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Hydro-Meteorological Disaster Incidents and Associated Weather Systems in Sri Lanka

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ABSTRACT. This paper presents a comprehensive seasonal analysis of disaster incidents with their associated weather systems happened in Sri Lanka since 1907 to 2019. Disaster incidents and weather records were collected from different reliable sources and analysed with the observed weather systems to understand the formation and development of the weather systems. According to the observations, frequent hydro-meteorological hazards experienced by the country are extreme winds, floods, and landslides. The seasonal analysis shows that majority of these hydro-meteorological disasters have occurred during the southwest monsoon, where the weather was mainly dominated by the monsoon winds entering from the southwest of Sri Lanka which creates torrential rainfall mainly in the wet zone of the country. The frequency of formation of depression and deep depression, from 1907 to 2019 shows that most of these are formed in the Bay of Bengal (BoB), North Indian Ocean, from October to January while having the highest frequency in November followed by December. The study will help to understand the possible damages, and thereby help the community to be prepared for such future hazards. The need for a central platform for generating timely impact-based warnings and helping the community to act was also identified. Further, the census block can be suggested as the smallest; Micro-Geographic Incident Response Unit (MG-IRU) to grant the decision-making power and connect the institution and community in the disaster risk management process.

Keywords: hydro-meteorological disasters, monsoon, tropical convergences, weather systems, preparedness

1. Introduction

Hydro-meteorological disasters can be identified as any process or phenomenon of atmospheric, hydrological, or oceanographic nature that may cause damages including loss of life, injury or other health impacts, property damage, loss of livelihoods, damages to services such as electricity and water supply, social and economic disruption, or damages to the environment. Hydro-meteorological disasters can result in significant damage to human lives and to properties. The statistics show around 80% of the disaster incidents in the world that caused fatalities are hydrological or meteorological disasters (Paul et al., 2018). These hydro-meteorological disasters may result in severe flood situations, landslides, cyclones, droughts, storm surges, extreme temperature events (heat waves and cold spells), heavy snowfalls, hailstorms, avalanches, tornadoes, and tropical cyclones. The frequency and intensity of these hydro-meteorological disasters differ among regions of the world (Feng and Chao, 2020). For example, though droughts occur due to hydro-meteorological extremes, they gradually develop over a long period of time and the consequences are not sudden, therefore, those can be well addressed and mitigated with the support of neighbouring countries and donor agencies. Future precipitation and temperature change projected might worsen the water stress and probability of the occurrence of severe events, hence mitigation strategies and management options to reduce such negative impact should be encouraged (Shaikh et al., 2022).

Out of these, the major types of hydro-meteorological hazards which affect Sri Lanka are presented in Figure 1. The most common hydro-meteorological hazards are associated with surplus and deficit of rainfall, which are floods and droughts. These floods and droughts can also be further categorized based on their location of formation, occurrence, and the basis of water availability. Storm surges are the abnormal rise of water levels

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in the sea mainly due to hurricanes and heavy storms (Jelesnianski, 1973; Jayawardena, 2014; NOAA, 2022; WMO, 2022) In addition, tropical cyclones are commonly observed in the region. Sustainable management of water resources in a country needs to be examined from a sociotechnology-knowledge context; analyzing issues on how they relate to and affect water resources (Zeinali et al., 2021).

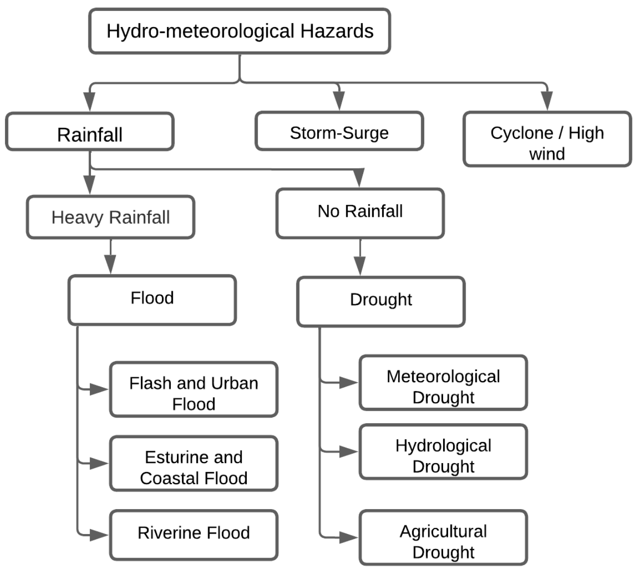

Figure 1. Types of hydro-meteorological hazards reported in Sri Lanka [source: Tillekaratne et al. (2021a)].

The hydro-meteorological disaster situations develop at different spatial and temporal scales, can cause significant damage to the infrastructure facilities claiming hundreds of lives. Sometimes multiple hazards can occur simultaneously or cause cascading impacts from one extreme weather event (Wu et al., 2016). For example, a tropical storm can also result in flooding and sediment flow (landslides), cause an overflow of toxic wastes, and increase the propagation of mosquito-borne diseases.

Among the different types of hydro-meteorological hazards, slow-onset droughts cannot be matched with a short lifespan weather system; yet floods have comparatively more rapid formation and occurrence than droughts, which allows for identifying the impact of the weather system (rainfall, wind) on such flood events. Further, if these heavy rainfalls occurred together with cyclonic storms, and sometimes cause landfalls, they can create extreme flooding which results in widespread damage to people's lives, property and critical public infrastructure. River flooding occurs when a water body exceeds its capacity to hold water and usually happens due to prolonged heavy rainfall (Mehta et al., 2022a).

Timely and effective visualizing is essential in providing early warnings for any disaster incident. In the case of extreme rainfalls, the prediction difficulty mainly depends on their location, intensity, and duration. Analysis of the seasonal variations of these hydro-meteorological disaster incidents, along with the seasonal weather patterns is of greater importance to have a clear understanding of the possible hazards and to develop the strategies to mitigate the risks associated with those hazards. In the literature, there are several studies (Suppiah and Yoshino, 1984; Srisangeerthanan et al., 2015; Hettiarachchi, 2018; Kumara et al., 2018; Weerasinghe et al., 2018; Disaster Management Center, 2022) carried out to analyse and predict the risks of hydro-meteorological hazards and to analyse the post-disaster damages of these hazards experienced in Sri Lanka. However, only a limited number of studies have considered the relationship between hazard events and the associated weather systems of these hazard events. Therefore, there is still a need for analysing these hydro-meteorological disaster incidents along with their associated weather systems, to have a better understanding of their formation, occurrence, and possible damages. The principal objective of the present study was to find out the seasonal variation of major hydro-meteorological disasters from 1908 to 2019 and to understand their formation and development pattern, using the historical records of associated weather systems in Sri Lanka. Further, the damages caused by these major hydro-meteorological disasters were matched with the relevant weather systems experienced during those events.

2. Materials and Methods

2.1. Study Area

Sri Lanka is an equatorial island country in South Asia, which is located between 5°55'10" ~ 9°50'06"N, and 79°31'19" ~ 81°52'36"E, the total land area being 65,610 km^2. The maximum length of the country is 432 km and the maximum width is 224 km (The World Factbook, 2023). The population of the country is 21.6 million with a population density of about 350 km^2 (The World Factbook, 2023) and in an increasing phase. The North Indian Ocean has a decisive role in the climate and influences the rainfall of the surrounding countries including Sri Lanka (Clark et al., 2000; Singh et al., 2001). Being an island country shown in Figure 2, precipitation is the way of receiving all its water and the contributions made by mist, fog, ground frost, and cloud capture are almost insignificant (Singh et al., 2001).

Figure 2. Location of Sri Lanka in the Indian Ocean.

The country is seasonally influenced by two monsoons which determine the seasonality since the temperature shows hardly any significant variation throughout the year. The South-West Monsoon (SWM) period activates from May to September while the North-East Monsoon (NEM) period is from December to February. The transition terms between two monsoon periods are called the inter-monsoon periods. The First Inter-Monsoon (FIM) period is from March to April, and the Second Inter-Monsoon (SIM) is from October to November. The main agricultural season in the country which is the Maha season is based on the NEM season; however, this is more towards the northeast of the country (considered as a drier area) (Figure 3) (Yoshino and Suppiah, 1984). However, the wet zone of the country (the southwest quadrant of the island) has ample rainfall throughout the year. In addition, the climate of Sri Lanka is dominated by the shifting of the Inter-Tropical Convergence Zone (ITCZ) and biannual migration of the ITCZ during April ~ May and October ~ November, 12 months period being separated into the four rainfall seasons as depicted. During the inter-monsoon seasons, Sri Lanka is influenced by tropical cyclones, depressions and thunderstorms associated with the migration of the ITCZ (Grodsky and Carton, 2003; Disaster Management Center, 2009).

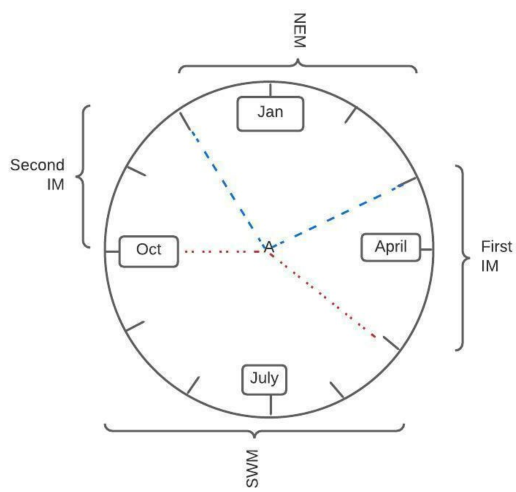

Figure 3. Annual monsoon clock of Sri Lanka [note: The climate of Sri Lanka is dominated with shifting of the ITCZ, during 12 months period into the four rainfall seasons that have been recognized as (i) First Inter-Monsoon (FIM: March to April); (ii) South-West-Monsoon (SWM: May to September, Yala season); (iii) Second Inter-Monsoon (SIM: October to November); (iv) North-East-Monsoon (NEM: December to February, Maha season)].

The specific geological formation of the island affects infiltration and landslide responses. Most of the land surface of the country is underlain by hard rocks of low permeability. This condition limits the infiltration of rainwater into the ground. Hence the percentage of rainfall that contributes to groundwater recharge is considerably low and a major part of the precipitation is converted to surface runoff (Panabokke, 1996). Land Use/Land Cover (LULC) have a distinct effect on the environment, and the changes in LULC lead to reduced evapotranspiration and heightened streamflow (Verma et al., 2023). Supplying flow in accordance with the Environmental Flow Requirements (EFR-flow required into a stream to maintain the river's ecosystem) ensures that a sufficient amount of water is delivered to the stream to maintain ecological integrity to prevent future degradation of the river (Umrigar et al., 2023).

The runoff from (higher rainfall) wet zone catchments is above 70% of the precipitation volume, while for (lower rainfall) dry zone catchments it is 20 to 30%. The average runoff from the entire island is around 45% (Chithranayana and Punyawardena, 2014). Availability of runoff has given rise to a dense dendritic stream network, creating a landscape driven by gullies, ravines, and closely spaced streams (Madduma-Bandara and Pathirana, 2000). Accordingly, Sri Lanka has 103 separate natural streams in a radial pattern, which originate from the central highlands.

2.2. Historical Records of the Hydro-Meteorological Hazards in Sri Lanka

Among the different types of hydro-meteorological hazards, floods have been the most frequent and common natural disaster in the past years, accounting for more than 50% of the natural hazard incidents in Sri Lanka (Edirisooriya, 2019). According to the statistics, Colombo, Gampaha, Kalutara, Ratnapura, Galle, and Matara Districts are affected by floods during the SWM. NEM mostly floods occur the parts of Ampara, Batticaloa, Trincomalee, and Polonnaruwa Districts. The major flood and heavy wind incidents experienced from 1907 to 2020 are tabulated in Table 1. Out of these flood records presented in Table 1, nine flood events have occurred during the SWM and eight events have been recorded during the First-IM. Only two major floods have occurred in the NEM. Further it represents a summary of the features including the origin and movement of weather systems that crossed or were in the vicinity of Sri Lanka for the studied time period.

2.3. Data Availability

The climatic data were obtained from the Department of Meteorology, Sri Lanka as stated in Table 1. The Disaster Information Management System database (DESINVENTAR) of Sri Lanka, developed by the Disaster Management Centre (DMC) with the support of the Disaster Information Management Program of UNDP and the UNDP Regional Centre in Bangkok (RCB), was also used. In addition to these, reanalysis data (from the JRA55 reanalysis data constructed by the Japan Meteorological Agency (JMA)) were used in identifying the circulation patterns associated with the weather systems. Details of the disaster impact during the four seasons are given in Tables S1 ~ S4 in the Supplementary Material.

2.4. Overall Methodology

Historical flood and cyclonic incidents are a good source of information to map the hydro-meteorological disasters and their associated weather systems. These disaster incidents were

Table 1. Major Flood and Heavy Wind Incidents Experienced by Sri Lanka from 1907 to 2020 and Features of the Weather Systems 1960 onwards That Crossed or Were in the Vicinity of Sri Lanka (Lewangamage et al., 2009; JICA, 2017; Desinventar, 2022)

Year	Month-Day	Period	Origin		Movement		Crossed	I*	II*	III*
			ON	OE	From	To				
1907	Mar.	FIM								
1922	Nov.	SIM								
1930	Oct.	SIM								
1937	May	SWM								
1940	May	SWM								
1947	Aug. 12 ~ 15	SWM						O	O	
	Oct.	SIM							O	
1952	May								O	
	Oct.								O	
1955	Oct.								O	
1957	Dec. 20 ~ 26	NEM						O	O	
1963	Oct.								O	
1964	Dec. 23 ~ 26	NEM	4.9	93	E	W/WNW/NW	C			
1966	Oct./Nov.	SIM							O	
1967	Oct. 1/Dec.	SIM							O	
1969	Dec. 29 ~ 30	NEM						O		
1971	Sept.								O	
1975	May								O	O
1978	May 10 ~ 15	SWM								
	Nov. 23 ~ 24	SIM	6.5	92.5	E	NW/WNW/NW	C	O		
1984	May 24	SWM								
1989	May 30 ~ June 4	SWM						O	O	
1992	Nov.	SIM	7.5	87.2	E	W/WNW/NW	C	O		
1993	May 21 ~ 29	SWM						O		
	Oct.	SIM						O		
1994	Nov.	SIM						O		
2000	Dec. 25	NEM	7.5	90	E	W/WSW/WNW	C	O		
2003	May 13 ~ 18	SWM	6.0	90.5	E	NW/Northerly	DNC	O		O
2004	Sept. 16 ~ 18							O		O
2005	Nov. 19 ~ 21	SIM						O		O
2006	June 19 ~ 21							O		O
2007	Dec.	NEM						O		O
2008	Apr. 2 ~ May 1	FIM						O		O
	May 30 ~ June 1	SWM						O		O
	Nov.	SIM						O		O
2010	May 15 ~ 18	SWM	9.8	90.4	E	NW/Northerly	DNC	O		O
	Nov. 10 ~ 11	SIM						O		O
2011	Dec. ~ Jan. 12	NEM	9.2	88.3	E	N/W/NW	DNC	O		O
2014	Dec. 14 ~ 19	NEM						O		O
2016	May 14	SWM						O		O
2017	May 18 ~ 19	SWM								O
2018	May 19 ~ 26	SWM								O
2020	Nov. 28 ~ Dec. 3	SIM					C			O

Note: I*: Refer to Hydrological Report of Hettiarachchi (2016); II*: Refer to "Country report" of Fernando (1999); III*: Recent events recorded by Department of Meteorology, Sri Lanka.

traced mainly based on the number of affected people, the severity of the damage and several other parameters using historical data. As it shown in Figure 3, these data were categorized according to the annual Monsoon Clock. The data on hydro-meteorological hazards faced by Sri Lanka from 1908 to 2019 were collected from the literature and Desinventar database on the past disaster incidents from 1974 to date. Before 1974, only the major flood and cyclones incident records were available. These include the date of occurrence, affected area (District, Divisional Secretary Division), Village level (Grama Niladari-GN Division), number of affected people and housing, and fatalities. Those Incidents were further categorized and tabulated with relevant streamline anomalies, accumulated rainfall, and wind speed.

Accumulated rainfall (mm) and streamline anomalies were collected from the meteorological observations and analysed to understand the formation and development patterns of weather systems. Then, these collected data were verified using satellite images and JRA55 reanalysis data. However, these reanalysis data are generated by feeding several newly available and improved past ground and satellite observations into a data assimilation (DA) system, which uses a global numerical weather prediction model (Dube et al., 1985; Chittibabu et al., 2002; Dube et al., 2004). Since the satellite images became available after 1960 and regular Radiosonde observations began on a global basis in 1958, the JRA55 reanalysis data is available only after 1958 (Kobayashi et al., 2015; Ai and Qian, 2020).

The accurate prediction of river discharge is an important factor in improving water resource management (Roushangar et al., 2021). Machine learning models have been applied in various domains, for water resource management and predicting river inflow accurately for making informed decisions regarding water allocation, flood management, and hydropower generation (Kumar et al., 2023a). Hydrological vulnerability for flooding was identified with the use of the above data together with the streamflow records and the hydrological model outputs. As the final step, computational framework reports were developed for the frequently flooded river basins (Kelani, Kalu, Deduru-Oya, Nilwala, Mahaweli, and Malwathu-Oya basins). Figure 4 showcases the flowchart for the overall methodology.

Hydro-meteorological parameters (air temperature, relative humidity, precipitation, wind speed, wind direction atmospheric pressure, solar radiation, potential evapotranspiration, soil moisture, stream flow) are essential for further studies in various applications, including weather forecasting, agriculture, water resource management, and climate studies. Monitoring and understanding of these parameters help in making informed decisions related to water availability, flood forecasting, drought management, and overall environmental sustainability.

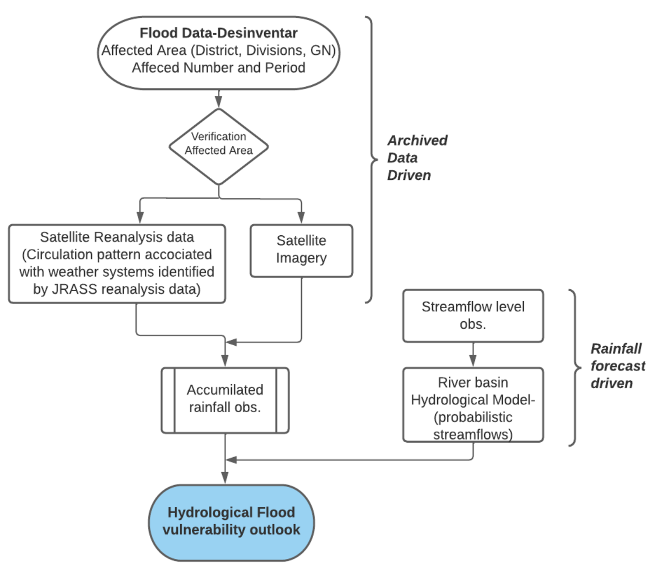

Figure 4. Hydrological outlook and the methodology used in the study.

Understanding some key assumptions, it is crucial for developing effective strategies for disaster risk reduction, and early warning systems, to mitigate the impact of hydro-meteorological disasters and underpin the scientific and policy frameworks. Meteorological parameters, play a crucial role in the formation and intensification of weather systems that can lead to disasters. Hydrological processes, including rainfall, runoff, soil moisture, and river discharge, are interconnected and influence the occurrence and magnitude of floods, landslides, etc. Sri Lanka, experiences distinct seasonal patterns, such as monsoons, which significantly influence precipitation and weather-related hazards. Disaster risk reduction strategies should address social and economic vulnerabilities, promote community resilience, and ensure that the most vulnerable populations are adequately prepared for and protected during disasters.

3. Results and Discussions

Monsoonal and convectional weather systems formed in the Bay of Bengal (BoB) account for a major share of the annual rainfall of Sri Lanka. The average annual rainfall varies from 900 mm (Maha-Lewaya, Hambantota South-eastern lowlands) to over 5,500 mm (Kenilworth Estate, Ginigathhena south-western slopes of the Central Highlands). Warm and dry adiabatic winds locally known as Kachchan (Yal-Hulang or Wesak hulang) blow over the dry zone as same as monsoonal wind, when the wet zone experiences Southwest Monsoon rains. The general wind speed of the Dry zone is 3 ~ 5 km/h and during this period, it may reach even 12 ~ 15 km/h (Panabokke, 1996).

Weather in Sri Lanka is characterized by two monsoon periods. However, half of the heavy rainfall occurrences are experienced in the four months of the Southwest Monsoon period. Based on the collected data, details of the hydro-meteorological disasters experienced in each monsoon season over 112 years (1908 ~ 2019) and the seasonal variation of the rainfall patterns and wind anomalies in Sri Lanka are explained below.

3.1. First Inter-Monsoon (FIM)

The first inter-monsoon is defined as the period from March to April which is the period during the Northeast and Southwest monsoon. Only 2 major events have been recorded during the first inter-monsoon period in the last 113 years and recent 30-year rainfall and average normal wind pattern shown in Figure 5. As mentioned in the methodology section, the data collected from DESINVENTAR were categorized according to the annual monsoon clock (Tables S1 ~ S4).

3.2. South-West Monsoon (SWM)

When the ITCZ (Inter Tropical Convergence Zone) moves toward the north side of the equator, the southerly wind tends to blow, and this is called the "South-West Monsoon season". During the Southwest Monsoon, moist winds blow from the Indian Ocean towards Sri Lanka, resulting in abundant rainfall across the south-western and central regions of the country. The presence of central mountains in Sri Lanka plays a crucial

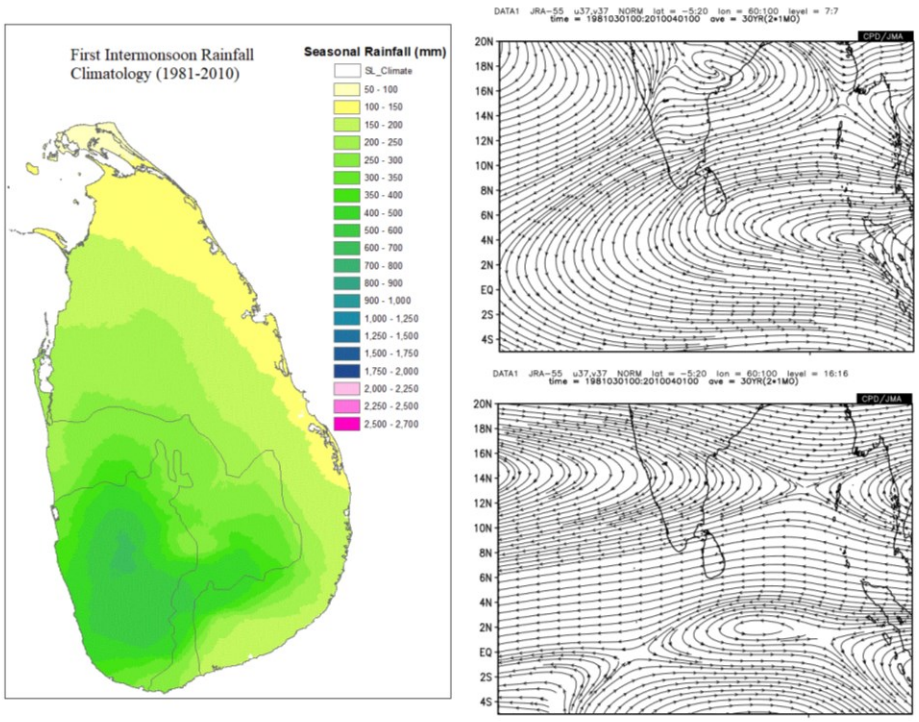

Figure 5. The 30-year (1981 ~ 2010) average long-term climatological pattern of first inter-monsoon rainfall and average normal wind pattern.

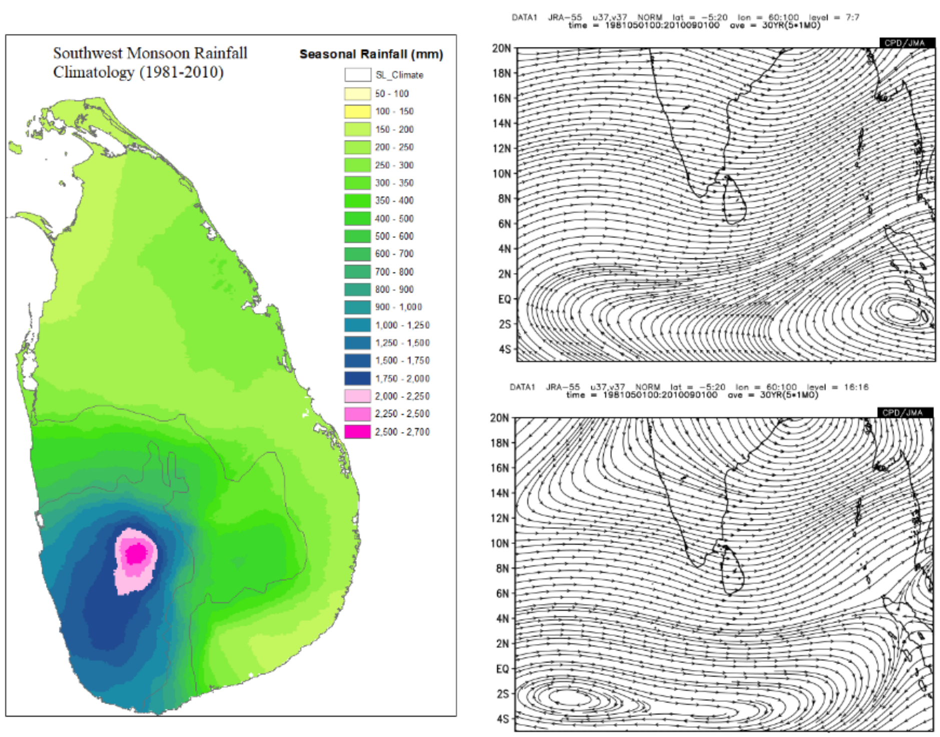

Figure 6. The 30-year (1981 ~ 2010) average long-term climatological pattern of south-west-monsoon rainfall and average normal wind pattern.

role in influencing the distribution and intensity of rainfall during the Southwest Monsoon. The island's topography, with its central mountain range, significantly impacts the monsoonal weather patterns.

The Southwest Monsoon winds carrying moisture from the Indian Ocean are forced to rise as they encounter the elevated terrain of the central mountains. As the air rises, it cools and condenses, leading to the formation of clouds and precipitation. This process is known as orographic lifting, and it enhances rainfall on the windward side of the mountains. As a result, the south-western and central regions of Sri Lanka, which lie on the windward side of the mountains, receive more substantial amounts of rainfall during the Southwest Monsoon. Recent 30-year rainfall and average normal wind pattern given in Figure 6.

From mid-May to September, winds originate in the southwest bringing moisture from the West Indian Ocean. When these winds encounter the slopes of the Central Highlands, they unload heavy rains on the mountain slopes and the south-western part of the island. Some of the windward slopes receive up to 2,500 mm of rain per month, but the leeward slopes in the east and northeast receive comparatively little rain.

The major hydro-meteorological disasters that occurred in the southwest monsoon period are listed in Table S1. The flood from 12th to 15th August 1947, was the most destructive flood recorded in past 100 years with unusually heavy rainfall within upper catchments in the Mahaweli River basin (Highest daily rainfall Blackwater Estate 485 mm, Watawala 478 mm, Oonagaloya 475 mm, Maskeliya 462 mm, Luscombe Estate 457 mm, and Nawalapitiya 447 mm) and Kelani River-basin (Disaster Management Center, 2022).

Rainfall maxima is located along western slopes of the central highlands. East west oriented trough axis can be seen over Sri Lanka at 850 mb level. Further this trough is associated with the anomalous cyclonic circulation located in the southeast Bay of Bengal (BoB) which are located closer to Southeast and Southern coast of Sri Lanka at 700 and 500 mb levels respectively. Westward tilt of circulation centre with height. Streamline anomalies averaged for the period from 30th May to 04th June 1989 at 850, 700, and 500 mb level (Figure S1).

The flash flood in May 2003 occurred due to an outer feeder band of a tropical cyclone in the Bay of Bengal, which produced the worst flooding in 56 years. Maximum sustained winds of 140 km/h on 13th May 2003, making it a very severe cyclonic storm with prolonged precipitation. It produced torrential rains across southwest Sri Lanka, while stationary in the central Bay of Bengal (Department of Meteorology, Sri Lanka). A station at Ratnapura recorded 345.2 mm of rainfall in 24 h on 17th May 2003. In south-western Sri Lanka, the rainfall caused flooding and landslides that damaged 24,750 homes and affected 32,426 others houses, displacing about 800,000 people. Overall damage totalled about $135 million (2003 USD) and there were 260 deaths. The accumulated rainfall and the streamline (low pressure) anomalies averaged at 850 mb (millibars) and 500 mb levels are given in Figure S2.

A tropical depression was developed in the southwest Bay of Bengal during the period from 16th to 18th September 2004. When a tropical depression moves to the west direction of the Bay of Bengal, it initially brings a southerly wind to Sri Lanka. But as it approaches Sri Lanka, the wind direction changes from the southwest to the northeast, resulting in heavy rains in the eastern part of Sri Lanka. Based on the Figure S3 of the Supplementary Material, there is an anomalous southwest-northeast oriented trough at low levels across Sri Lanka providing favourable conditions for cloud formation.

The 2016 flood originated with an atmospheric disturbance in the Bay of Bengal. The Figure S4 shows 2016 wind "anomaly", which is the departure of the climatology. Mean wind pattern shows formation of low-level disturbance in north Bay of Bengal at low levels and east central Bay of Bengal at mid-levels creating anomalous southwest-northeast oriented trough across Sri Lanka in low and mid-levels of the atmosphere providing favourable conditions to form multiple thunderstorms.

Streamline anomalies averaged for the period from 28th April to 1st May 2008 at 850 mb (millibar) level, 700 mb level, and 500 mb level, and the accumulated rainfall during this period is given in Figure S5. The rainfall maxima are located on western slopes of the central highlands. Strengthening of southwesterly flow with the convergence of cross-equatorial flow due to the depression type disturbance in BoB is evident in the 850 mb level. Northeast-southwest oriented trough axis can be seen over Sri Lanka at 700 mb level. Further, this trough is associated with the anomalous cyclonic circulation located in the BoB. Strengthening of southwesterly flow associated with the anomalous cyclonic circulations is also evident at 500 mb levels. According to the wind analysis of the 2008 May flood events, anomalous wind convergence is apparent to the west of Sri Lanka at low levels and an anomalous north-south oriented trough is evident over Sri Lanka at mid-levels.

A spell of extremely heavy rain and multiple thunderstorms associated with a feeder band of moisture entering the tropical cyclone "Laila" from the southwest caused very heavy rainfalls from 15th to 18th May 2010. It is obvious that the rainfall maximum is located in the low-lying areas of the western and south-western coast. Northwest-southeast and southwest-northeast oriented low-level trough (at 850 and 700 mb levels, respectively) extended from the cyclonic circulation at the Bay of Bengal over Sri Lanka provided rising motion and positive vorticity. High amounts of low-level and middle-level moisture together with rising motion provide a favourable environment for the occurrences of excessive rainfall over the south-western parts of Sri Lanka. The west-south-westward tilt of circulation centre with height is evident (Figure S6).

The analyses suggested that an enhancement of southwesterly wind flow over Sri Lanka, associated with anomalous cyclonic circulation located in the Bay of Bengal at low levels (850 mb) over most flood events occurred in the month of May 2017. Southwest-northeast oriented mid-level troughs (at 500 mb) extended from the cyclonic circulation in the Bay of Bengal provided favourable conditions in both uplift and positive vorticity. High amounts of low-level and middle-level moisture together with the uplift provided a favourable environment for excessive rainfall over the south-western parts of Sri Lanka (Figure S7).

Floods resulted from a heavy southwest monsoon, beginning around 18th to 19th May 2017. Flooding was worsened by the arrival of the precursor system to cyclone Mora, causing flooding and landslides throughout Sri Lanka. The floods affected 15 Districts, killed at least 208 people, and a further 78 people were missing. 698,289 people have been displaced due to the floods; while 11,056 houses were affected, and another 2,093 houses were partially damaged. Severely affected Provinces were, Western, Sabaragamuwa, Southern and part of Central Province. Flooding of the Kalu River also triggered several mudflows (Agalawatte in Kalutara District), reporting 47 deaths and 62 people missing.

The floods and landslides in 2018 caused by an annual heavy southwest monsoon beginning around 19th May, affected 19 Districts, killed at least 21 people, affected 150,000 people and 23 people were missing. Deaths were due to lightning, floods, drowning and fallen trees. The DMC report claimed about 400,000 people have been displaced to safer locations. About 105 houses were reported to have been fully damaged and over 4,832 houses have been partially damaged (Figure S8).

3.3. Second Inter-Monsoon (SIM)

The disaster incidents recorded in the second inter-monsoon are presented in Table S2 and recent 30-year rainfall and average normal wind pattern shown in Figure 7.

The 1967 flood incident occurred during the second inter-monsoon season. Figure S9 represents the streamline anomalies on 1st October 1967 at low levels (850 and 700 mb) and mid-level (500 mb) of the atmosphere. It is clearly evident that anomalous twin vortices, one located over Sri Lanka and the other located over Southwest BoB at all 3 levels. There is no tilt in the circulation centre with height and the circulation centre located over the West coast of Sri Lanka provides a favourable environment for the occurrences of excessive rainfall over western parts of Sri Lanka with high positive vorticity and strong rising motion.

1978 severe flood event occurred due to a tropical cyclone, that crossed the Sri Lanka's east-coast near Batticaloa, on the night of 23rd November 1978. Initially, it was developed as a cyclonic storm near (8º N, 91º E) on 20th and intensified further into a severe cyclonic storm on 21st when it was centred near (7.5º N, 88.5º E). The storm progressively intensified further and crossed the Sri Lanka coast near Batticaloa on 23rd night. After the landfall, the system weakened into a tropical storm and crossed the Gulf of Mannar into southern India on 24th November. The anomalous cyclonic circulation over Sri Lanka is apparent at low levels (850 mb) and mid-levels (500 mb) as shown in Figure S10.

A Landslide occurred on 29th October 2014, 7:30 am at Miriyabedda and Haldummulla in Badulla District, killing 16 people. Continuous rainfall for three consecutive days, triggered the landslide with widespread floods. The cyclonic storm, "Burevi" originated as a low-pressure area that developed over South Andaman Sea and adjoining areas on 28th November 2020. It intensified into a depression in the early morning of 30th November over Southeast Bay of Bengal (BoB). It has further intensified into the cyclonic storm, "Burevi" over southwest BoB in the evening of 1st December 2020. Moving across northern parts of Sri Lanka, it emerged into the Gulf of Mannar in the morning and lay cantered close to Pamban, India around noon of 3rd December. The system remained stationary over the Gulf of Mannar close for 36 hours, before gradually weakening into a well-marked low-pressure area around noon of 5th December. Even after weakening into a low-pressure area, the system significantly influenced the weather over the Northern Province bringing nearly 200 mm of rainfall on 6th December 2020 (Figure S11).

3.4. North-East Monsoon (NEM)

Hydro-meteorological disaster incidents that occurred during the Northeast monsoon are discussed in this section based on the collected data on disaster incidents and the weather records and recent 30-year rainfall and average normal wind pattern shown in Figure 8.

The disaster incidents recorded in the second inter-monsoon are presented in Table S3. For flood events that occurred during December 1957, December 2014, and February 2011, anomalous cyclonic circulation to the south-southeast of Sri Lanka in the southwest Bay of Bengal was apparent at low levels (850 mb) and mid-levels (500 mb). The low-level moisture transport is enhanced by this vortex circulation and strong low-level moisture flux convergence over eastern parts of Sri Lanka by strong cross-equatorial moisture flux transportation at low and mid-levels (850 and 500 mb levels). The moisture convergence in the northeast part is related to the interaction of the low-level north-easterly monsoon flow with the terrain effects.

By end of November 1957, irrigation tanks reached spilling level and on 17th of December eastern torrential rainfall (daily average 400 mm) expanded to North and Central highlands, leading to flooding (some locations in Anuradhapura, Polonnaruwa, Vavuniya, Mannar and Puttalam Districts submerged up to over 30 ft. Landslides were reported in Kurunegala, Matale, Kandy, Nuwara-Eliya and Badulla Districts). On 23rd ~ 26th December 1957, 171 deaths, damages to 65,000 houses and damages to 35 major irrigation works and 53 minor irrigation works and breaching of 1,300 village tanks were reported (Srisangeerthanan et al., 2015). According to the wind analysis of the 1957 December flood event, anomalous wind convergence is apparent over the northern part of Sri Lanka at low and mid-levels (Figure S12).

The Colombo floods in 2010 were an isolated incident that took place from 10th November to approximately noon on 11th November 2010, in Colombo. As a low-pressure area developed over the city, up to 490 mm of rain fell during the short period of 15 hours (overnight), causing widespread damage and flooding in the area; the highest amount of rainfall in 18 years. Heavy rains displaced over 260,000 people in Colombo and the suburbs. Heavy rains also submerged the parliament in Kotte under 4 ft of water and damaged 257 houses, while completely destroying 11 houses while the death toll was 1.

Due to the January 2011 flood event, Eastern (Batticaloa, Ampara and Trincomalee Districts), Northern and Central Provinces got affected. According to the records, 23 died and over

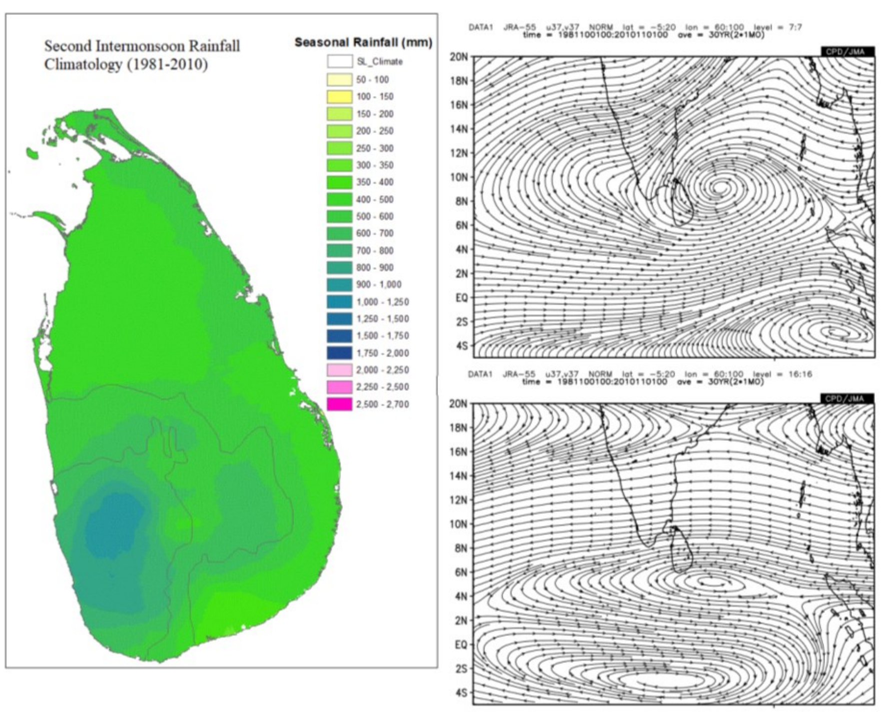

Figure 7. The 30-year (1981 ~ 2010) average long-term climatological pattern of second inter-monsoon rainfall and average normal wind pattern.

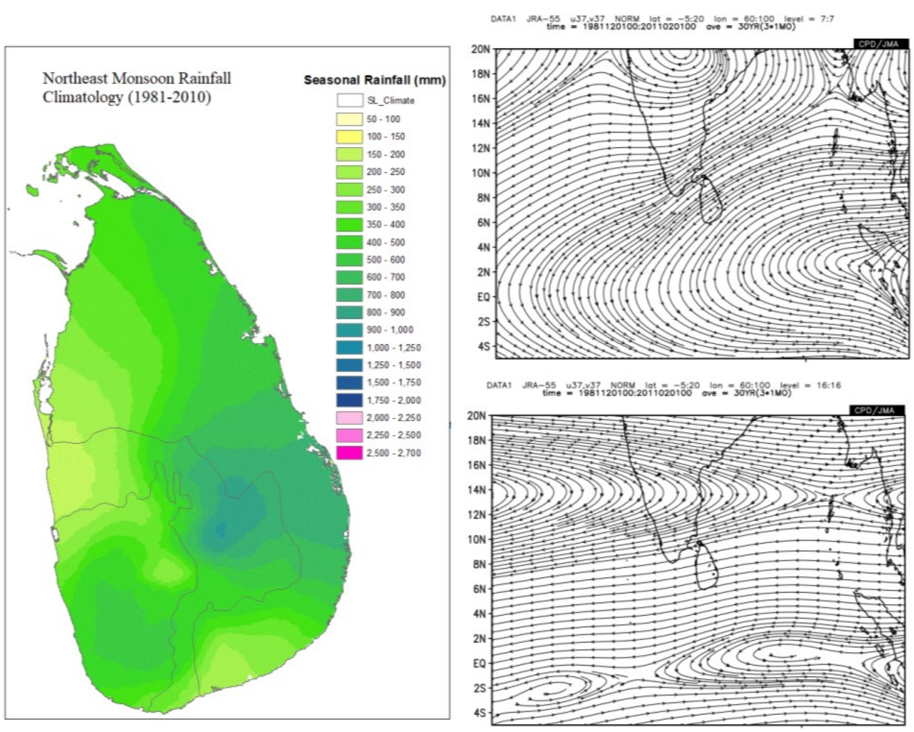

Figure 8. The 30-year (1981 ~ 2010) average long-term climatological pattern of north-east-monsoon rainfall and average normal wind pattern.

541,000 persons were displaced and had to take shelter in 275 safety centers (Figure S13). Accumulated Rainfall (mm) for the period from 19th to 21st November 2005 and Streamline anomalies are shown in Figure S14.

3.5. Comparison of Affected River Basins

According to the records of hydro-meteorological disasters that occurred during the past 112 years from 1907 to 2019, the highly affected river basins were identified as Kelani, Kalu, Gin, Nilwala, Ma-Oya and Mahaweli (Soolangaarachi and Vithanage, 2005). The occurrences of hydro-meteorological disasters in each river basin are discussed in this section based on the affected river basin while the map in Figure 9 depicted frequent flooding river-basins in Sri Lanka.

Gin Ganga river basin is located in the Southern part of the country with a catchment area of 932 km^2 and an average annual runoff of 1,268 MCM (Wickramaarachchi et al., 2012). The five major incidents that affected the basin, are namely the floods of May 2017, May 2008, May 2003, May 1978 (Figure S15) and May 1993. These incidents all occurred in May and June, close to the start of the southwest monsoon season, although the analyses suggest that rainfall durations varied significantly, from about 2 ~ 3 days in 2003 and 2008 to 8 ~ 9 days in 1993, the end date for each incident generally corresponded to the days of peak flooding. Although in one case (2008) it was slightly earlier and in another (1978) heavy rainfall continued after the flood peak had been reached.

All five incidents discussed above occurred in the south-western part of Sri Lanka reaching as far north as Colombo in

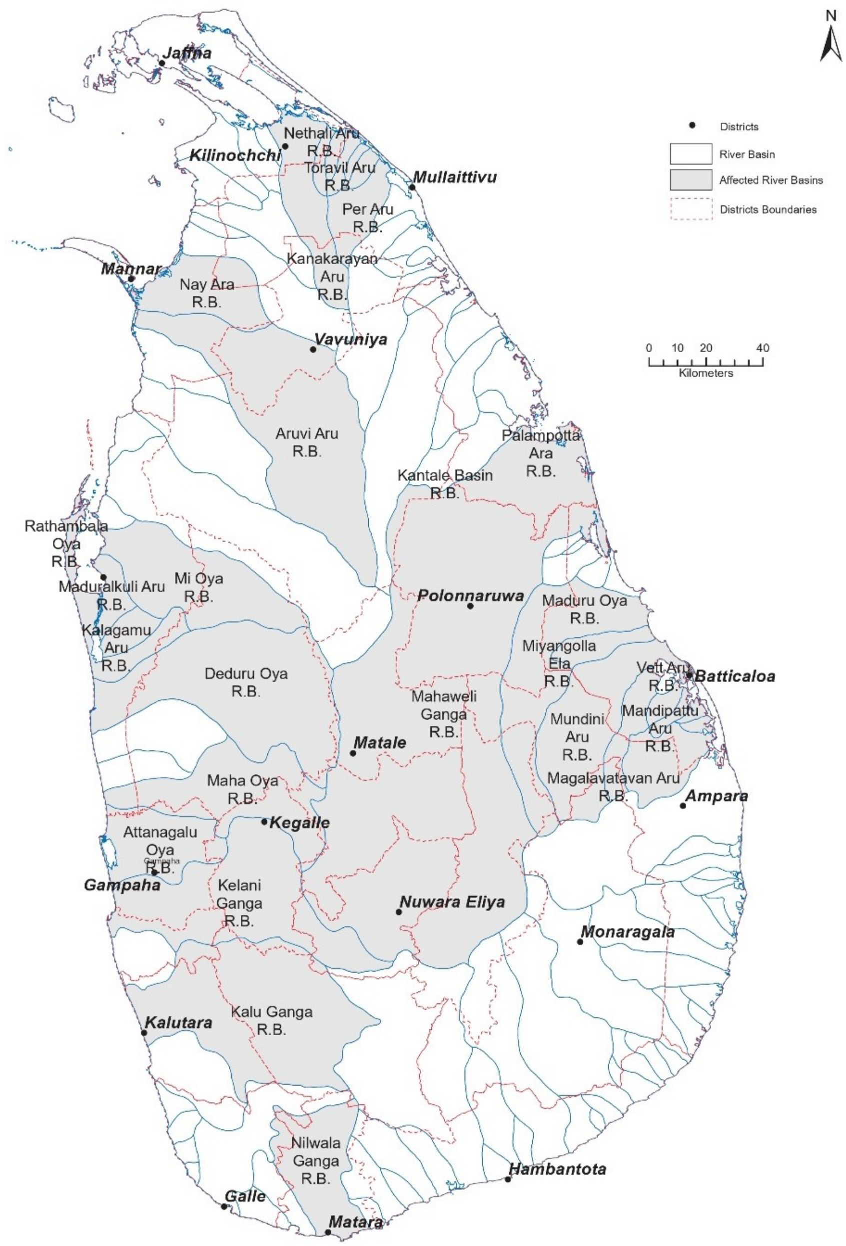

Figure 9. The 25 administrative Districts, 103 river basins and provincial boundaries of Sri Lanka (note: frequent flooding river-basin areas are highlighted; namely, basins or rivers Kelani, Kalu, Deduru-oya, Nilwala, Mahaweli and Malwathu-Oya).

some cases with, as expected, the highest rainfall in regions with higher elevation. However, for three of the incidents, rainfall in the coastal regions of the west was of a similar magnitude and extended to the southern coast in the May 2017 incident. In general terms, the extent of the highest rainfall roughly corresponded to the boundaries of the 'Wet Zone', with the 2017 incident covering the greatest area and the 2003 and 2008 incidents the most localized. As noted earlier, some insights into the meteorological causes of each incident can be obtained by examining stream flow anomalies at different levels.

With the exception of the May 1993 incident (Figure S16) the analyses suggest that the heavy rainfall was due to an enhancement of the southwesterly wind flow over Sri Lanka associated with anomalous cyclonic circulation located in the Bay of Bengal at a low level. At higher levels, southwest-northeast oriented mid-level troughs extended from the cyclonic circulation to provide favourable conditions for both uplift and positive vorticity. As a result, the large amounts of low- and middle-level moisture together with the uplift provided a favourable environment for excessive rainfall over the south-western parts of Sri Lanka. In contrast, for the May 1993 incident, anomalous wind convergence is apparent to the west of Sri Lanka at low levels and an anomalous north-south oriented trough is evident at mid-levels.

Similarly, the Nilwala river basin which is located in southern Sri Lanka was mostly affected by the same disaster incidents, as for the Gin River basin, which are the floods of May 2017, May 2003, May 1978, and May 1993. All these disaster incidents occurred in the first month of the southwest monsoon season. The effect of weather systems can be obtained by analyzing the meteorological features of each incident with the use of streamline anomalies presented in the previous subsections and in Supplementary Material.

Mahaweli is the longest river in Sri Lanka (335 km) and has a total catchment area of about 10,448 km^2 (Shelton and Lin, 2019). From the historical disaster incidents, the three major incidents that affected the basin, are the floods of December 2014, November 1978, and December 1957. These incidents all occurred in November and December; that is, towards the end of the second inter-monsoon period or early in the northeast monsoon season. Based on the analyses, though, the duration of heavy rainfall varied significantly from about 2 days in 1978 to 6 ~ 7 days for the other two incidents, the end date for each incident generally corresponded to the days of peak flooding. Although in one case (1978) was slightly before the peak had been reached.

The 1957 and 2014 incidents were remarkable for the extent of heavy rainfall which affected all but the south-western part of Sri Lanka, with a localized region of heavy rainfall even there in the 2014 incident. In contrast, the 1978 incident was generally more concentrated in higher elevation regions. In general terms, the two more severe incidents affected both the "Dry Zone" and "Intermediate Zone" climate regions whilst the 1978 incident was primarily in the "Intermediate Zone".

For the 1957 and 2014 incidents, the analyses suggest that, in the south-west Bay of Bengal, anomalous cyclonic circulation to the south-southeast of Sri Lanka was apparent at low levels (850 mb) and mid-levels (500 mb). As a result, low-level moisture transport was enhanced by this vortex circulation and by convergence over eastern parts of Sri Lanka linked to strong cross-equatorial moisture flux transportation at low and mid-levels. The moisture convergence in the northeast was related to the interaction of the low-level North-easterly monsoon flow with the terrain.

In contrast, the 1978 November flood incident was due to a tropical cyclone. Initially, it developed as a cyclonic storm near (8º N, 91º E) on the 20th and intensified further into a severe cyclonic storm on the 21st when it was centred near (7.5º N, 88.5º E). After intensifying further, the storm crossed the Sri Lanka coastline near Batticaloa on the night of the 23rd. Following landfall, the system weakened into a tropical storm and crossed the Gulf of Mannar into southern India on 24th November 1978. The anomalous cyclonic circulation over Sri Lanka is apparent at both low levels (850 mb) and mid-levels (500 mb).

The main hydro-meteorological disaster incidents which affected the Malwathu-Oya River basin are the floods of December 2014, February 2011 (Figure S17), December 1967 (Figure S16) and December 1957. Three of these incidents occurred in December around the start of the northeast monsoon but the 2011 incident was much later in the season; however, based on the analyses, the durations of heavy rainfall were similar, and in the range of 4 ~ 7 days. The end date for each incident generally corresponded to the days of peak flooding (although in one case (1967) was slightly before the peak had been reached). 1957 and 2014 incidents were remarkable for the extent of heavy rainfall which affected most part of Sri Lanka, except the southwest. The two other incidents, although still widespread, were more concentrated in the eastern part of the country and in the north as well in 1967. In general terms, the first two incidents affected both the "Dry Zone" and "Intermediate Zone" climate regions, whilst the remaining incidents were primarily in the "Dry Zone".

For the 1957, 2011 and 2014 incidents, the analyses suggest that, in the southwest Bay of Bengal, anomalous cyclonic circulation to the south-southeast of Sri Lanka was apparent at low levels (850 mb) and mid-levels (500 mb). As a result, low-level moisture transport was enhanced by this vortex circulation and by convergence over eastern parts of Sri Lanka linked to strong cross-equatorial moisture flux transportation at low and mid-levels. The moisture convergence in the northeast was related to the interaction of the low-level north-easterly monsoon flow with the terrain. In contrast, for the December 1967 incident, the heavy rainfall seems to have been due primarily to anomalous wind convergence at both low and mid-levels over the northern part of Sri Lanka (Figure S18).

3.6. Classification of Floods Based on A Severity Index

Based on the simulated models of worst-case scenarios, floods for a particular river basin were classified based on a severity index, defined using three indicators including the percentage of population affected by the flood, the percentage of the flooded area in the river basin and the flood retention period.

Table 2. Definition of Flood Severity Index for Flood Classification in a River-Basins, Sri Lanka Based on Past Experience

Parameter	Level I	Level II	Level III	Level IV
	Minor	Major	Severe	Enormous
Affected Population in River-Basin (Table 3)	< 1%	5%	< 10%	> 10%
Flooded Land Area in River-Basin	< 1%	1 ~ 5%	< 10%	> 10%
Flood Retention Period	< 12 hrs	12 ~ 36 hrs	36 ~ 72 hrs	> 72 hrs

Table 3. Affected/Exposure Level Index to be Used to Standardize Affected Level Based on the Score Given to Four Indicators for Improve the Visualization Process [Source: Tillekaratne et al. (2021b, 2023)]

No.	Affected Indicators	Affected/Exposure Level		
		Level I	Level II	Level III
1	Indirect Losses			
	Access Blocked/Isolated	1	1	1
	Diseases	1	1	1
	Environmental Damage	1	1	1
2	Economic Damage			
	Livelihood (Crop/Livestock Damage)	0	1	1
	Business Damage	0	1	1
3	Physical Damage			
	Non-Structural Damage to Contents	0	1	1
	Structural (House) Damaged (Fully/Partially)	0	0	1
4	Human-Social Damage			
	Injuries	0	0	1
	Fatalities	0	0	1
Total		3	6	9

When the water level reached the "Severe-flood" situation, buffer zones also got inundated (Table 2).

The severity of the damages experienced by the affected families was categorized using nine indicators that represent the economic, social, physical, and indirect exposure of the affected families. The categories were decided based on the total score gained. Affected families are to be categorized based on the score of the exposure as shown in Table 3. It is shown in Figure 10 that a vulnerable village/GN Division-1 (with 02 census-blocks), during the Severe-Flood situation. Buffer Zone-I Families are in Affected Level-III; Buffer Zone-II Families are in Affected Level-I and II.

As the smallest, Micro-Geographic Incident Response Unit (MG-IRU) census block is suggested to be granted the decision-making power to connect the institution and community in the disaster risk management process smallest administrative unit to function as local early warning systems. Watershed as a naturally occurring hydrologic unit, which contributes storm runoff to a single waterway, classified on the basis of its geographical area (Mehta et al., 2022b). Flood is the most frequent in Sri Lankan disaster context. River-basin and sub-river-basin findings reveal significant differences in stream density at the sub-basin level (Tillekaratne et al., 2021c). It indicates that the flood risk management approach through sub-basin geographical units based on natural drainage basins would help the MG-IRU to forecast their flood. However, for this to work effectively it is needed to increase the density of the rainfall network to correct rainfall forecast bias to account for the spatial variability at that scale, especially in urban areas. Srikantha et al. (2019) placed real-time weather stations at 3 km intervals in Colombo and it showed a high variation of rain, especially during extreme events (Dantanarayana et al., 2020). This could be another area for future research. Different models have been developed to predict the effects of climate and land cover change on the hydrological process. Semi-distributed models allow the spatial variation of the parameters by dividing the basin into a number of sub-basins (Zahabiyoun et al., 2013). The use of deep learning (Deep Learning and Machine learning are two subfields within the artificial intelligence) in flood forecasting and management has the potential to revolutionize the field by increasing the accuracy and timeliness of flood predictions (Kumar et al., 2023b). To increase the precision and effectiveness of flood models, emerging technologies such as remote sensing, cloud computing, and artificial intelligence are essential (Kumar et al., 2023c). The present study analyses the extreme events and climate systems associated with them. It is slightly different from analysing the weather patterns based on some classification, identifying extremes and then checking how they match with observed/experienced disaster events. Such an approach can be used to set up operational weather forecasting systems where forecasting model parameters are dynamically selected according to weather type (Johns et al., 1985).

These Physical demarcations of the affected area are to be used towards the effective utilization of land and water resources adjacent to the "identified vulnerable river". Then the residents and visitors of such areas can calculate their risk andwhether their houses and properties are vulnerable to the future cases of flooding and take necessary precautions. For example, Timely Early-Warning (EW) at the grass-roots level.

Sending EW text messages can be explored, as in Tsunami warnings in Sri Lanka, New Zealand and many other countries (Hsiao, 2012; Gunasekera et al., 2018; India Meteorological Department, 2020; Leitmaan, 2021).

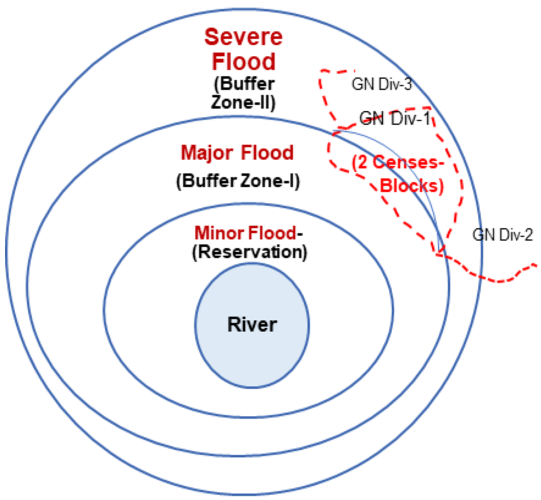

Figure 10. Conceptual demarcation of affected river-basin (note: Buffer-Zone-I not for Permanent Buildings; for example, during the Severe-Flood in GN Div-1, Buffer Zone-I Families are in Affected Catogory-3; Buffer Zone-II Families are in Affected Catogory-1 and 2).

4. Conclusions

During the past 112-year period (1907 ~ 2019), only 11 cyclonic storms and 5 severe cyclonic storms crossed the coasts of Sri Lanka. During the months of November to December, depressions forming in the Bay of Bengal tend to intensify into cyclonic storms and move closer to Sri Lanka bringing much rain and wind; but chances of landfall along the east coast are low. Although the frequency of landfall of cyclonic storms in Sri Lanka is not high, the coastal regions suffer in terms of loss of life and property caused by the surges. The number of causalities would be much lower if these surges could be predicted reasonably well in advance allowing effective warnings and evacuations in the threatened areas. The present analysis approach can provide valuable insights to improve such systems. Based on the seasonal analysis of the disaster incidents and the associated weather systems, the following conclusions were made.

The first half of the Southwest monsoon season (May ~ June) In accordance with the northward movement of the ITCZ (Inter Tropical Convergence Zone), the monsoon trough is generated and goes up continuously toward the north side. Along the monsoon trough, atmospheric disturbance is generated, which causes the Southwest monsoon, and the warm and humid southwest wind brings heavy rainfall, specially to the southwest sector of Sri Lanka.

The second half of the Southwest monsoon season (July ~ September) The ITCZ goes up further north and is blocked by Himalaya Mountains which is often know as monsoon trough. From July to September, heavy rainfalls are often associated with cross interception of monsoon flow with equatorial waves but we do not have enough analysis to include that in the conclusion.

During the second inter-monsoon season (October ~ November), the Intertropical Convergence Zone (ITCZ) moves southward, crossing over Sri Lanka. This movement, coupled with atmospheric disturbances, low-pressure areas, and tropical depressions originating within the ITCZ and in the Bay of Bengal, results in heavy downpours across Sri Lanka. These intense rainfalls often lead to devastating floods and landslides in the region. In general, ITCZ moving down to Sri Lanka in December and the North-East monsoon season starts. Formation of low-pressure areas and tropical depression is common in the Bay of Bengal which are sometimes intensify into a cyclone, moving across Sri Lanka or moving closer to Sri Lanka like in year 2000.

Unexpected flash floods and gusty winds have caused heavy damages according to the available data. Formation and development of weather systems should be properly understood by analysing the Streamline Anomalies. Accordingly, the prediction of accumulated rainfall (mm) in the last 6 hours, would be beneficial to issue accurate early warning to the exact vulnerable location. Wind zonation maps should be updated based on the recent gusty winds, reported in several parts of the island. To minimise the confusion, classification of tropical wind extremes (Table S4) are to be visualised into the local context.

Heavy winds, lightning, floods and landslides are the possible hazards due to the discussed weather systems generated in the North Indian Ocean. The establishment of a Central Platform will be necessary for the rainfall stations to provide reliable timely forecasting and generate early warnings. Community originated Timely Response Mechanisms should be designed and should be tested in a natural desegregated geographical space. Preferably Census-Block will be selected as the smallest desegregated Micro-Geographic Incident Response Unit (MG-IRU), granting decision-making power and capacity to the Community through Disaster Risk Management (DRM) interventions, covering all sectors (e.g., Community Hazard mapping and hazard-watching practices).

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