

CLIMATE-INFORMED SPILLWAY DESIGN FOR HORUWILA WEWA UNDER FUTURE RAINFALL UNCERTAINTY

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Abstract

Intensity-Duration-Frequency (IDF) curves for water infrastructure are traditionally developed assuming climate stationarity. However, human-induced climate change has altered extreme rainfall patterns in recent decades, rendering historical curves untenable and raising global flood risk. Horuwila Wewa, an ancient reservoir in Anuradhapura with a catchment area of 26.4 km² within Sri Lanka's Dry Zone tank cascade system, faces growing challenges managing extreme rainfall under future climate change. This study aims to quantify climate projection uncertainty in future extreme rainfall and assess its implications for Horuwila Wewa's spillway design. Using observed rainfall (1995–2024) and downscaled projections from three Coupled Model Intercomparison Project Phase 6 (CMIP6) general circulation models (GCMs) (CNRM-CM6-1, HadGEM3-GC31-LL, MRI-ESM2-0) under shared socioeconomic pathways (SSPs) SSP2-4.5 and SSP5-8.5, 50-year return-period IDF curves were developed for 2041–2060 and 2081–2100. Daily extremes were estimated using the Gumbel distribution and disaggregated into sub-daily intensities using regional temporal distributions. The resulting IDF curves were incorporated into an uncalibrated HEC-HMS model to simulate reservoir inflows and determine the spillway length required to maintain target peak-pool stage under a 0.8 m bund-height increase. Peak inflow varied from **–13.1% to +57.8%** relative to the 283.8 m³/s baseline, reflecting substantial inter-model uncertainty. The most severe scenario (MRI-ESM2-0, SSP5-8.5, 2081–2100) required an **84% increase** in spillway length. The results demonstrate that climate projection uncertainty can substantially influence spillway design requirements. Incorporating multiple GCMs and SSPs into climate-informed IDF analysis can provide a more robust basis for adapting reservoir infrastructure to future extreme rainfall.

Keywords: Climate change, IDF curves, CMIP6, HEC-HMS, Spillway design

1. Introduction

Climate change is altering extreme rainfall events worldwide and raising flooding risk, which makes historically designed water infrastructure inadequate. Sri Lanka's North Central Dry Zone contains ancient tank cascade systems over two millennia old, whose bunds, sluices, and spillways were designed using historical rainfall data, an assumption that is increasingly untenable as extreme events intensify [1]. Consequently, infrastructure designed from historical IDF curves may be inadequate for current and future extreme events. This study aims to quantify uncertainty in future extreme rainfall projections from climate models and assess its implications for the spillway design of Horuwila Wewa. Figure 2 shows the study area.

2. Methodology

Limited research links climate-model uncertainty to IDF curves and spillway design in Sri Lanka's tank systems. This study addresses this gap by developing 50-year IDF curves using observed rainfall data from 1995–2024, three Coupled Model Intercomparison Project Phase 6

(CMIP6) general circulation models (GCMs), two SSPs, and two future periods, and assessing their implications at Horuwila Wewa using HEC-HMS. With a fixed 0.8 m bund enhancement, the study checks scenario-specific spillway requirements, providing a climate-informed basis for future water infrastructure design. Daily rainfall records from Anuradhapura station (1995–2024) were first checked and corrected for consistency and gaps. The Gumbel distribution was then fitted to the observed data to estimate the 50-year return period daily rainfall, which was disaggregated into sub-daily intensities using a region-specific temporal distribution [2]. An IDF curve for a 50-year return period was developed from this data, and the baseline 50-year design storm was estimated from the resulting curve. Coarse-resolution outputs from three GCMs (CNRM-CM6-1, HadGEM3-GC31-LL, and MRI-ESM2-0) were downscaled with Long Ashton Research Station-Weather Generator (LARS-WG) [3] for SSP2-4.5 and SSP5-8.5 across two future periods (2041–2060 and 2081–2100). Repeating the baseline procedure, future IDF curves and 50-year design storms were estimated for all twelve future scenarios. The 50-year return period was held fixed across all scenarios, as it is consistent with established Sri Lankan practice [2], so that the resulting variation in spillway length reflects climate-model and scenario uncertainty rather than differences in design standard. All 13 design storms (baseline plus projections) were routed through an identical uncalibrated HEC-HMS model of Horuwila Wewa, developed using the SCS method for transformation and unit hydrograph generation. A 0.8 m bund augmentation, required for the baseline, was kept constant across all 12 future scenarios. Spillway length was varied for each scenario until the target peak was achieved, making the required spillway length a direct measure of climate-driven infrastructure adaptation needs. Due to the lack of observed streamflow data, the HEC-HMS models could not be calibrated; therefore, the simulated peak inflows remain subject to uncertainty.

3. Results and Discussion

Figure 1 compares the baseline (1995–2024) IDF curve with SSP2-4.5 and SSP5-8.5 projections for two future periods. Baseline intensity starts near 1,100 mm/h at 5 minutes, dropping below 50 mm/h after 3 hours. Since the same regional temporal distributions derived from existing IDF curves were used to disaggregate daily rainfall for all scenarios, the projected percentage change in rainfall intensity is similar across durations. However, the absolute change is much larger for shorter durations because their baseline intensities are substantially higher.

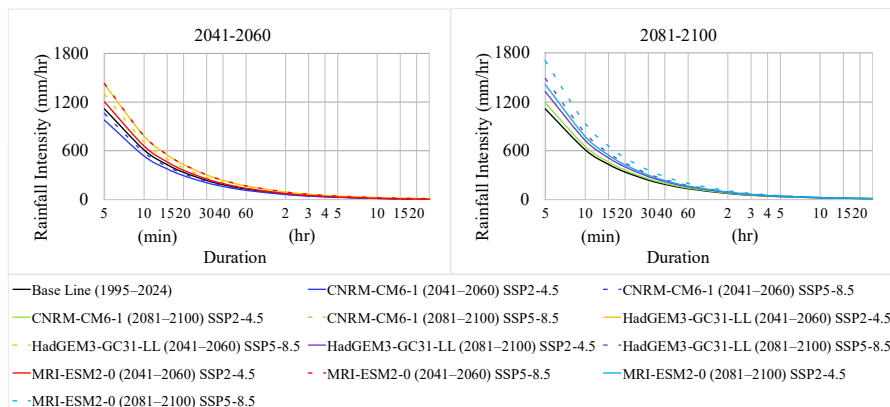


Figure 1: Comparison of baseline and future projections (three CMIP6 GCMs, two SSPs, and two future periods) IDF curves.

For instance, MRI-ESM2-0 SSP5-8.5 (2081–2100) shows a ~53% increase at both the 5-minute and 1-hour durations, but because baseline intensity is far higher at 5 minutes, the resulting absolute increase is much larger there (591.45 mm/h vs. 69.28 mm/h). The IDF curves show divergence peaks at short durations (5–30 min), especially under SSP5-8.5/2081–2100, indicating that short-duration extremes are among the factors affecting spillway and inflow requirements. Table 1 summarises the peak reservoir inflow and required spillway length for all thirteen scenarios.

Table 1: Baseline and projected 50-year return-period peak reservoir inflow and required spillway length to maintain the target peak-pool elevation under 13 HEC-HMS simulations.

Model	SSP	Period	Peak Inflow (m ³ /s)	Δ Peak Inflow (%)	Spillway (m)	Δ Spillway (%)
Baseline	—	1995–2024	283.8	—	25	—
CNRM-CM6-1	SSP2-4.5	2041–2060	246.6	–13.1	20	–20.0
		2081–2100	304.3	+7.2	28	+12.0
	SSP5-8.5	2041–2060	269.0	–5.2	23	–8.0
		2081–2100	342.0	+20.5	33	+32.0
HadGEM3-GC31-LL	SSP2-4.5	2041–2060	368.8	+30.0	36	+44.0
		2081–2100	341.9	+20.5	33	+32.0
	SSP5-8.5	2041–2060	333.8	+17.6	32	+28.0
		2081–2100	387.9	+36.7	38	+52.0
MRI-ESM2-0	SSP2-4.5	2041–2060	308.0	+8.5	29	+16.0
		2081–2100	367.0	+29.3	36	+44.0
	SSP5-8.5	2041–2060	371.1	+30.8	36	+44.0
		2081–2100	447.7	+57.8	46	+84.0

Ten of twelve scenarios project inflow increases above the 283.8 m³/s baseline; only CNRM-CM6-1 (2041–2060) shows decreases (–13.1% SSP2-4.5, –5.2% SSP5-8.5). MRI-ESM2-0 yields the largest increases, and CNRM-CM6-1 the lowest. The most extreme scenario (MRI-ESM2-0/SSP5-8.5/2081–2100) shows a 57.8% inflow increase, requiring an 84% longer spillway. Required spillway lengths range from 20 to 46 m. Climate change intensifies short-duration rainfall extremes, driving inflow and spillway needs up to 84% above baseline, underscoring the need for climate-informed IDF curves in water infrastructure planning.

Acknowledgements

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Significance & Aim

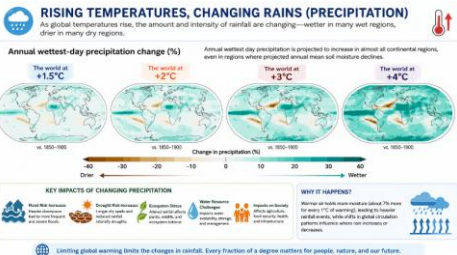
Significance

- Intensity-Duration-Frequency (IDF) curves for water infrastructure have traditionally been developed under the assumption of climate stationarity.
- Human-induced climate change has altered extreme rainfall patterns over the past few decades, rendering historical IDF curves increasingly unreliable.
- Water infrastructure designed using historical IDF curves may be inadequate for future extreme events.

Aim

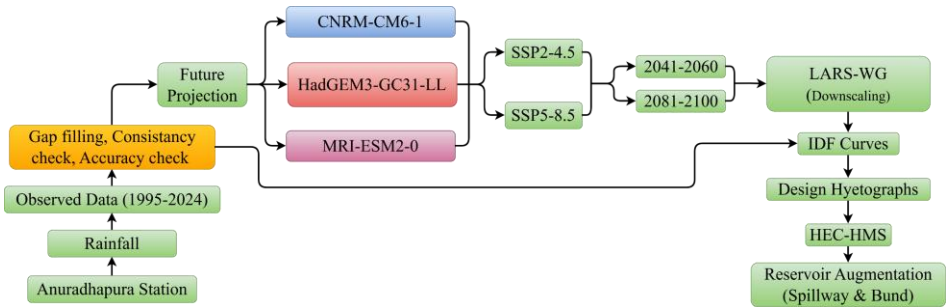
To develop climate-informed IDF curves for designing future water management infrastructure and their implementations.

Significance



Source: ChatGPT (OpenAI)

Methodology



Study Area, Results & Discussion

Study Area

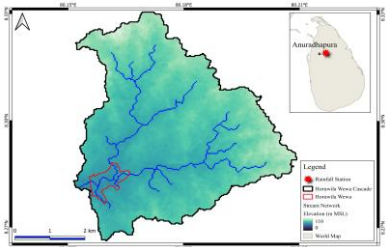
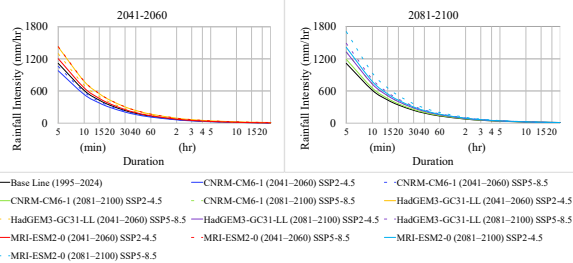


Figure 2: Horuwila Wewa Cascade.

Results



Discussion

- Short-duration rainfall extremes intensify disproportionately, with the greatest IDF changes at 5–30 minutes, increasing peak inflow risks.
- Most scenarios increase peak inflow and spillway requirements, with the extreme scenario showing a **57.8%** inflow increase and requiring an **84%** longer spillway.

Model	SSP	Period	Peak Inflow (m³/s)	ΔPeak Inflow (%)	Spillway (m)	ΔSpillway (%)
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