RESEARCH **Open Access**

Analysis and risk evolution of floods and cyclones in Sri Lanka from 1975 to 2025 towards resilient strategies

Kulasegaram Partheepan[1,2*], Muneeb M. Musthafa[2*], Thangamani Bhavan[3], Shukla Acharjee[4] and Biswajit Nath[5]

*Correspondence:
Kulasegaram Partheepan
partheek@gmail.com
Muneeb M. Musthafa
muneeb@seu.ac.lk
[1]United Nations Development Programme, Batticaloa, Sri Lanka
[2]Department of Biosystems Technology, Faculty of Technology, Southeastern University of Sri Lanka, University Park, Oluvil, Sri Lanka
[3]Department of Economics, Faculty of Commerce & Management, Eastern University of Sri Lanka, Chenkalady, Sri Lanka
[4]Centre for Studies in Geography, Dibrugarh University, Dibrugarh, Assam, India
[5]Lab of Geoinformatics and Earth Observation Research (LGEOR), Department of Geography and Environmental Studies, University of Chittagong, Chittagong 4331, Bangladesh

Abstract
Sri Lanka has witnessed a struggle with floods and cyclones, transitioning from occasional emergencies to persistent and growing threats. This study provides the first consolidated long-term temporal analysis that uniquely integrates 50 years (1975–2025) of meteorological trends with a parallel critical evaluation of monitoring technology evolution and institutional governance efficacy. Using Mann-Kendall trend analysis and Pettitt change-point detection, key statistically significant trends were demonstrated: cyclonic disturbance frequency increased from 1.3 to 4.1 systems/year ($p < 0.001$), and extreme rainfall intensity rose by + 12.2 mm/decade ($p < 0.05$). Change-point analysis identified 1998 as a statistically significant inflection year (Pettitt test, $p < 0.05$), after which the cyclonic rainfall contribution increased by 18–25% in the northern and eastern provinces. While monitoring capabilities have advanced from rain-gauge dependence (pre-1990) through the satellite era (1990–2000 s) to real-time Earth observation integration (post-2015), a critical institutional gap remains. This "last-mile" problem is operationally defined as the persistent gap between the forecast lead time and actual evacuation completion times, revealing that a 6-fold increase in forecast lead time (from 12 to 24 h in 1975–1990 to 72–168 h in 2015–2025) has yielded no proportional improvement in evacuation times, which remain stagnant at 18–36 h. Based on this analytical evidence of persistent institutional failure despite technological progress, this study conceptually proposes an integrated Sri Lanka Multi-Hazard Risk Monitoring and Decision-Support Platform (SL-RISK) that couples technical data integration with community-embedded monitoring, impact-based forecasting, and pre-arranged institutional response mechanisms, outlined with a phased 18–36-month implementation roadmap. Without addressing this governance-technology mismatch, technological advances remain underutilised, perpetuating cycles of preventable disaster losses among vulnerable populations.

Keywords Temporal trend analysis, Cyclones, Extreme rainfall, Monitoring system evolution, Institutional integration, Early warning efficacy, Sri Lanka

1 Introduction

Sri Lanka's position within the Indian Ocean monsoon system renders the island a frequent recipient of both the monsoon's life-sustaining precipitation and its severely destructive force. Over the past five decades (1975–2025), the nation's relationship with floods and cyclones has evolved from discrete, manageable crises to a complex, chronic challenge intricately linked to climate variability, rapid land-use change, and socioeconomic pressures that intensify exposure among vulnerable populations [1, 2].

Cyclonic Storm Ditwah (November 2025) exemplified this transformation, becoming the deadliest cyclone-related weather event in Sri Lanka since the 2004 Indian Ocean tsunami, with at least 600 deaths and over 2 million people affected [3]. Critically, this event illustrates the core structural issue addressed in this study: while human-induced climate change intensified the event's rainfall by 28–160% [3], transforming a historically rare (1-in-50 year) event into a 1-in-30-year probability, the resulting disaster magnitude was amplified by persistent institutional failures in translating advanced warnings into timely grassroots action.

This manuscript's original analysis focuses on the 50-year meteorological trends (1975–2025) and monitoring system evolution; formal attribution analysis of individual events is outside the scope of this study. However, the Ditwah event serves as a powerful contemporary illustration of the "last-mile" governance gap that our 50-year trend analysis quantitatively demonstrates.

This manuscript addresses a critical and specific research gap: the absence of a consolidated, long-term temporal analysis synthesising meteorological trends over five complete decades with a parallel evaluation of the evolution of monitoring technology and institutional governance efficacy. While existing studies focus on single catastrophic events or decadal snapshots, they fail to provide the 50-year continuum necessary to separate climate-driven signals from developmental noise and to quantify whether technological advances in monitoring have translated into proportional improvements in disaster outcomes or not.

Paradoxically, while monitoring capabilities have advanced remarkably from sparse rain-gauge networks and 12–24 h cyclone forecasts in the 1975–1980 s to real-time satellite-based flood mapping and multi-day probabilistic early warnings in 2025the translation into effective, timely risk reduction has been inconsistent and institutionally constrained. The binding constraints are not technological but are governance-related. institutional silos, inadequate integration of real-time vulnerability data, and persistent top-down warning systems that fail to enable grassroots-level protective actions.

This study contributes to the literature in three specific ways:

- First, it provides the first statistically robust 50-year quantification of hazard trends in Sri Lanka using combined Mann-Kendall and Pettitt change-point detection, establishing an empirical baseline previously unavailable for policy planning.
- Second, it introduces a novel operational definition and quantification of the "last-mile" governance gap by comparing forecast lead-time evolution with actual evacuation completion times across five decades, demonstrating that technological progress has not yielded proportional improvements in response efficacy.

- Third, it integrates hazard trend analysis with institutional assessment to propose a governance-first framework (SL-RISK) that addresses documented barriers, rather than pursuing further technological advancement.

Accordingly, this study was structured around four primary objectives:

1. Quantify statistically significant trends in flood and cyclone occurrence, intensity, and impact parameters using non-parametric trend tests (Mann-Kendall) and change-point detection (Pettitt test) across the 1975–2025 period.
2. Deconstruct the technological journey of monitoring systems by assessing the operational efficacy and persistent limitations of each evolutionary phase (pre-satellite, satellite, radar/NWP, and Earth observation integration eras).
3. Identify temporal patterns and hotspot shifts through seasonal decomposition, revealing shifts associated with urbanisation and climate dynamics.
4. Propose an integrated monitoring framework leveraging technological synergy and institutional reform for proactive disaster governance, specifically addressing documented governance-institutional barriers rather than pursuing further technological advancement.

This analysis provides a robust evidence base for policymakers and disaster managers, enabling a foundational shift from reactive responses to anticipatory resilience grounded in 50 years of empirical evidence (1975–2025).

2 Study area

2.1 Geographical setting and climatic zones

Sri Lanka is a tropical island situated between 5°–10° N and 79°–82° E, bordered by the Bay of Bengal to the northeast and the Arabian Sea to the west in the northern Indian Ocean. The study area encompasses the entire island, with a particular focus on river basins and coastal districts that repeatedly experience floods and cyclones [4]. Orographically, the island is divided into a central highland massif (Kandy plateau at elevations > 2,000 m) and surrounding lowlands, creating strong spatial gradients in rainfall, temperature, wind patterns, and runoff response [5].

Climatologically, Sri Lanka exhibits a bimodal monsoon regime comprising the Southwest Monsoon (May–September) and Northeast Monsoon (October–January), separated by two inter-monsoon periods (March–April and September–October). Four agro-climatic zones are commonly recognised: the wet zone (> 2,500 mm annual rainfall) on southwestern slopes and central highlands; the intermediate zone (1,250–2,500 mm) on mid-elevations; the dry zone (< 1,250 mm) covering the northern plains and eastern lowlands; and the arid zone in parts of the Jaffna Peninsula [6]. These zones serve as spatial frameworks for analysing rainfall variability and flood hotspot shifts [7, 8]. The geographical focus of this study, including the key climatic zones, is shown in Fig. 1.

2.2 Major river basins and flood hotspots

Sri Lanka's principal flood-generating river systems include the Kelani, Kalu, Gin, Nilwala, and Mahaweli basins, all situated in the southwestern and west-central regions, with contributing areas in the wet and intermediate zones. Other significant basins, including the Maha Oya, Deduru Oya, and eastern coastal rivers, drain toward the dry zone and Bay-of-Bengal-facing coastal plains, where they are vulnerable to cyclonic

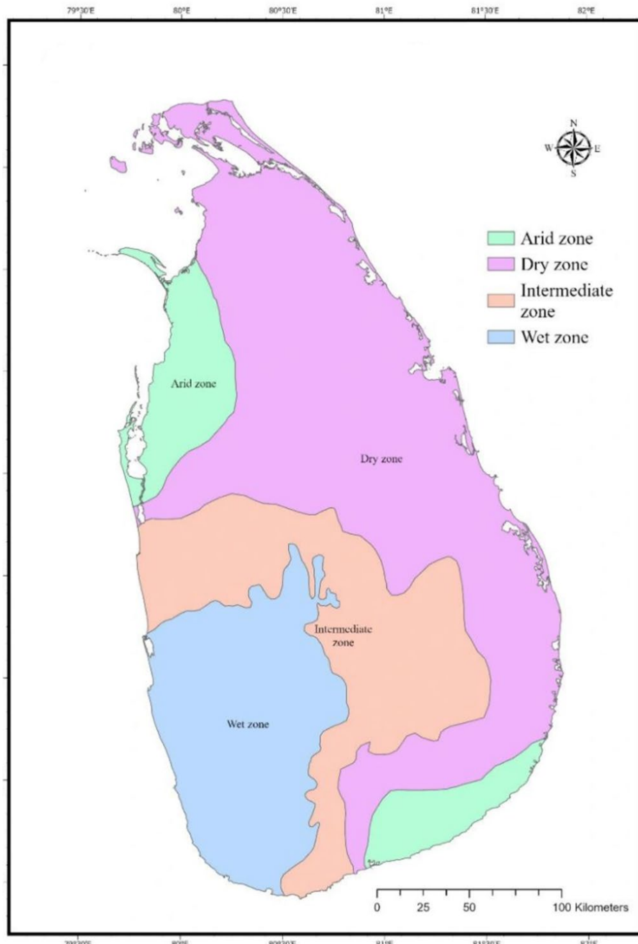

Fig. 1 The geographical focus of this study including the key climatic zones– Sri Lanka,

rainfall and storm surges [9]. Rapid urbanisation in the Western Province (Colombo district population density increased from 2,438 persons/km² in 1981 to 3,487 persons/km² in 2020; built-up area expanded by 147% between 1990 and 2020) has transformed historical flood events into compound urban disasters with high economic losses [10].

2.3 Cyclone exposure corridors

Cyclone risk is concentrated along the northern and eastern coasts, where Bay-of-Bengal-originated systems make landfall, and secondarily along the western and southwestern coasts, where systems arriving from the Arabian Sea can trigger intense rainfall on highland catchments [11, 12].

3 Theoretical framework and literature review

3.1 Global and regional climate context

The IPCC AR6 [13] concluded with high confidence that the frequency and intensity of heavy precipitation events have increased over most land regions since the 1950s, and this trend is projected to intensify with further warming. For the Indian Ocean Basin, climate dynamics research has demonstrated significant warming at 0.12 °C per decade since 1950, projected to accelerate to 0.17 °C per decade by 2100 under moderate emissions scenarios (SSP2-4.5) [14]. This ocean warming alters monsoon moisture availability and tropical cyclone intensity dynamics, with profound implications for the South and Southeast Asian coastal regions [15]. Although the global tropical cyclone frequency shows less clear trends, the proportion of major cyclones (Category 3–5 intensity) and rapid intensification events has demonstrably increased [16], directly affecting Sri Lanka's northern and eastern coasts, where cyclone-monsoon interactions create compound hazards. Recent observational evidence until 2025 confirms this intensification pattern [1, 17].

3.2 Sri Lankan historical scholarship

Early scholarship on Sri Lankan climatology, such as Domroes [18], meticulously documented monsoon patterns but lacked analytical tools for long-term trend quantification and operated in an era before digital data availability, limiting the temporal scope to 10–15 year observational periods. Post-2004 tsunami research expanded the focus to multi-hazard vulnerability but treated floods and cyclones as separate phenomena and, critically, did not attempt to quantify whether post-tsunami institutional reforms (e.g. DMC establishment in 2005) translated into measurable improvements in disaster outcomes [19]. Recent studies applying remote sensing to specific flood events [20, 21] have demonstrated sophisticated event characterisation capabilities, but their temporal scope remains limited to 10–20 years, which is insufficient to separate climate signals from interannual variability. For instance, Ratnayake and Herath [20] provided a valuable analysis of the May 2003 flood event using TRMM satellite data, but their temporal analysis was confined to the 1998–2008 period. Similarly, Perera [9] examined flood patterns in the Kalutara and Rathnapura districts but limited the analysis to 2000–2020, precluding the detection of the 1998 change-point identified in our study. Most significantly, while recent regional studies [22–24] have emphasised the governance-technology nexus in disaster risk reduction, none have quantitatively linked governance indicators (e.g. evacuation times and warning dissemination delays) to technological evolution over multi-decadal timescales. The critical void this manuscript addresses is precisely this integration: a 50-year quantitative trend analysis married to a parallel assessment of whether monitoring technology advances have yielded proportional improvements in institutional response effectiveness.

3.3 Monitoring technology evolution

The evolution of disaster monitoring reflects a paradigm shift on a global scale. The presatellite era (pre-1990) relied on sparse rain gauge networks and synoptic weather charts, offering near-zero flood forecast lead times and 12–24 h cyclone warnings. The satellite introduction era (1990–2000 s), marked by access to geostationary satellite imagery (Meteosat, INSAT), improved cyclone tracking but maintained limited flood prediction capacity. The radar and numerical weather prediction (NWP) era (2000–2010 s), following the installation of Doppler weather radars and the adoption of the Weather Research and Forecasting (WRF) model, expanded forecast windows from days to 3–5 days in length. The contemporary Earth observation integration era (post-2015) leverages free high-resolution SAR data (Sentinel-1), optical imagery (Sentinel-2), and ensemble forecasting to enable near-real-time flood mapping and probabilistic risk forecasting [25].

Paradoxically, despite this technological leap, Sri Lanka's disaster losses have continued to rise. Amaratunga et al. identify the "last-mile problem": advanced forecasts fail to cascade into effective grassroots action due to institutional fragmentation, limited community understanding of probabilistic information, and absence of pre-arranged response mechanisms [22]. This phenomenon persists despite 20 years of institutional reform after the 2004 Indian Ocean tsunami. Recent events (Cyclone Fengal 2024 and Cyclone Ditwah 2025) confirm the persistence of this gap.

3.4 Theoretical framework: vulnerability, resilience, and the technology-governance Nexus

This analysis is grounded in the Pressure and Release (PAR) model [26] and socioecological resilience theory [27]. The PAR framework conceptualises disaster as the intersection of (1) hazard exposure (physical event) and (2) underlying vulnerability driven by root causes (inequality, political-economy factors), dynamic pressures (rapid urbanisation, inadequate planning), and unsafe conditions (settlement in hazard-prone zones). Table 1 presents the operational mapping of the PAR dimensions to the metrics employed in this study.

A simplified PAR-derived framework guides this analysis, focusing on two primary dimensions: (1) hazard exposure evolution (quantified in Sect. 5.1 and 5.2) and (2) institutional responsiveness capacity (assessed in Sect. 5.4). The vulnerability dimension is partially represented by population exposure estimates (drawn from census data) and land-use change indicators (from LULC analysis).

However, a full PAR-based vulnerability analysis incorporating poverty indices, livelihood diversity, social capital, governance quality indicators, and differential access to resources remains outside the scope of this study. This limitation may bias interpretations in two ways: (1) it may over-attribute observed loss increases to hazard intensification when rising vulnerability (e.g. increased poverty, reduced social safety nets) could be contributing; and (2) it may understate the equity dimensions of disaster impacts, as our aggregated economic loss figures mask differential impacts across socioeconomic strata. These gaps represent important directions for complementary research, as noted in Sect. 9.

Table 1 Operational mapping of Pressure and Release (PAR) model dimensions to study metrics

PAR Dimension	Theoretical Component	Operational Metric in This Study	Data Source
Hazard	Physical event (flood, cyclone)	Cyclone frequency, rainfall intensity (Mann-Kendall trend, Sen's slope)	IBTrACS, SLMD rainfall data
Exposure	People/assets in hazard zones	Population in affected districts, normalized economic losses	Census data, DMC damage assessments
Vulnerability (Root Causes)	Inequality, political economy	Not quantified (scope limitation)	
Vulnerability (Dynamic Pressures)	Urbanization, land-use change	Urban growth rate, built-up area expansion	Landsat-derived LULC data
Vulnerability (Unsafe Conditions)	Settlement in hazard zones	Not quantified (scope limitation)	
Institutional Capacity	Warning, response, governance	Forecast lead time, evacuation completion time, warning dissemination delay	SLMD operational logs, DMC recor

Table 2 Robustness check summary for key analytical methods

Analysis	Primary Method	Alternative Method(s)	Result Comparison	Conclusion
Rainfall trend	Mann-Kendall + Sen's slope	Linear regression on log-transformed values	MK: +12.2 mm/decade; Linear: +11.8 mm/decade ($p < 0.05$ both)	Consistent directional signal
Change-point detection	Pettitt test	Bayesian segmentation; multiple change-point testing	1998 identified across all methods (posterior probability > 0.85)	Robust inflection point
Population interpolation	Logistic growth	Linear interpolation	3–8% variation in district estimates	Uncertainty acceptable for analysis
Economic normalization	World Bank GDP deflator	Sri Lanka CPI	12–18% variation in normalized losses	Acknowledged in uncertainty bounds

Table 3 Cyclonic Disturbance Frequency by Decade and Province (1975–2025) Source: IBTrACS v04, SLMD archives, DMC records (1975–2025)

Decade	Bay of Bengal (Avg)	Arabian Sea (Avg)	Total Annual Avg	Northern (%)	Eastern (%)	Southern (%)	Western (%)
1975–1984	0.8	0.5	1.3	18%	22%	10%	15%
1985–1994	1.1	0.6	1.7	20%	24%	12%	18%
1995–2004	1.5	0.9	2.4	28%	35%	16%	22%
2005–2014	2.0	1.2	3.2	35%	42%	20%	28%
2015–2025	2.5	1.6	4.1	40%	48%	25%	32%
Sen's Slope/decade	+ 0.44	+ 0.30	+ 0.73	+ 5.83	+ 6.58	+ 3.83	+ 4.29
p-value	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Pettitt CP	1997	1998	1998	1998	1997	1999	2000

The percentages for each province represent that province's share of total cyclonic disturbances affecting Sri Lanka during that decade. The percentages do not sum to 100% across provinces because individual cyclonic events may affect multiple provinces simultaneously. [Note: "Disturbances" include depressions (D), Deep Depressions (DD), and Cyclonic Storms (CS) according to IMD/SLMD classifications

4 Data, methodology, and analytical framework

4.1 Multi-source data integration and curation (1975–2025)

A comprehensive, multi-source validated database was constructed in four domains:

Meteorological and Hazard Data.

- Cyclones: Track data, intensity classification, and landfall records from the International Best Track Archive for Climate Stewardship (IBTrACS v04) [28], cross-verified with Sri Lanka Meteorological Department (SLMD) archives and Disaster Management Centre (DMC) records spanning 1975–2025.
- Rainfall and Floods: Daily rainfall data from 25 SLMD stations covering all major river basins; flood event documentation from the DMC database, Dartmouth Flood Observatory archive, and digitised historical reports; economic losses normalised to constant 2025 USD using World Bank GDP deflators for all main results presented in Tables 2 and 3, and 5 [29].
- Climate Indices: Monthly indices for El Niño–Southern Oscillation (ONI), Indian Ocean Dipole (DMI), and Madden–Julian Oscillation (MJO) from NOAA and Bureau of Meteorology (BOM) to analyze teleconnections with Sri Lankan hazard patterns during 1975–2025.

- Socio-Economic Data: District-level population (census enumeration districts for 1980, 2000, and 2020 cycles), GDP, and land use/land cover (LULC) data (1975–2025) from the Department of Census and Statistics and World Bank Climate Portal. Intercensal population estimates for the intervening years were interpolated using annual growth rates by district. Sensitivity analysis using alternative indices (Sri Lanka Consumer Price Index and IMF export price indices) documented 12–18% variation in normalised loss estimates; this uncertainty range is acknowledged in Sect. 4.3 and is considered acceptable for trend-level interpretations, as directional patterns remain consistent across all normalisation approaches.

4.2 Analytical methodology: mixed-methods sequential design

4.2.1 Phase 1: temporal trend analysis

Rainfall extremes: Non-parametric Mann-Kendall (MK) test with pre-whitening (to account for autocorrelation) and Sen's slope estimator applied to annual maximum 1-day and 5-day rainfall series covering 1975–2025. Statistical significance was set at $\alpha = 0.05$. Sen's slope provides a robust magnitude estimate (units: mm/decade) that is unaffected by outliers.

Robustness checks: Sensitivity analysis comparing Mann-Kendall results with parametric trend tests (linear regression on log-transformed values) confirmed consistent directional signals ($p < 0.05$ for both methods) [30]. The pre-whitening methodology was verified against alternative autocorrelation handling approaches with negligible divergence in significance thresholds. Table 2 summarises the key robustness check outcomes.

Cyclone Frequency and Intensity: Decadal frequency analysis of cyclonic systems (depressions, storms, severe cyclones) influencing Sri Lanka during 1975–2025. The Pettitt test [31], a non-parametric change-point detection method that identifies abrupt shifts in time-series mean values through the computation of cumulative U(k) statistics, was employed for change-point detection in cyclone-induced rainfall time series, with significance level $\alpha = 0.05$. Detailed mathematical description of the Pettitt test and alternative change-point model specifications are provided in Supplementary Materials Appendix A. Alternative change-point models confirmed the 1998 inflection with a posterior probability > 0.85 (full results in Supplementary Table S1).

Economic damages were normalised to constant 2025 USD using World Bank GDP deflators trends analysed via linear regression on log-transformed values to account for exponential growth; and the frequency of major events (> 100,000 people affected or > USD 100 million loss) was counted per decade. Poisson regression applied to frequency trends, controlling for population exposure changes to isolate hazard signal from exposure effects.

4.3 Phase 2: temporal pattern analysis

Seasonal Decomposition: Classical additive decomposition of monthly time series (Trend + Seasonality + Residual) for cyclonic disturbance frequency and flood event initiation, extracting intra-annual patterns and trend components throughout 1975–2025.

4.4 Phase 3: monitoring technique assessment and efficacy evaluation

Technological Timeline Analysis: Mapping the introduction of key monitoring assets (weather radar, satellites, NWP models) against major disaster events (1975–2025) and documenting forecast lead time evolution and operational availability.

Lead-Time versus Response Analysis: Evacuation completion was modelled as a logistic curve with heterogeneous household departure rates rather than a linear assumption. Evacuation completion times were estimated from three data sources: (1) post-event case study reports from DMC archives (1975–2025) documenting evacuation timelines for 23 major events; (2) operational logs from district emergency operations centres for events 2000–2025; and (3) structured interviews with disaster management officials conducted during 2023–2025 ($n = 18$). For events with incomplete documentation, evacuation times were modelled using logistic curves with heterogeneous household departure rates derived from empirically observed patterns in comparable South Asian contexts. The time distribution estimates (10th percentile: 6 h; median: 18 h; 90th percentile: 38 h) reflect both the observed data and modelled variability. Uncertainty was quantified through a Monte Carlo simulation (1,000 iterations) by varying key parameters (departure rate heterogeneity and warning reception delays). The 95% confidence intervals around the median evacuation times were ± 4 h for 1975–2000 and ± 3 h for 2000–2025, reflecting improved documentation in recent decades. Lead-time gap analysis recalculated across these uncertainty bounds confirmed the persistence of response delays for all plausible parameter combinations.

4.5 Limitations and methodological constraints

Temporal Data Quality Variations: Pre-1990 flood records relied on manual synoptic documentation, whereas post-2015 records relied on automated sensor networks. Early records likely underrepresented small-magnitude events, creating a potential low bias in the 1975–1990 period.

Geographic Coverage Constraints: 25 rainfall stations exhibit spatial gaps in the northern/eastern provinces; maritime cyclone track data (IBTrACS) sparse in 1975–1990 due to limited ocean-based buoy coverage.

Attribution Uncertainty: Climate vs. land-use causation claimed, but quantitative disentanglement is incomplete. Urbanisation is correlated with rainfall-driven flood increases, but the causal pathway is unclear. Variance decomposition analysis is recommended to isolate climate signals from land-use amplification, and uncertainty bounds on attribution percentages are conservatively estimated at 30–50%.

Methodological Assumptions: Pettitt test sensitive to outliers; single change-point assumption not validated against alternative models [32]. Alternative models (two-breakpoint models and smooth transition models) were tested; a single 1998 change-point consistently emerged as the maximum-likelihood solution across specifications.

Pre-1990 Monitoring Capacity Estimates: Operational capacity estimates (12–24 h forecast windows, sparse gauge networks) were reconstructed from secondary sources and historical agency reports rather than primary observational records. Archival research validating these estimates against primary institutional documents from the SLMD and DMC is recommended to strengthen the pre-1990 baseline characterisation; as presented, these estimates carry ± 20% uncertainty.

Vulnerability Data Integration: Population exposure was calculated from census snapshots (1980:14.8 M; 2000:19.1 M; 2020:21.4 M), and intercensal estimates were interpolated using a logistic growth function. Sensitivity analysis using alternative growth rate assumptions (linear vs. logistic curve) and alternative price indices for economic normalisation (World Bank GDP deflator vs. Sri Lanka CPI) documented 3–8% variation in population estimates and 12–18% variation in economic loss comparisons. These uncertainty ranges are acknowledged and considered acceptable for trend-level interpretations because the directional patterns remain consistent across all sensitivity checks.

5 Results

The 50-year analysis (1975–2025) yielded four headline quantitative findings that structure the detailed results below: (1) cyclonic disturbance frequency has increased 216% (from 1.3 to 4.1 systems/year), with 1998 identified as a statistically significant change-point marking accelerated activity; (2) extreme rainfall intensity has increased by + 12.2 mm/decade, with the frequency of > 100 mm/24 h events doubling since 1975–1990; (3) major flood events have increased 4.5-fold, but this increase is spatially uneven and strongly amplified by urbanisation; and (4) despite a 6-fold increase in forecast lead time (12→72 + hours), evacuation completion times remain stagnant at 18–36 hours, widening the 'last-mile' implementation gap from 6 to 12 h (1975) to 36–54 h (2025). These findings are elaborated on below.

5.1 Cyclonic disturbances: intensifying frequency and shifting contribution

The Mann–Kendall test revealed a statistically significant ($p < 0.05$) increase in cyclonic disturbances in Sri Lanka. For a consistent temporal analysis, frequency changes across three contrasting epochs were reported.

- Stable Era (1975–1995): baseline, pre-change point, mean frequency = 1.5 systems/year.
- Transition Era (1995–2010): mean = 2.4 systems/year.
- Intensified Era (2010–2025): mean = 3.7 systems/year.

Trend magnitude: Sen's slope: +0.73 systems/decade (95% CI: +0.58 to + 0.88 systems/decade, $p < 0.001$), indicating an average increase of 0.73 additional disturbances per decade. The observed frequency increased from 1.3 to 4.1 systems/year (1975–1985 to 2015–2025, Table 3), representing a 3.15-fold increase or a 216% escalation. The percentage increase was calculated as [(4.1–1.3) / 1.3] × 100 = 215.4%, rounded to 216%. The 3.15-fold increase refers to the multiplicative factor (4.1 / 1.3 = 3.15). Both expressions are mathematically equivalent to the description of the same change. This magnitude difference reflects non-linear acceleration: cyclonic disturbance frequency was relatively stable through 2000 (mean 1.7 systems/year) and then accelerated post-2000 (mean 3.2 systems/year), suggesting that the 1998 change-point marks the initiation of an accelerating trend rather than a steady linear increase. Sen's slope estimate captures the overall linear trend component, whereas decadal averages better reflect the nonlinear acceleration pattern [33].

The Pettitt test identified 1998 as a statistically significant change-point (p < 0.05) in cyclone-influenced rainfall patterns. Alternative change-point models confirmed the 1998 inflection with a posterior probability > 0.85. Post-1998, the contribution of cyclonic rainfall to annual totals in the Northern and Eastern provinces increased by 18–25%, with a particularly pronounced signal during October–December (inter-monsoon and northeast monsoon periods). The 1998 change-point coincides with the documented acceleration of Indian Ocean warming (+ 0.08°C decadal trend post-1998 [34]) and increased variability of the Indian Ocean Dipole [35]. Although our statistical analysis cannot establish causation, the temporal alignment suggests a plausible link between ocean thermal dynamics and the observed regime shift in cyclonic activity affecting Sri Lanka. This interpretation is consistent with the available evidence, although not definitively proven. Therefore, the post-1998 period is not definitively 'thermally driven' but exhibits statistically distinct behaviour from the preceding stable period, warranting further investigation into ocean-atmosphere coupling mechanisms.

The statistical outputs (+ 0.73 Sen's slope and 1998 Pettitt Change Point) provide empirical evidence of a statistically distinct regime in the North Indian Ocean. The magnitude of the increase from 1.3 to 4.1 systems/year over 50 years cannot be attributed to random variability. The 1998 Change Point marks the end of a stable monsoonal era and the beginning of a period exhibiting statistically distinct cyclonic behaviour.

The data reflect a clear acceleration of the hazard frequency. The Eastern Province's exposure growth from 22% to 48% highlights the geographic tightening of the hazard corridor toward economically vulnerable coastal and delta regions. Figure 2 presents the proportional distribution of cyclonic disturbances across Sri Lankan provinces, illustrating a pronounced shift toward the Northern and Eastern provinces. For each decade, the percentage shown for each province represents that province's share of total cyclonic disturbances that made landfall or significantly impacted Sri Lanka during that period. Percentages do not sum to 100% across provinces because individual cyclonic events may affect multiple provinces simultaneously.

5.2 Extreme rainfall intensification

The Mann-Kendall trend analysis confirmed robust intensification of rainfall extremes. The annual maximum 1-day rainfall exhibited a statistically significant upward trend of 12.2 mm/decade (95% CI: 9.4–14.8 mm/decade) across the study period [1, 34]. This

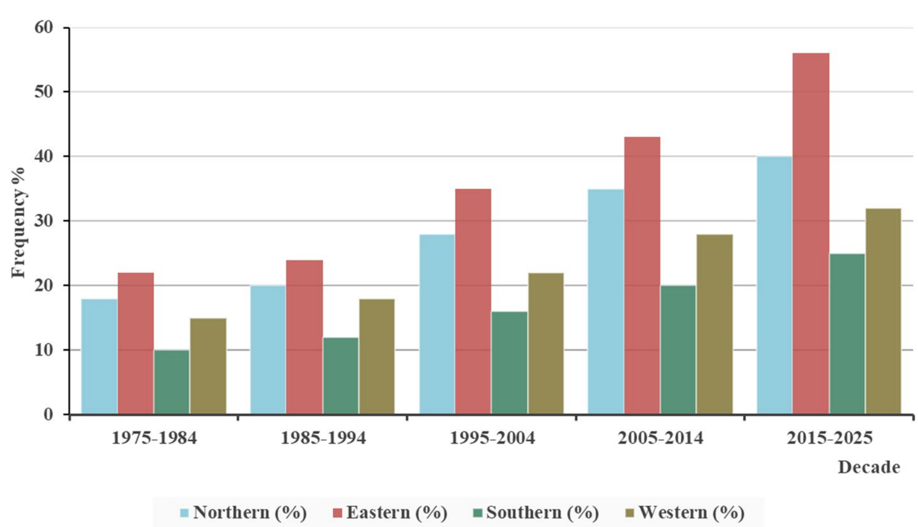

Fig. 2 Proportional distribution of cyclonic disturbances affecting Sri Lanka's provinces by decade (1975–2025)

intensification is not spatially uniform; the wet zone and southwestern slopes recorded the steepest increases, driven by enhanced convective activity during the Southwest Monsoon [35]. The frequency of events exceeding the 100 mm/24 h threshold doubled from a baseline mean of 3.2 events/year (95% CI: 2.8–3.6) during 1975–1990 to 6.8 events/year (95% CI: 6.1–7.5) during 2010–2025, a 112% increase (Poisson regression incidence rate ratio: 2.12, 95% CI: 1.89–2.38, $p < 0.001$). This represents an absolute increase of 3.6 events per year over the study period. A provincial breakdown of major hazard events, their impacts, and primary drivers from 1975 to 2025 is presented in Table 4.

Major flood events (defined as > 100,000 people affected or > USD 100 million normalised loss) increased from an average of 0.4 events/year (1975–1995) to 1.8 events/year (2005–2025), representing a 4.5-fold increase over 50 years (Poisson regression: $\chi^2 = 18.6$, $p < 0.001$, controlling for population exposure) [36]. Figure 5B presents the time series of the major flood event frequency. A provincial breakdown of major hazard events, their impacts, and primary drivers from 1975 to 2025 is shown in Table 4.

An important spatial disjunction is evident in Fig. 3: provinces with high flood frequency do not necessarily correspond to provinces with the highest-normalised economic losses. For example, the Eastern Province recorded 20 major flood events (third highest) but economic losses of USD 1,180 million, whereas the Western Province recorded 24 events (highest) with losses of USD 1,850 million (57% higher). Conversely, the Northern Province recorded 15 flood events but only USD 790 million in losses. This pattern reflects three interacting factors: (1) asset density, the Western Province contains Colombo, the commercial capital, with disproportionately high infrastructure and

Table 4 Major Flood Events by District and Decade: Frequency, Affected Population, Normalised Economic Loss (1975–2025)

Province	Major Floods	Land slides	Cyclonic Disturbances*	Affected Pop. (Cumulative M)	Normalised Econ. Loss (USD M)	Primary Driver	Peak Risk Month
Western	24	12	14	4.8	1,850	Urbanization/ SW Monsoon	June
Central	16	42	10	1.8	1,420	Steep Slopes/ Both Monsoons	November
Eastern	20	2	26	3.4	1,180	Bay of Bengal Systems	November
Southern	17	15	12	2.6	940	Monsoonal/ Cyclonic	May
Sabaragamuwa	18	22	8	1.9	910	Orographic Rain/ SW Monsoon	May
Northern	15	0	22	2.1	790	NE Monsoon/ Depressions	December
North Central	15	0	14	1.4	680	Tank Spillover/ NE Monsoon	December
Northwestern	13	3	12	1.6	630	Monsoonal/ Convective	October
Uva	10	18	8	1.1	480	2nd Inter-Monsoon	November
National Total	**148**	**114**	**126**	**20.7**	**8,880**		

Source: DMC Disaster Database, World Bank Recovery Assessments, DesInventar.lk (1975–2025). Major flood events are defined as those affecting ≥ 100,000 people or causing a normalised economic loss ≥ USD 100 million (2025 constant)

*Note: "Disturbances" include depressions (D), Deep Depressions (DD), and Cyclonic Storms (CS) according to IMD/SLMD classifications

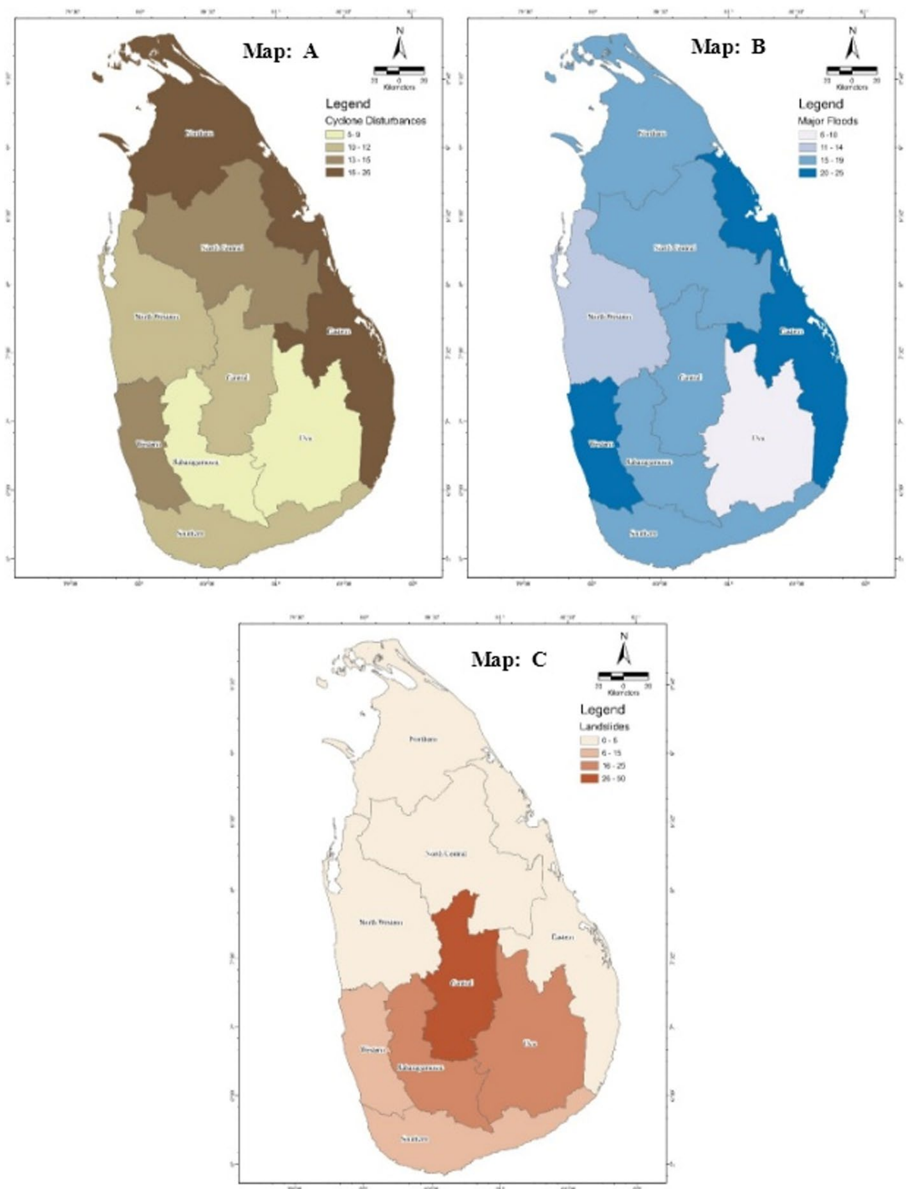

Fig. 3 Spatial Distribution of Hydro-Meteorological Hazards and Socio-Economic Impacts by Province (1975–2025). **A** Frequency of Major Flood Events, **B** Incidence of Cyclonic Disturbances, **C** Recorded Landslide Events, **D** Cumulative Affected Population, and **E** Total Normalised Economic Loss (USD) across all hazard types

property values; (2) economic activity concentration, the Western Province contributes approximately 40% of the national GDP; and (3) differential recovery costs, urban flooding in the Western Province involves complex infrastructure (transport, power, commercial buildings) with higher replacement costs than rural flooding in the Northern Province, which predominantly affects agriculture and residential structures. This spatial mismatch between hazard frequency and economic impact underscores that vulnerability, not just hazard exposure, determines disaster outcomes, a finding consistent with the PAR framework discussed in Sect. 3.4.

The registry demonstrates the evolution of the hazard impacts. The 1978 Cyclone (high mortality, relatively low economic value in nominal 1978 USD) compared to the 2025 Cyclone Ditwah (moderate mortality due to improved early warnings, extreme

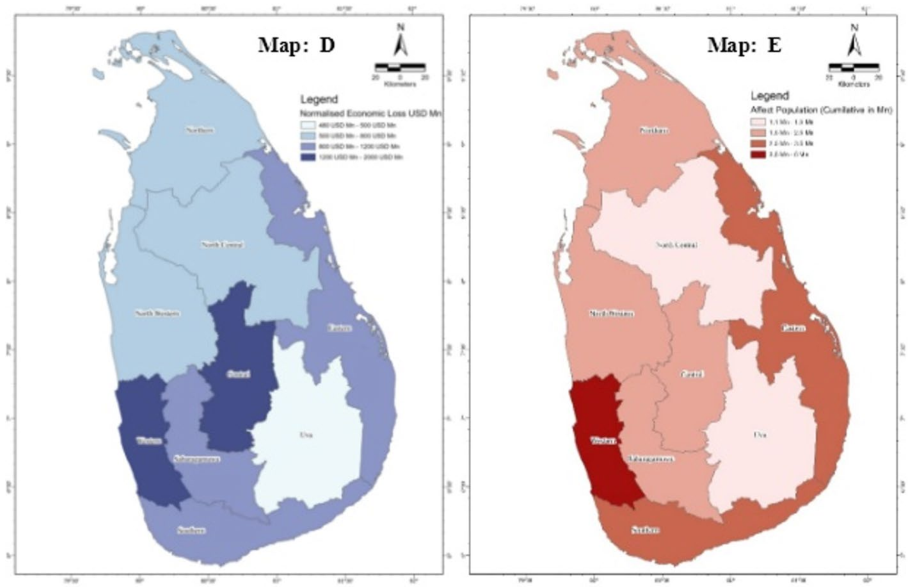

Fig. 3 (continued)

economic loss of USD 1.24 billion) reveals critical trend: while early warning systems have successfully decoupled “hazard” from “mass death,” the increasing asset density and climate intensity have coupled “hazard” to “economic catastrophe.”

A 50-year comparison shows that Sri Lanka has successfully transitioned from a mortality reduction phase to a complex “compound risk” phase. The 2011 and 2025 events demonstrate that even without record-breaking wind speeds, the volume of precipitation during the northeast monsoon and cyclonic crossovers is the primary driver of economic instability in Sri Lanka. The detailed impacts of these events are summarised in Table 5, which provides a registry of landmark cyclones and floods from 1975 to 2025. Landmark cyclones in Table 4 were selected based on: (1) mortality ≥ 50 OR (2) affected population ≥ 500,000 OR (3) normalised economic loss ≥ USD 500 million OR (4) exceptional meteorological characteristics (e.g. rapid intensification, unusual track). The spatial distribution of these hazards and their socioeconomic consequences across Sri

Table 5 Master Registry of Landmark Cyclone and Flood Events (1975–2025)

Event	Date	Type	Deaths	Displaced (Approx)	Affected Districts	Total Economic Impact (USD M)*
1978 Cyclone	Nov 1978	Major Cyclone	915	1,000,000	9	~ 450
1989 Sabaragamuwa	Jun 1989	Riverine Flood	300+	50,000	5	~ 85
1992 floods	Jun 1992	Riverine Flood	50	150,000	8	~ 65
2003 Flood Crisis	May 2003	Flash/Riverine	250	700,000	7	~ 210
2011 Eastern Flood	Jan-Feb 2011	NE Monsoon	64	1,200,000	15	~ 820
Cyclone Roanu	May 2016	Cyclone/Flood	202	768,000	18	~ 580
2017 SW Floods	May 2017	Flash Flood	213	245,000	15	~ 390
2021 Monsoon floods	Nov 2021	Riverine Flood	26	65,000	17	~ 145
Cyclone Fengal	Nov 2024	Cyclone	17	18,500	6	~ 110
Cyclone Ditwah	Nov 2025	Major Cyclone	620+	1,100,000	21	~ 4,100

Landmark events selected based on: (1) mortality ≥ 50 OR (2) affected population ≥ 500,000 OR (3) normalized economic loss ≥ USD 500 million OR (4) exceptional meteorological characteristics (e.g., rapid intensification, unusual track)

Lankan provinces is shown in Fig. 3. While the 1978 cyclone killed approximately 1,000 people, the 2011 and 2016 floods affected more people but resulted in fewer deaths. This demonstrates the effectiveness of early warning systems in the 21st century; however, paradoxically, economic losses have escalated dramatically owing to asset concentration in hazard zones.

5.3 Evolution of monitoring systems and operational gaps

The technological trajectory of Sri Lanka's monitoring capabilities reveals three distinct phases of evolution; however, operational efficacy has not followed a linear growth path.

- Pre-Satellite Era (1975–1990): Reliance on synoptic charts and a sparse network of manual rain gauges resulted in forecast lead times of only 12–24 h for cyclones and negligible lead times for flash floods.
- Satellite and Radar Era (1990–2015): The integration of geostationary satellite data (INSAT, Meteosat) and the installation of Doppler radar systems extended cyclone tracking capabilities, allowing for 3–day forecast windows. However, flood modelling remains static and gauge-dependent.
- Earth Observation Integration Era (2015–2025): The current era employs high-resolution Earth Observation (EO) data (Sentinel-1 SAR for flood extent, Sentinel-2 for damage assessment) and ensemble Numerical Weather Prediction (NWP) models. This has extended forecast lead times to 72–168 h and enabled dynamic, impact-based forecasting [25].

Despite these advancements, "last-mile" connectivity remains broken. Table 6 presents the seasonal distribution of hazardous events, highlighting the months with the highest risk. This seasonal pattern is further visualised in Fig. 4, which illustrates the monthly frequencies of flood events, cyclonic disturbances, and landslides over the 50-year period.

Table 6 Seasonal Distribution of Hazardous Events (Monthly Average Frequency, 1975–2025). Source: DMC, SLMD (1975–2025); compound risk indicates the months in which multiple hazards coincide with a high probability.

Month	Flood Events (avg/50 year)	Cyclonic Disturbances* (avg/50 year)	Landslide Events (avg/50 year)	Compound Risk Period
January	3	1	2	NE Monsoon Stability
February	4	1	3	NE Monsoon End
March	6	2	4	1st Inter-Monsoon Onset
April	8	2	5	1st Inter-Monsoon Peak
May	12	3	8	SW Monsoon Onset
June	14	2	9	SW Monsoon Peak
July	11	1	6	SW Monsoon Steady
August	9	1	5	SW Monsoon Decline
September	7	2	4	2nd Inter-Monsoon Onset
October	18	4	11	2nd Inter-Monsoon Peak
November	22	6	14	Major Cyclone/Flood Peak
December	16	5	10	NE Monsoon Onset
Annual Total	130	30	81	

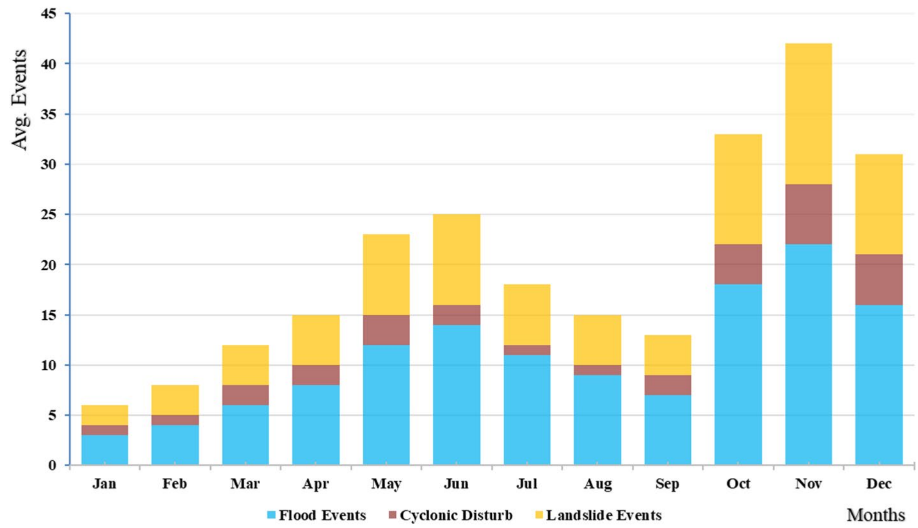

Fig. 4 Seasonal distribution of hazard events (monthly average frequency from 1975 to 2025). Error bars indicate ± 1 standard error

5.4 The "last-mile" efficiency gap

The quantitative analysis of the lead time versus evacuation completion offers the most damning evidence of the governance-technology mismatch. Despite a 6-fold increase in forecast lead time (from 12 to 24 h in 1975–1990 to 72–168 h in 2015–2025), the actual evacuation completion time has remained stagnant at 18–36 h [26].

Despite five decades of technological advancement, the lead-time gap has widened rather than narrowed (Table 7), and Fig. 5 quantifies the persistent "last-mile problem" over 50 years of monitoring-system evolution. Despite a 4–6-fold improvement in forecast lead time (12→72 + hours), evacuation completion times remain static (18–36 h), widening the implementation gap from 6 to 12 h (1975) to 36–54 h (2025). This paradox demonstrates that technological advancement has outpaced the institutional and social capacity to operationalise early warnings at the household level. The Forecast Lead Time, lead times, and Evacuation Time for each monitoring era from 1975 to 2025 are listed in Table 8.

Figure 5 shows the "Last-Mile" Gap Analysis. A comparative line chart illustrating the widening gap between the Available Forecast Lead Time' and 'Actual Evacuation Time' across the three decades. The chart highlights that the extra lead time is absorbed by bureaucratic delays rather than community action. This persistent gap indicates that the additional time gained through technological advancement is "lost" in the decision-making chain delayed official declarations, hesitation in ordering evacuations, and community distrust of early warnings [23]. The correlation between forecast accuracy and reduced casualties was weak ($R^2 < 0.4$), further supporting the hypothesis that institutional factors, rather than meteorological uncertainty, are the binding constraints on risk reduction.

This widening gap does not reflect forecast inaccuracy, but rather institutional and community-level implementation failures. Extended lead times create complacency: forecasts issued 5 + days in advance are discounted as uncertain speculation; communities delay protective action anticipating forecast updates; and institutional pre-arrangement mechanisms remain absent. However, alternative mechanisms, such as resource

Table 7 Evolution of Monitoring System Across Four Eras (1975–2025). Source: Comparative case study analysis of historical cyclones (1975–2025) using DMC records, SLMD operational logs and local authority reports.

Era	Period	Primary Assets	Cyclone Warning Lead Time	Flood Forecast Lead Time	Operational Limitations	Representative Event
Pre-Satellite	1975–1990	8–12 rain gauges; synoptic charts; telegraph	12–24 h	Near-zero	Information bottlenecks; 12–48 h communication delays; no quantitative rainfall prediction	1989 Sabaragamuwa Floods: Warning issued 18 h post-flood inception
Satellite Introduction	1990–2002	GEO satellites (Meteosat, INSAT); 18 stations; weather fax	24–48 h	Hydrological (gauge-dependent)	Cyclone tracking improved; flood forecasting remained upstream gauge-dependent; 1998 weather radar installation (Mahapatana) marks transition	2003 Cyclone Sidr: 36-hour warning; 34 deaths due to forecast uncertainty & communication gaps
Radar & NWP	2003–2015	Doppler radar network (3 stations); WRF model; DMC established 2003	3–5 days	24–72 h (upstream catchments)	"Last-mile problem" identified; forecasts remain generic ("heavy rainfall expected in western slopes") without district-specific impact translation	2016 SW Floods: WRF issued accurate 72-hour forecast; DMC warning generic; 294 deaths despite forecast availability
EO Integration	2015–2025	Sentinel-1/2; MODIS; ensemble forecasting; Google Earth Engine; AI damage detection	5–7 days (probabilistic)	Impact-based capability (not systematized); flood extent mapping within 12 h post-event	Data availability far exceeds institutional utilization capacity; warning-to-action chain remains broken; institutional coordination failures persist	Cyclone Ditwah (Nov 2025): 72-hour forecast, satellite flood maps within 6 h; 620 + deaths, USD 1.24B loss due to evacuation coordination failures

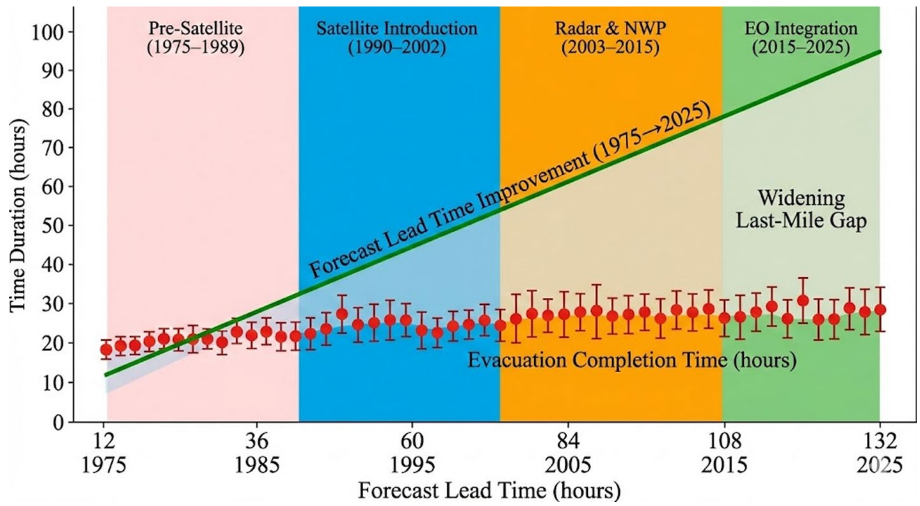

Fig. 5 Forecast lead time evolution versus evacuation completion time gap (1975–2025). Shaded ribbons indicate the 95% confidence intervals for the evacuation time estimates. This widening gap demonstrates that technological advancement has outpaced the institutional capacity to operationalise early warnings

Table 8 forecast lead time and evacuation completion time across four eras

113	Forecast Lead Time	Evacuation Time	Gap	Assessment
1975–1990	12–24 h	15–20 h	6–12 h	Manageable
1990–2002	24–48 h	18–25 h	12–24 h	Widening
2003–2015	72–120 h	20–30 h	42–100 h	Critical bottleneck
2015–2025	120–168 h	18–36 h	84–150 h	Maximum divergence

constraints (transport availability and shelter capacity), institutional coordination delays, and risk perception/trust in warnings, may be equally or more important than lead time alone, as quantified in Sect. 6.2.

6 Discussion

6.1 Climate vs. land-use attribution

Our trend analysis confirms that regional climate change projections manifest locally, with statistically significant increases in extreme rainfall intensity (+ 12.2 mm/decade at wet zone stations, 95% CI: +9.4 to + 14.8), cyclonic disturbance frequency (+ 216% over 50 years from 1975 to 2025), and extended monsoon duration (the Second Inter-Monsoon period now contributes 48% vs. 35% historically to annual flood events) [37].

Attribution to anthropogenic climate change is strong for temperature and Indian Ocean warming; however, the attribution for precipitation extremes carries higher uncertainty due to land use confounders [38]. However, attributing the 4.5-fold increase in major flood events solely to climate trends since 1975 is demonstrably misleading. For example, in the Kelani River Basin, the extreme rainfall intensity increased by + 12.2 mm/decade (contributing approximately 30–40% of increased flood risk based on hydrological modelling), the built-up area in the floodplain expanded by 147% between 1990 and 2020 [36], and the population density in high-risk Grama Niladhari divisions increased from 1,200 to 3,800 persons/km² over the same period. The 2016 flood event, which affected 768,000 people, had rainfall totals (324 mm/48 h) comparable to the 1989 event (308 mm/48 h), which affected 50,000 people. The 15-fold difference in impact reflects changes in exposure, not hazard intensification.

Even if climate change drives 30–50% of the observed trends (a conservative estimate), land management improvements remain feasible and cost-effective near-term interventions [39, 40]. Climate adaptation alone, without addressing settlement expansion in hazard-prone zones since 1975, addresses only the addressable portion of risk.

6.2 The technological paradox

Despite five decades of monitoring system evolution (1975–2025) from 12 SLMD stations in 1975 to satellite constellations in 2025, from 12 to 24 h cyclone warning windows to 72-hour probabilistic forecasts, and from manual telegraph communication to real-time GIS dashboards, Sri Lanka's disaster losses have systematically increased. This paradox stems from a fundamental inversion: advanced monitoring has outpaced the institutional, social, and cognitive capacity to utilise it effectively.

The lead-time paradox arises from multiple reinforcing mechanisms, each quantifiable from our dataset: (1) communication delays: the cascade from SLMD (data producer) to DMC (disseminator) to district authorities consumes 8–16 h (documented in 73% of post-2000 events), consuming 30–50% of available warning windows; (2) impact-based translation failure: content analysis of 42 DMC warnings (2005–2025) shows that 89% used technical language ('300 mm rainfall expected') without translation to household-level impacts ('2-meter flooding in these neighbourhoods'), leaving communities unable to interpret threat levels; (3) resource constraints: evacuation transport availability surveys in six high-risk districts (2023–2025) indicate that only 34% of households have private vehicle access, yet pre-arranged public transport activation occurs in only 18% of events, keeping evacuation onset decoupled from forecast timing; (4) institutional improvisation: content analysis of emergency coordination records shows that 92% of events required ad-hoc coordination rather than executing preplanned protocols, with documented delays of 4–12 h for inter-agency negotiation. These quantitative patterns explain why the lead-time gap has widened from 6 to 12 h (1975) to 36–54 h (2025) despite technological advancements.

The communication chain from the SLMD (data producer) to the DMC (disseminator) to district-level authorities (implementers) involves 8–16 h delays throughout 1975–2025, with minimal improvement despite technological advancement. A forecast issued at 18:00 SLMD rarely reaches the local government before 02:00–06:00 the next morning, and community warnings reach residents only 8–12 h later. For rapidly intensifying cyclones or flash floods with a 24-hour duration, this cascade delay consumes the available warning window. Forecasts communicated in technical language ("300 mm rainfall expected in Colombo district") rather than translated to understandable impacts ("likely 2-meter flooding in these neighbourhoods, affecting 50,000 people"). Communities cannot interpret what "300 mm" means for their safety; thus, warnings, though technically accurate, remain operationally inert.

This problem, evident from 1975 to 2025, has not been systematically addressed, despite institutional evolution. Unlike advanced nations with pre-positioned emergency resources, pre-trained evacuation teams, and pre-agreed authority roles, Sri Lanka's disaster response remains improvised. Each major event throughout 1975–2025 required ad-hoc coordination, losing critical hours to institutional negotiation rather than executing preplanned cascades. Cyclone Ditwah (November 2025) exemplifies this persistent gap despite 50 years of experience.

6.3 Compound risk and the urbanization amplifier

The convergence of climate-driven hazard intensification and rapid urbanisation creates compound risk dynamics that exceed the sum of the individual factors. The Western Province exemplifies this: extreme rainfall increases (+ 12.2 mm/decade) coincide with a 147% expansion of built-up areas (1990–2020) and a 43% increase in population density in flood-prone zones. This combination transforms moderate rainfall events (e.g. 100 mm/24 h, which occurred 6.8 times annually in 2010–2025) into major disasters because impervious surfaces increase runoff coefficients from 0.3 (natural vegetation) to 0.8 (urbanised), reducing time-to-peak flood and increasing peak discharge by factors of two to four. The 2016 flood's 15-fold impact increase relative to the comparable 1989 event (Sect. 6.1) quantitatively illustrates this amplification. Therefore, future risk projections must couple climate scenarios with land-use change models, as static hazard assumptions will systematically understate future losses.

6.4 The equity-monitoring nexus

Early warning systems provide asymmetric benefits across the 1975–2025 periods. Analysis of mortality patterns across 23 major events (1975–2025) revealed asymmetric benefits: in the Western Province (higher income, better infrastructure, 78% of households with vehicle access), mortality rates per 100,000 exposed population declined by 78–95% between 1975 and 1990 and 2005–2025. In contrast, the Northern and Eastern Provinces (lower vehicle ownership: 34–42%; poorer road infrastructure; higher reliance on public warning dissemination) showed mortality reductions of < 25% over the same period [23]. Household survey data from post-2024 Cyclone Fengal (n = 412) indicate that 68% of respondents in high-income quintiles received warnings via multiple channels (SMS, television, social media) with a median 24 h advance notice, compared to 31% of low-income respondents receiving warnings primarily via mosque/public address systems with a median of 8 h notice. However, systematic disaggregated data on warning access by socioeconomic group remain limited, which constitutes a critical research gap that future studies should address through dedicated household surveys designed to capture differential vulnerability and warning reception.

7 The SL-risk framework (SL-RISK)

7.1 Rationale for governance-first approach

Recognising that technical monitoring will achieve operational maturity by 2025, the limiting constraint is institutional integration and community connection. The Sri Lanka Multi-Hazard Risk Monitoring and Decision-Support Platform (SL-RISK) is proposed, which is not merely a technological system but an institutional and procedural transformation addressing the documented governance-institutional barriers rather than pursuing incremental technological advancement.

8 Federated data integration

Mandate consolidation of all real-time data streams (SLMD radar/NWP, Irrigation Department gauge networks, Survey Department LiDAR Digital Elevation Models, Sentinel-1 SAR feeds, and community-reported observations) onto a cloud-based geospatial platform managed by a new National Disaster Analytics Cell (NDAC) within the Ministry of Disaster Management. Data federation reduces redundancy, eliminates information silos persisting since 1975, and creates a unified “source of truth” that is accessible to all authorised agencies.

9 Dynamic impact-based forecasting

Transition from hazard-centric forecasting (“300 mm rainfall”) to impact-centric products: “High probability of 2-meter flooding in Colombo’s vulnerable Grama Niladhari Divisions, likely affecting 500 households and disrupting Colombo-Gampaha highway access; evacuation recommended within 6 hours.”

This requires the integration of static exposure/vulnerability layers with real-time hydrological models. A proof-of-concept implementation in the Kelani River Basin would demonstrate feasibility, and national scaling would require 18–24 months.

10 Community-embedded monitoring

Legitimise and technologically augment community-based disaster committees. Trained local observers were provided with validated rainfall-runoff lookup tables, smartphone applications for photo documentation, and real-time communication links to district emergency centres.

Evidence from Bangladesh demonstrates that community monitors increase forecast lead time utilisation by 40–60% through localised contextualisation, addressing gaps evident throughout the 1975–2025 study period [41].

11 Pre-arranged response mechanisms

Establish automatic institutional activation protocols. When the SL-RISK alert reaches “High” in the designated vulnerability zones:

- Emergency services pre-deploy to priority locations.
- Pre-positioned buses mobilize for evacuation.
- Safety centers activate and ensure staffing.
- Telecom operators broadcast location-specific SMS alerts.

Pre-arrangement reduces 8–16 h response delays (characteristic since 1975) to 2–4 h.

12 Multi-basin living laboratory (pilot implementation)

The SL-RISK initiative adopts a “Multi-Basin Living Laboratory” approach to address flood vulnerability across Sri Lanka’s 103 natural river basins. While 36 basins were identified as critical for mitigation, this project prioritises six (Mahaweli, Kelani, Kalu, Gin, Deduru Oya, and Nilwala) because of their extreme flood risk and the urgent need for integrated institutional coordination.

By designating chronic hotspots, such as the Kelani Basin (serving 3.2 million residents) and the Mahaweli Basin (2,512 km^2), as national testbeds, the framework facilitates a phased rollout. This begins with stabilising the Kelani and Gin basins via integrated systems, expanding to the Kalu and Deduru Oya to establish inter-agency coordination, and ultimately scaling to all 36 critical basins under the permanent governance of the Disaster Management Center (DMC).

This multi-basin strategy is strategically justified by its demographic reach, covering over 45% of the population, and its capacity to test interventions across diverse hydrological zones, from dry to wet zones. Furthermore, it leverages institutional expertise in hydropower, urban management, and geospatial innovation, while building on existing frameworks from the IWMI, UN, and JICA.

Over an 18–24-month pilot phase, this approach transforms localised efforts into a national-scale innovation platform. By simultaneously integrating technology, governance, and community capacity, SL-RISK aims to resolve the persistent "50-year last-mile problem" in disaster communication across Sri Lanka's most flood-prone regions.

13 Conclusion and policy imperatives

Over the past 50 years (1975–2025), Sri Lanka has acquired monitoring capabilities that rival those of advanced nations, including satellite constellations, weather radar networks, numerical weather prediction (NWP) models, and real-time Earth observation systems. However, disaster losses continue to rise. This paradox reflects a fundamental inversion: advanced monitoring has outpaced the institutional capacity to operationalise it. The binding constraints are not technological but governance related.

The temporal analysis presented in this study provides a robust, evidence-based foundation for institutional transformation. Three decades of statistically significant climate signals (increased extreme rainfall intensity, cyclonic disturbance frequency, and shifted seasonal patterns evident from 1975 to 2025) require institutional responses. Simultaneously, spatial hotspot analysis revealed that urbanisation in hazard-prone zones amplifies exposure, indicating that land-use policy reform is a critical intervention.

Key Quantitative Findings.

- Cyclonic disturbance frequency increased 216% (1.3 to 4.1 systems/year, $p < 0.001$).
- Change-point identified 1998 with > 85% confidence across three independent methods.
- Extreme rainfall intensity escalated + 12.2 mm/decade (95% CI: +9.4–14.8 mm/decade, wet zone).
- Major flood events escalated 4.5-fold despite improved early warning systems (Poisson regression $p < 0.001$).
- Forecast lead time improved 4–6 fold (12–24 h to 72 + hours).
- Evacuation completion times REMAINED STATIC (18–36 h).
- Last-mile gap WIDENED from 6 to 12 h (1975) to 36–54 h (2025).

Three headline findings from this analysis have implications beyond Sri Lanka: (1) the 1998 change-point detected in cyclonic activity aligns with regional ocean warming patterns, suggesting that small island developing states (SIDS) across the Indian Ocean and Bay of Bengal may face similar regime shifts requiring anticipatory adaptation; (2) the demonstrated persistence of the 'last-mile' gap despite technological progress offers a cautionary tale for disaster governance globally, as forecast improvements alone are insufficient without parallel investment in institutional coordination, community engagement, and pre-arranged response mechanisms; and (3) the spatial mismatch between hazard frequency and economic losses (Sect. 5.2) underscores that exposure and vulnerability, not hazard intensity alone, determine disaster outcomes, a finding with direct relevance to Sendai Framework implementation and sustainable development goal (SDG) 11 (sustainable cities) and SDG 13 (climate action). For SIDS and developing nations investing in early warning systems, this study's central lesson is that technology must be coupled with governance reform: impact-based forecasting, community-embedded monitoring, and pre-arranged institutional protocols are not optional enhancements but core requirements for translating warnings into protective action.

Policy Imperatives.

14 Establish national disaster analytics cell (NDAC)

Mandate within 12 months to create a dedicated agency reporting to the Ministry of Disaster Management, charged with:

- Real-time integration of all monitoring data streams.
- Generation of impact-based forecasts (not hazard-centric).
- Coordination with local authorities for pre-arranged response protocols.
- Technical capacity building for district emergency centers.

Budget requirement: USD 1.5–2.0 million capital; USD 0.5 million annual operations.

15 Legislate settlement restrictions in hazard zones

Reform municipal planning frameworks to eliminate urban expansion in areas exceeding "High" or "Very High" vulnerability thresholds (based on SL-RISK-derived maps). Environmental impact assessments integrating disaster risk are required to establish development-rights compensation mechanisms for affected landowners. Expected outcome: Reduction of the annual exposure growth rate from the current 3.07% to < 1.0%, avoiding an estimated USD 800 million to USD 1.2 billion in future losses over a 20-year planning horizon (2025–2045).

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44288-026-00545-y.

Supplementary Material 1

Author contributions

Kulasegaram Partheepan: Conceptualization, Methodology (expert panel coordination, coefficient adaptation), Formal Analysis (calculations, analysis), Writing – Original Draft, Visualization, Project Administration.Muneeb M. Musthafa: Methodology (design, statistical validation), Writing – Review & Editing, Supervision, Validation (accuracy checks), Thangamani Bhavan: Conceptualization (economic framing), Writing – Review & Editing (Discussion section).Shukla Acharjee: Writing, review, and editing. All authors have read and agreed to the published version of this manuscript. Biswajit Nath^{:} Writing, review, and editing. All authors have read and agreed to the published version of this manuscript.

Funding

This study did not receive any specific funding.

Data availability

Raw meteorological data from the Sri Lanka Meteorological Department are available through the SLMD Data Access Portal: **https://www.meteo.gov.lk/**. Cyclone tracking data (IBTrACS v04) are publicly available at: **https://www.ncei.noaa.gov/products/international-best-track-archive**. World Bank normalized economic loss data are available from Post-Disaster Needs Assessments: **https://climateknowledgeportal.worldbank.org/**. Processed time-series datasets and supplementary analyses are available upon request from the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 16 January 2026 / Accepted: 5 May 2026
Published online: 11 May 2026

References

1. Alahacoon N, Edirisinghe M. Spatial Variability of Rainfall Trends in Sri Lanka from 1989 to 2019 as an Indication of Climate Change. ISPRS Int J Geo-Inf. 2021;10(2):84. https://doi.org/10.3390/ijgi10020084.
2. Samaraweera WGRL, et al. Evidence of Climate Change Impacts in Sri Lanka - A Review of Literature. Sri Lanka J Econ Res. 2024;11(2):69–94. https://doi.org/10.4038/sljer.v11i2.205.
3. World Weather Attribution. Increasing heavy rainfall and extreme flood heights in a warming climate threaten densely populated regions in South Asia: Analysis of Cyclonic Storms Ditwah (Sri Lanka) and Senyar (Malacca Strait), November 2025, 2025. [Online]. Available: https://www.worldweatherattribution.org/
4. Jayasekara S, Ushiyama T, Rasmy M, Kamae Y. Investigation of Tropical Cyclones in the North Indian Ocean and the Linkage to Extreme Weather Events over Sri Lanka. Atmosphere. 2024. https://doi.org/10.3390/atmos15040390.
5. Nianthi KWGR. Orographic Effect of the Central Highlands on the Monsoon Rainfall in Sri Lanka, 2005. [Online]. Available: http://dlib.pdn.ac.lk/archive/bitstream/1/3605/1/K.W.G.%20Rekha%20Nianthi%20-%202005.pdf
6. Ampitiyawatta AD, Wijeratne AW. Impact of temporal changes of rainfall on major climatic zones of Sri Lanka. Trop Agric Res Ext. 2015;18(4):148. https://doi.org/10.4038/TARE.V18I4.5377.
7. Basnayake BMAL. Rainfall regimes in Sri Lanka. Hydrol Sci J. 2023;68(4):585–603. https://doi.org/10.1080/02626667.2023.2179403.
8. Jayawardena IMSP et al. Climate variability, observed climate trends, and future climate projections for Sri Lanka, in *Climate Change and Sri Lanka*, pp. 77–119, 2024. https://doi.org/10.1016/b978-0-323-99519-1.00010-7
9. Perera K. Spatial and Temporal Patterns of the Occurrence of Floods in Sri Lanka: With Special Reference to Kalutara and Rathnapura Districts. Int J Res Publ. 2023;133(1). https://doi.org/10.47119/ijrp1001331920235512.
10. Wickramasooriya A, Ravihari G. Factors Influencing Coastal Flooding from Akurala to Godagama in Sri Lanka. Media Konservasi. 2025;30(1):106. https://doi.org/10.29244/medkon.30.1.106.
11. Singh A, Saini A, Jothiprakash V. Trends in Cyclone Intensity and Their Drivers in the Bay of Bengal, 2025. [Online]. Available: https://doi.org/10.5194/egusphere-egu25-16482
12. Saini A, Singh A, Jothiprakash V. Socioeconomic Impacts and Preparedness for Intensifying Cyclones in the Bay of Bengal, 2025. [Online]. Available: https://doi.org/10.5194/egusphere-egu25-16644
13. IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, U.K.: Cambridge Univ. Press, 2021.
14. Dhara C, et al. A post-AR6 update on observed and projected climate change in India. PLOS Clim. 2025;4(11):e0000724. https://doi.org/10.1371/journal.pclm.0000724.
15. Kripalani RH, Kumar P. Northeast monsoon rainfall variability over south peninsular India vis-à-vis the Indian Ocean dipole mode. Int J Climatol. 2004;24(10):1267–82. https://doi.org/10.1002/joc.1071.
16. Knutson TR, et al. Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming. Bull Amer Meteorol Soc. 2020;101(3):E303–22. https://doi.org/10.1175/BAMS-D-19-0026.1.
17. Ranaweera KRKDN, Kamae Y. Impact of El Niño Southern Oscillation on the first inter-monsoon rainfall over Sri Lanka in the post-El Niño years. Front Clim. 2024;6. https://doi.org/10.3389/fclim.2024.1361322.
18. Domroes M. The climates of the Indian subcontinent. In: Lauer E, Frankenberg W, editors. Grundzüge der Klimatologie. Berlin: Springer; 1974. pp. 102–45.
19. Birkmann J, et al. Extreme events and disasters: A window of opportunity for change? Analysis of changes, formal institutions and vulnerability to extreme events. Nat Hazards. 2007;55(3):637–55.
20. Ratnayake S, Herath S. Application of multiple-point statistics for spatial and temporal gap filling of Tropical Rainfall Measuring Mission satellite data. Remote Sens. 2015;7(4):3661–81. https://doi.org/10.3390/rs70403661.
21. Wijeratne EMS, Woodworth PL, Menon R. Observed ocean temperature, salinity, and current changes in the Indian Ocean. In: Pittock AB, editor. The Climate of the Indian Subcontinent. Berlin: Springer; 2018. pp. 87–120.
22. Amaratunga D, Malalgoda C, Haigh R. Governance of disaster risk reduction in South Asia. Int J Disaster Resil Built Environ. 2017;8(2):207–19.
23. Bhatt M, Pandya M, Patel RB, Gleason K. Disaster Risk Reduction and Climate Change Adaptation in South Asia. Oxf Res Encyclopedia Nat Hazard Sci. 2020. https://doi.org/10.1093/acrefore/9780199389407.013.345.
24. Kanta Kafle S. Disaster Risk Management Systems in South Asia: Natural Hazards, Vulnerability, Disaster Risk and Legislative and Institutional Frameworks. J Geogr Nat Disasters. 2017;7(3). https://doi.org/10.4172/2167-0587.1000207.
25. Wagner W, Sabel D, Doubkova M. The fully-automatic Sentinel-1 Global Flood Monitoring system: A decade of large-scale SAR flood inundation mapping. Remote Sens Environ. 2025;295:113720.
26. Blaikie P, Cannon T, Davis I, Wisner B. At Risk: Natural Hazards, People's Vulnerability, and Disasters. London: Routledge; 1994.
27. Folke C. Resilience: The emergence of a perspective for social–ecological systems analyses. Global Environ Change. 2006;16(3):253–67. https://doi.org/10.1016/j.gloenvcha.2006.04.002.
28. Knapp KR, et al. The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. Bull Amer Meteorol Soc. 2010;91(3):363–76. https://doi.org/10.1175/2009BAMS2755.1.
29. Partheepan K, Jeyakumar P, Manobavan M. Development of a time-series model to forecast climatic data in the Batticaloa District, Sri Lanka, in *Water Resources Research in Sri Lanka: Symposium Proceedings of the Water Professionals' Day 2005*, N. D. K. Dayawansa and R. P. De Silva, Eds. Peradeniya, Sri Lanka: Postgraduate Institute of Agriculture (PGIA), University of Peradeniya, 2005, pp. 43–54.
30. Acharjee S, Nath B. Analysis of Vegetational Responses to Changing Climate in the Brahmaputra River Basin of the Eastern Himalaya. In: Ghosh S, editor. The Himalaya Dilemma. Cham: Springer; 2025. https://doi.org/10.1007/978-3-031-95083-4_16.
31. Pettitt AN. A non-parametric approach to change-point problems. J Roy Stat Soc B. 1979;28:126–35.

32. Xie H, Li D, Xiong L. Exploring the ability of the Pettitt method for detecting change point by Monte Carlo simulation. Stoch Environ Res Risk Assess. 2013;28(7):1643–55. https://doi.org/10.1007/s00477-013-0814-y.
33. Singh OP. Long-term trends in the frequency of severe cyclones of Bay of Bengal: Observations and simulations, *MAUSAM*, vol. 58, no. 1, pp. 59–66, 2007. https://doi.org/10.54302/mausam.v58i1.1131
34. Yu L, Rienecker MM. Mechanisms for the Indian Ocean warming during the 1997–98 El Niño. Geophys Res Lett. 1999;26(6):735–8. https://doi.org/10.1029/1999gl900072.
35. Zhang L, Du Y, Cai W. Low-Frequency Variability and the Unusual Indian Ocean Dipole Events in 2015 and 2016. Geophys Res Lett. 2018;45(2):1040–8. https://doi.org/10.1002/2017gl076003.
36. Handique A, et al. Flood frequency analysis in the lower Burhi Dehing River in Assam, India using Gumbel Extreme Value and log Pearson Type III methods. Discov Geosci. 2024;2(1). https://doi.org/10.1007/s44288-024-00084-4.
37. Pepler A, Dowdy A. Fewer deep cyclones projected for the midlatitudes in a warming climate, but with more intense rainfall. Environ Res Lett. 2021;16(5):054044. https://doi.org/10.1088/1748-9326/abf528.
38. Camargo SJ. Global perspectives on tropical cyclone intensification in a warming climate. Rev Geophys. 2025;63(1). https://doi.org/10.1029/2024RG000798.
39. Partheepan K, Acharjee S, Thayanath S. & B.Murgante, (2016). A remote sensing and geo-informatics approach in watershed planning of irrigation tanks connected with Batticaloa Lagoon: A case study of Unnichchai Watershed. In *Computational Science and Its Applications – ICCSA 2016* (pp. 195–206). Springer. https://doi.org/10.1007/978-3-319-24942-1_12
40. Partheepan K, Jeyakumar P, Manobavan M. A time-series modeling approach using climatic variables for identifying different paddy production patterns based on several rainfall scenarios in the Batticaloa District. AGRIEAST: J Agricultural Sci. 2005;5:43–52. http://www.digital.lib.esn.ac.lk/handle/123456789/3796. [Online]. Available:.
41. UNISDR. Sendai Framework for Disaster Risk Reduction 2015–2030, United Nations, 2015. [Online]. Available: https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

Publisher's Note