

ASSESSING THE INFLUENCE OF RAINFALL-INTENSITY-DEPENDENT TIME OF CONCENTRATION ON SPILLWAY DESIGN UNDER FUTURE CLIMATE SCENARIOS IN THE KNUCKLES BASIN, SRI LANKA

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Abstract

Although conventional hydrological design treats time of concentration (T_c) as a static constant, T_c is inversely related to rainfall intensity, making its dynamic representation important under climate change. This study assesses how rainfall-intensity-dependent T_c affects spillway design under future climate scenarios in the Knuckles Basin, Sri Lanka. Future climate projections were obtained from three CMIP6 GCMs (CNRM-CM6-1, HadGEM3-GC31-LL, MRI-ESM2-0) under SSP2-4.5 and SSP5-8.5, statistically downscaled to watershed level for 2041–2060 and 2081–2100 using LARS-WG. The resulting daily rainfall series were then used to develop future Intensity-Duration-Frequency (IDF) curves, with daily rainfall values disaggregated using a regionally developed by Engr. Ponrajah. An existing rainfall intensity– T_c relationship, developed using Detrended Moving-Average Cross-Correlation Analysis (DMCA), was adopted to estimate rainfall-intensity-dependent T_c , and hydrological simulations were performed in HEC-HMS using the SCS Unit Hydrograph method. The dynamic T_c relationship was incorporated into design-storm simulations to evaluate hydrograph shape, peak discharge, and spillway response. Results demonstrate an inverse relationship between rainfall intensity and T_c , with T_c decreasing from approximately 2.5 to 1.0 hours as intensity increases from 25 to 45 mm/h. Projected peak discharge varied substantially across climate projections, ranging from 81.6 to 205.4 m³/s. MRI-ESM2-0 under SSP5-8.5 for 2081–2100 produced the highest projected peak, reaching 205.4 m³/s, approximately 2.5 times the baseline peak discharge of 82.2 m³/s. To convey this maximum inflow, the spillway design required an increase in crest length from 58 m to 80 m and crest elevation from 72 m to 73 m, which attenuated the reservoir peak discharge from a baseline of 525 m³/s to 179.6 m³/s. These findings highlight the importance of dynamic T_c and multi-model climate projections for climate-resilient spillway design.

Keywords: Climate change, Hydrological modelling, Flood risk, Time of concentration, Spillway design

1. Introduction

Time of concentration (T_c) is the time required for water from the hydraulically most distant point of a catchment to reach the catchment outlet after the start of rainfall. Research has demonstrated that increasing rainfall intensity shortens catchment response time, producing sharper and higher flood peaks than conventional fixed- T_c approaches would predict [1,2]. However, the implications of this dynamic response for spillway design under future climate scenarios remain inadequately explored, particularly in data-scarce tropical watersheds. This study aims to assess the influence of rainfall-intensity-dependent T_c on spillway design in the Knuckles Basin, with the specific objective of evaluating how this dynamic relationship affects

design hydrograph peaks and consequently the required spillway crest length, elevation, and discharge efficiency under climate projections.

2. Methodology

The Pahala Halmillewa Wewa, situated at the Knuckles Basin, was selected as the study area owing to its critical role as a water source and its recognised vulnerability to climate-induced extreme events. Daily precipitation data for 30 years, from 1995 to 2024, were obtained from the Anuradhapura gauging stations following World Meteorological Organization (WMO) guidelines, while future climate projections were derived from three GCMs, CNRM-CM6-1, HadGEM3-GC31-LL, and MRI-ESM2-0, under the SSP2-4.5 and SSP5-8.5 scenarios for the 2041–2060 and 2081–2100 periods using the LARS-WG statistical downscaling tool [3]. The resulting daily rainfall series were then used to develop future Intensity-Duration-Frequency (IDF) curves, with daily rainfall values disaggregated using regionally developed by Engr. Ponrajah. Hydrological modelling was performed using HEC-HMS with the SCS Unit Hydrograph Method. The relationship between rainfall intensity and T_c was established using the Detrended Moving-Average Cross-Correlation Analysis (DMCA) approach established in the literature [1]. The resulting hydrographs were evaluated in terms of peak discharge, time to peak, and overall hydrograph response to identify the influence of varying T_c on flood magnitude and catchment response. Reservoir routing was then used to assess the attenuation of peak inflows and the resulting outflow response. The analysis further considered the implications of the projected flood peaks for spillway design, particularly in relation to spillway crest elevation, crest length, and discharge efficiency under future climate conditions.

3. Results and Discussion

The design hydrographs demonstrate substantial inter-model variability in peak discharge and catchment response under future climate scenarios. The highest plotted peak, approximately $205 \text{ m}^3/\text{s}$, is produced by MRI-ESM2-0, exceeding the baseline peak by approximately 150%, indicating considerable uncertainty in projected flood magnitude.

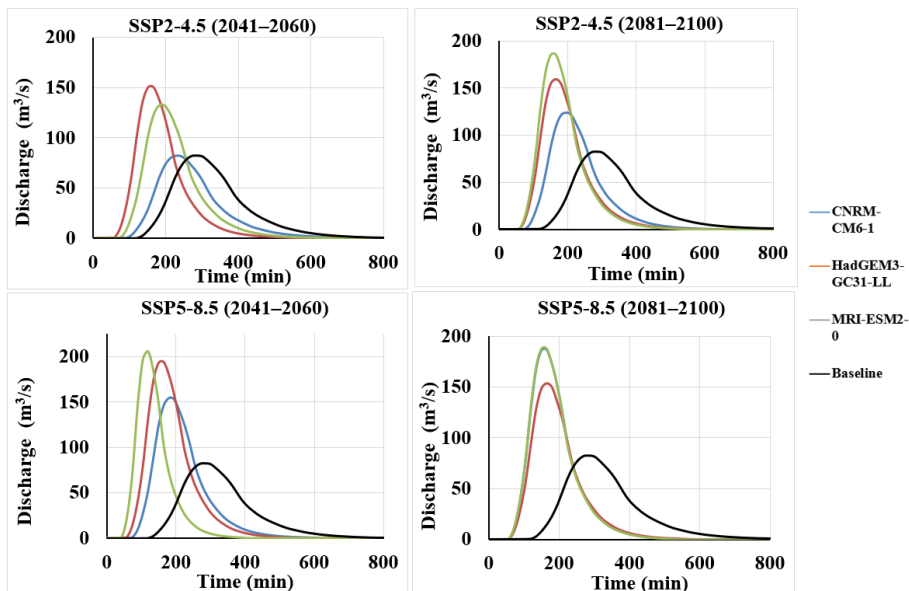


Figure 1: Design hydrograph.

Under baseline conditions, the spillway crest length was 58 m, the crest elevation was 72 m, and the reservoir peak discharge was 525 m³/s. To manage a maximum peak inflow of 205.4 m³/s, the design was revised to a crest length of 80 m and crest elevation of 73 m, which successfully attenuated the peak discharge at the reservoir to 179.6 m³/s.

The Tc vs. rainfall intensity analysis reveals a strong inverse linear relationship between rainfall intensity and time of concentration (Tc), where Tc decreases from approximately 2.5 hours to 1.0 hour as intensity increases from 25 mm/h to 45 mm/h. This finding challenges the conventional static Tc assumption and aligns with the HEC-HMS application-guide example demonstrating that reducing Tc produces a unit-hydrograph peak approximately 50% higher than the original estimate.

Table 1 indicates that the maximum projected peak discharge occurs under the MRI-ESM2-0 model for SSP5-8.5 during 2081–2100, representing approximately 2.5 times the baseline peak discharge (82.2 m³/s).

Table 1: Peak discharge projections under future climate scenarios.

Projection Model	Duration	Peak Discharge(m ³ /s)	Projection Model	Duration	Peak Discharge(m ³ /s)
CNRM-CM6-1, SSP 2-4.5	2041–2060	81.6	HadGEM3-GC31-LL, SSP 5-8.5	2041–2060	153.8
	2081–2100	124.1		2081–2100	193.7
CNRM-CM6-1, SSP 5-8.5,	2041–2060	186.8	MRI-ESM2-0, SSP 2-4.5	2041–2060	132.2
	2081–2100	154.3		2081–2100	185.6
HadGEM3-GC31-LL, SSP 2-4.5	2041–2060	150.2	MRI-ESM2-0, SSP 5-8.5	2041–2060	188.1
	2081–2100	159.6		2081–2100	205.4

References

[1] Bandara K, Pabasara K, Gunawardhana L *et al.* Coupling Rainfall Intensity and Satellite-Derived Soil Moisture for Time of Concentration Prediction: A Data-Driven Hydrological Approach to Enhance Climate Responsiveness. *Hydrology* 2025;12(10). <https://doi.org/10.3390/hydrology12100264>.

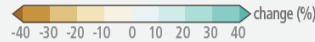
[2] Calvin K, Dasgupta D, Krinner G *et al.* *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland, ed. Arias P, Bustamante M, Elgizouli I et al. 2023.* <https://doi.org/10.59327/IPCC/AR6-9789291691647>.

[3] Semenov MA. The use of multi-model ensembles from global climate models for impact assessment of climate change. In: *Geophysical Research Abstracts*, vol. 11. 2009. www.ipcc-data.org.

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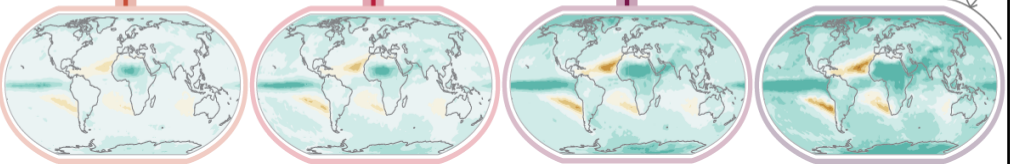
Background

c) Annual wettest-day precipitation change



Annual wettest day precipitation is projected to increase in almost all continental regions, even in regions where projected annual mean soil moisture declines.

small absolute changes may appear large as % or σ changes in dry regions

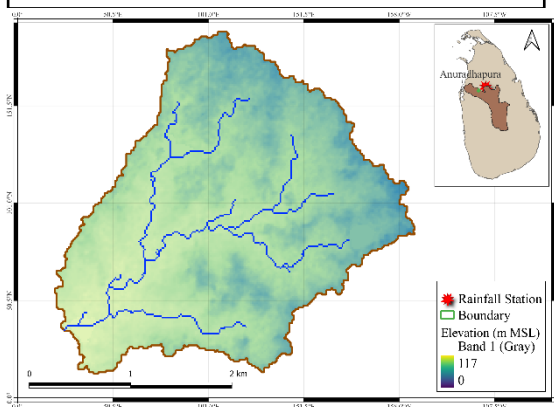


The projected increase in frequency and intensity of heavy precipitation (high confidence) will increase rain-generated local flooding (medium confidence). [2]

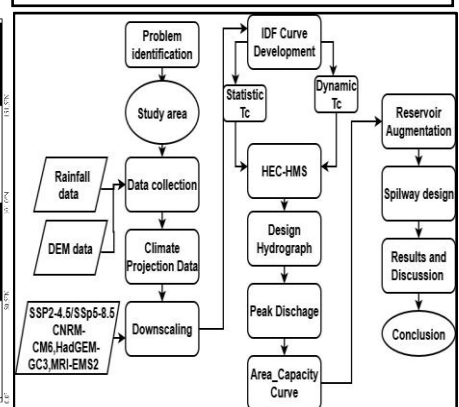
Source: IPCC (2023), AR6 Synthesis Report, Figure SPM.2.

Research Methodology

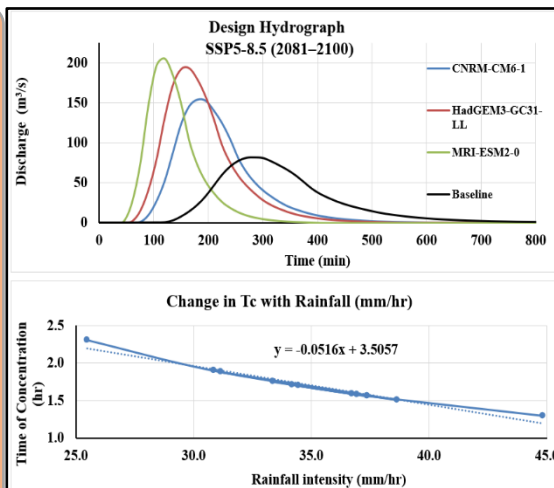
Study area: Pahala Halmillewa Wewa, Knuckles Basin, Sri Lanka



Methodological flowchart



Results and Conclusion



- Rainfall intensity and T_c showed a strong inverse relationship, decreasing from ~2.5 h to 1.0 h as intensity increased from 25–45 mm/h.
- Spillway design summary:**
 - I. Required crest length increase: 58 m to 80 m
 - I. Required crest elevation increase: 72 m to 73 m
 - I. Reservoir peak discharge reduction: 525 m³/s to 179.6 m³/s