

ASSESSING DESIGN HYDROGRAPH AND SPILLWAY CAPACITY SENSITIVITY TO ANTECEDENT SOIL MOISTURE CONDITIONS, RAINFALL PATTERNS AND HYDROLOGICAL TRANSFORMATION UNCERTAINTY IN THE KNUCKLES BASIN

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Abstract

Reservoir operation under extreme events requires reliable estimation of design floods while accounting for uncertainties in catchment runoff generation and rainfall temporal distribution. This study evaluates the flood response and capacity adequacy of the Maminiyawa Reservoir, Sri Lanka, using a scenario-based HEC-HMS modelling approach. A 50-year return period design storm was developed, and multiple hydrological scenarios were generated by systematically varying key runoff transformation parameters (Curve Number and the Peak Rate Factor) and rainfall temporal patterns representing front-loaded, centrally loaded, and back-loaded storms. Peak discharge, reservoir pool elevation, and routing response were evaluated to identify the critical condition. Peak discharge ranged from 196.5 to 372.9 m³/s, representing an 89.8% variation among the scenarios. Variations in runoff transformation parameters produced increases of up to 24.8% in peak discharge, while rainfall temporal distribution had a comparatively smaller influence, with a maximum increase of 14.5% for the back-loaded pattern relative to the front-loaded pattern. The critical scenario produced a peak discharge of 372.9 m³/s and a pool elevation of 140.2 m. With a full supply level of 137 m and a bund level of 140 m, the simulated water level exceeded the bund by 0.2 m, indicating potential overtopping under the 50-year design event. The findings demonstrate that explicitly accounting for uncertainty in hydrological transformation and rainfall temporal distribution is important for robust reservoir flood-safety assessment and capacity enhancement planning.

Keywords: Hydrological modelling, Extreme rainfall, Runoff generation, Reservoir routing

1. Introduction

Reliable design flow estimation is fundamental to reservoir safety and spillway design. The design flow estimation is subject to uncertainties associated with rainfall characteristics, land use, runoff generation, and rainfall-runoff transformation. Previous studies have shown that uncertainty in rainfall inputs and hydrological model parameters can substantially affect simulated flood response, while the temporal distribution of rainfall can influence flood magnitude and timing even when the total storm rainfall remains unchanged [1]. Despite the importance of these uncertainties, their combined influence on design floods and reservoir spillway response remains insufficiently investigated in Sri Lankan catchments. In particular, limited attention has been given to how variations in runoff generation, rainfall temporal distribution, and hydrological transformation interact to influence the flood response of existing reservoirs. Therefore, this study aims to evaluate the sensitivity of design floods and spillway capacity to land-use-related runoff generation, rainfall temporal pattern, and

hydrological transformation uncertainty in the Knuckles Basin, using Maminiyawa Reservoir as a case study.

2. Study Area

The study was conducted in the Maminiyawa Reservoir-based cascade system, located within the Knuckles Basin of Sri Lanka. Maminiyawa Reservoir has a storage capacity of 1.8 million m^3 at full supply level and an irrigable extent of approximately 188 ha [2]. The contributing catchment considered in this study covers approximately 23.39 km^2 , with an average basin slope of approximately 4.27%.

3. Methodology

Daily rainfall data from the nearest rain gauge station, Maradankadawala, were used for the analysis. Extreme rainfall was estimated using Weibull and Gumbel distributions, with the Weibull distribution selected based on the higher estimated extreme rainfall. QGIS 3.44.11 was used for land use classification, Curve Number estimation and development of the reservoir area elevation curve using a 30 m $\times$ 30 m digital elevation model (DEM). The absence of hourly rainfall observations required daily rainfall to be disaggregated into hourly data using the temporal disaggregation method, while the 30 m DEM resolution introduced additional uncertainty in the area-elevation relationships. The baseline Curve Number (CN_2) was 78, while $CN_1 = 61$ and $CN_3 = 90$ were derived using NRCS conversion relationships [3]. Rainfall-runoff simulations were performed using HEC-HMS 4.13. Three peak rate factors (PRF): 300, 484, and 600, and three rainfall temporal patterns (front-loaded, centrally peaked, and back-loaded) were considered based on the HEC-HMS Technical Reference Manual [4]. PRF represents the hydrological transformation of excess rainfall into runoff and influences the magnitude and timing of the peak discharge. The combinations of three CN values, three PRFs and three rainfall patterns resulted in 27 simulation scenarios, which were compared to assess this influence on design flood response.

4. Results and Discussion

The 27 HEC-HMS simulations demonstrate that CN, PRF, and rainfall temporal distribution collectively influence the reservoir flood response. Peak discharge varied from 196.5 to 372.9 m^3/s , corresponding to an 89.8% variation across the scenarios. Uncertainty in CN and PRF produced pronounced effects on peak discharge, with increases of 21.7% and 24.8%, respectively, under controlled comparisons. The rainfall temporal pattern produced a comparatively smaller but significant influence, with the maximum difference between back-loaded and front-loaded patterns reaching 14.5%. The critical condition occurred at $CN = 90$ and $PRF = 600$, where the centrally and back-loaded patterns produced the maximum peak discharge of 372.9 m^3/s and a pool elevation of 140.2 m. Figure 2 shows selected outflow hydrographs, with the critical scenario exceeding the 140 m bund level by 0.2 m.

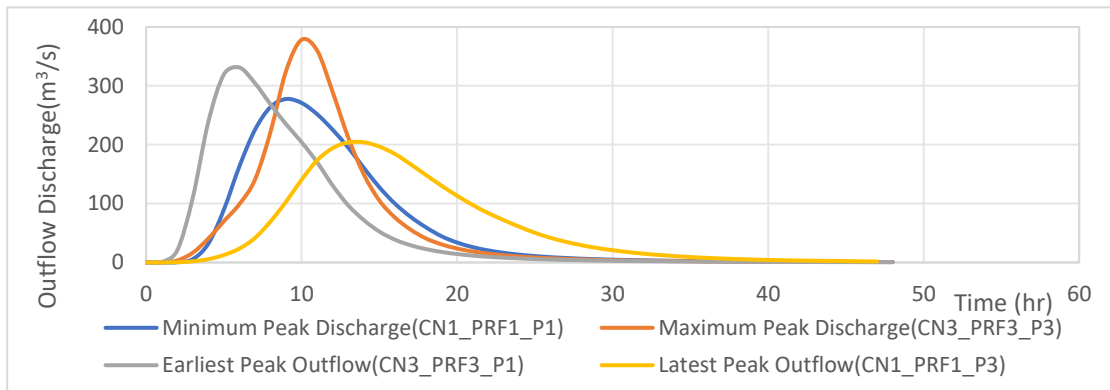


Figure 2: Representative reservoir outflow hydrograph (CN1 = 61, CN3 = 90, PRF1 = 300, PRF3 = 600, P1 = front-loaded pattern, P3 = back-loaded pattern).

5. Conclusion

The results demonstrate that uncertainty in the Curve Number (CN), peak rate factor (PRF), and rainfall temporal pattern can substantially influence the estimated design flood and reservoir response. Among these factors, CN and PRF introduced the greatest uncertainty in peak discharge, while rainfall temporal distribution had a comparatively smaller but still significant influence. The 27 simulation scenarios resulted in an 89.8% variation in peak discharge, highlighting the importance of explicitly accounting for hydrological transformation and catchment-condition uncertainties in design flood estimation. The critical design condition occurred under the combination of high CN, high PRF, and centrally or back-loaded rainfall. These findings emphasise the need to consider parameter and rainfall-pattern uncertainty when selecting design floods and assessing spillway capacity, rather than relying on a single deterministic hydrological transformation scenario.

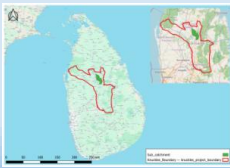
References

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Assessing Design Hydrograph and Spillway Capacity Sensitivity to Antecedent Soil Moisture Conditions, Rainfall Patterns and Hydrological Transformation Uncertainty in the Knuckles Basin

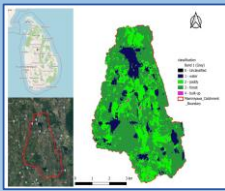
Input Data

Study Area

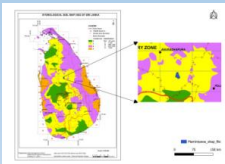


Maminiyawa Reservoir,
Knuckles Basin

Land use land cover
from QGIS classification



Soil Data: Soil Group C



Rainfall Data:

Maradankadawala Rain
Gauge Station/Maha
Illuppallama Rain Gauge
Station

Design Storm:

50-year return period

3 rainfall patterns: (Front-
loaded, Centrally peaked,
Back-loaded)

Hydrological Modelling (HEC-HMS)

Basin Delineation



Model Setup:

Loss method:
Initial and
Constant rate

Transform
Method: SCS unit
hydrograph

Area = 23.385 km²

Longest Flow Path = 10.65 km

Avg. Slope = 4.2%

Sensitivity (Change in Peak Discharge)

CN
(PRF = 600, Front-
loaded) Increase
21.7%
CN62 - CN90

PRF
(CN = 90, Front-loaded) Increase
24.8%
PRF300 - PRF600

Rainfall Pattern Effect
(CN = 90, PRF = 484) Max
Increase
Front-Centre (12.8%) 14.5%
Front-Back (14.8%)

Scenario Development

Curve Number

61

78

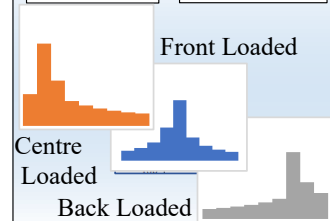
90

Peak Rate Factor

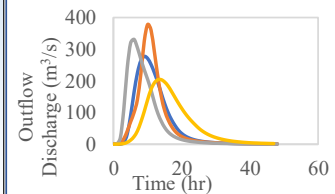
300

484

600



Results and Summary



Critical Scenario

(CN= 90, PRF = 600, Back-
loaded R/F pattern)

Peak Discharge= 372.9 m³/s

Pool Elevation = 140.2 m

Lag from inflow peak = 2 hr

Key Conclusions

1. PRF has the greatest influence on peak discharge, followed by CN
2. A back-loaded rainfall produces higher peaks than a front-loaded pattern.
3. The critical scenario exceeds the bund level by 0.2 m under the 50-year design storm