



When anticipation fails: A forensic analysis of Tropical Cyclone Ditwah reveals whole-system performance limits in a small-island flood-risk system

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Abstract. Tropical Cyclone (TC) Ditwah, which impacted Sri Lanka in November 2025, was one of the most damaging
20 hydrometeorological disasters in the country's recent history, affecting more than two million people through widespread
flooding and landslides. Early explanations attributed the disaster to failures in forecasting, reservoir operations, or institutional
response. We argue instead that TC Ditwah revealed a breakdown in whole-system performance under extreme temporal stress.
Using a forensic reconstruction spanning atmospheric evolution, hydrological response, reservoir operations, warning
dissemination, institutional coordination, and community experience, we examine how multiple interconnected subsystems
25 interacted during the event. Rapid cyclogenesis unusually close to Sri Lanka compressed forecast lead times, while the island's
steep, rainfall-dominated catchments translated extreme rainfall into rapid flood responses across multiple basins. Reservoir
preparedness, warning escalation, institutional decision processes, and community response operated on slower timescales,
reducing the time available to convert anticipation into protective action. The resulting mismatch between fast physical
processes and slower institutional and societal response generated an anticipation–action gap, despite the availability of hazard
30 information. Rather than revealing isolated component failures, TC Ditwah exposed structural limitations in the design and
operation of coupled flood-risk systems. We argue that improving forecasts alone is unlikely to substantially reduce future
disaster risk unless forecasting, reservoir management, emergency governance, and community response are explicitly
integrated into coordinated operational frameworks. More broadly, TC Ditwah illustrates the need to complement advances in
prediction with simulation-based training, pre-defined decision protocols, and whole-system emergency operating modes
35 capable of functioning under rapidly evolving compound hazards. The lessons extend beyond Sri Lanka to flood-risk
management in small-island states and other catchments where rapidly evolving hazards leave little time for coordinated action.

Keywords: Tropical Cyclone Ditwah; forensic socio-hydrology; anticipation–action gap; small-island flood-risk systems;
flood early warning



1. Introduction

40 Tropical Cyclone (TC) Ditwah, which struck Sri Lanka in late November 2025, was one of the most damaging hydrometeorological disasters in the country's recent history. Although classified as a moderate tropical cyclone in conventional global wind-speed terms, the storm generated exceptional rainfall across much of the island, triggering widespread river flooding, more than a thousand landslides, and severe disruption to critical infrastructure and essential services (Kulkarni and Hillier, 2026). More than two million people were affected, over one million required humanitarian
45 assistance (Office of the Resident Coordinator in Sri Lanka and OCHA, 2025), and economic losses were estimated at approximately USD 4.1 billion, equivalent to nearly four percent of Sri Lanka's gross domestic product (World Bank and GFDRR, 2025).

The magnitude of the disaster immediately prompted debate over its underlying causes. Initial explanations focused variously on shortcomings in weather forecasting, reservoir operations, warning dissemination, institutional coordination, land-use
50 planning, or public response (Amaratunga and Kodituwakku, 2026). While each of these perspectives identified genuine weaknesses, none adequately explained why an event for which substantial warning information existed nevertheless resulted in such widespread losses. The central scientific question is therefore not simply what failed, but why a flood-risk system possessing many of the necessary technical and institutional capabilities was unable to translate anticipation into effective protection.

55 This question extends well beyond Sri Lanka. Around the world, flood disasters often emerge from the interaction of physical, technical, institutional, and social processes rather than from a single triggering hazard (Merz et al., 2021; Raymond et al., 2020). Advances in meteorological forecasting, hydrological monitoring, hydraulic infrastructure, and emergency management have substantially improved society's ability to anticipate extreme events. Yet catastrophic losses continue to occur, indicating that disaster outcomes are governed not only by the performance of individual system components but, more fundamentally,
60 by how effectively those components interact under rapidly evolving conditions. Understanding such events therefore requires analytical approaches that move beyond single-cause explanations towards integrated analyses of coupled socio-hydrological systems (Sivapalan et al., 2012; Di Baldassarre et al., 2013).

This study adopts such an approach. Drawing on the emerging field of forensic socio-hydrology, we reconstruct TC Ditwah across multiple interacting domains, including atmospheric evolution, catchment response, reservoir operations, warning
65 systems, institutional decision-making, and community experience. Rather than evaluating these components in isolation, we examine how their interactions shaped the evolution of the disaster. The analysis is therefore structured around system interactions rather than attribution of responsibility to individual organisations or decisions.

A central proposition of this paper is that TC Ditwah exposed a fundamental timescale mismatch within the coupled flood-risk system. Rapid cyclogenesis close to Sri Lanka compressed forecast lead times. As the cyclone moved inland, its translation
70 speed decreased, prolonging heavy rainfall and increasing cumulative rainfall over the island. In Sri Lanka's steep, rainfall-dominated catchments, this prolonged rainfall was rapidly transformed into runoff, generating destructive flooding across



several river basins. In contrast, warning generation, reservoir operations, institutional coordination, and community response depended on slower processes involving observation, interpretation, authorisation, communication, and action. This temporal compression reduced the time available to convert hazard information into protective action, producing an anticipation–action gap and exposing whole-system performance limits. In this formulation, the timescale mismatch is the primary mechanism, while the anticipation–action gap and whole-system performance limits are its consequences.

This interpretation provides the organising framework for the remainder of the paper. We therefore examine TC Ditwah as a whole-system stress test in which fast physical processes increasingly outpaced slower operational, institutional, and societal responses. Although the case study is rooted in Sri Lanka, the mechanisms identified are relevant to many rainfall-dominated catchments and small-island environments facing increasingly frequent and intense hydrometeorological extremes (IPCC, 2021). Such settings are particularly sensitive to temporal compression because short distances between coastlines, steep uplands, reservoirs, rivers, and exposed communities can leave little time for sequential forecasting, warning, reservoir operation, evacuation, and emergency response.

Accordingly, this study has three objectives: (1) to reconstruct the evolution of TC Ditwah across atmospheric, hydrological, operational, and societal domains; (2) to determine how timescale mismatches among these domains constrained the translation of available anticipation into protective action; and (3) to develop a transferable forensic framework for diagnosing whole-system performance limits under temporally compressed extreme events.

1.1. Why single-cause explanations fail: the “elephant” problem

Complex disasters are often explained by identifying individual failures. Following major flood events, public and scientific debate typically centres on questions such as whether weather forecasts were sufficiently accurate, reservoirs were operated appropriately, warnings were issued in time, or communities responded adequately. Each of these questions is important because it addresses a critical element of the flood-risk system. Considered in isolation, however, they provide only partial explanations of how disasters develop (Merz et al., 2015).

Disaster investigations frequently encounter this limitation. Meteorologists may focus on deficiencies in weather prediction, hydrologists on catchment and river response, reservoir operators on operational constraints, emergency managers on warning dissemination, and social scientists on governance, communication, or community preparedness. Each perspective offers valuable insight, yet none, considered in isolation, explains how an anticipated hazard ultimately became a catastrophe. Disasters are rarely the consequence of a single failure; rather, they emerge from the interactions among interconnected physical, technical, institutional, and societal processes (Merz et al., 2021; Mohr et al., 2023).

The well-known parable of the blind men and the elephant provides a useful analogy. In the story, each observer examines only one part of the elephant and reaches a different, but individually reasonable, conclusion about its nature. Their disagreement arises not because any observer is entirely wrong, but because each interprets only one part of a much larger whole. Understanding emerges only when these partial observations are integrated into a coherent picture.



105 *It was six men of Indostan*
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind). ...
Though each was partly in the right,
 110 *And all were in the wrong!*

▪ *(John Godfrey Saxe's adaptation (1816–1887) of the traditional Indian parable.)*

This analogy is particularly relevant to extreme hydrometeorological disasters, where multiple subsystems evolve simultaneously and interact through feedbacks, dependencies, and operational constraints. Crucially, these subsystems also operate on different timescales. Fast atmospheric and hydrological processes may leave insufficient time for slower operational, institutional, and community responses, even when individual components function broadly as intended. System behaviour therefore depends not only on interaction among components, but also on whether their characteristic timescales remain compatible (Di Baldassarre et al., 2013; Raymond et al., 2020).

115 TC Ditwah exemplifies this challenge. Forecast information, river observations, reservoir-storage information, and institutional warnings were available during the event, while communities were simultaneously responding within increasingly compressed time windows. TC Ditwah therefore illustrates the central proposition of this study: a timescale mismatch across a coupled flood-risk system can limit the conversion of available anticipation into timely protection.

120 Accordingly, the forensic analysis that follows examines not simply how individual components performed, but where mismatches among their characteristic timescales emerged and propagated across the coupled system.

1.2. Why existing explanations remain incomplete

125 Understanding why hazardous events escalate into disasters has long been a central objective of flood-risk research. Research has produced major advances in forecasting, hydrological modelling, infrastructure design, warning systems, governance, and disaster response. Yet catastrophic losses can still occur despite substantial anticipatory and response capacity (Merz et al., 2015; Merz et al., 2021). Much of this literature nevertheless remains organised around individual domains: meteorological prediction, hydrological response, infrastructure performance, warning and communication, governance, and community preparedness (Komori et al., 2012; Losee and Joslyn, 2018; Seebauer and Babicky, 2018; Mohr et al., 2023). Such studies provide essential component-level understanding, but are less able to explain outcomes that emerge from interactions across subsystem boundaries.

Recent developments in socio-hydrology, systems thinking, and disaster forensics have begun to address this limitation by explicitly examining the interactions between natural and human systems (Sivapalan et al., 2012; Di Baldassarre et al., 2013).
 135 Rather than treating hazards and society as separate domains, these approaches recognise that disaster risk emerges through dynamic feedback linking atmospheric processes, catchment response, hydraulic infrastructure, institutions, governance, and



human behaviour. From this perspective, disasters are viewed as emergent outcomes of coupled socio-hydrological systems whose behaviour depends on the timing, coordination, and adaptability of their interacting components (Raymond et al., 2020). However, less attention has been given to the temporal compatibility of these interacting subsystems during rapidly evolving extremes. Physical hazards often evolve over hours, whereas institutional decision-making, infrastructure operations, communication, and community response may require different and sometimes longer response times. This temporal mismatch is especially important in small-island and fast-response catchments, where short distances between cyclone landfall, steep terrain, river networks, reservoirs, and exposed communities can sharply reduce the time available for sequential warning, decision-making, and protective action. The specific research gap addressed here is therefore not simply whether system components interact, but whether their characteristic timescales remain compatible as an extreme event unfolds (Sivapalan and Blöschl, 2015).

TC Ditwah provides a useful opportunity to investigate these processes. The event generated extensive meteorological observations, hydrological measurements, reservoir-storage records, warning information, and documented community experiences, enabling reconstruction of the event cascade from atmospheric forcing to societal consequences. By integrating these diverse sources of evidence within a forensic socio-hydrological framework, this study seeks to explain where timescale mismatches emerged across the coupled flood-risk system and how they constrained the conversion of available anticipation into timely protective action.

2. Data and forensic methodology

2.1. Forensic approach

The forensic approach adopted in this study is centred on diagnosing system behaviour across the full event timeline, prior to, during, and following the tropical cyclone, rather than attributing failure to individual components. The objective is not to attribute responsibility for failure to individual components, but to identify how interconnected subsystems interacted under stress, where performance limits emerged, and where mismatches among their characteristic timescales constrained effective response. The emphasis is therefore on understanding how physical, infrastructural, institutional, and societal processes interacted through time and how these interactions shaped whole-system performance.

Accordingly, the study adopts a multi-domain, process-based approach. It begins by examining the atmospheric drivers that led to the formation and evolution of TC Ditwah, followed by an assessment of the hydrological translation of rainfall into basin-scale flooding and its societal impacts. Building on this reconstruction, a system-level diagnosis is conducted, evaluating forecast performance, reservoir storage conditions and operational constraints, warning timing and dissemination, institutional coordination, and community response.

The analysis focuses particularly on where the characteristic timescales of interacting subsystems became incompatible as the event evolved. The resulting *anticipation–action gap* is treated as a consequence of this mismatch: situations in which hazard information was available but could not be translated into timely and effective protective action. By tracing where such



170 mismatches emerged and propagated across subsystem boundaries, the forensic approach moves beyond event description toward a structured diagnosis of whole-system performance and transferable lessons for preparedness.

2.2. Data inventory

175 A multi-source dataset was assembled to support the forensic reconstruction of TC Ditwah across atmospheric, hydrological, operational, and societal domains. The analysis integrates observational records, institutional data, and community-based information to capture both the physical evolution of the event and the corresponding system responses. The datasets provide complementary spatial and temporal coverage across the principal components of the coupled flood-risk system, although their temporal resolution varies among data types.

Table 1 summarises the datasets used in this study, including their temporal coverage, spatial extent, and sources. These datasets collectively support the assessment of rainfall generation, hydrological translation, reservoir dynamics, warning dissemination, and community-level impacts.

180 **Table 1: Data used in the study.**

Data type	Period	Spatial coverage/ number of records		Source	Use in analysis
Rainfall	November – December 2025, selected historical calibration/validation events	46 stations		Department of Meteorology	Event rainfall reconstruction, forecast verification, and basin rainfall estimation
Streamflow	November – December 2025, selected historical calibration/validation events	8 stations		Department of Irrigation	Hydrological model calibration, validation, and event hydrograph assessment
River water level data	November – December 2025	24 stations across major rivers		Department of Irrigation	Flood threshold exceedance analysis and warning lead-time assessment
Flood early warnings	24–30 November 2025	20 basin-level warnings		Department of Irrigation and Disaster Management Centre	Assessment of warning coverage, language accessibility, and lead time



Reservoir data	November – December 2025	79 reservoirs	Department of Irrigation; Mahaweli Authority of Sri Lanka	Reservoir storage and buffering-capacity analysis
Community survey	December 2025 – May 2026	58 responses	Post-event community survey conducted by the authors	Assessment of warning receipt, interpretation, protective action, and experienced impacts
Tropical Cyclone Track Data	1960–2025	Sri Lanka-proximal and North Indian Ocean tropical cyclone tracks	IBTrACS	Historical TC-track analysis and comparison with TC Ditwah
Damage Data	1960–2025	Historical cyclone-related losses in Sri Lanka	Disaster Management Centre, Sri Lanka	Historical comparison of cyclone impacts
Population Data	2024	National scale / local administrative boundary level	Department of Census and Statistics	Population exposure mapping
Infrastructure Data	2024	National scale / local administrative boundary level	Department of Census and Statistics	Infrastructure exposure mapping
Landslide locations	November 2025	1,200 reported landslide locations	National Building Research Organisation (NBRO)	Mapping of landslide occurrence and multi-hazard exposure

2.3. Methodology

This study adopts a structured forensic methodology to diagnose the performance of the coupled socio-hydrological system during TC Ditwah. The approach integrates multi-source datasets within a multi-stage analytical framework that progresses from event reconstruction to system diagnosis, and ultimately to the development of transferable insights. The methodology is designed to capture both the physical evolution of the event and the response dynamics across institutional and societal domains.



The first stage involves event reconstruction, which establishes a coherent, multi-domain representation of the TC. This includes (i) characterization of the atmospheric drivers responsible for TC formation and rainfall generation, (ii) assessment of hydrological translation through basin-scale analysis, including hydrological modelling and evaluation of critical basin responses, and (iii) mapping of human exposure and impacts using inundation data and community-based observations. To support this community-level reconstruction, a post-event field survey was conducted in areas affected by TC Ditwah. Field visits were undertaken across locations affected by flooding and/or landslides, and respondents were recruited from individuals living or working in these areas who had directly experienced the event. The survey was administered through face-to-face interviews and yielded 58 responses from residential, commercial, and community locations. Participation was voluntary, the purpose of the survey was explained to respondents before the interview, and verbal informed consent was obtained prior to participation. This stage provides an integrated reconstruction of how the hazard evolved and propagated through the landscape and affected exposed communities.

The second stage focuses on the diagnosis of system stresses and operational limits. Here, the study evaluates how different components of the system responded under rapidly evolving conditions. Key elements include the assessment of forecast performance and uncertainty, the timing and effectiveness of early warnings, the behavioural response of affected communities, reservoir storage conditions and operational constraints, and institutional coordination and governance arrangements. This analysis identifies where differences in the characteristic timescales of interacting subsystems became incompatible, including mismatches between the pace of hazard evolution and the capacity of institutional and societal systems to respond.

Building on this diagnosis, the third stage synthesizes lessons learned by identifying recurrent patterns of system behaviour, critical bottlenecks, and performance limits across domains. Rather than isolating individual shortcomings, the focus is on understanding how interactions among subsystems contributed to the overall outcome, with particular attention to where timescale mismatches constrained the conversion of available anticipation into timely protective action. The resulting anticipation–action gap is therefore examined as a manifestation of these cross-domain mismatches.

Finally, the study develops a generalization framework that extends the findings beyond the specific case of TC Ditwah. This framework distills the key insights into a transferable approach applicable to other rainfall-dominated, small-island, or data-constrained settings. It emphasizes the role of timescale compatibility and mismatch, system coupling, and coordinated response mechanisms in shaping disaster outcomes, thereby providing a basis for improving preparedness and resilience under future extreme events. The intention is not to generalize the specific losses observed during TC Ditwah, but to generalize the diagnostic logic by which similar whole-system performance limits can be identified in other fast-response flood-risk systems. Figure 1 provides an overview of the methodological framework, illustrating the analytical progression from data integration to event reconstruction, system diagnosis, learning, and generalization.

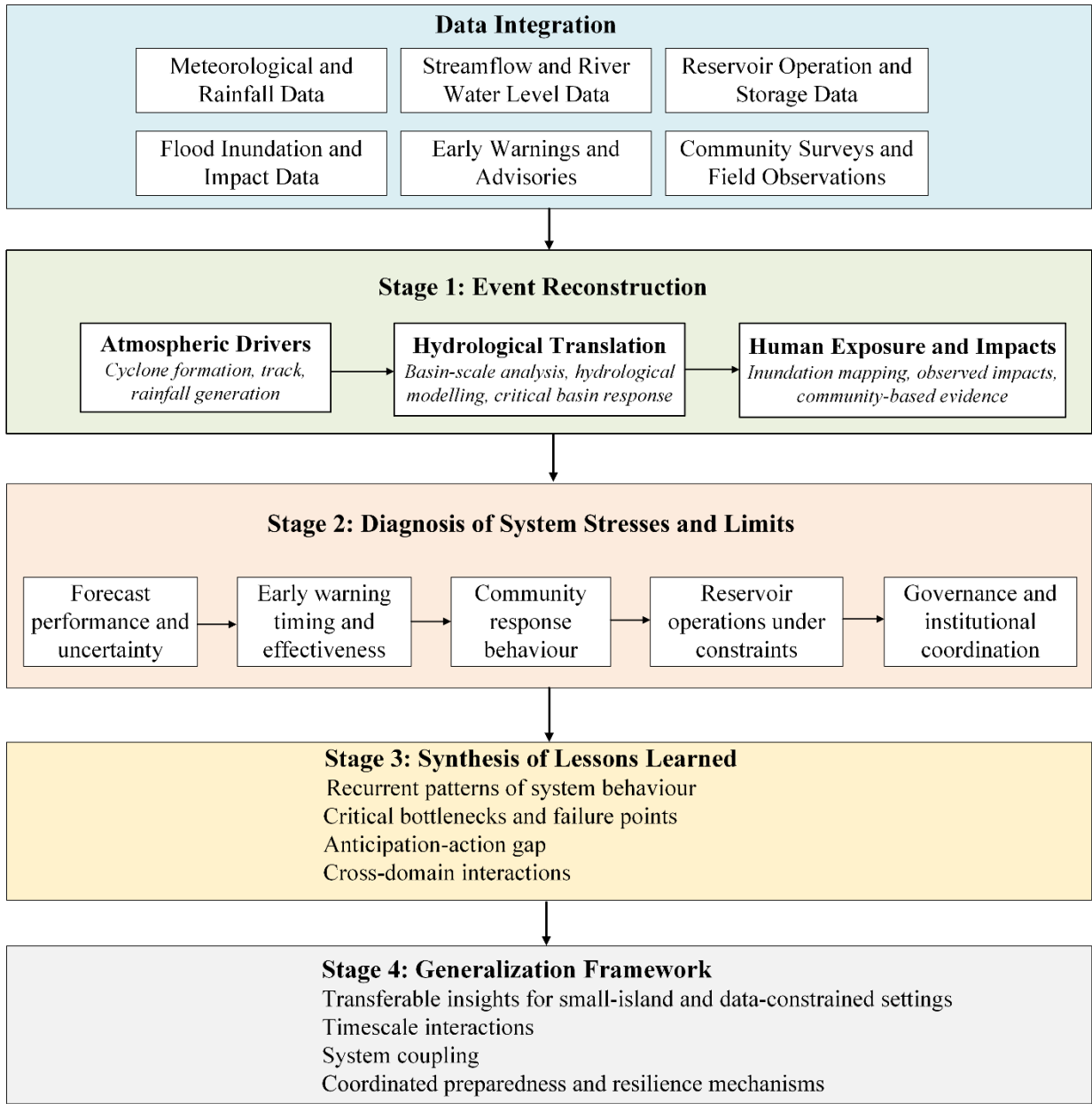


Figure 1: Methodological framework for the forensic analysis of TC Ditwah, showing the integration of multiple data sources and the four analytical stages from event reconstruction to system diagnosis, synthesis of lessons learned, and generalization of transferable insights.

3. Tropical cyclones near the equator: context and rarity

Nearly 7% of global TC activity occurs in the North Indian Ocean (NIO) basin (Gray, 1985). The basin comprises two sub-regions, the Arabian Sea (AS) and the Bay of Bengal (BoB), each characterized by distinct dynamical and thermodynamic conditions. Although the overall TC frequency in this basin is lower than in other global TC-prone regions, the associated impacts are disproportionately severe. Notably, seven of the ten deadliest TCs recorded worldwide between 1970 and 2019, as documented by the World Meteorological Organization, originated in the NIO (Najah et al., 2025).

The high mortality and damage potential in this region are attributed to a combination of shallow bathymetry, low-lying coastal plains, and funnel-shaped coastlines that can amplify storm-surge impacts (Bhaskar Rao et al., 2009). Previous studies indicate that approximately 75% of NIO tropical cyclones form over the BoB, while the AS accounts for the remaining 25% (Mohanty et al., 2012). TC activity in the NIO exhibits a bimodal seasonal distribution, with peak occurrences during the pre-monsoon season (March–May) and the post-monsoon season (October–December) (Bhaskar Rao et al., 2009; Li et al., 2022).

Sri Lanka, located between 5°–10°N latitude and 79°–82°E longitude, lies in close proximity to both the BoB and the AS. This geographic positioning renders the island particularly vulnerable to cyclonic systems developing within the NIO basin. Figure 2(a) shows the historical tracks of tropical cyclones crossing the defined Sri Lanka region, whereas Figure 2(b) shows tropical cyclones with genesis within the 77°–85°E, 3.5°–12°N grid surrounding Sri Lanka. Together, these records distinguish cyclones that pass through the broader Sri Lankan region from the smaller subset that originate in close proximity to the island.

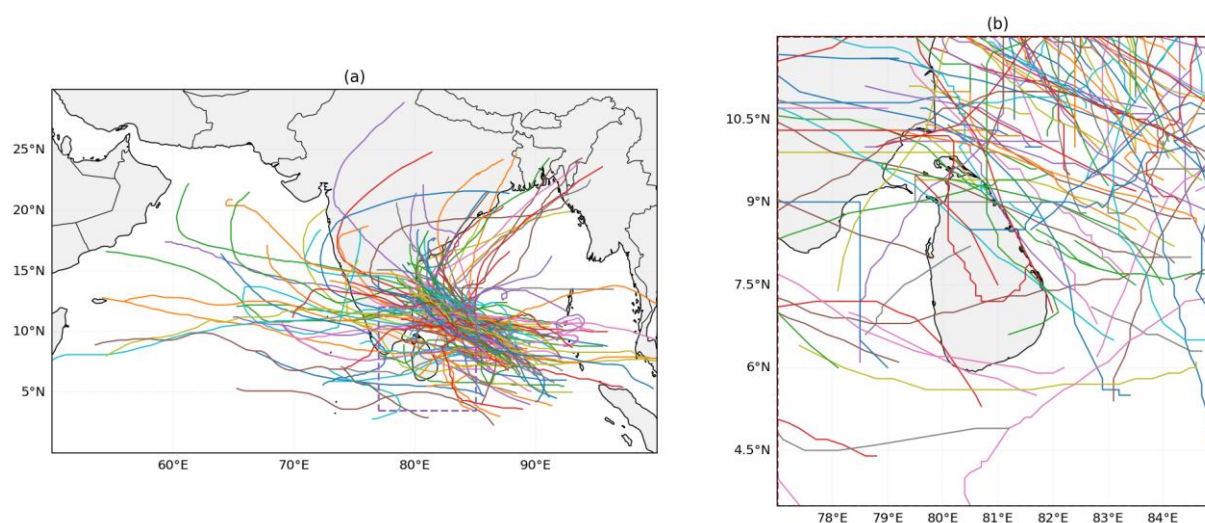


Figure 2: Historical cyclone tracks derived from IBTrACS (Knapp et al., 2010): (a) tropical cyclone tracks crossing the Sri Lanka region; and (b) tropical cyclones initiated within the 77°–85°E and 3.5°–12°N grid surrounding Sri Lanka.

Table 2 summarises the historical record of major TCs that have affected Sri Lanka. Among these, Cyclone Rameswaram (1964) and the Batticaloa cyclone (1978) stand out in the available historical record for their severe human and infrastructure impacts, with reported death tolls exceeding 1,000 and approximately 900, respectively.



245 **Table 2: Summary of selected historical cyclones affecting Sri Lanka based on IBTrACS meteorological records (Knapp et al., 2010) and Disaster Management Centre (DMC) impact records (DMC, 2025). Missing values are indicated by “NA”.**

Year	Cyclone name	Duration	Max. wind speed (km/h)	Min. sea level pressure (hPa)	Damage
1964	Rameswaram	17 Dec–24 Dec	NA	978	Deaths: over 1,000; houses damaged: 5,800
1978	04B	19 Nov–29 Nov	220	NA	Deaths: 900; houses damaged: 100,000
2000	BOB 06	23 Dec–28 Dec	165	970	Deaths: 9; houses damaged: 480
2003	BOB 01	10 May–20 May	140	980	Deaths: 254; houses damaged: 24,750
2005	Fanoos	10 Dec–15 Dec	85	996	NA
2008	Nisha	24 Nov–29 Nov	85	996	Deaths: 15
2012	Nilam	27 Oct–11 Nov	85	987	Deaths: 10
2013	Madi	5 Dec–12 Dec	120	986	Deaths: 5
2013	Viyaru	10 May–17 May	85	990	Deaths: 16
2016	Roanu	15 May–22 May	85	983	Deaths: 204
2016	Nada	29 Nov–2 Dec	75	1,000	Deaths: 12
2017	Mora	28 May–31 May	110	978	Deaths: 203; missing: 96
2017	Ockhi	28 Nov–5 Dec	155	976	Deaths: 13
2019	Fani	26 April–4 May	215	932	Deaths: 3; houses damaged: 1,137
2019	Maha	28 Oct–11 Nov	185	956	Deaths: 1; houses damaged: 771
2020	Amphan	16 May–21 May	240	920	Deaths: 5; houses damaged: 500
2020	Burevi	29 Nov–5 Dec	85	996	Deaths: 6; houses damaged: 3,586
2021	Tauktae	14 May–19 May	185	950	Deaths: 5
2021	Yaas	23 May–28 May	120	974	Deaths: 4; houses damaged: 200
2024	Fengal	23 Nov–4 Dec	85	996	Deaths: 16

250 Historical analyses indicate that cyclone impacts in Sri Lanka are typically more severe along the northern and eastern coastal regions, where direct landfall and storm-surge effects are more pronounced, than in central areas of the country (Alahacoon et al., 2024). However, TC Ditwah represented a notable deviation from this historical pattern. Rather than producing impacts concentrated predominantly along coastal areas, TC Ditwah-induced extreme rainfall affected a large part of the island, triggering widespread flooding and landslides across multiple river basins.



Although TCs rarely form within 5° latitude of the equator due to the weak Coriolis force, which is insufficient to initiate the spin-up of a cyclonic vortex (Gray, 1968), their formation becomes more favourable slightly poleward, where adequate Coriolis forcing and conducive environmental conditions exist (Roose et al., 2023). These low-latitude cyclones (LLCs), originating between 5° and 11° latitude, are generally smaller in spatial scale than higher-latitude systems but tend to intensify more rapidly (DeMaria and Pickle, 1988). Their potential for rapid intensification has been associated with stronger boundary-layer inflow toward the cyclone centre under reduced Coriolis influence and lower inertial stability. Enhanced inflow can increase diabatic heating (Smith et al., 2015), strengthen the secondary circulation, and promote greater boundary-layer moisture convergence (Hack and Schubert, 1986; Vigh and Schubert, 2009). The development and intensification of TC Ditwah close to Sri Lanka are therefore consistent with mechanisms that can support cyclone development and intensification at low latitudes in the southern Bay of Bengal.

TC Ditwah initially developed as a well-defined low-pressure system over the southwestern BoB and subsequently intensified into a depression centred near 5.9°N and 82.6°E on 26 November 2025. The system further strengthened into a cyclonic storm on 26 November and made landfall in Sri Lanka shortly thereafter. Following landfall, its slow movement and persistent moisture supply contributed to prolonged rainfall over the island, creating conditions for widespread flooding and landslides. The cumulative rainfall recorded during 26–28 November accounted for approximately 15.8% of Sri Lanka's mean annual rainfall (Perera et al., 2026), highlighting the exceptional magnitude of the event.

Although TC Ditwah was a relatively weak cyclonic storm by wind-based measures, with a maximum sustained wind speed of approximately 65 km h⁻¹ and a minimum central pressure of 1,002 hPa, it produced exceptionally severe human and societal impacts despite its comparatively modest wind intensity. This contrast highlights a key limitation of interpreting cyclone severity principally through wind intensity: such measures do not directly represent rainfall magnitude, storm duration, translation speed, moisture transport, river flooding, storm surge, or landslide potential. Similar contrasts between wind intensity and overall disaster severity have been observed in other high-impact tropical cyclones. Hurricane Harvey (2017), for example, weakened after landfall but produced extraordinary rainfall, with storm totals exceeding 1.5 m at locations in southeastern Texas (Blake and Zelinsky, 2018), while Hurricane Katrina (2005), despite making landfall as a Category 3 hurricane, generated catastrophic impacts through storm surge and failures of flood-protection infrastructure around New Orleans (Bloemendaal et al., 2021). Together, these examples illustrate why cyclone impacts must be interpreted through multiple interacting hazard pathways rather than wind intensity alone. In the case of TC Ditwah, intense rainfall, slow storm evolution, rapid catchment response, and cascading flood and landslide hazards were particularly important in compressing the time available for protective action.

Regional cyclone records further support this limitation. For TCs passing through the region bounded by 77°–85°E and 3.5°–12°N since 1978, maximum wind speed does not show a clear relationship with maximum daily rainfall (Figure 3a). TC Ditwah produced the highest recorded daily rainfall among these events despite not having the highest wind speed. Similar patterns are observed in cyclone records from Vietnam, Myanmar, Indonesia, and Bangladesh (Figure 3b), indicating that wind speed



alone is insufficient to characterize rainfall intensity and associated hydrological hazard in rainfall-dominated and compound-hazard settings.

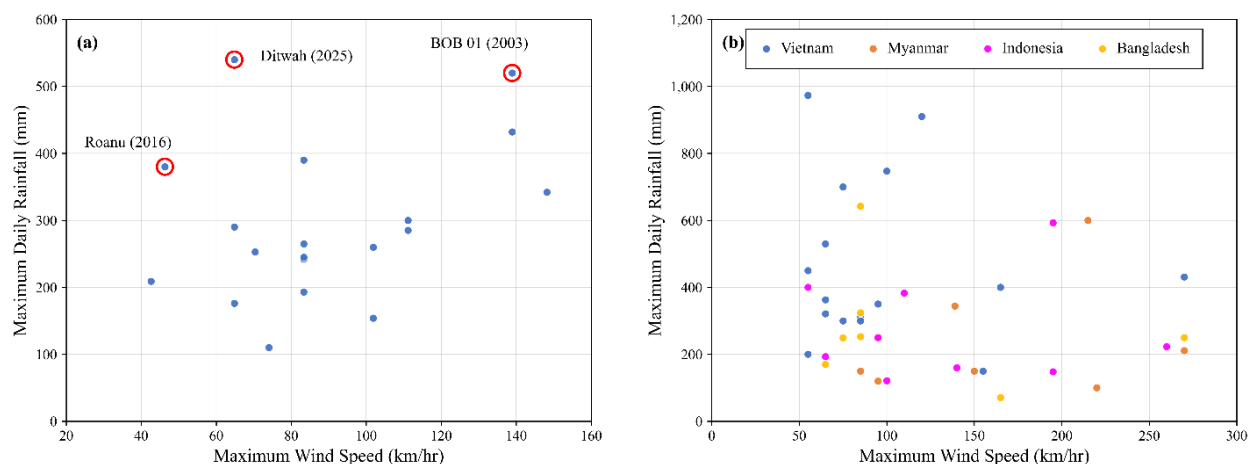


Figure 3: Relationship between maximum daily rainfall and maximum wind speed for tropical cyclone events affecting Sri Lanka and selected Asian countries. Panel (a) shows tropical cyclones passing through the region bounded by 77°–85°E and 3.5°–12°N since 1978 and (b) tropical cyclones affecting Vietnam, Myanmar, Indonesia, and Bangladesh. The references used to compile the cyclone records are provided in Supplement Sect. S1.

The broader climatic context in which TC Ditwah occurred reflects the combined influence of anthropogenic warming and natural climate variability. Kew et al. (2025) reported that elevated sea surface temperatures increased ocean heat content and strengthened the thermodynamic support for cyclone development, while a warmer atmosphere with greater moisture-holding capacity contributed to more intense rainfall. At the same time, Roose et al. (2023) showed that low-latitude cyclone formation in the post-monsoon NIO declined during 1981–2010 relative to 1951–1980, mainly due to weakened low-level vorticity associated with the Pacific Decadal Oscillation (PDO) and increased vertical wind shear. However, sustained warming of the Indian Ocean under anthropogenic forcing (Dong et al., 2014; Gnanaseelan et al., 2017) may alter the environmental conditions governing cyclone formation, intensification, and rainfall production, particularly when interacting with natural variability such as the PDO. These interacting influences highlight the importance of preparedness and risk assessment approaches that account for both cyclone dynamics and rainfall-related hazards in the post-monsoon NIO.

Taken together, these observed patterns and projected changes strengthen the case for multidimensional cyclone hazard assessment and communication. Although intense winds associated with TCs can cause severe property damage and loss of life, torrential rainfall under weakened or slow-moving systems can trigger extensive flooding and landslides (Alipour et al., 2020; Touma et al., 2019; van Oldenborgh et al., 2017). Slow-moving TCs can be particularly destructive because prolonged rainfall, river discharge, and storm surge may interact to produce compound flooding (Kossin, 2018). The IPCC Sixth Assessment Report further indicates, with high confidence, that TC rainfall rates are projected to intensify under a warming climate, while compound flooding risks may increase due to sea-level rise and precipitation extremes (Seneviratne et al., 2021). In this context, TC Ditwah should not be interpreted merely as an anomalous Sri Lankan event, but as an illustration of the



broader risk posed by rainfall-dominant tropical cyclones whose hydrological and societal impacts may be severe despite comparatively moderate wind intensity.

4. Event reconstruction

4.1. Atmospheric drivers

Typically, TCs experience a reduction in precipitation intensity after landfall, primarily due to increased surface friction and reduced moisture supply from the ocean. However, under favourable environmental conditions, TCs can continue to produce substantial precipitation after landfall, resulting in prolonged heavy rainfall (Sun and Xu, 2021; C.-C. Wu, 2013). TC Ditwah illustrates this behaviour, as it remained over land for an extended period after landfall, contributing to three consecutive days of intense rainfall across Sri Lanka during 26–28 November. Furthermore, owing to Sri Lanka's island geography, parts of the cyclone's circulation remained over the surrounding ocean even while its centre was over land, allowing continued moisture transport towards the island and potentially sustaining heavy rainfall.

Several factors influence the intensity and duration of TC precipitation after landfall. The characteristics of the water vapour field play a critical role in determining both the spatio-temporal distribution and intensity of TC precipitation (Zhu et al., 2019). Warm surrounding ocean waters can enhance atmospheric moisture availability and tropical-cyclone precipitation, while continued access to nearby oceanic moisture can help sustain rainfall as a cyclone interacts with land (Yang and Toumi, 2025; Matyas, 2013). Additionally, the interaction between cyclonic circulation, monsoonal flow, and persistent low-level moisture transport can contribute to the sustained maintenance of cyclone-related convection and prolonged heavy precipitation (Wang et al., 2012; L. Wu et al., 2011).

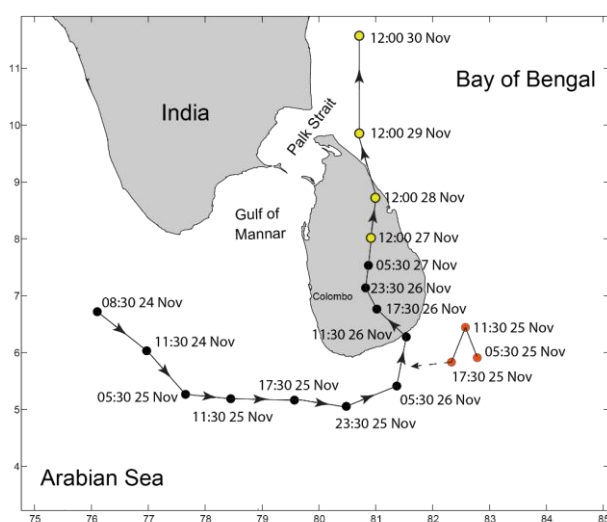


Figure 4: Track evolution of TC Ditwah and its precursor low-pressure systems near Sri Lanka developed through the analysis of multiple sources including the modelling performed by Dr E.M.S. Wijeratne, UWA.



Another important atmospheric feature associated with the evolution of TC Ditwah was the presence of a complex multi-vortex environment over the eastern Indian Ocean and the adjoining seas around Sri Lanka. As shown in Figure 4, two low-pressure systems were observed in the broader region prior to the development of TC Ditwah, with one disturbance moving eastward to the south of Sri Lanka and a second disturbance located near the southeastern coast of the island. The close interaction between neighbouring cyclonic vortices is commonly referred to as the Fujiwhara, or binary, interaction, in which two cyclonic systems rotate around a common centre, altering each other's motion and, in some cases, merging or reorganizing into a more coherent vortex. In the case of TC Ditwah, this interaction and apparent merger may have contributed to the consolidation of low-level vorticity and the organization of deep convection near Sri Lanka, thereby supporting the formation and persistence of the cyclonic circulation. From a forensic perspective, this is important because the rainfall hazard was not only controlled by the mature cyclone track, but also by the precursor low-pressure interactions that helped establish a moisture-rich, dynamically active environment before and during landfall. Therefore, the TC Ditwah event can be interpreted as the outcome of both pre-landfall vortex interaction and post-landfall moisture maintenance, which together prolonged rainfall generation over Sri Lanka.

Topography further amplified the rainfall hazard during TC Ditwah. Previous studies have shown that terrain can play a significant role in enhancing heavy precipitation after TC landfall by forcing moist air masses to rise, strengthening local convergence, and sustaining convective activity over windward slopes (Gao et al., 2009; Lin et al., 2001). This mechanism is particularly relevant to Sri Lanka, where steep central highlands are located within a short distance from the coast. During TC Ditwah, moisture-laden circulation from the surrounding seas interacted with this compact and elevated terrain, favouring orographic lifting and persistent rainfall over the central hills and downstream river basins. More generally, interactions between tropical-cyclone circulation and mesoscale topography can modify the local airflow and vertical-motion structure as the cyclone encounters complex terrain (C.-C. Wu et al., 2015). In the Sri Lankan setting, such terrain-enhanced precipitation could have contributed to the persistence of heavy rainfall over the central highlands and, consequently, to rapid runoff generation in the steep headwater catchments. Taken together, the cyclone's near-island development, persistent moisture supply, slow evolution, and interaction with Sri Lanka's topography provide a physically plausible explanation for the exceptional rainfall generated by a system of comparatively moderate wind intensity.

4.2. Hydrological translation

Of Sri Lanka's 103 river basins, 20 were included in official flood warnings and advisories during TC Ditwah, indicating widespread hydrological concern across the island. However, modelling the hydrological response of all affected basins was constrained by the availability of rainfall, streamflow, and water-level data for both the TC Ditwah event and previous flood events required for model calibration and validation. Therefore, nine representative flood-affected basins were selected to establish a modelling-based understanding of event-scale hydrological translation. These basins were selected based on flood severity, data availability, spatial coverage, and their relevance to understanding the diversity of basin responses during the event. The selected basins were modelled using the Rainfall–Runoff–Inundation (RRI) model developed by the International



Centre for Water Hazard and Risk Management (ICHARM) (Sayama et al., 2012). The RRI model was implemented using a 450 m digital elevation model available within the modelling framework, which was considered appropriate for the basin-scale diagnostic objectives of this study. For the TC Ditwah event, basin-specific simulation periods were selected to capture antecedent conditions, the main flood response, and the post-event recession, with the simulation windows collectively spanning 1 November to 10 December 2025. Daily rainfall observations were used as meteorological forcing, and the RRI model generated simulated hydrological outputs at 1 h intervals. Eight basin models were calibrated and validated using available historical flood events and were subsequently forced with TC Ditwah rainfall to simulate event hydrographs and estimate total event discharge volumes. For Deduru Oya, observed streamflow data were unavailable for calibration and validation; therefore, parameters calibrated for the neighbouring Maha Oya basin were transferred for the TC Ditwah simulation. These simulated discharge volumes were then compared with basin-scale rainfall volumes to derive event discharge-to-rainfall volume ratios, which provide a first-order indicator of the proportion of estimated rainfall volume represented in modelled river discharge over the selected event period. The simulated event hydrographs were examined alongside these ratios to assess differences in the magnitude and temporal concentration of basin response. Details of the rainfall and streamflow stations used for model calibration and validation are provided in Table A1, while the rainfall stations used for the TC Ditwah event simulations are listed in Table A2. The corresponding model calibration and validation performance results are summarised in Table B1.

Rainfall and streamflow data were available at daily time steps, which introduced uncertainty in representing sub-daily flood dynamics and made model calibration and validation challenging. Although the model generated simulated hydrological outputs at 1 h intervals, this temporal resolution does not overcome the limitations associated with the daily rainfall forcing and streamflow data used for model calibration and validation. Nevertheless, the eight calibrated basin models achieved Nash–Sutcliffe Efficiency (NSE) values ranging from 0.60 to 0.91 during calibration and from 0.50 to 0.93 during validation. These performance values indicate that the models were adequate for reconstructing basin-scale event response and comparing relative hydrological translation across basins, while sub-daily timing should be interpreted cautiously. Calibration and validation results, TC Ditwah event hydrographs, and performance statistics are provided in Appendix B. The spatial distribution of the modelled basins, rainfall gauges, streamflow gauges, and total event rainfall and discharge volumes is shown in Figure 5.

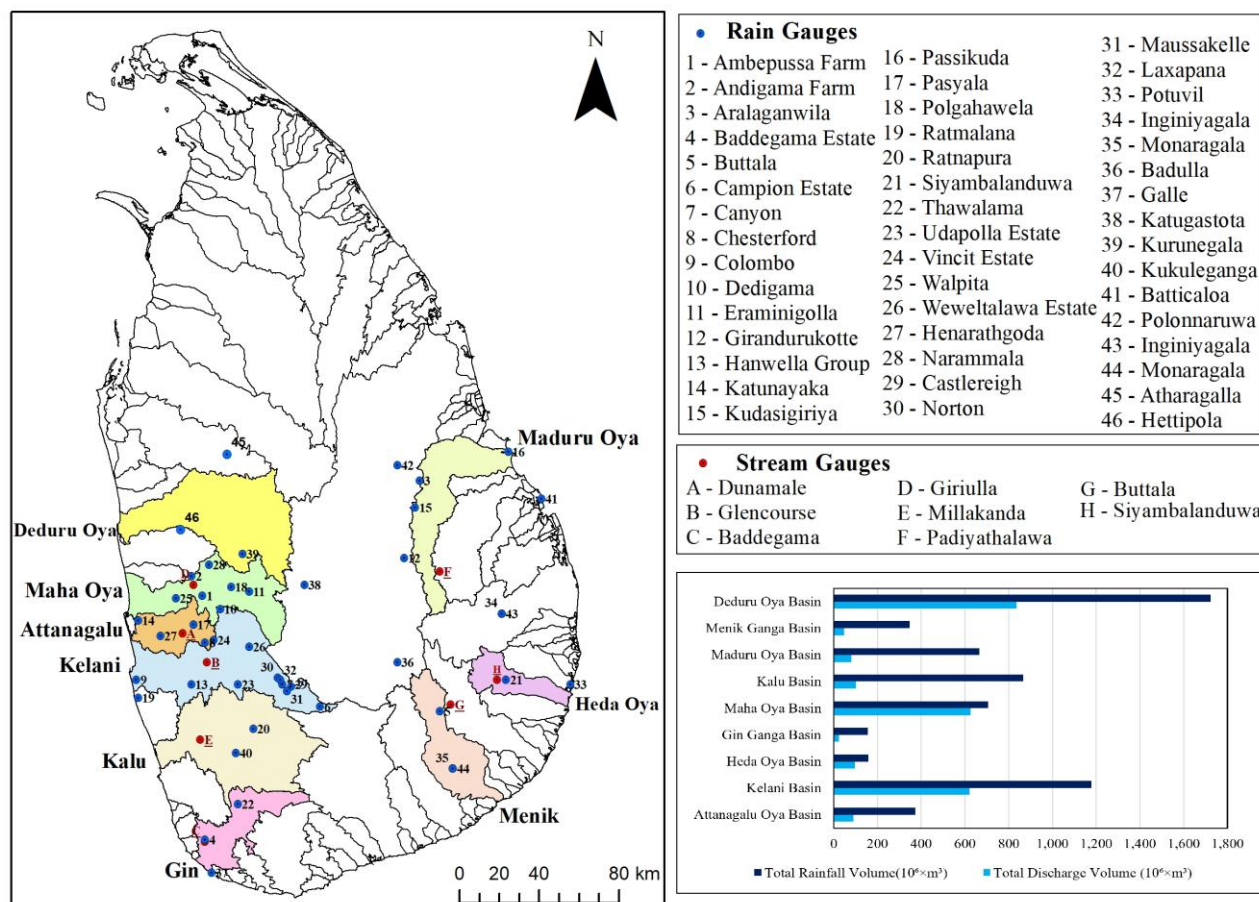


Figure 5: Modelled river basins and hydrometeorological stations used to assess event-scale hydrological translation during TC Ditwah.

395 The event discharge-to-rainfall volume ratios showed substantial differences among the nine modelled basins, indicating that TC Ditwah rainfall was not translated into river discharge uniformly across Sri Lanka. Maha Oya exhibited the highest ratio, with approximately 89% of the estimated rainfall volume represented in modelled discharge over the event period. This represents the strongest event-scale discharge response relative to estimated rainfall volume among the analysed basins. Heda Oya, Kelani River, and Deduru Oya also showed relatively high ratios of 0.62, 0.53, and 0.49, respectively, while Attanagalu

400 Oya showed an intermediate ratio of 0.24. Gin Ganga, Menik Ganga, Kalu Ganga, and Maduru Oya recorded lower ratios ranging from 0.12 to 0.16. These lower values may reflect differences in basin storage, floodplain attenuation, reservoir influence, infiltration, spatial rainfall representation, model structure, or the selected event window.

From a forensic perspective, the volume ratios are most informative when interpreted together with the simulated event hydrographs. In Maha Oya, the combination of the highest discharge-to-rainfall ratio (0.89) and a sharply rising event hydrograph indicates a strong and temporally concentrated hydrological response during the principal event period.

405 Pronounced event peaks are also evident in the simulated hydrographs of several other basins, although their magnitude, shape,



and recession characteristics differ substantially. These hydrographs provide complementary evidence that hydrological response was concentrated over relatively short event timescales in several basins; however, the daily resolution of the observational rainfall and streamflow data limits precise interpretation of sub-daily response times.

410 Conversely, the lower ratios in Kalu Ganga, Maduru Oya, Menik Ganga, and Gin Ganga should not be interpreted simply as lower hazard. Rather, they indicate that the rainfall–discharge relationship during TC Ditwah was mediated by basin-specific controls, including catchment storage, floodplain retention, reservoir effects, rainfall distribution, and possible uncertainties in volume estimation. In such cases, hydrological translation may have occurred through delayed flow, localized inundation, storage changes, or spatially uneven runoff generation that is not fully captured by a single basin-scale volume ratio. Therefore, 415 the discharge-to-rainfall volume ratio is best interpreted as an event-scale forensic indicator of basin response, rather than as a fixed runoff coefficient or a direct measure of response speed.

Overall, the modelling demonstrates that the hydrological consequences of TC Ditwah depended not only on rainfall magnitude but also on basin-specific differences in the partitioning, storage, and transmission of rainfall. The discharge-to-rainfall ratios reveal substantial spatial variation in event-scale hydrological translation, while the simulated hydrographs provide 420 complementary evidence on the temporal concentration of basin response. Together, these results indicate that the physical response developed over comparatively short event timescales in several basins. The precise operational significance of this timing is assessed more directly in the subsequent river-water-level and warning analyses, which evaluate threshold exceedance and available warning lead time. This combination of hydrological modelling and observed river response provides the basis for the later system-level diagnosis of whether physical response times became incompatible with the time required 425 for warning escalation, institutional action, and community response.

4.3. Human exposure and impact

Figure 6 illustrates the spatial distribution of rainfall, associated hazards and exposure across Sri Lanka during TC Ditwah. Three-day rainfall during 26–28 November 2025 varied substantially among river basins, with the highest mapped category reaching $2,001\text{--}5,000 \times 10^6 \text{ m}^3$ (Figure 6(a)). These values represent basin-integrated rainfall volumes and therefore reflect 430 both rainfall depth and basin area. The mapped flood extent affected multiple basins (UNDP and DMC, 2025), while landslide locations were concentrated mainly in the central and southwestern interior. Event discharge-to-rainfall volume ratios for the assessed basins ranged from 0.12 to 0.89, indicating substantial variation in event-scale hydrological translation, with the highest value occurring in the Maha Oya basin (Figure 6(b)).

Population and infrastructure exposure also varied considerably among Divisional Secretariat Divisions (DSDs). Higher 435 population exposure was concentrated particularly in western and southwestern areas, whereas infrastructure exposure showed a more dispersed pattern. The highest mapped categories reached 30,000–50,000 people (Figure 6(c)) and 25,000–45,000 infrastructure units (Figure 6(d)) per DSD. These DSD-level indicators should be interpreted as spatial exposure indicators rather than direct loss estimates, because they identify where people and infrastructure were located in relation to the broader hazard footprint.

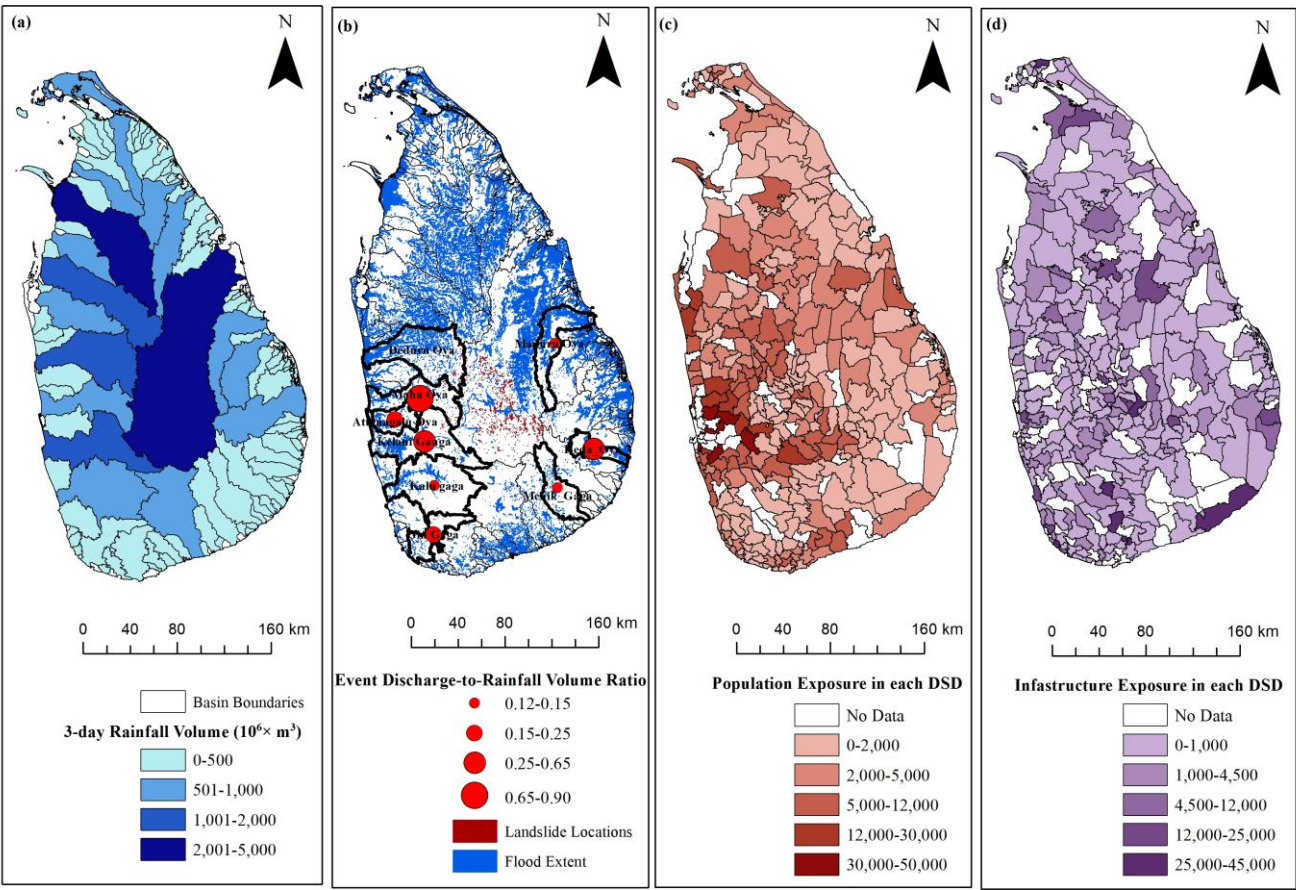


Figure 6: Spatial footprint of TC Ditwah across Sri Lanka. (a) Basin-integrated three-day rainfall volume during the event. (b) Flood extent, reported landslide locations, and model-derived event discharge-to-rainfall volume ratios for selected basins. (c) Population exposure by Divisional Secretariat Division (DSD). (d) Infrastructure exposure by DSD. The figure illustrates the island-wide distribution of rainfall forcing, hydrological and landslide impacts, and exposed population and infrastructure during TC Ditwah.

Together, these spatial patterns illustrate the geographical breadth of the event and the challenge of coordinating warnings, evacuation planning, and emergency support across multiple simultaneously affected areas. To complement this spatial assessment with community-level evidence on hazard experience and protective response, a post-event survey was conducted in affected areas. The survey yielded 58 responses from residential, commercial, and community locations, providing insights into how warnings were received, interpreted, and acted upon, alongside the impacts experienced.

Responses were analysed along six analytical dimensions: hazard experience, warning receipt, understanding, decision-making, protective action, and impact. Frequencies and linked responses were examined to identify gaps between warning information and timely, actionable support. Percentages were calculated using the relevant question or subgroup denominator, with overlapping selections permitted for multiple-response questions. These dimensions were used as an analytical structure



rather than as a presumed causal sequence; understanding was assessed through perceived message clarity and action guidance, while protective action could precede reported warning receipt. The analysis therefore connects the spatial patterns of hazard and exposure with the practical challenges of translating anticipation into effective community protection.

4.3.1. Hazard experience: nighttime arrival and rapid progression to maximum flooding

Forty-five respondents (77.6%) had lived or worked at their location for at least 11 years, yet 46 (79.3%) described TC Ditwah as worse or much worse than previous events. Floodwater entered the house or property for 41 respondents (70.7%), including 10 of the 13 who described their area as having no historical flood or landslide hazard. Thus, long local experience did not necessarily correspond to prior experience of an event of comparable severity.

The reported chronology indicates limited separation between initial inundation and maximum flooding at many locations. Initial floodwater arrival and maximum water level fell on the same calendar date in 31 of 39 records with paired dates. Among 33 records with paired date and time-band information, 20 reported arrival and maximum flooding within the same six-hour band on the same date. Flood arrival was also predominantly at night or in the early morning. This combination is consistent with short local response windows under difficult mobilization conditions.

4.3.2. Warning receipt: warning gaps extended to respondents reporting deeper inundation

In the warning-timing question, 38 respondents (65.5%) reported no warning, six (10.3%) received one after impacts began, 11 (19.0%) received one before local impact, and three were unsure. Overall, 44 of 58 respondents (75.9%) reported either no warning or warning receipt after local impact had begun. The absence of advance information was not confined to locations with little reported exposure. Of the 26 respondents selecting depth bands beginning at 1.5 m or higher, 16 (61.5%) reported no warning and three (11.5%) received one after impact onset. Thus, 19 of these 26 records (73.1%) combined reported deeper inundation with no warning or a late warning.

4.3.3. Warning interpretation: broad information did not always provide local action guidance

Nineteen (19) respondents evaluated warning content. Thirteen (68.4%) described the warning as very or somewhat clear, but only six (31.6%) reported receiving clear instructions about what to do. Five (5) received insufficient advice, while seven (7) received only a hazard description. Moreover, seven (7) of the 13 respondents who considered their warning clear nevertheless reported insufficient advice or a hazard description without clear instructions. Perceived clarity therefore did not necessarily translate into actionable guidance.

Source-linked responses sharpen this distinction. Eighteen (18) respondents cited television/radio or social media as warning sources; nine (9) selected “the warning was too general” as a reason for not fully trusting or acting on it. Only six of the 20 respondents who reported a warning type cited local authorities/Grama Niladhari officers or police/military; three of these six indicated that the warning came too late. Together, these findings suggest that access to warning information did not consistently translate into timely, locally relevant guidance for protective action.



4.3.4. Decision-making: trust could not compensate for lost time or practical constraints

Of the 19 respondents who evaluated warning content, seven (7) trusted the warning, nine (9) trusted it partly, and three (3) did not trust it. Among the six (6) respondents who cited local authorities/Grama Niladhari officers or police/military as warning sources, five (5) reported full or partial trust. However, three (3) of these six respondents also reported receiving the
490 warning only after local impacts had begun. This indicates that credibility alone was insufficient when warning receipt occurred too late to support effective protective action. Together, these accounts distinguish credibility from timeliness: a warning may be trusted but still arrive after conditions have deteriorated or too late for the intended protective action.

Practical constraints further separated awareness from the ability to act. Fourteen (14) respondents selected “did not expect severe flooding or landslides” as a reason for not evacuating or acting earlier, eight (8) reported having no safe place to go,
495 seven (7) did not know where to go, and six (6) lacked transport. Security concerns and difficulties involving elderly people, children, sick people, or persons with disabilities were each selected by four respondents. Respondents’ assessments of institutional coordination also indicated delayed responses (34), no visible coordination (18), and conflicting instructions (15). These reported shortcomings suggest that effective community protection depends not only on clear and trusted warnings, but also on timely, coordinated institutional support that enables households to convert warning information into feasible protective
500 action.

4.3.5. Protective action: some respondents acted before receiving the warning they recalled

Evacuation before impact and moving valuables or documents were each selected by 28 respondents (48.3%); 16 selected both, giving 40 respondents (69.0%) who reported at least one of these actions. Most notably, all three respondents who cited local authority or police/military sources and placed warning receipt after impact onset also selected evacuation before impact.
505 Taken as reported, their accounts suggest that protective action occurred before receipt of the warning they recalled. This is consistent with warning communication reaching some respondents after protective action had already begun, rather than necessarily serving as the trigger for that action. The responses do not identify the original evacuation trigger or verify the timing of a particular agency message.

4.3.6. Impact: damage and prolonged inundation created extended recovery needs

The impact dimension captures the consequences experienced by respondents. Building damage was selected by 38
510 respondents (65.5%), furniture or appliance loss by 36 (62.1%), and livelihood or income loss by 25 (43.1%). Thirty of the 46 respondents who reported the duration of above-floor inundation (65.2%) selected more than two days. The impacts therefore extended beyond the initial arrival of floodwater to include prolonged disruption and recovery needs.



4.3.7. Synthesis: timing, local relevance and practical support

515 The combined evidence indicates that the community protection problem extended beyond the existence of hazard information. Nighttime arrival and closely spaced reports of initial and maximum inundation describe conditions in which delays could consume much of the local opportunity to act. Yet warning receipt remained limited even among respondents reporting deeper inundation: 16 of the 26 reporting depth bands beginning at 1.5 m or higher received no warning. Among those reached, perceived message generality and incomplete action guidance limited the practical usefulness of information. The small local-
 520 source subgroup further shows that reported trust could coexist with late receipt, while three respondents reported evacuating before receiving the warning they later recalled.

These findings are consistent with an anticipation–action gap in which available hazard information did not consistently translate into timely and feasible community protection, alongside the severity of the physical hazard. They support the need for warning systems to connect timely local receipt with clear protective instructions, feasible transport and refuge
 525 arrangements, and coordinated support. Respondents’ priorities align with these requirements: 47 of 56 requested earlier and clearer warnings, 31 requested better agency coordination, 29 requested clearer explanations of protective actions, and 25 requested better evacuation support. Such links provide concrete targets for the coordinated preparedness exercises discussed in Section 7.

These descriptive findings apply to the surveyed locations and do not establish population-wide rates or a causal chain from
 530 warning failure to loss. Many respondents acted without a warning, source groups overlapped, and some chronology and household/business responses were inconsistent. Exact institutional delays and message effectiveness require comparison with warning archives and the physical reconstruction. The principal conclusion is that information becomes protective when its timing, local relevance, and supporting arrangements enable action before flooding constrains communities’ options.

5. Diagnosing system stress and performance limits

535 5.1. Forecast performance and spatial resolution

Figure 7 compares the daily rainfall forecasts issued by the Department of Meteorology with observed rainfall during 26–28 November 2025. The comparison reveals two important limitations in the spatial and intensity resolution of the operational rainfall forecasts during the event.

First, the rainfall forecast was mainly issued at the provincial scale. However, the observed rainfall distribution shows strong
 540 spatial variability within several provinces. For instance, some areas within the same province recorded relatively low rainfall, while other locations experienced very high rainfall exceeding 300 mm/day. This indicates that a province-level forecast may not fully resolve the localized nature of rainfall associated with the tropical cyclone event. Such broad spatial generalization may limit the actionability of forecast information, particularly for locally targeted preparedness, warning escalation, and identification of areas experiencing the highest rainfall intensities.



545 Second, the forecast rainfall categories provided limited discrimination of the upper-end magnitude of extreme rainfall at
several locations, particularly during the first two days of the event. On 26 and 27 November, when most of the cyclone-related
rainfall was received, several observed stations recorded rainfall above 200 mm/day, with some locations approaching 300–
400 mm/day. However, the highest forecast category was defined only as >200 mm/day. Therefore, although the forecast
captured the general likelihood of heavy rainfall, the open-ended >200 mm/day category did not distinguish between rainfall
marginally exceeding 200 mm/day and the exceptional 300–400 mm/day totals subsequently observed at some locations.
550 Consequently, the forecast did not adequately communicate the upper-end severity of the localized rainfall extremes during
the most critical period of the event. This limitation in upper-intensity discrimination is important because rainfall amounts
between 150 and 200 mm/day are not uncommon during intense monsoon periods in Sri Lanka. As a result, communities may
perceive such warnings as routine and underestimate the potential severity of the event. In contrast, rainfall approaching 300–
400 mm/day represents a substantially higher hazard level, with greater potential for floods, landslides, and rapid runoff
555 generation.

In contrast, on 28 November, the forecast indicated a broader spatial extent of >200 mm/day rainfall than was reflected in the
station observations. The forecast indicated widespread rainfall above 200 mm/day, whereas many observed stations recorded
comparatively lower rainfall, mostly within the 1–100 mm/day and 101–150 mm/day ranges. This apparent overestimation of
560 the spatial extent of very heavy rainfall on the third day was less consequential than the limited upper-intensity discrimination
during the first two days, because the major rainfall accumulation had already occurred earlier in the event.

Overall, Figure 7 demonstrates that the forecast captured the general occurrence of heavy rainfall but did not adequately
represent its spatial concentration or discriminate the upper-end intensity of the observed rainfall during the most important
phase of the cyclone. The limited upper-intensity discrimination on 26 and 27 November is particularly important because
565 these were the main rainfall-contributing days, whereas the apparent overestimation of the spatial extent of >200 mm/day
rainfall on 28 November occurred after much of the event rainfall had already been received. This highlights the need for more
spatially detailed rainfall forecasts and improved intensity classification during tropical cyclone-related extreme rainfall events.
A finer-scale forecasting approach would provide more actionable information for disaster risk reduction and emergency
response.

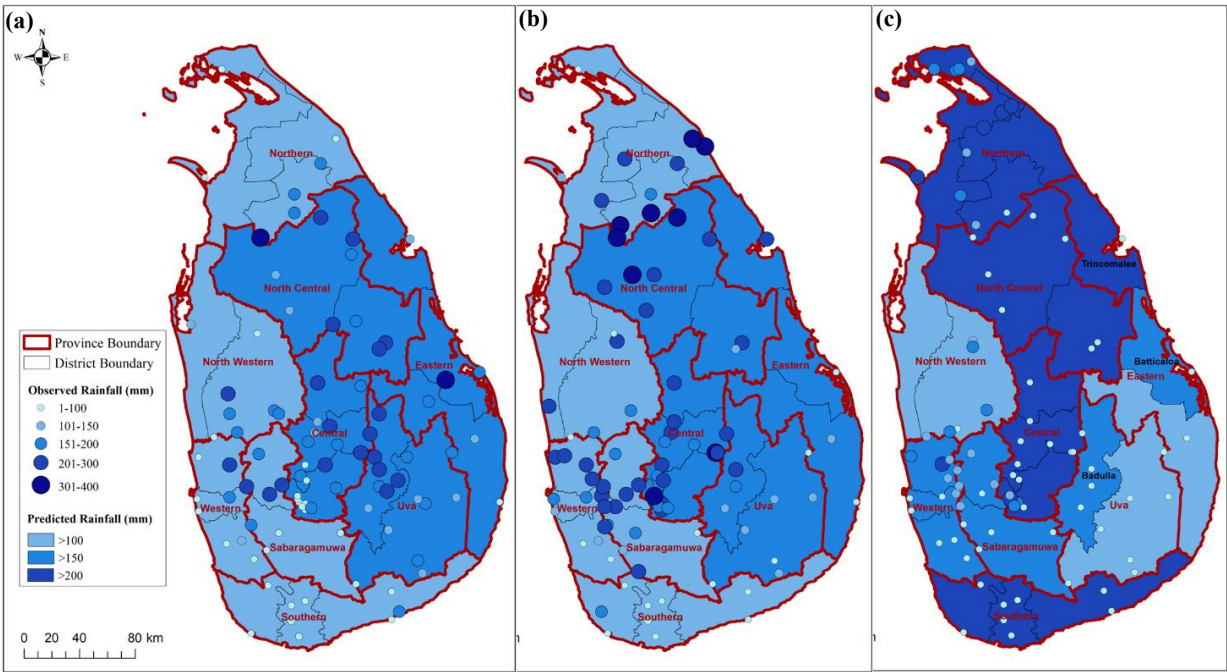


Figure 7: Comparison of Department of Meteorology daily rainfall forecasts and observed rainfall during the extreme rainfall event from 26–28 November 2025: (a) 26 November, (b) 27 November, and (c) 28 November. The background shading represents the forecast rainfall categories, while the circular markers indicate station-based observed rainfall totals. Red lines indicate province boundaries, and black lines indicate district boundaries.

5.2. Early warnings

5.2.1. Warning dissemination

In response to TC Ditwah, national emergency protocols were activated, and multiple agencies initiated anticipatory preparedness actions. The Department of Meteorology issued “Red” alerts approximately 72 hours before the cyclone’s landfall, while the Disaster Management Centre (DMC) activated emergency response plans and coordinated preparedness measures in collaboration with relevant stakeholders (Amaratunga and Kodituwakku, 2026). During the same period, river-basin-based flood warnings were disseminated through coordinated efforts between the Department of Irrigation and the DMC. Flood warnings and advisories were issued for twenty river basins (Figure 8a), including major basins such as the Mahaweli, Kelani, Deduru, Nilwala, Malwathu, Maha Oya, Menik Ganga, and Kalu Ganga basins (DMC, 2025). For all twenty basins, warning messages were disseminated in Sinhala and English by the Department of Irrigation and the DMC. The broad spatial distribution of warned basins reflects the island-wide extent of anticipated flood risk during the event, spanning river systems with diverse climatic, topographic, and land-use characteristics.

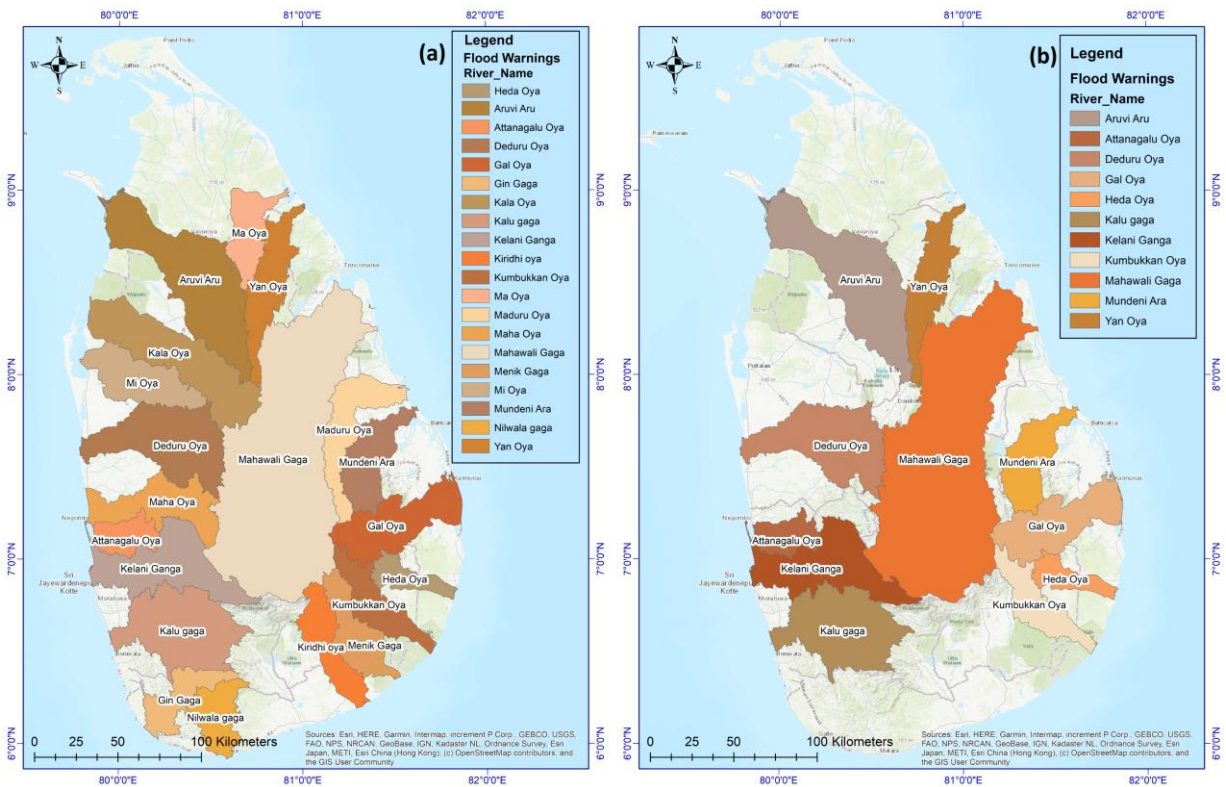


Figure 8: Spatial distribution of flood-warning dissemination during TC Ditwah: (a) river basins where flood warnings were issued; and (b) the subset of warned basins where warnings were also disseminated in Tamil.

In addition, Figure 8(b) shows that warning dissemination was not uniform in language across all basins. While Sinhala and English warnings were issued for all twenty basins, Tamil-language warnings were disseminated in eleven basins, primarily located in the Northern, Eastern, and parts of the North-Central regions. Several of these basins overlap areas with substantial Tamil-speaking populations, according to Department of Census and Statistics data. The availability of Tamil-language warnings therefore represents an important element of linguistic accessibility, although the present analysis does not establish whether language coverage was sufficient across all exposed communities.

5.2.2. Warnings and lead times

Early-warning systems are a principal mechanism for communicating impending flood risk and enabling protective action. The effectiveness of these warnings, however, depends partly on the lead time, defined here as the time between issuance of a flood warning and observed exceedance of the corresponding river-level threshold (ICIMOD, 2019). Longer lead times generally provide a greater opportunity for institutions and communities to undertake preparatory and protective measures. In the context of flood events, where the timing of the hazard is often critical, lead time is especially important for informing key



decisions, such as evacuation planning, emergency-resource mobilization, and flood-defence activation (Asri et al., 2023; Chalermyanont et al., 2022).

In Sri Lanka, the Department of Irrigation is the responsible line agency for river-flood hazards, with hazard information from relevant line agencies supporting the Disaster Management Centre in issuing early warnings to the public (Siriwardana et al., 2018). Operational assessment combines observed river water levels and catchment rainfall with meteorological forecasts, reservoir information, river-level trends, and, where available, flood models. Predefined alert, minor-flood, and major-flood thresholds at monitoring stations provide important operational reference points. Rising water levels at upstream stations can therefore provide advance indication of downstream flooding, with part of the available warning lead time arising from flood-wave travel time between upstream and downstream locations. The resulting warning window nevertheless depends strongly on station location, the timing of threshold exceedance, and flood-wave propagation, and may become limited in rapidly responding catchments or at upstream locations where critical river levels are reached quickly.

To evaluate the operational timing of flood warnings during TC Ditwah, lead times were assessed at monitored river stations within the warned basins. Two parameters were calculated: minor-flood lead time (ΔT_{minor}) and major-flood lead time (ΔT_{major}), defined as the time of observed threshold exceedance minus the issuance time of the corresponding warning. Figure 9 illustrates this calculation for the Glencourse station in the Kelani River Basin. A negative lead time indicates that the relevant threshold had already been exceeded before the corresponding warning was issued; in Figure 10, zero and negative values are grouped within the 0-h category. These metrics therefore quantify the response window available between warning issuance and observed threshold exceedance.

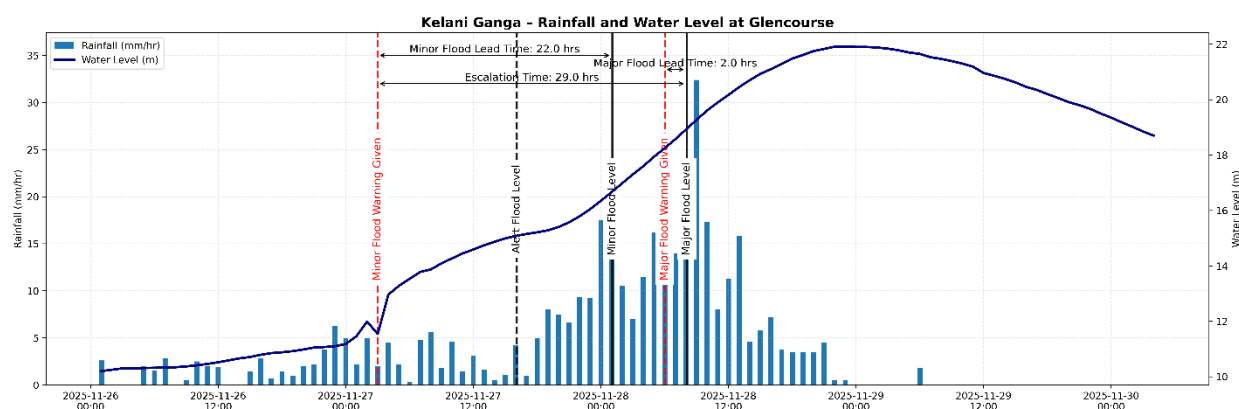
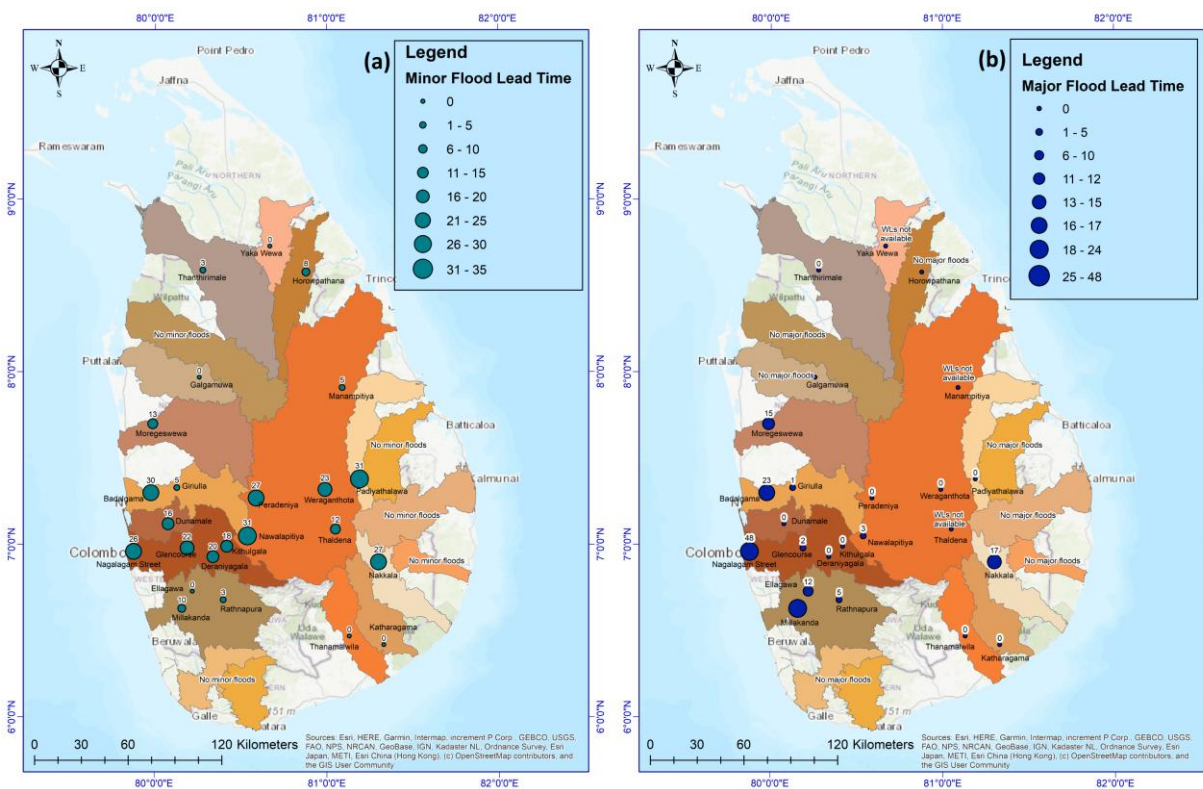


Figure 9: Illustration of minor- and major-flood lead-time calculations at the Glencourse water-level monitoring station in the Kelani River Basin during TC Ditwah.

Under minor-flood warning conditions, among stations for which minor-flood threshold exceedance was evaluated, lead times exceeded 3 h at most locations, with exceptions including Ellagawa in the Kalu Ganga basin, Katharagama in the Menik Ganga basin, Yaka Wewa in the Maha Oya basin, Galgamuwa in the Mee Oya basin, and Thanamalwila in the Kirindi Oya basin (Figure 10(a)). Further, at several critical stations, including Dunamale in the Attanagalu Oya basin and the monitored stations

within the Kelani River basin, ΔT_{minor} values were substantially longer, with lead times commonly exceeding 10–25 h, as illustrated in Figure 10(a). These longer lead times provided a greater potential window for evacuation planning, emergency mobilization, and other protective actions, although the practical usefulness of that time depended on warning receipt, message actionability, institutional response, and community capacity. However, this early advantage was not consistently carried over

630



635

Figure 10: Spatial distribution of flood-warning lead times during TC Ditwah: (a) minor-flood lead times and (b) major-flood lead times at monitored river stations across warned basins in Sri Lanka. Stations with zero or negative lead times are grouped within the 0-h category.

640

Figure 10(b) indicates that, at several water-level monitoring stations, including Dunamale in the Attanagalu Oya basin, Deraniyagala and Kithulgala in the Kelani River basin, Katharagama in the Menik Ganga basin, Thanamalwila in the Kirindi Oya basin, Thanthirimale in the Malwathu Oya basin, Giriulla in the Maha Oya basin, and Peradeniya, Nawalapitiya, and Weraganthota in the Mahaweli River basin, the ΔT_{major} value was either very short, zero, or negative. Zero or negative values indicate that the major-flood threshold had already been reached or exceeded when the corresponding warning was issued, whereas short positive values indicate only a limited interval between warning issuance and threshold exceedance. In such cases, the operational value of the major-flood warning for evacuation decision-making was substantially reduced. Such narrow response windows can constrain evacuation, emergency mobilization, and other protective actions that require time for communication, transportation, coordination, and access to safe refuge. The contrast between relatively long ΔT_{minor} and



645 compressed or delayed ΔT_{major} highlights a critical limitation in the timing of warning escalation. While early detection and communication at the minor-flood stage provided a greater potential window for preparedness, short, zero, or negative major-flood lead times reduced the system's ability to support decisive protective actions at the most critical phase of the flood event. Further, Figure 10(b) highlights notable upstream–downstream differences in available warning lead time in basins such as the Maha Oya, Kalu Ganga, and Kelani River. As flood waves propagate downstream, later threshold exceedance at downstream
650 locations can provide additional time between an earlier warning and the arrival of critical water levels. This is evident in the Maha Oya basin, where the major-flood lead time increases from approximately 1 h at the upstream Giriulla station to about 9 h at the downstream Badalgama station. A similar pattern appears in the Kelani River Basin, where upstream stations such as Kithulgala and Deraniyagala recorded zero or negative lead times, yet the downstream Nagalagam Street station exhibited approximately 48 h of lead time. These patterns are consistent with the influence of flood-wave travel time on spatial
655 differences in available lead time and highlight the potential value of incorporating upstream-triggered alerts and downstream travel-time information into flood early-warning systems.

Additionally, in some basins, including Heda Oya, Nilwala Ganga, Gal Oya, Gin Ganga, and Yan Oya, warnings were issued at the basin scale, but the corresponding minor- or major-flood thresholds were not exceeded at some of the monitoring stations examined. This should not be interpreted directly as forecast failure, because basin-level warnings may represent anticipated
660 conditions across a wider river system, whereas the threshold analysis reflects conditions at individual monitoring locations. The mismatch nevertheless illustrates an important spatial-scale issue: warning coverage at basin scale does not necessarily correspond to threshold exceedance at every monitored station. Differences in rainfall distribution, catchment response, river routing, local hydraulic conditions, and station location may all contribute to such spatial variability. These cases therefore reinforce the need to interpret warning lead time together with spatial specificity and observed hydrological conditions rather
665 than treating warning issuance alone as a measure of forecast performance.

5.3. Reservoir storage conditions and operational constraints

5.3.1. Estimating reservoir buffering conditions

Reservoir flood-buffering conditions were assessed using daily effective storage data for 79 major reservoirs across 27 river basins, obtained from the Irrigation Department and Mahaweli Authority of Sri Lanka. Flood buffering capacity was calculated
670 as the difference between active storage and effective storage and normalized by active storage to derive Buffering Index (BI) as in Equation 1. The analysis was conducted over a 7-day window surrounding TC Ditwah, from 24 to 30 November 2025.

$$BI_{i,t} = \frac{B_{i,t}}{A_i} = \frac{A_i - ES_{i,t}}{A_i} \quad (1)$$

Where $BI_{i,t}$ is the dimensionless Buffering Index, representing the relative available storage margin and $B_{i,t}$ is the available flood-buffering capacity. A_i is the active storage, defined as the storage volume between the full supply level and the minimum operating level, and $ES_{i,t}$ is the effective storage at reservoir i on day t , defined as the storage above dead storage after
675 accounting for operational losses and water allocations.



To assess basin-scale reservoir buffering conditions during the cyclone event, the Buffering Index (BI) was first calculated individually for each reservoir using daily effective storage data. Subsequently, reservoirs were grouped according to their respective river basins to characterize basin-level spatial and temporal patterns. For each basin, the daily BI values of all reservoirs located within the basin were aggregated using the median to represent the typical reservoir buffering condition within that basin. The resulting median value provides a robust indicator of typical buffering performance at the basin scale and enables comparative analysis of spatial and temporal dynamics across river basins during the event.

To characterize basin-scale hydrometeorological forcing during the event, daily basin rainfall was estimated using available 24-hour rainfall observations within each river basin. Rainfall data were obtained from multiple sources, including rainfall gauges associated with river-monitoring locations and selected reservoir stations located within the basin boundaries. In basins where more than one rainfall observation was available, the daily basin-average rainfall was calculated as the arithmetic mean of all available station records to provide a representative measure of observed rainfall across the basin.

To examine the temporal evolution of reservoir buffering conditions in relation to hydrometeorological forcing, the Buffering Index (BI) and corresponding basin-average 24-hour rainfall were jointly analysed over the cyclone period from 24 November to 30 November. For each basin, daily BI values and daily mean rainfall were plotted as time series to enable comparative assessment of spatial and temporal variability across basins. This visualization framework allowed the identification of changes in buffering conditions before, during, and after the cyclone landfall, as well as the examination of the timing and intensity of rainfall relative to basin-scale buffering responses at the national level.

5.3.2. Spatio-temporal dynamics of reservoir buffering

To examine how reservoir buffering conditions evolved across Sri Lanka during TC Ditwah, the daily basin-scale Buffering Index (BI) was mapped from 24 to 30 November 2025 (Figure 11). For each river basin, the basin-scale BI represents the typical reservoir storage-margin condition rather than the total buffering volume of the basin. For diagnostic interpretation, BI values >0.25 indicate comparatively greater available storage margins, values between 0 and 0.25 indicate moderate buffering conditions, and negative values indicate no available active-storage margin under the adopted metric. These categories are used as diagnostic classes for comparative interpretation rather than as universal operational thresholds. The sequence of daily maps therefore enables assessment of both the spatial variability among basins and the progressive change in reservoir buffering conditions before, during, and after the principal rainfall period.

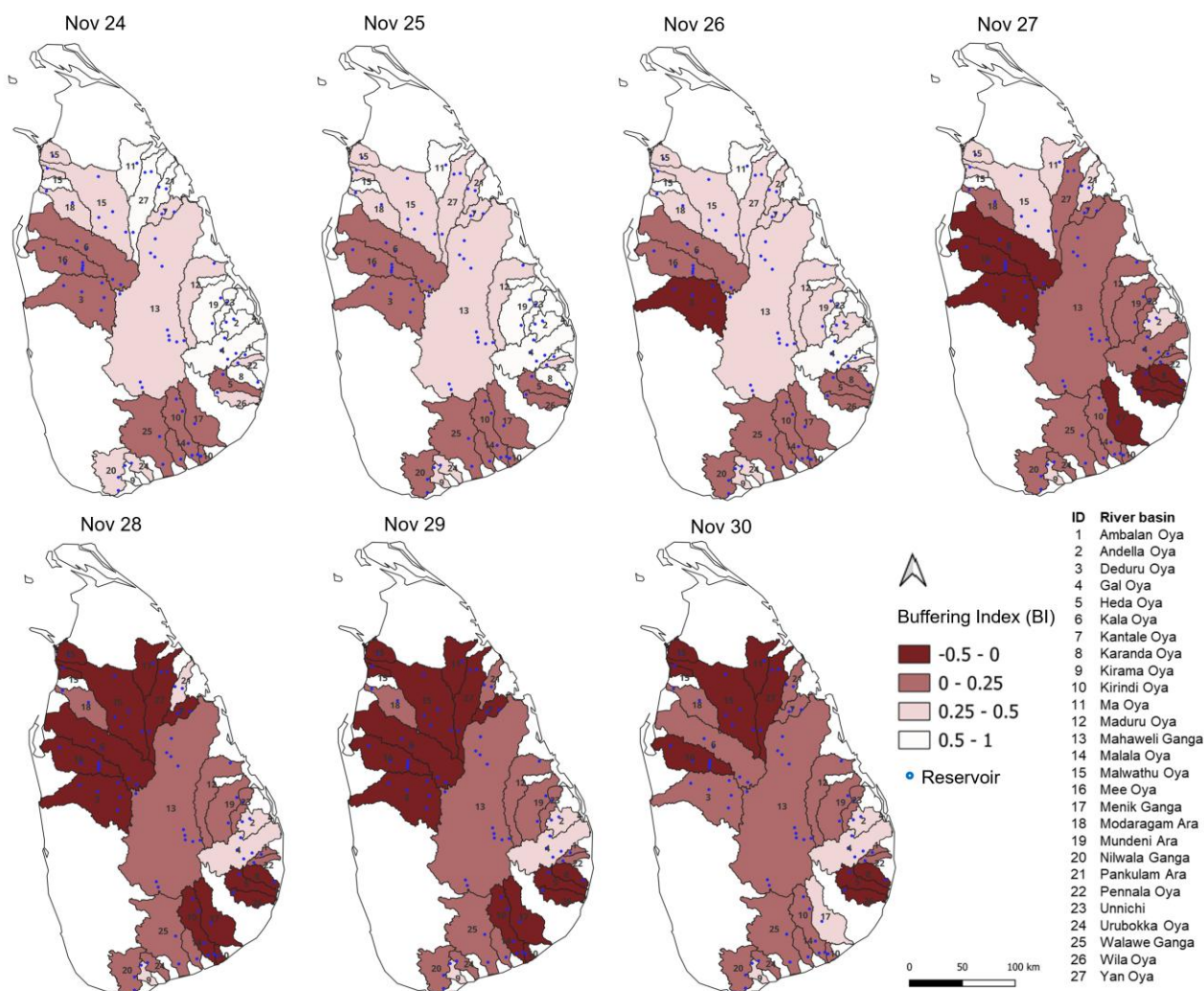


Figure 11: Spatio-temporal evolution of the basin-scale Buffering Index (BI) across Sri Lankan river basins from 24 to 30 November 2025 during TC Ditwah.

705 To characterize the spatial and temporal evolution of rainfall forcing during TC Ditwah, basin-level 24-hour rainfall was estimated for each river basin from 24 to 30 November 2025 (Figure 12). Basins without available rainfall observations were classified as NA, indicating data unavailability rather than an absence of rainfall. The sequence of maps illustrates how observed rainfall magnitude and its spatial pattern evolved throughout the event and provides the hydrometeorological context for interpreting concurrent changes in reservoir buffering conditions.

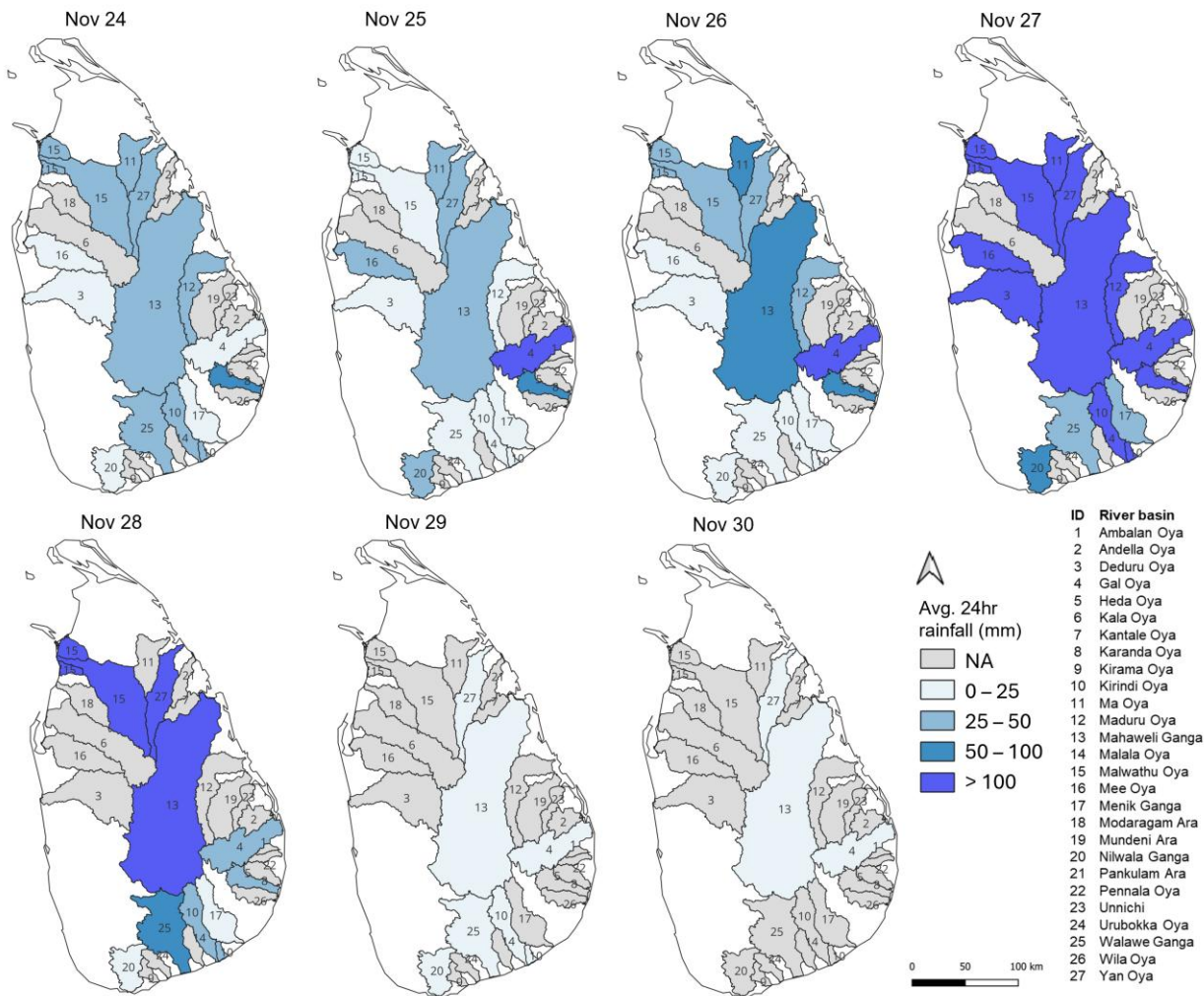


Figure 12: Spatio-temporal variation of basin-average 24-hour rainfall across Sri Lankan river basins from 24 to 30 November 2025 during TC Ditwah.

5.3.3. Basin-level temporal dynamics

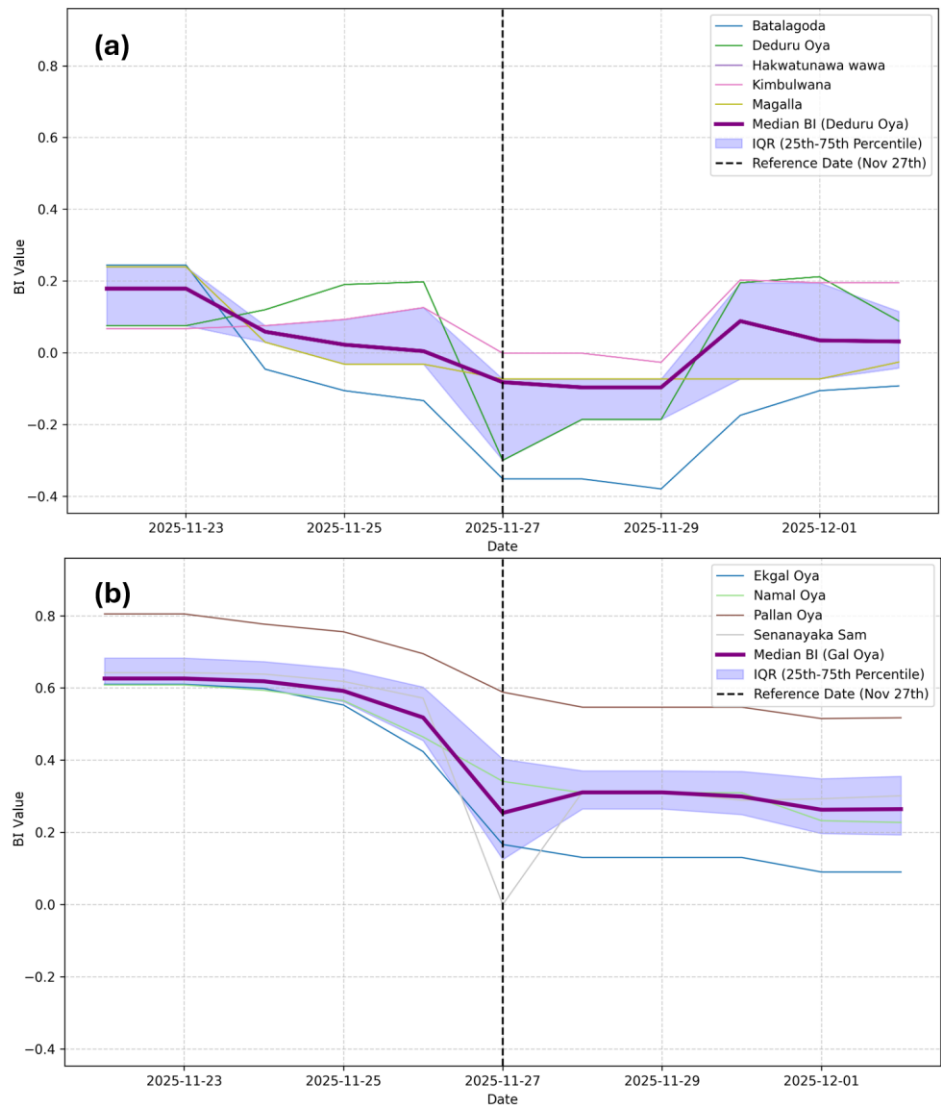
The temporal evolution of basin buffering capacity and rainfall (Figures 11 and 12) shows a clear contrast between Deduru Oya (ID-3) and Gal Oya (ID-4) during the cyclone period. Rainfall began intensifying from 25 November in Gal Oya, whereas significant rainfall in Deduru Oya occurred later, mainly from 27 November. Despite earlier rainfall exposure, Gal Oya maintained strong buffering capacity, with Basin Buffering Index (BI) values remaining above 0.5 until the landfall date. In contrast, Deduru Oya exhibited a rapid deterioration in buffering conditions, declining from an initially low buffering range (0–0.25) to negative buffering conditions (–0.5 to 0) by 26 November, around the time of cyclone landfall, and remained in this reduced buffering state until 29 November. While Gal Oya experienced a slight reduction in buffering around the landfall period, it retained marginally positive buffering on 27 November and showed a relatively rapid recovery to moderate buffering



725

levels (0–0.25) in the subsequent days. Overall, these results highlight pronounced differences between the two basins in terms of the timing, magnitude, and recovery trajectory of buffering capacity during the same cyclone event, which may reflect differences in reservoir system dynamics and operational practices between the basins.

To examine the basin-level pattern observed in Deduru Oya and Gal Oya in greater detail, reservoir-level BI trajectories were analysed for all reservoirs within the two basins from 22 November to 2 December 2025 (Figure 13). Individual reservoir trajectories are shown together with the basin median and interquartile range (IQR), allowing the temporal evolution and within-basin variability of reservoir buffering conditions to be assessed. The reference line at 27 November marks the critical phase of the cyclone event.



730

Figure 13: Reservoir-level Buffering Index (BI) trajectories from 22 November to 2 December 2025 in (a) the Deduru Oya Basin and (b) the Gal Oya Basin, showing the basin median and interquartile range (IQR).



The IQR captures the variability in buffering conditions within the basin. The contrasting behaviours in Figures 13 (a) and (b) suggest that the two basins responded differently to the event. In Deduru Oya, the IQR widened substantially around the cyclone landfall, reflecting increasingly divergent responses among individual reservoirs, with some experiencing markedly negative BI values (e.g. Deduru Oya reservoir) while others retained comparatively higher buffering conditions. Gal Oya also exhibited an increase in within-basin variability around landfall. However, most reservoirs remained within the positive BI range consistently, resulting in potentially greater operational flexibility during the event.

5.3.4. Water management implications

The observed buffering dynamics provide important insights into basin-scale flood preparedness, although they do not permit direct evaluation of reservoir operating decisions. Since inflow and outflow data were unavailable, the Buffering Index primarily reflects the reservoir storage state and the available storage margin for accommodating additional inflows. Basins that entered the cyclone period with low pre-event BI values had limited available storage margins, and were therefore more constrained in their capacity to accommodate additional cyclone-driven inflows. Conversely, basins with higher pre-event BI values retained greater storage margins and were able to maintain positive buffering conditions for longer as rainfall intensified. Importantly, an available pre-event storage margin does not necessarily imply that the same buffering capacity can be maintained throughout an extreme event. If inflows are substantially greater than anticipated or arrive earlier than forecast, the available storage margin may be depleted rapidly, shortening the time available for operational adjustment. Maintaining adequate buffering capacity may therefore require timely operational releases before peak inflows arrive, where such releases are compatible with dam safety, downstream flood risk, and other reservoir-management objectives. The practical effectiveness of the available storage buffer consequently depends not only on the initial storage condition, but also on inflow-forecast accuracy, forecast lead time, and the ability to make timely operational decisions.

These patterns suggest three key water-management implications. First, maintaining adequate pre-event storage margins can enhance reservoir-system preparedness for forecast extreme rainfall, where this is compatible with other reservoir objectives and operating constraints. Second, basins exhibiting rapid depletion of buffering capacity highlight the need for real-time integration of rainfall forecasts, reservoir storage conditions, and inflow information to identify systems approaching critical storage states sufficiently early for operational response and, where appropriate, to support timely adjustments to reservoir releases. Third, the pronounced spatial and reservoir-to-reservoir variability in buffering conditions underscores the importance of basin- and reservoir-specific preparedness strategies rather than uniform operational responses. More broadly, the results demonstrate that the value of meteorological anticipation depends partly on whether sufficient reservoir storage flexibility exists when extreme rainfall arrives, further illustrating the importance of translating advance hazard information into timely water-management action.



6. Why did anticipation not translate into protection?

The preceding sections show that TC Ditwah was not an event without anticipatory information. Rainfall forecasts, observed precipitation, river-stage measurements, reservoir-storage information, and institutional warnings were all available at different stages of the event. Yet their translation into timely protective action was incomplete and spatially uneven. The central forensic question is therefore why this information could not consistently be converted into coordinated protective action before conditions became critical.

A timescale perspective helps explain this anticipation–action gap. Cyclogenesis occurred close to Sri Lanka, limiting the time available for forecast refinement and preparedness. Rainfall was subsequently concentrated over a short period, while several river basins translated intense rainfall into rapidly rising river levels. Atmospheric forcing and hydrological response therefore unfolded over hours to a few days, compressing processes that would otherwise occur sequentially, forecasting, warning, preparation, and response, into overlapping time windows.

In contrast, institutional and community responses required additional time. Warnings had to be translated into locally relevant messages and disseminated; reservoir systems required sufficient storage flexibility and timely information; and communities needed time to receive, interpret, and act on warnings. When flood conditions evolved faster than these response processes, the time required for protective action increasingly approached or exceeded the time remaining to act.

This mismatch is evident across several components of the TC Ditwah event. Meteorological forecasts identified the potential for widespread heavy rainfall, but their spatial and upper-intensity resolution did not consistently distinguish where the most extreme rainfall would occur. Minor-flood warnings generally provided several hours of advance notice, but major-flood lead times became very short, zero, or negative at several stations. Reservoir preparedness was similarly heterogeneous, with some systems entering the critical rainfall period with restricted storage margins. At the community level, 44 of 58 respondents reported either no warning or warning receipt after impacts had begun, while incomplete guidance and constraints involving transport and safe refuge further limited action. Taken together, the evidence shows that anticipation existed at several points in the system, but its protective value diminished as the available response window narrowed.

The resulting limitation was therefore not simply one of hazard detection, but of continuity along the information-to-action chain. Forecasts had to become basin-specific operational awareness, changing river and reservoir conditions had to trigger escalating preparedness, and warnings had to reach communities with sufficient time and specificity for action. Delays at any of these transitions reduced the protective value of otherwise useful information.

This limitation is particularly important where warning escalation depends strongly on observed river levels and threshold exceedance. Such observations provide essential information on the evolving flood, and upstream measurements can create valuable downstream lead time; however, during rapidly developing events they may provide only a short response window at upstream or fast-responding locations. The TC Ditwah results therefore point to the need to complement observation-based monitoring with more anticipatory meteorological–hydrological forecasting that translates forecast rainfall into expected river response before critical levels are reached. Coupling meteorological forecasts with hydrological models, real-time river



observations, and upstream–downstream travel-time information could extend the decision horizon and allow preparedness and warning escalation to begin earlier. Such forecasting should complement, rather than replace, observed river-level information, with forecast uncertainty explicitly considered in operational decisions.

800 The reservoir evidence should nevertheless be interpreted cautiously: because inflow, outflow, and gate-operation records were unavailable, the observed storage margins indicate preparedness and available buffering flexibility rather than operational failure.

805 The deeper issue is that response capacity during an extreme event is partly shaped by institutional and social arrangements established long before the event itself. Warning protocols, reservoir operations, coordination mechanisms, evacuation arrangements, and community preparedness evolve over much longer timescales than the hazard itself. The flooding in the Mahaweli River highlights a potential governance constraint arising where responsibilities for reservoirs and downstream river systems are distributed across different agencies. Major dam reservoirs within the basin are managed by the Mahaweli Authority of Sri Lanka, while responsibility for the Mahaweli River lies with the Irrigation Department. During extreme events, such institutional separation increases the importance of basin-scale coordination across the reservoir–river system. Strengthening integrated water-resources governance could therefore complement improvements in forecasting and emergency response. In this sense, TC Ditwah tested not only short-term forecasting and response, but also longer-term preparedness and governance arrangements.

815 TC Ditwah can therefore be understood as a case of temporal compression across a coupled flood-risk system. Near-island cyclone development constrained meteorological anticipation; rapid hydrological response narrowed downstream reaction time; some reservoir systems had limited storage flexibility; major-flood warning lead times contracted; and many surveyed respondents lacked timely, actionable warnings. These time-sensitive constraints accumulated into a whole-system timescale mismatch, rather than an isolated failure of forecasting, reservoir management, warning, or community response. Anticipation becomes protective only when emerging signals are connected rapidly enough to operational triggers, appropriate authority, locally relevant communication, and feasible action. Flood-risk systems need to ensure that forecasting, reservoir preparedness, warning escalation, governance, and community response operate on timescales compatible with the evolving hazard.

820 Table 3 synthesizes the available anticipation, response timescales, observed bottlenecks, supporting evidence, and proposed interventions across the coupled system.

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Table 3: Synthesis of available anticipation, response timescales, observed bottlenecks, supporting evidence, and proposed interventions across the coupled flood-risk system during TC Ditwah.

Subsystem	Available anticipation	Response timescale	Observed bottleneck	Evidence	Proposed intervention
Atmospheric hazard and rainfall forecasting	Cyclone monitoring, rainfall forecasts, and red alerts issued approximately 72 h before landfall	Hours to days: cyclone development and intensification close to Sri Lanka during 26–27 November; principal rainfall during 26–28 November	Short forecast-refinement window; provincial-scale forecasts and an open-ended >200 mm/day category provided limited spatial and upper-intensity discrimination	Cyclone-track reconstruction and forecast–observation comparison (Secs. 3, 4.1, 5.1; Figs. 4, 7)	Higher resolution, impact-based forecasts linked to predefined preparedness and escalation triggers
Catchment and river response	Rainfall and river-stage observations; upstream water-level information providing anticipation for downstream reaches	Hours: rapid local flood development, with longer warning lead times at some downstream locations	Rapid river-level rise compressed local action windows; available lead time varied substantially among basins and river reaches	In 20 of 33 timed survey records, initial inundation and maximum flooding occurred within the same six-hour period; strong spatial variation in warning lead times (Secs. 4.3.1, 5.2; Fig. 10)	Sub-daily monitoring and forecasting, with upstream-triggered downstream warnings informed by flood-wave travel time
Reservoir storage and operations	Daily reservoir-storage information, rainfall observations, and meteorological forecasts	Days: storage margins evolved before and during the main rainfall period; operational decision times were not directly quantified	Some reservoir systems entered the critical rainfall period with limited available storage margins, reducing flexibility for additional flood buffering	Contrasting BI conditions and trajectories in Deduru Oya and Gal Oya (Sec. 5.3; Figs. 11–13)	Forecast-informed, basin-coordinated reservoir preparedness accounting for reservoir safety, downstream flood risk, and competing water-use objectives



Subsystem	Available anticipation	Response timescale	Observed bottleneck	Evidence	Proposed intervention
Warning escalation and dissemination	Basin-level minor- and major-flood warnings; minor-flood warnings generally provided several hours of advance notice	Hours: major-flood lead times ranged from zero or negative at some stations to approximately 48 h at downstream locations	Warning lead time contracted as flood severity escalated at several stations; warning issuance did not ensure timely community receipt or actionable guidance	Station-based lead-time analysis; 44 of 58 respondents reported either no warning or warning receipt after local impacts began (Secs. 4.3.2, 5.2; Fig. 10)	Forecast- and upstream-triggered warning escalation, multilingual localized messaging, and mechanisms to verify last-mile receipt
Institutional coordination and basin governance	Meteorological alerts, river and reservoir information, and established agency response mechanisms	Hours to days during the event, superimposed on longer-term institutional and governance arrangements	Reported delays and conflicting instructions; institutional separation between reservoir and river-management mandates may constrain basin-scale coordination	Thirty-four respondents reported delayed institutional responses and 15 reported conflicting instructions; Mahaweli River institutional arrangements illustrate separated reservoir and river-management responsibilities (Secs. 4.3.4, 6)	Pre-agreed decision authority, shared basin-scale information and governance mechanisms, and multi-agency simulation exercises
Community reception and protective action	Institutional warnings, media and social-media information, local observations, and previous hazard experience	Hours: short local response windows, frequently during nighttime or early morning; mobilization times were not directly measured	Warning non-receipt or late receipt, incomplete action guidance, and practical constraints involving safe refuge, transport, and assistance	Only 6 of 19 respondents assessing warning content reported clear action instructions; 8 reported no safe place to go and 6 lacked transport (Secs. 4.3.3–4.3.5)	Practiced evacuation plans, clearly identified safe refuges, transport arrangements, locally actionable warning instructions, and targeted support for vulnerable groups



7. Lessons learned: simulation-based preparedness as a path forward

830 Building on the whole-system timing limitations identified in Section 6, we propose simulation-based preparedness as a practical mechanism for strengthening coordinated flood response under uncertainty. Rather than testing forecasting, reservoir management, warning, and community response separately, such exercises should evaluate how these components interact when decisions must be made within compressed time windows.

835 Safety-critical sectors such as aviation, medicine, and nuclear emergency management routinely use simulation (e.g., flight simulator training) and scenario-based exercises to rehearse low-frequency, high-consequence situations before they occur in practice. Such exercises develop not only technical capability, but also coordination, timing, decision-making, and responses to uncertainty. Flood-risk management could adopt the same principle by complementing predictive capability with rehearsed operational competence.

840 Simulation-based preparedness should place decision makers within realistic, time-compressed scenarios that integrate atmospheric forecasting, hydrological translation, reservoir storage and operating constraints, institutional coordination, warning dissemination, and community response. The objective should extend beyond procedural compliance to stress-test the information-to-action chain by identifying where information is delayed or lost, whether decision authority becomes unclear, whether agencies develop conflicting interpretations of evolving risk, whether warning escalation becomes disconnected from rapidly changing hydrological conditions, and where communities lack sufficient time or practical capacity to respond. Such exercises can therefore reveal system-level performance limits before they are exposed during a real emergency.

845 For Sri Lanka, this would require periodic multi-agency flood-crisis exercises involving relevant meteorological, irrigation, reservoir-management, disaster-management, local-government, emergency-response, and community actors. Scenarios should reflect plausible high-impact conditions such as near-island cyclone development, widespread multi-basin rainfall, rapidly rising rivers, constrained reservoir storage margins, nighttime flooding, compound flood–landslide conditions, communication disruptions, and evacuation constraints. Exercises could incorporate explicit decision points such as forecast escalation, changes in reservoir operating readiness, downstream warning escalation, evacuation advisories, emergency-resource deployment, and public communication under uncertainty. Scenarios should also deliberately introduce incomplete forecasts, conflicting information, communication delays, and rapidly changing conditions so that the system is tested under uncertainty rather than under idealized conditions.

855 Repeated exercises can help test and refine operational triggers, clarify institutional responsibilities, evaluate data-sharing pathways, assess warning timing and language, identify evacuation constraints, and strengthen coordination between agencies and communities. They can also reveal whether actions that appear feasible in formal plans remain feasible when several basins, reservoirs, agencies, and exposed communities are simultaneously under stress. Importantly, such exercises can also expose practical constraints in data availability, technical capacity, institutional coordination, staffing, and sustained financing that may limit the implementation and maintenance of more advanced forecasting and warning systems. Over time, lessons from these exercises can be incorporated into operating procedures, training, and preparedness plans, helping transform post-



event learning into institutional practice. The objective is not to remove uncertainty, but to develop a system capable of acting coherently in the presence of uncertainty.

Strengthening anticipatory forecasting should therefore not be viewed simply as a matter of transferring more sophisticated models or technologies. Sustainable systems need to combine modern meteorological–hydrological forecasting with local hydrological knowledge, historical flood experience, operational expertise, and community understanding of how hazards develop and affect particular places. This requires co-development among national researchers, operational agencies, local authorities, and communities, supported where appropriate by international research and technical partners. Such collaboration should emphasise shared learning, capacity development, adaptable methods, and long-term institutional ownership, rather than one-way technology transfer. In this way, advances in forecasting can be matched to local data, resources, decision processes, and practical response capabilities.

Simulation-based stress testing therefore provides a practical pathway for converting post-event learning into preparedness. It allows scientists to examine how forecast uncertainty propagates into decisions, water managers to test reservoir responses under extreme scenarios, institutions to rehearse coordination and emergency authority, and communities to participate directly in preparedness. It can also provide a practical platform for bringing scientific forecasting, operational experience, and local knowledge together within the same decision environment. Repeated whole-system exercises can progressively strengthen the capacity to make coordinated decisions under the compressed timescales characteristic of extreme flood events.

8. A generalizable forensic framework for extreme events

Building on the forensic analysis developed in this study, we propose a generalizable framework for diagnosing performance limits across coupled flood-risk systems. Figure 14 presents seven interacting dimensions: (1) hazard evaluation and prediction; (2) precipitation forcing; (3) hydrological translation; (4) infrastructure operations; (5) warning generation and dissemination; (6) institutional coordination and emergency response; and (7) community reception and response. These dimensions are arranged as a connected sequence, but are interpreted as an interacting system in which feedback processes, delays, and constraints can propagate across subsystem boundaries.

The first four dimensions reconstruct how the physical hazard propagates through the system. Hazard evaluation and prediction characterize storm evolution and predictability; precipitation forcing describes the magnitude, duration, spatial extent, and temporal concentration of rainfall; hydrological translation evaluates how this forcing becomes runoff, discharge, inundation, and associated hazards; and infrastructure operations assess how reservoirs, drainage systems, and other control structures modify that response under existing storage and operational constraints. Together, these dimensions establish the physical and infrastructural timescales against which subsequent response processes can be evaluated.

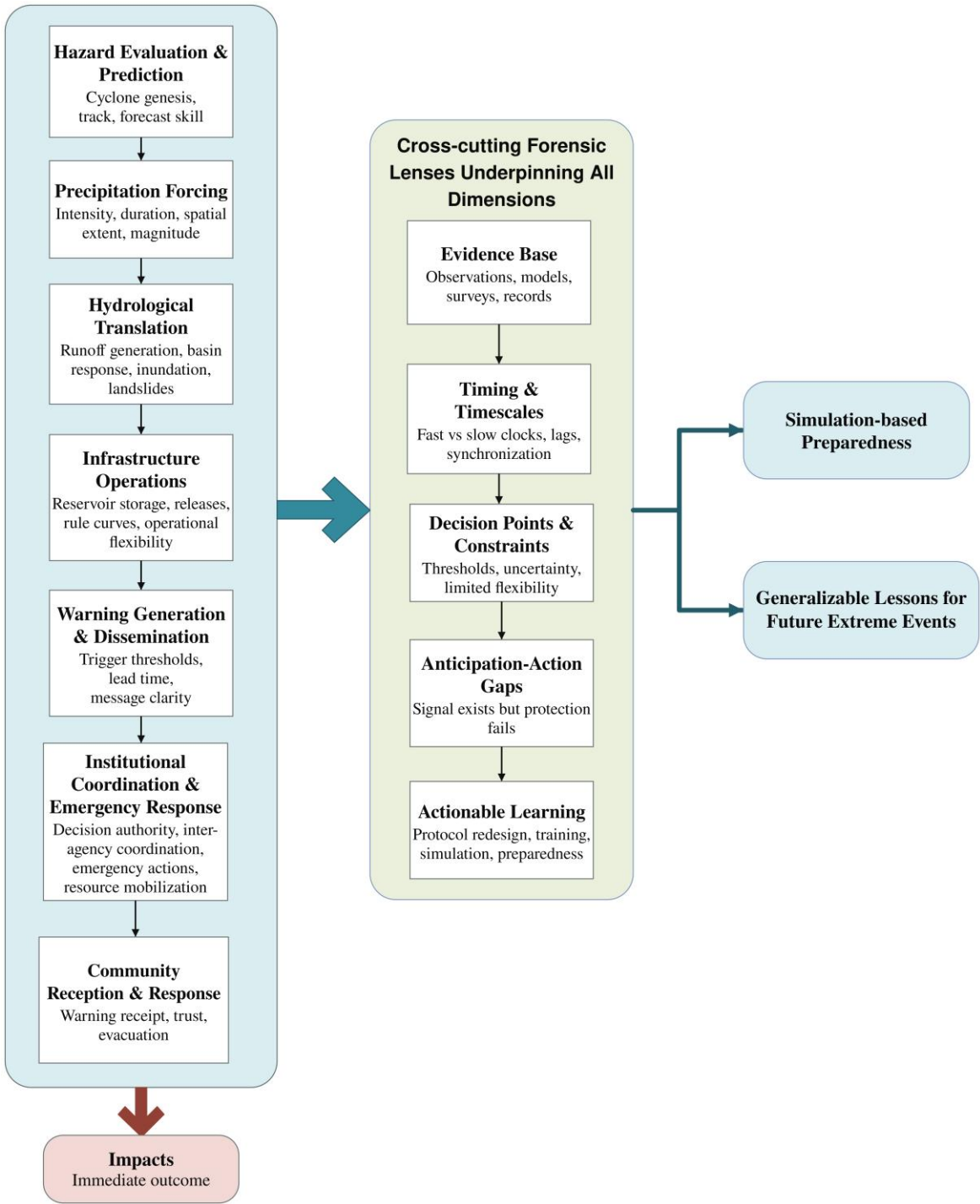
The remaining three dimensions examine how hazard information is converted into protective action. Warning generation and dissemination assess trigger thresholds, lead time, spatial specificity, message accessibility, and communication pathways. Institutional coordination and emergency response examine decision authority, inter-agency information exchange, resource



895 mobilization, and evacuation planning. Community reception and response then evaluate whether warnings were received and
actionable and whether people had the capacity to undertake protective action. The resulting impacts are treated as the
immediate outcome of the interactions among the physical, infrastructural, institutional, and community-response dimensions.
These dimensions trace the transition from hazard information to institutional and community action and, ultimately, to societal
impacts.

900 Across all seven dimensions, the framework applies five cross-cutting forensic lenses. First, the Evidence Base integrates
observations, models, institutional records, field information, and community surveys. Second, Timing and Timescales identify
where fast physical processes outpace slower operational, institutional, or social responses, and where lags or synchronization
alter system performance. Third, Decision Points and Constraints examine thresholds, uncertainty, and limitations in
operational flexibility. Fourth, Anticipation–Action Gaps identify situations in which hazard signals were available but did not
translate into timely protective action. Finally, Actionable Learning converts forensic diagnosis into targeted improvements in
905 preparedness and system operation.

The framework is intended to be transferable across extreme-event settings rather than tied to a particular hazard or location.
By tracing the pathway from hazard evolution through institutional and community response to societal impact, while applying
the same cross-cutting lenses at each stage, it provides a structured basis for identifying where performance limits emerge,
how they propagate across subsystem boundaries, and which interventions are most relevant. Its principal contribution is
910 therefore to shift post-event analysis from isolated sectoral assessment toward a consistent diagnosis of whole-system
performance under temporal stress.



915 **Figure 14: Generalizable forensic framework for diagnosing extreme-event performance limits across coupled physical, infrastructural, institutional, and social subsystems.**



9. Conclusions

TC Ditwah demonstrates that catastrophic flood impacts can arise not from a single failure, but from a timescale mismatch across an interconnected flood-risk system. Rapid cyclone development, concentrated rainfall, and fast hydrological response compressed the time available for forecast refinement, warning escalation, reservoir preparedness, institutional coordination, and community action. Although anticipatory information was available at several stages, its protective value diminished as the remaining response window narrowed, producing an anticipation–action gap.

The central lesson is therefore that improving prediction alone is insufficient. Effective protection requires forecasting, hydrological monitoring, reservoir management, warning dissemination, governance, and community response to operate on timescales compatible with the evolving hazard. Simulation-based, multi-agency preparedness offers a practical means of testing these interactions, clarifying decision authority, identifying bottlenecks, and strengthening coordinated action before future extreme events occur. The forensic framework developed here provides a transferable basis for diagnosing similar whole-system performance limits in other rapidly responding and data-constrained flood-risk settings.

Appendix A

Table A1: Coordinates of rainfall/streamflow stations for calibration and validation.

Basin	Rainfall station		Streamflow station	
	Name	Coordinates (lat, lon)	Name	Coordinates (lat, lon)
Attanagalu Oya Basin	Katunayake	7.17, 79.88	Dunamale	7.11, 80.08
	Pasyala	7.15, 80.13		
	Henarathgoda	7.1, 79.98		
	Chesterford	7.07, 80.18		
	Vincit	7.08, 80.22		
Kelani Basin	Dedigama	7.22, 80.25	Glencourse	6.98, 80.19
	Colombo	6.9, 79.87		
	Chesterford	7.07, 80.18		
	Canyon	6.88, 80.53		
	Campion	6.78, 80.7		
	Hanwella	6.88, 80.12		
	Udapolla	6.88, 80.33		
	Weweltalawa	7.05, 80.38		
Heda Oya Basin	Siyambalanduwa	6.91, 81.54	Siyambalanduwa	6.90, 81.54
Gin Ganga Basin	Baddegama	6.18, 80.18	Baddegama	6.17, 80.18
	Thawalama	6.34, 80.33		
Maha Oya Basin	Ambepussa	7.28, 80.17	Giriulla	7.33, 80.13
	Andigama	7.37, 80.12		
	Walpita	7.27, 80.05		



	Eraminigolla	7.3, 80.37		
	Narammala	7.42, 80.2		
	Polgahawela	7.32, 80.3		
Kalu Ganga Basin	Colombo	6.9, 79.87	Millakanda (kalawellawa)	6.63, 80.16
	Ratmalana	6.82, 79.89		
	Ratnapura	6.72, 80.36		
Maduru Oya Basin	Aralaganwila	7.8, 81.15	Padiyathalawa	7.39, 81.24
	Girandurukotte w/s	7.45, 81.08		
	Kudasigiriya	7.68, 81.13		
	Passikuda	7.93, 81.55		
Menik Ganga Basin	Buttala	6.76, 81.24	Buttala	6.79, 81.29

930

Table A2: Coordinates of rainfall stations used for the TC Ditwah event simulations.

Basin	Rainfall station (lat, lon)	
	Name	Coordinates
Attanagalu Oya Basin	Katunayake	7.17, 79.88
Kelani Basin	Castlereigh	6.87, 80.57
	Norton	6.91, 80.51
	Maussakelle	6.85, 80.55
	Canyon	6.88, 80.53
	Laxapana	6.9, 80.52
	Colombo	6.9, 79.87
	Katunayake	7.18, 79.88
Heda Oya Basin	Siyambalanduwa	6.91, 81.54
Gin Ganga Basin	Galle	6.029, 80.21
Maha Oya Basin	Katugastota	7.33, 80.63
	Katunayake	7.17, 79.88
	Kurunegala	7.47, 80.35
Kalu Ganga Basin	Ratmalana	6.82, 79.89
	Ratnapura	6.68, 80.4
	Norton	6.83, 80.6
	Kukuleganga	6.57, 80.32
Maduru Oya Basin	Batticaloa	7.72, 81.7
	Polonnaruwa	7.87, 81.05
	Inginiyagala	7.2, 81.52
Menik Ganga Basin	Monaragala	6.5, 81.3
Deduru Oya Basin	Moragaswewa	7.7, 79.99
	Giriulla	7.33, 80.13
	Peradeniya	7.27, 80.59
	Galgamuwa	7.97, 80.26



Appendix B

Table B1: Calibration and validation performance of the modelled river basins.

River basin	Calibration period	Calibration NSE	Validation period	Validation NSE
Attanagalu Oya River Basin	2016-05-01 to 2016-07-01	0.91	2010-04-15 to 2010-07-01	0.54
Kelani River Basin	2016-05-01 to 2016-06-01	0.90	2018-05-01 to 2018-06-01	0.84
Heda Oya River Basin	2014-12-13 to 2015-01-09	0.80	2024-11-09 to 2024-12-09	0.72
Gin Ganga Basin	2016-05-01 to 2016-06-01	0.70	2017-05-09 to 2017-06-09	0.93
Maha Oya Basin	2014-12-09 to 2015-01-09	0.81	2021-11-01 to 2021-12-01	0.71
Kalu Ganga Basin	2016-05-01 to 2016-06-01	0.87	2017-05-01 to 2017-06-01	0.80
Maduru Oya River Basin	2024-11-20 to 2024-11-29	0.60	2010-12-15 to 2011-02-08	0.58
Menik Ganga River Basin	2022-10-27 to 2022-11-09	0.81	2024-11-17 to 2024-11-29	0.50

Note: Deduru Oya is not included because observed streamflow data were unavailable for model calibration and validation;
935 parameters calibrated for the neighbouring Maha Oya basin were used for the TC Ditwah event simulation.

Calibration and validation performance for all eight calibrated river-basin models is summarised in Table B1; for conciseness,
the Attanagalu Oya River Basin is presented as a representative example of the model calibration, validation, and event
simulation results in Figures B1 and B2.

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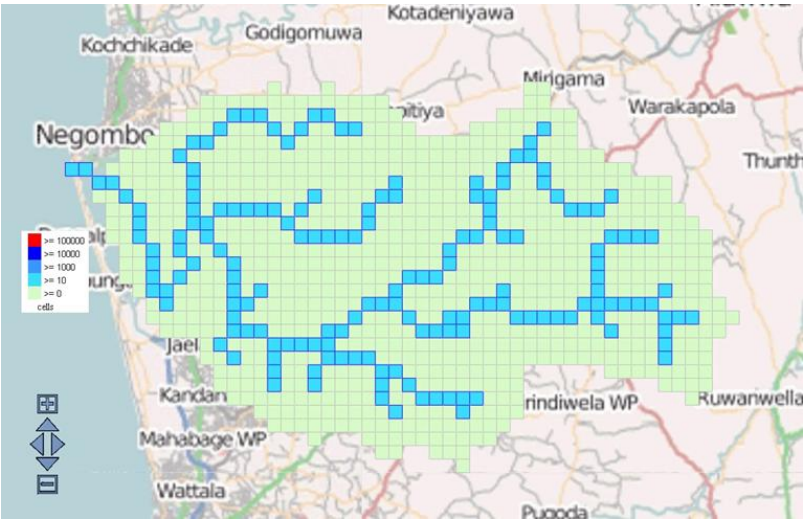
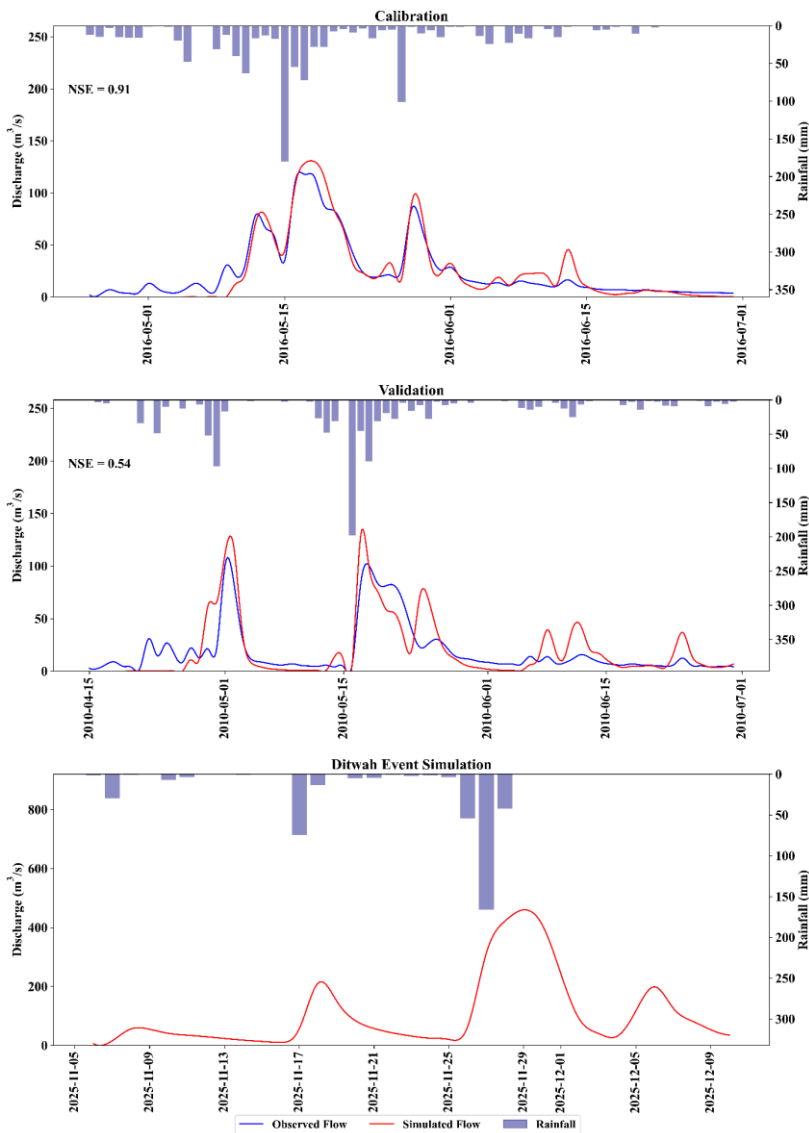


Figure B1: Attanagalu Oya River Basin and RRI model domain, shown over an OpenStreetMap (OSM) Standard basemap. Basemap © OpenStreetMap contributors.



945 **Figure B2: RRI model calibration, validation, and TC Ditwah event simulation for the Attanagalu Oya River Basin.**

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Data availability. The datasets used in this study were obtained from the relevant Sri Lankan government agencies and other sources cited in the manuscript. Several of the government datasets are third-party data provided under the access and redistribution conditions of the respective data providers and therefore cannot be redistributed publicly by the authors. Some of these datasets are available directly from the originating agencies, subject to their applicable access procedures and charges. Publicly available datasets used in the study are identified and cited in the manuscript.

Author contributions. CPe, MS, and LR contributed to conceptualization and methodology. CPe, SI, PJ, CPa, and NaW contributed to data curation. CPe, NP, PJ, RW, and CD performed the formal analysis. GB and LR were responsible for funding acquisition. CPe, NP, PJ, and RW conducted the investigation and contributed to software implementation. CPe was responsible for project administration. LR and MS provided resources. MS, GB, LR, and CPe contributed to supervision, while MS, GB, CPa, and SN contributed to validation. NP, PJ, RW, CD, CPa and NaW contributed to visualization. CPe, NP, PJ, and RW prepared the original draft. CPe, MS, GB, SN, CPa, SI, LR, LG, NiW, and KS reviewed and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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