibration.

- ➢ Reservoir Flood Routing and Storage Analysis. Hydrological analyses in reservoirs, such as flood routing, contribute to a better understanding of the interactions among inflow, storage, and spillway discharge under extreme conditions. This, in turn, enables more realistic assessments of water levels and overtopping risk.
- ➢ Dam Safety and Emergency Action Plans (EAP) Development. Establishing a comprehensive dam safety management system is possible through the incorporation of various interlinked elements, such as:

- Inspection and maintenance of facilities regularly
- Early warning system for communities downstream of the dam
- Emergency response and preparedness plans
- Operational guiding rules for flood events

- ➢ Model Updating and Validation Periodically. The rainfall-runoff model must be regularly updated and recalibrated with new hydrological data to remain robust to evolving catchment and climatic conditions.

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