Climatic-Geomorphological Investigation of the World's Wettest Areas around Cherrapunji and Mawsynram, Meghalaya (India)

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Abstract: This research paper comprehensively examines the climate and geomorphological features of Cherrapunji and Mawsynram, aiming to understand the factors and environmental implications of their extreme precipitation. The study investigates climatic patterns, identifies geomorphological characteristics, and explores the factors influencing the occurrence of heavy rainfall in these areas, and displays unique rainfall patterns with high precipitation levels and notable spatio-temporal variation influenced by topographic interactions. Trend analysis reveals stable rainfall conditions over the past 122 years. The shift of the world's wettest place from Cherrapunji to Mawsynram in recent decades have been attributed to various factors such as geographical location, geomorphology-local topography, LULC-human influence, rain shadow effect, and orographic lifting effects. Cherrapunji recorded maximum rainfall of 24.55 thousand mm, while Mawsynram received 26 thousand mm of rainfall in the last century. The analysis of long-term rainfall data indicates distinct dry and wet seasons, with recent trends (2000-2020) suggesting a decline in rainfall for both locations. Furthermore, extreme value analysis techniques are employed to estimate maximum rainfall for different return periods, offering insights into extreme rainfall events. The return period of one day's highest rainfall of 1340.82 mm is about 100 years. The findings contribute to our understanding of climate change impacts, support sustainable development practices, and inform strategies for water resource management and erosion mitigation in similar geographic contexts. This research enhances our knowledge of these unique regions and their significance within the broader context of global climate systems.

Key-words: Rainfall, climate change, geology, geomorphology, Cherrapunji, Mawsynram.

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1 Introduction

Cherrapunji and Mawsynram, located in Meghalaya, India, are globally recognized as the wettest regions on Earth, experiencing exceptionally high annual rainfall [1]. These areas have attracted considerable scientific interest and have become subjects of research for their unique climate-geomorphological characteristics [2]. The aim of this study is to comprehensively investigate the climate and geomorphological features of Cherrapunji and Mawsynram, with a primary focus on understanding the factors contributing to their extreme precipitation and assessing the environmental implications. The research entails analysing climatic patterns, including rainfall distribution, seasonality, and variability in the region. Additionally, a detailed examination of the geomorphological features, such as landscape morphology and geology, has been conducted. Special attention has been given to identifying the factors influencing extreme precipitation, such as monsoon dynamics, orographic lifting, local topography, and atmospheric moisture sources. The study also involved field observations and measurements of water circulation parameters and geomorphic processes in selected sites within these wettest areas [3]. Despite similarities in their location within the monsoonal circulation zone and proximity to uplifting mountains or horsts separated by active tectonic lines from subsiding forelands, Cherrapunji and Mawsynram differ in terms of substratum lithology, tectonics, and human impact reflected in land use. These variations provide an opportunity to explore the influence of these factors on the observed climate-geomorphological characteristics.

Northeast India, home to the Meghalaya plateau, is a distinct region characterized by high rainfall and complex interactions with its topography. The area experiences significant spatio-temporal variation in rainfall, making it challenging to detect trends in extreme rain events [4]. However, trend analysis indicates a stable rainfall pattern in northeast India over the past 150 years at regional, sub-division, and station levels [5]. The interaction between large-scale circulation and local topography is instrumental in determining the spatial distribution of rainfall over the Meghalaya plateau [1, 5] which serves as the first barrier for the southwest monsoon winds from the Bay of Bengal to the Himalayas. The annual rainfall distribution is controlled by the southern escarpment of the plateau, ranging from 6,000 mm in the southern foothills to 11,000-12,000 mm in Cherrapunji (1313.7 m), and Mawsynram (1401.5 m). Rainfall gradually decreases with distance from the southern edge of the plateau, reaching 2,200 mm in Shillong (1520.3 m) and 1,600 mm in Guwahati (55.5 m) in the Brahmaputra valley. The majority of the annual rainfall, about 80%, occurs between June and September. Despite covering only 2% of the Ganges, Brahmaputra, and Meghna basins, they account for about 20-25 % of the rainfall input between March and June [6]. The Meghalaya plateau contributes significantly to rainfall input between March and June, playing a vital role in the flood processes observed in Bangladesh [7].

Previous studies conducted on the Meghalaya plateau have primarily focused on the exceptional rainfall recorded at Cherrapunji, which holds the world record for high precipitation over a period of 150 years [1, 3]. Notably, between August 1860 and July 1861, Cherrapunji received a staggering 26,461 mm of rain [8]. The consensus among researchers is that orography, particularly the steep southern side of the plateau, plays a crucial role in the occurrence of such immense rainfall. However, other factors contributing to the enhanced precipitation have also been identified. These include the presence of a monsoon trough in the foothills of the Himalayas, which facilitates the lifting of southerly flow over the plateau's steep slopes [7]. Additionally, the region benefits from additional moisture extraction over the Bangladesh wetlands as maritime moisture flows into the area from the Bay of Bengal. The presence of a synoptic-scale low-pressure anomaly over Meghalaya further enhances the rainfall [9]. Recent research on Cherrapunji's stable isotopes confirms that the main source of monsoon air in Meghalaya is the Bay of Bengal, with a smaller influence from the western Arabian Sea [10]. The northern Bay of Bengal, in particular, emerges as a significant moisture source for the Meghalaya Hills.

Numerous studies have investigated the factors responsible for the exceptionally high rainfall in Cherrapunji and Mawsynram. The steep slopes of the region cause the ascent of saturated southwest winds, resulting in dynamic cooling and significant condensation [11-14]. Proximity to the transition zone between dry easterlies and moisture-laden southerlies and south-westerlies contributes to enhanced moisture availability and convergence of air masses [1, 15-17]. Morning uplift of moisture-laden air trapped within the valley leads to convective processes and rainfall [4, 18-19]. Factors like westerly circulations, atmospheric perturbations, and air mass mixing ratios also influence heavy precipitation [20-22]. Studies indicate varying trends in extreme rainfall events, with an increase in short spells of heavy rain and a decrease in moderate rain days in Northeast India [4, 23-24]. However, there are contrasting findings regarding extreme events with more than 150 mm rainfall per day [4].

2 About the Study Area

Cherrapunji and Mawsynram are globally recognized for their extraordinary rainfall and exhibit distinctive climatic and geomorphological features. Cherrapunji, located at latitude 25° 17' 27.55" N and longitude 91° 43' 59.01" E, holds the title of the world's wettest spot with an average annual rainfall of 11,430 mm, based on 122 years of data from 1901 to 2022. During the peak of the monsoon season, Cherrapunji experiences continuous rainfall for up to two weeks. Cherrapunji holds multiple Guinness World Records and in 1861, it recorded an astounding 26,000 mm of rain [25]. Mawsynram, located at latitude 25° 17' 2.44" N and longitude 91° 34' 27.75" E, is positioned at the southern edge of the East Khasi Hills, overlooking the plains of Bangladesh, and is recognized as the wettest place on Earth. Based on 48 years of data from 1975 to 2022, Mawsynram has an average annual rainfall of 11,871 mm. Remarkably, between June and August alone, an average of 3,000 mm of rain is reported.

Das [15] conducted a study on Cherrapunji's orographic features and their influence on heavy rainfall. The location of Cherrapunji on the southern slope of the Khasi hills, with an average slope ratio of 1:110 towards the southwest to southeast sector, and an elevation of 1313.7 m above sea level, contributes significantly to its rainfall [26]. Mawsynram, situated approximately 16 km west of Cherrapunji and at a higher elevation of 1401.5 m, exhibits similar orographic characteristics [26-27] (Figure 1). Additionally, Mawsynram's positioning on the edge of a narrow valley, which opens to the south and undergoes a change in direction, creates favourable conditions for convergence of maritime air during the monsoon, resulting in intense vertical currents and heavy rainfall on the surrounding hills [26]. These combined factors contribute to Mawsynram receives abundant rainfall. A list of the world's rainiest places, along with their average annual rainfall data is given in Table 1 [28].

Table 1. Rainiest Places in the World

Position	Rainiest Places	Country	Average Annual Rainfall (mm)	Sources
1	Mawsynram, Meghalaya	India	11,871	India Meteorological Department (IMD)
2	Cherrapunji, Meghalaya	India	11,430	India Meteorological Department (IMD)
3	Tutunendo, Chocó Department	Colombia	11,270	NOAA National Centers for Environmental Information
4	Mount Waialeale, Kauai, Hawaii	USA	10,272	National Weather Service, Honolulu
5	Debundscha	Cameroon	10,299	NASA Earth Observatory
6	Cropp River	New Zealand	7,470	MetService New Zealand
7	Big Bog, Maui, Hawaii	USA	6,957	

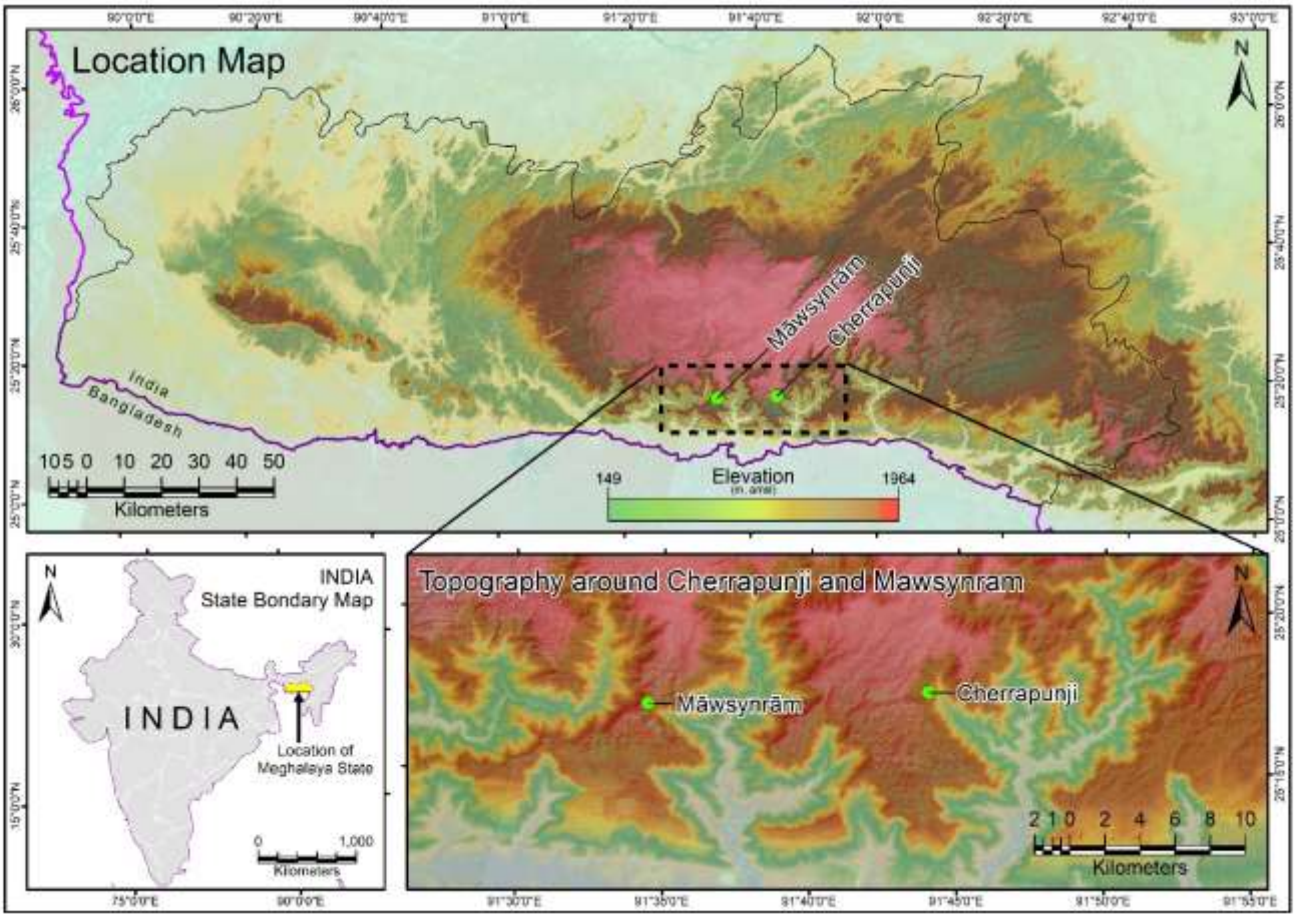

Figure 1. Location Map of the Study Area

3 Methodology

3.1 Data Collection

The initial phase of this research involves the collection of relevant data from multiple sources. Meteorological data, including rainfall records, temperature measurements, and wind data, have been obtained from reputable sources such as the National Data Centre of the Indian Meteorological Department (IMD) in Pune, the Meteorological Centre in Shillong, and the Meghalaya Planning Department in Shillong. To understand the landscape features and landforms in the study area, valuable geomorphological data and geological reports have been sourced. Furthermore, topographic maps, SRTM DEM data, and satellite imageries have been acquired to gain a comprehensive understanding of the area and facilitate updates to the geology and geomorphology of the study area. The specific data used for this research, along with their respective sources, are detailed in Table 2.

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Table 2. Data Type and their Sources

S. No.	Data Type	Period	Sources
1.	Topographical Maps	2005	Toposheet No.: 78/G, J, K, N, O; and 83/B, C Scale: 1:250,000 Source: Survey of India (SoI) Link: https://onlinemaps.surveyofindia.gov.in/
2.	Landsat Satellite Imageries	2000 2023	Landsat-5 TM Satellite Imagery Landsat-9 OLI-2 Satellite Imagery Spatial Resolution: 30 m Path/Row: 136/042, 136/043, 137/042, 137/043, 138/042 Source: USGS Earth Explorer Link: http://earthexplorer.usgs.gov
3.	Elevation information	2014	Shuttle Radar Topography Mission (SRTM) DEM Data Spatial Resolution: 30 m Source: USGS Earth Explorer Link: http://earthexplorer.usgs.gov
4.	Geology and Geomorphology	2009	Source: Geological Survey of India (GSI) Scale: 1:50,000 Link: http://www.portal.gsi.gov.in
5.	Measured Daily Precipitation Data Station: Cherrapunji	1978-2023	Meterological Observatory, Govt. of India, Cherrapunji Link: https://cherrapunjee.com/daily-weather-data/
6.	Measured Monthly Precipitation Data Station: Cherrapunji	1901-2022	Indian Meteorological Department (IMD), Pune; and IMD, Meteorological Centre Shillong Rainfall and surface temperature data collected from meterological Observatory, Govt. of India, Cherrapunji. Link: https://cherrapunjee.com/daily-weather-data/
7.	Measured Yearly Precipitation Data Station: Mawsynram	1975-2022	Meghalaya Planning Department, Shillong Link: https://megplanning.gov.in/handbook/
8.	Measured Precipitation Data Station: State Average	1901-2022	Department of Agriculture and Farmers' Welfare, Govt. of Meghalaya Link: https://megagriculture.gov.in/PUBLIC/agri_scenario_RainFallStats.aspx
9.	Grided Precipitation Data from various satellite imageries Station: Cherrapunji and Mawsynram *Note: DHI Water Data Portal (available at: https://www.flooddroughtmonitor.com/DataApp/) has integrated all grided precipitation data in the portal. We have obtained these datasets from DHI Water Data Portal.*	1981-2023	CHIRPS: Climate Hazards Group InfraRed Precipitation with Station data Spatial Resolution: 0.05°×0.05° Degree Link: https://data.chc.ucsb.edu/products/CHIRPS-2.0/
		2000-2023	GPM: Global Precipitation Measurement Spatial Resolution: 0.1°×0.1° Degree Link: https://gpm.nasa.gov/missions/GPM
		2003-2023	PERSIAN: Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks Spatial Resolution: 0.25°×0.25° Degree Link: https://chrsdata.eng.uci.edu/

It is important to acknowledge that the available measured precipitation data for Mawsynram were collected from various annual reports of the Meghalaya Planning Department. Unlike Cherrapunji, Mawsynram does not have a dedicated meteorological office or trained meteorological observers stationed in the area. Instead, the rainfall readings are taken by a peon from the Meghalaya Public Works Department who is posted there. However, the nature of his methods for measuring rainfall remains uncertain, especially when he is absent or not feeling well, as there is no provision for a substitute or clear guidelines on his approach. Despite these limitations, the peon consistently sends monthly rainfall data to the meteorological office at Cherrapunji. Due to concerns about the data's authenticity, meteorologists consider comparing rainfall between these two places to be meaningless. Ideally, Mawsynram should have its own meteorological observatory with qualified staff, similar to the one at Cherrapunji. Until then, experts argue against making such comparisons without reliable and standardized data sources.

3.2 Basic Mechanism Affecting Precipitation Clouds by Hills and Mountains

The size and shape of a hill or mountain have a profound effect on the ultimate distribution of precipitation on the ground [29]. The distribution of precipitation over and near a terrain feature is determined by a combination of microphysics, fluid flow dynamics, and thermodynamics of moist air [30]. When airflow encounters terrain, its response varies depending on several factors. In buoyantly unstable flow, convection and precipitation can be triggered as the oncoming air rises to pass over the obstacle [29, 31-32]. In a stable flow approaching a barrier, the flow's response depends on the strength of the cross-barrier airflow, the thermodynamic stability of the oncoming flow, and the height of the terrain barrier [33]. These factors can be combined into a nondimensional ratio U/Nh, where U represents the cross-barrier flow strength, N denotes the Brunt-Väisälä frequency, and h represents the maximum terrain height [34-37]. This ratio serves as a measure of the importance of nonlinear effects in the flow.

Another significant factor influencing precipitation distribution over mountains is the exponential decrease in the saturation vapor pressure of the atmosphere with temperature and height [38]. Precipitation generated through upward air motion and microphysical growth processes on the windward side of a barrier is typically more pronounced at lower levels [29, 39-41]. Consequently, higher mountains often exhibit greater precipitation on their lower slopes [42-43]. This interaction between humidity and other microphysical and dynamical factors can result in drier conditions in the upper regions of taller mountains [44-46]. Our study investigates the fundamental mechanisms underlying the influence of hills and mountains on precipitation cloud formation and dynamics in the Meghalaya Plateau of Northeast India. With its notable topographic features, including prominent hills and mountains, the plateau provides an ideal setting to examine the interplay between topography and atmospheric processes [29, 47-48]. Through the analysis of meteorological data and numerical simulations, this research aims to elucidate the key mechanisms shaping precipitation patterns in this region [49-52].

The Meghalaya Plateau, situated in Northeast India, is renowned for its remarkable rainfall and rugged topography (Figure 2). The presence of hills and mountains significantly influences the local climate and precipitation patterns [53]. With extensive hill ranges and elevated peaks, the plateau's proximity to the Bay of Bengal allows for the inflow of moisture-laden air masses [7, 10, 54]. The intricate interplay between these air masses and the complex terrain creates favourable conditions for cloud formation and rainfall [55]. Various mechanisms come into play when hills and mountains affect cloud formation [56]. Orographic lifting occurs as air encounters elevated terrain, leading to upward motion, cooling, and enhanced condensation, resulting in cloud development [57-58]. This phenomenon is particularly notable on windward slopes, where moist air is forced to rise, leading to orographic precipitation [59]. The interaction between the atmosphere and topography also impacts cloud dynamics. Uplifted air masses over hills and mountains can trigger the formation of convective clouds associated with intense rainfall [29, 60]. The complex terrain further influences local circulations, such as valley and mountain breezes, which play a role in shaping cloud behavior and precipitation patterns [61-62].

Initial results indicate that the presence of hills and mountains on the Meghalaya Plateau has a notable impact on the characteristics of precipitation clouds. Orographic lifting and intensified convection over elevated terrain play a significant role in generating the localized heavy rainfall observed in this area. The simulations demonstrate the intricate interaction between topography, atmospheric dynamics, and cloud microphysics.

3.3 Why Mawsynram getting more rainfall than Cherrapunji.

Mawsynram and Cherrapunji are renowned for their extraordinary rainfall, with Mawsynram actually receiving slightly higher average annual precipitation than Cherrapunji. The reasons for Mawsynram highest rainfall compared to Cherrapunji can be attributed to several factors, including differences in geographical location, local topography, human impact, the rain shadow effect, and orographic lifting effects [3, 7].

Geographical location: Both Cherrapunji and Mawsynram are situated on the southern slopes of the Khasi Hills, with elevations ranging from 1313 m to 1401 m (Figure 1). Cherrapunji is positioned at the northern edge of a deep valley that runs from south to north, while Mawsynram is located atop a hill within the same valley.

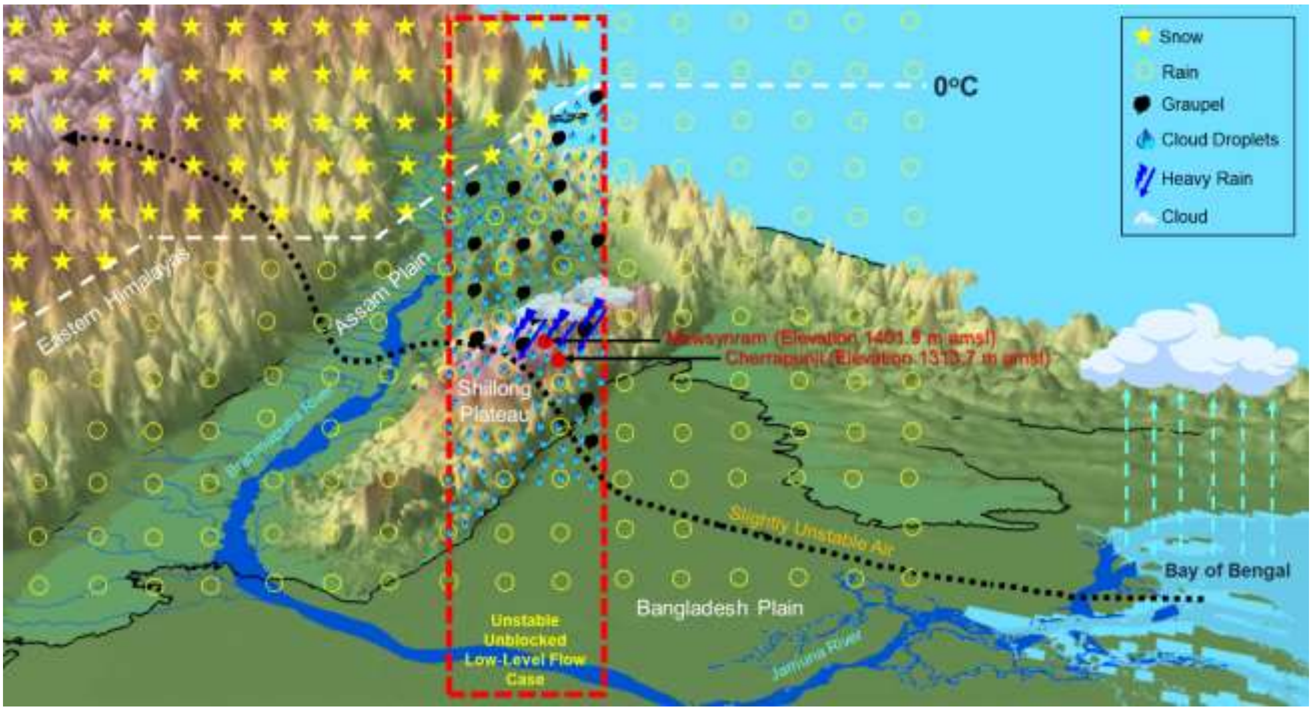

Figure 2. Conceptual Model of the Airflow and Microphysics of Orographic Precipitation Mechanisms in Shillong Plateau

Local topography: The local topography of the region influences the distribution of rainfall. Mawsynram, characterized by a more undulating terrain and surrounded by hills (Figure 1), is situated at a slightly higher elevation and in closer proximity to the Bay of Bengal compared to Cherrapunji. These hills act as barriers, causing the moist air to rise and undergo condensation, resulting in higher rainfall amounts in Mawsynram.

Human influence: Analysis of Landsat satellite imageries for the years 2000 and 2023 has revealed changes in land use and land cover in the Cherrapunji and Mawsynram areas. The study shows a reduction in vegetation cover over the past 25 years, indicating the influence of human activities on the changing rainfall patterns. Specifically, the practice of Jhum cultivation or shifting cultivation, as well as deforestation, has contributed to the decrease in forest and tree-covered areas. The land use-land cover maps, illustrated in Figure 3, demonstrate an increase in crop land and built-up areas, particularly in the vicinity of Cherrapunji and Mawsynram. The study estimates an annual decrease of 105.3 km^2 in vegetation cover, while crop land and built-up areas have increased by 184.5 km^2 and 0.34 km^2 per year, respectively. These human-induced changes in land use are impacting the rainfall patterns in the Cherrapunji and Mawsynram regions.

Rain Shadow Effect: Cherrapunji is positioned on the side of the Khasi Hills that faces the prevailing moisture-laden winds, resulting in direct exposure to their impact. Conversely, Mawsynram is situated on the opposite side of the hills, experiencing the rain shadow effect. This phenomenon causes the descending air to warm, leading to reduced rainfall in Cherrapunji compared to Mawsynram [63].

Orographic lifting effects: It is worth noting that while Mawsynram and Cherrapunji are both known for their exceptionally high rainfall, the difference in precipitation between the two is relatively small. The specific ranking of these locations as the wettest can vary annually, with Cherrapunji occasionally receiving higher rainfall than Mawsynram in certain years due to weather pattern variability [64]. However, on average, Mawsynram receives slightly more rainfall than Cherrapunji.

Cherrapunji and Mawsynram are both impacted by the Bay-of-Bengal arm of the Indian Summer Monsoon (Figure 2). As the monsoon clouds traverse the plains of Bangladesh, they encounter the formidable Khasi hills, which abruptly rise to heights of around 1300 meters above sea level within a short distance. The rugged topography of these hills, characterized by deep valleys, acts as a funnel, channelling the low-flying moisture-laden clouds (ranging from 155 to 320 meters) towards Cherrapunji and Mawsynram. However, one notable distinction between Cherrapunji and Mawsynram is that Cherrapunji is situated at the convergence of multiple gorges, while Mawsynram lacks this feature. Mawsynram is positioned in the central part of a parallel range, with Laitkynsew Hill to its south, forming a valley that runs from east to west. The southern opening of this valley directly faces Mawsynram, where the monsoon winds, blowing from the south, collide with Laitkynsew Hill before being channelled through the valley and ascending the slopes of Mawsynram. When the clouds are carried by the southward winds over the hills, they are channelled through the valley that lies between Laitkynsew Hill and Mawsynram Hill. This valley includes the Umwai, Wahlong, Mawsmai, and Kutmadan valleys. As a result, the clouds strike Cherrapunji and Mawsynram in a perpendicular direction, causing the low-flying clouds to be pushed up the steep slopes. It is not surprising that the heaviest rainfall occurs when the winds directly hit the Khasi Hills. Factors such as climate change, human influence near Cherrapunji, and the unique topography of Mawsynram have led to Mawsynram receiving more rainfall than Cherrapunji in recent years. Remarkably, despite the heavy downpours, these areas do not experience flooding, as the deluge drains off to the Sylhet floodplains in Bangladesh.

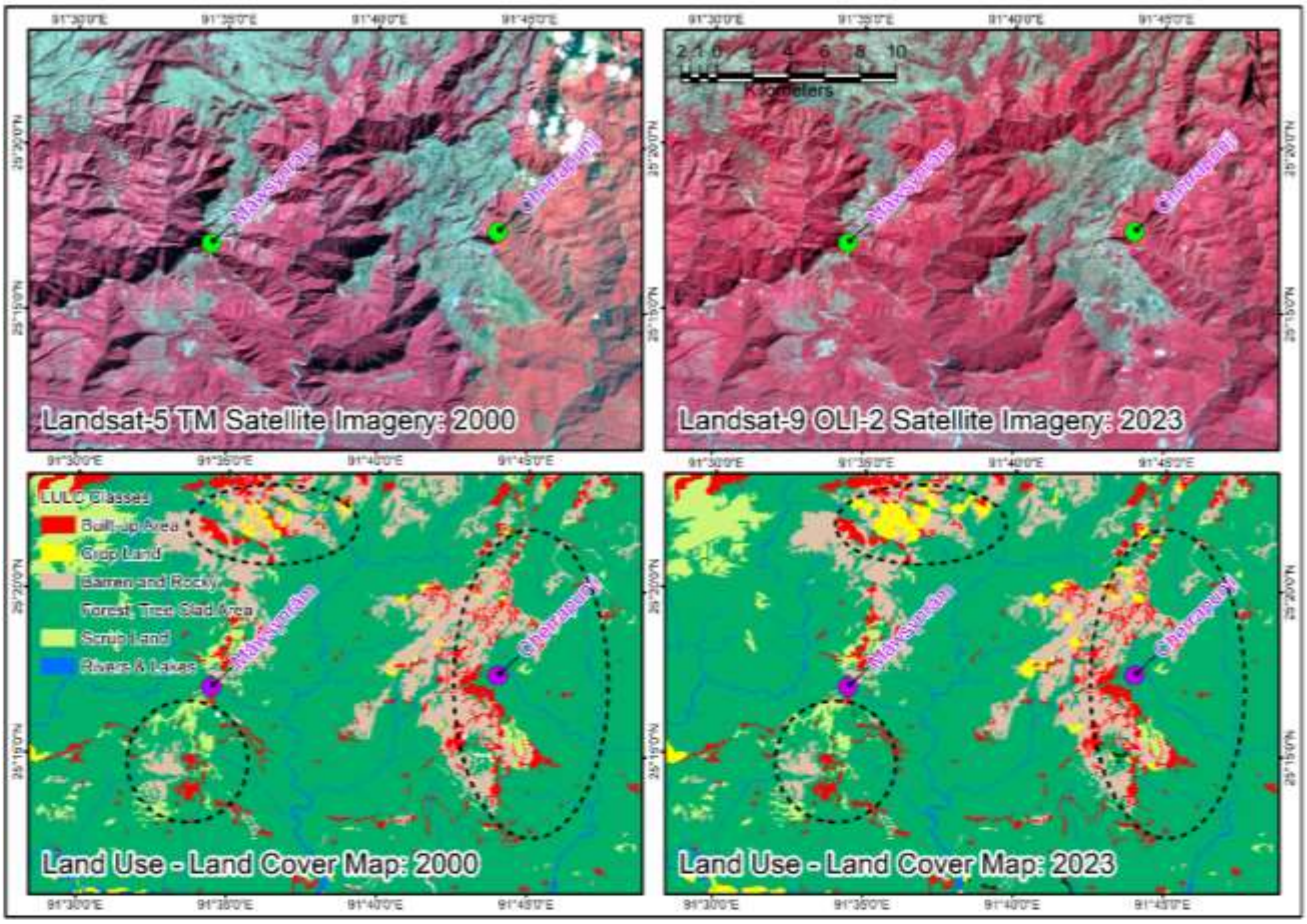

Figure 3. Satellite Imageries and LULC Maps for Year 2000 and 2023

3.4 Cause of Heavy Precipitation

Northeast India, characterized by its hilly terrain and its connection to the Indo-Gangetic Plains, is highly susceptible to regional and global climate variations. The rainy seasons in this region are the pre-monsoon and monsoon periods. Over the past few decades, long-term changes in rainfall patterns have resulted in a notable shift in the world's wettest place from Cherrapunji to Mawsynram, which are separated by a distance of 16 km. Mawsynram now holds the title with an average annual rainfall of 11,871 mm, while Cherrapunji continues to experience heavy rainfall, averaging 11,430 mm per year.

The Meghalaya Plateau, with its steep and parallel mountains (Garo, Khasi, and Jaintia hills), experiences heavy precipitation due to the interaction of rain-bearing summer air currents and the unique topography of the region. As the monsoonal air currents move north from the hot and humid floodplains of Bangladesh, they encounter the funnel-shaped relief of the Meghalaya hills, characterized by deep valleys and gorges. These mountains act as barriers, impeding the northward movement of the clouds. Instead, the clouds are funneled through the narrow gorges and forced to ascend the steep slopes, resulting in significant rainfall in the area.

Through research, it has been identified that various factors contribute to the occurrence of heavy precipitation in the Meghalaya Plateau. These factors include the dynamic cooling of saturated southwest winds as they are forced to rise vertically along the steep slopes, the proximity to the line of discontinuity between different air masses, such as dry easterlies, north easterlies, moist southerlies, and southwesterlies, the early morning lifting of moist air trapped in the valleys overnight, and the influence of westerly circulations, perturbations, meso-scale factors, and variations in the mixing ratio. Additionally, the orography of the region plays a significant role [11, 13-14, 17, 19, 24].

4 Geomorphological Features

A comprehensive understanding of the geo-morphological characteristics of Cherrapunji and Mawsynram is crucial in studying the correlation between the landscape and the remarkable rainfall patterns observed in these areas. Various aspects of the geomorphology have been thoroughly analyzed to gain insights into this relationship.

4.1. Geology

The geological characteristics of Cherrapunji and Mawsynram in Meghalaya, India, are marked by a combination of sedimentary rocks, limestone formations, and distinct landforms (Table 3).

Table 3. Geological Succession of the Study Area

Age	Group	Formation	Lithology
Pleistocene	Alluvium	Older Alluvium	Mix Sedimentary Deposits
Mid-Pliocene	Dupitila	Unclassified	Feldspathic Sandstone and Conglomerate
- - - Unconformity - - -			
Middle-Miocene	Garo	Chengapara	Coarse Sandstone, Siltstone
Lower-Miocene		Baghmara	Coarse, Feldpathic Sandstone
Oligocene		Simsang	Siltstone and Fine Sandstone
- - - Unconformity - - -			
Eocene-Oligocene	Barail	Jenum	Sandstone, Shale
Upper Paleocene	Jaintia	Lakadong Limestone	Crystalline Limestone
- - - Unconformity - - -			
Mid-Cretaceous	Khasi	Basal Conglomerate	Conglomerate and Sandstone Grit
- - - Unconformity - - -			
Mid-Cretaceou	Sung	Unclassified (alkaline ultramafic carbonate complex)	Pyroxene-Serpentinite
- - - Unconformity - - -			
Lower Cretaceous	Sylhet trap	Unclassified	Basalt, Alkali Basalt, Rhyolite, and acid Tuff
- - - Unconformity - - -			
Carboniferous-Permian	Lower Gondawana	Talchir	Basalt Tillite with Sandstone Bands
- - - Unconformity - - -			
Neo-Proterozoic to Early Paleozoic	Granite Plutons	Mylliem Granite	Porphyritic Coarse Grain Granite
Mid-Proterozoic	Khasi Green stone	Unclassified (basic-ultrabasic intrusives)	Epidiorite, Dolerite Amphibolite
- - - Unconformity - - -			
Early Proterozoic	Shillong	Lower Shillong	Mainly Schists with Calc-Silicate Rocks
- - - Unconformity - - -			
Archean-Proterozoic	Basement Gneissic Complex		Biotite Gneiss, Granite Gneiss, Mica Schist

Source: Geological Survey of India, 2009 [68].

These geological attributes contribute significantly to the region's varied landscapes and have a significant impact on its hydrological systems and geomorphology. The geology of both Cherrapunji and Mawsynram is predominantly composed of sedimentary rocks belonging to the Shillong Group, which is a part of the Meghalaya Plateau [65-66]. The Shillong Group encompasses various rock formations, such as sandstones, shales, and conglomerates, which were deposited during the

Paleogene and Neogene periods [65]. Notably, the presence of extensive limestone formations is a prominent feature in the region, giving rise to vast cave systems and underground drainage networks [66]. The limestone formations found in Cherrapunji and Mawsynram are attributed to the Sylhet Limestone Formation, which is believed to have originated during the Eocene period through the accumulation of marine sediments. The distinctive karst topography observed in the area is a consequence of the limestone's dissolution caused by rainwater percolation through fractures and joints in the rock [66]. This process has given rise to an intricate network of underground caves, sinkholes, and disappearing streams. Several notable caves in the region, including the Mawsmai Cave, Krem Phyllut, and Krem Liat Prah, exemplify the fascinating underground features shaped by this geological phenomenon [67].

The geological composition of Cherrapunji and Mawsynram is characterized by porous limestone formations, which play a significant role in the hydrological processes of the region [66]. The presence of limestone facilitates high rates of groundwater infiltration and promotes rapid surface runoff, resulting in the formation of numerous streams and waterfalls. The abundant rainfall in the area further intensifies the erosive forces of water, contributing to the creation of deep valleys, steep slopes, and gorges. These unique geological features have captured the attention of geologists and researchers studying karst systems and their hydrological implications. To visualize the geological makeup of the study area, a comprehensive geological map has been prepared using various sources, including published geological maps from the Geological Survey of India (GSI), Landsat-9 OLI-2 satellite imagery, SRTM DEM data, and Survey of India (SoI) topographical maps. The resulting geological map provides valuable insights into the geological characteristics of the region (Figure 4).

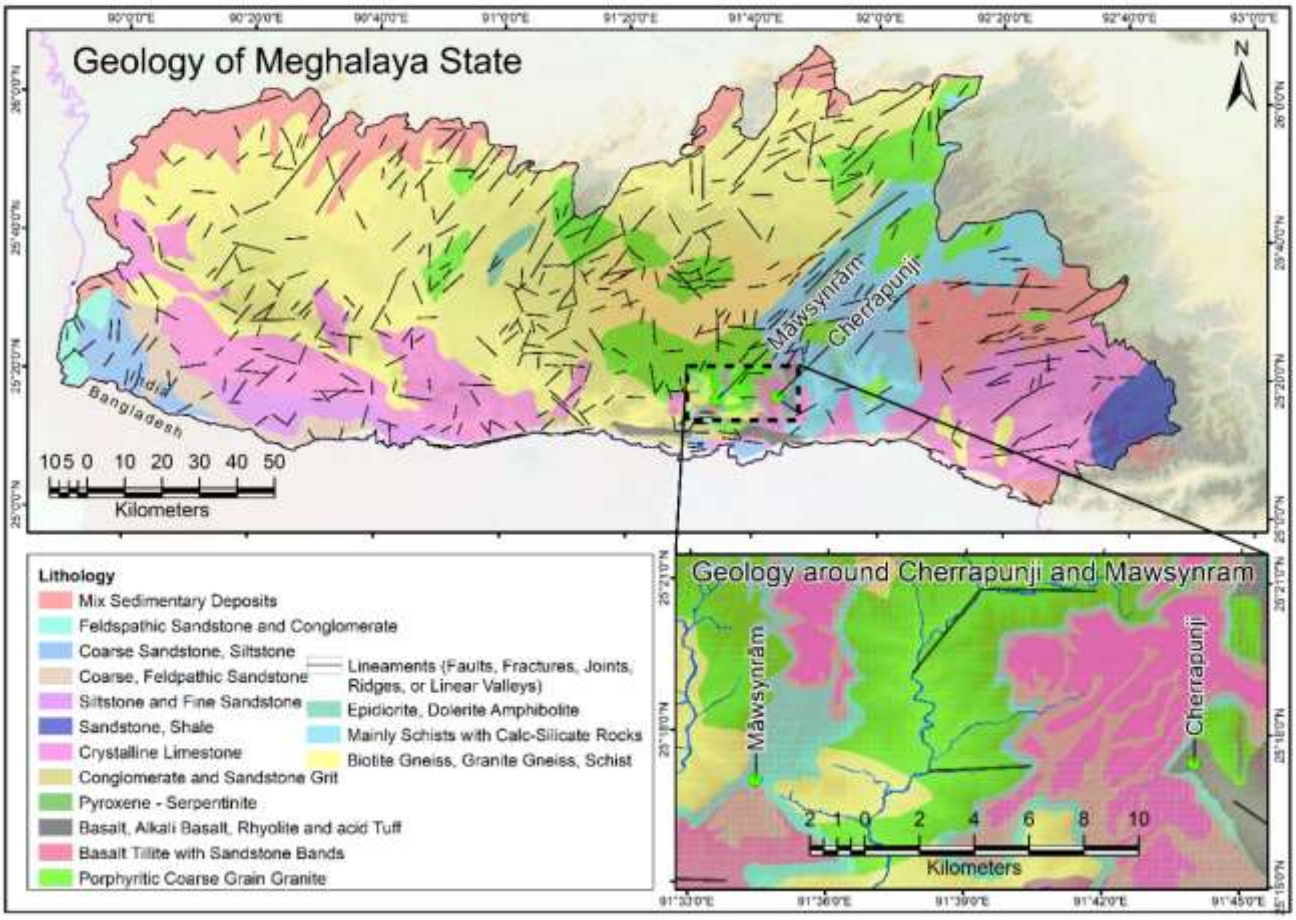

Figure 4. Geological Map of Meghalaya State, and Area around Cherrapunji and Mawsynram

4.2. Geomorphological Mapping

Geomorphology is a scientific discipline focused on studying the origins, forms, and development processes of landforms [69-71]. Cherrapunji and Mawsynram, located on the Meghalaya Plateau, exhibit steep slopes and undulating terrain that are characteristic of the region. The combination of heavy rainfall and the erodible nature of the sedimentary rocks has shaped various landforms in the area [72]. These landforms include ridges, escarpments, terraces, and interfluves, which contribute to the complex relief pattern of the landscape [73]. The topography of the landscape showcases intricate relief patterns, which arise from the differential erosion processes and the varying resistance of the rock formations [74]. Geomorphological mapping serves as a valuable tool for land management, assessing geomorphological risks, and providing baseline data for other environmental research fields such as landscape ecology, forestry, and soil science [75-77].

The development of a geomorphological map has greatly benefited from the utilization of satellite remote sensing data. Through the visual interpretation of Landsat-9 OLI-2 satellite imagery with a spatial resolution of 30 meters, as well as the incorporation of SRTM DEM data at the same resolution, published geological maps from the Geological Survey of India (GSI) at a scale of 1:50,000, and topographical maps from the Survey of India (SoI) at a scale of 1:250,000, a comprehensive geomorphological map of the study area has been created. This map, presented in Figure 5, is accompanied by additional references such as structural geological maps, slope maps, and landform maps. Field observations were also conducted, although limited in scope, to further enhance the accuracy of the map.

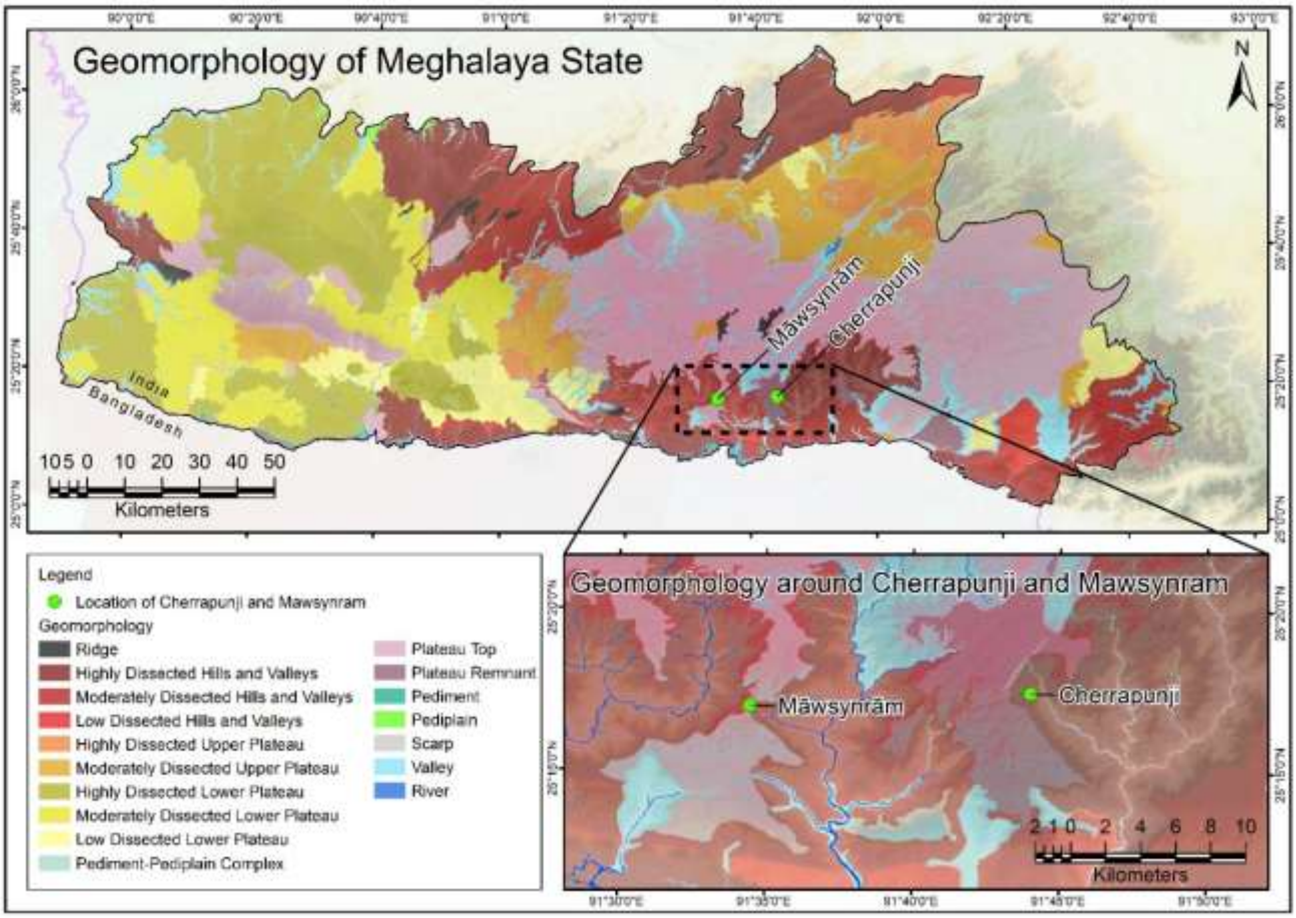

Figure 5. Geomorphological Map of Meghalaya State, and Area around Cherrapunji and Mawsynram

5 Climate Analysis

The meteorological data collected has undergone thorough analysis to investigate the climatic patterns in Cherrapunji and Mawsynram. Statistical techniques have been employed to examine the distribution, seasonality, and variability of rainfall over the study period. However, comparing the rainfall records between Cherrapunji and Mawsynram has presented challenges due to the difference in data lengths available. Cherrapunji has a longer record spanning approximately 122 years, while Mawsynram's data covers a shorter period of around 50 years. To ensure meaningful conclusions, careful consideration has been given to this disparity in data length when conducting comparative analyses.

5.1. Climatic Patterns in Cherrapunji and Mawsynram

Cherrapunji and Mawsynram, situated in the northeastern state of Meghalaya, India, are globally renowned for their extraordinary rainfall patterns and distinctive climatic characteristics. These regions exhibit some of the highest average annual precipitation levels in the world, making them remarkable for their climatic extremes. We observed a noticeable change in measurements before and after 1960, prompting us to analyze the trends before (1901-1960) and after (1960-2022) this pivotal year. To comprehensively understand the climatic variations, we conducted statistical analyses for the four distinct seasons in northeast India [27]: winter (January to February), pre-monsoon (March to May), summer monsoon (June to September), and post-monsoon (October to December), as well as for the annual average measurements. Employing statistical techniques, we carefully analyzed and interpreted the collected data, utilizing time-series analysis to identify long-term trends or cyclic patterns in the rainfall data.

Cherrapunji and Mawsynram exhibit a distinctive climatic pattern characterized by a monsoon climate influenced by the Indian Ocean and the Himalayan Mountain range [18, 78]. These areas receive copious amounts of rainfall during the monsoon season, which typically spans from June to September [27]. The southwest monsoon winds carry moisture-laden air, leading to abundant rainfall and creating a lush and vibrant landscape [26]. An interesting climatic phenomenon observed in the region is the occurrence of "pre-monsoon" showers in March and April, preceding the main monsoon season [9]. These early showers significantly contribute to the overall high annual precipitation in the area. Additionally, the region experiences a relatively drier period referred to as the "winter dry season" from December to February [79].

Cherrapunji and Mawsynram are renowned for their intense and localized rainfall, often accompanied by heavy downpours, leading to substantial daily precipitation amounts [5]. The unique topography, characterized by hilly terrain and proximity to the Bay of Bengal, plays a crucial role in enhancing rainfall through orographic uplift of moist air [60]. These climatic conditions have shaped the landscape, contributing to the presence of numerous waterfalls, caves, and dense forests [80]. Recent studies have focused on analysing the climatic patterns and trends in Cherrapunji and Mawsynram, examining the variability of rainfall, identifying long-term trends, and assessing the potential impact of climate change on precipitation patterns [64, 81-84]. The distinct monsoon climate of these regions, characterized by heavy and intense rainfall, has significant implications for local ecosystems, water resources, and the livelihoods of the communities residing in these areas [5].

The annual rainfall data for Cherrapunji, Mawsynram, and the average rainfall for the state of Meghalaya is depicted in Figure 6, using a color-coded representation to highlight the disparities in rainfall between the two locations. The color pink indicates instances when Mawsynram has received lower rainfall compared to Cherrapunji, while the color green represents periods when Mawsynram has received higher rainfall. Notably, there has been a consistent significant excess of rainfall in Mawsynram compared to Cherrapunji since 1977, which aligns with a similar pattern observed during the period from 1948 to 1957. These findings raise important questions and emphasize the need for further investigation to better understand the factors contributing to the divergent rainfall patterns between these two locations.

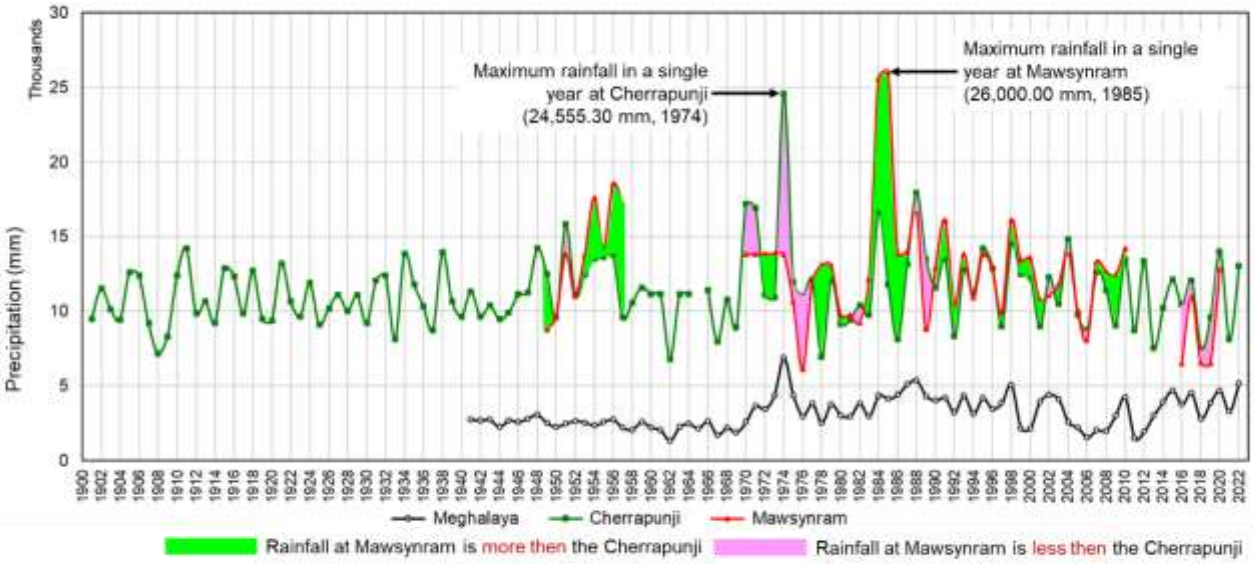

Figure 6. Annual Variation of Rainfall at Cherrapunji, Mawsynram and Meghalaya State

The divergent rainfall patterns observed in Cherrapunji and Mawsynram stem from a complex interplay of multiple factors, which have been extensively discussed in Section 5.2. These factors encompass local topography, atmospheric circulation patterns, and regional climate dynamics. Investigating and understanding these underlying causes will provide valuable insights into the mechanisms driving the contrasting rainfall patterns between the two locations. Additionally, our analysis has identified two notable peaks in single-year rainfall records for both Cherrapunji and Mawsynram. Cherrapunji recorded a maximum rainfall of 24.55 thousand mm, while Mawsynram experienced a peak of 26.00 thousand mm. This extreme rainfall events demand attention due to their potential impacts on local ecosystems, water resources, and human settlements [85].

Over the years, the average winter precipitation in the region has been recorded at 73.89 mm. Winter precipitation tends to be lower compared to pre-monsoon and summer monsoon precipitation. The average pre-monsoon precipitation is 2187.02 mm, with variations ranging between 1500 to 4000 mm. Pre-monsoon precipitation stands out as the highest among the seasons, indicating a substantial amount of rainfall occurring before the onset of the monsoon season. In contrast, the average summer monsoon precipitation is 8761.35 mm, with a range of 6-to-10 thousand mm (Figure 7). The summer monsoon season exhibits the highest precipitation levels, signifying the dominance of the monsoon period characterized by heavy rainfall. Lastly, the average post-monsoon precipitation is recorded at 504.07 mm, typically lower than both pre-monsoon and summer monsoon precipitation.

According to Oldham [86], the heavy rainfall in Cherrapunji is primarily concentrated during nighttime hours. Das [15] conducted an analysis of hourly rainfall data spanning four years and found that a significant portion of the rainfall occurred early in the morning, specifically between 01:00 to 07:00 IST. This observation was further supported by Starkel [87], who reported a high frequency of intense hourly rainfall during the nighttime period, as observed by an automatic weather station. Ohsawa [88] utilized Geostationary Meteorological Satellite (GMS) data on equivalent black body temperature (TBB) and also highlighted a nocturnal maximum of rainfall in the region.

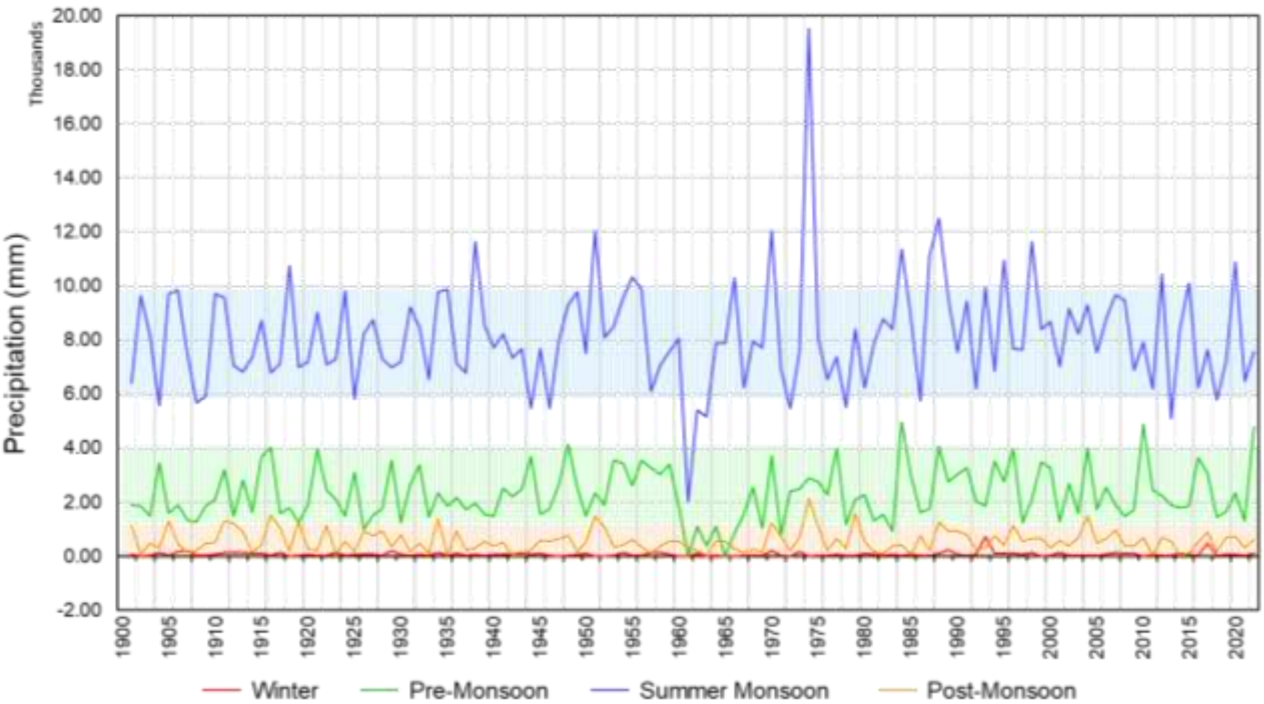

Figure 7. Temporal Evolution of Seasonal Rainfall at Cherrapunji (1901-2022)

5.2. Trend Analysis of Annual Rainfall

The analysis of the percentage departure from mean rainfall spanning from 1901 to 2022 reveals distinct climatic patterns in both Cherrapunji and Mawsynram. Cherrapunji experienced a dry season from 1901 to 1950, followed by a wet period between 1960 and 2000. However, from 2000 to 2020, Cherrapunji entered another dry season. Similarly, Mawsynram exhibited a dry phase from 1950 to 1970, transitioning into a wet period from 1970 to 2000. However, both locations experienced a decline in rainfall from 2000 to 2020, resulting in a prolonged dry spell (Figure 8). These observed variations in rainfall patterns have significant implications for the local climate and various aspects of the environment. The identified dry and wet seasons signify changes in precipitation distribution over time, affecting water availability, ecosystems, and human activities in the region. The dry seasons observed in Cherrapunji from 1901 to 1950 and from 2000 to 2020 indicate periods of reduced rainfall, potentially impacting water resources and agricultural practices. Similarly, the dry period from 1950 to 1970 in Mawsynram, along with the subsequent decline in rainfall, pose challenges for water availability and ecosystem dynamics.

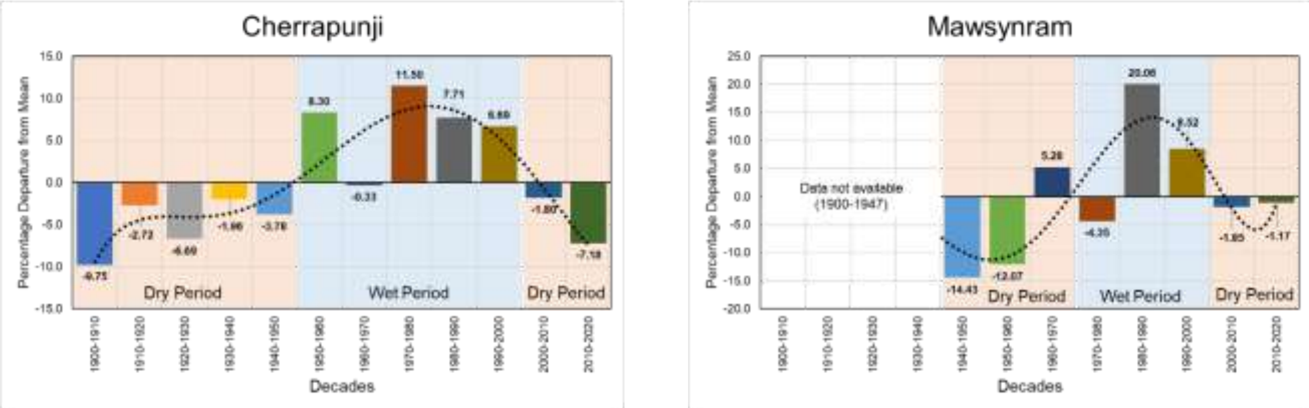

Figure 8. Decadal Variation of Rainfall between 1901 and 2022 at Cherrapunji and Mawsynram

The observed decline in rainfall from 2000 to 2020 in both Cherrapunji and Mawsynram raises concerns about the long-term sustainability of these regions [64]. Factors such as climate change and other environmental influences may contribute to this downward trend, highlighting the need for further investigation. It is important to acknowledge that this analysis provides valuable insights into historical rainfall patterns and trends [81]. Continued monitoring and research are crucial to assess the ongoing changes in precipitation patterns and understand their potential implications for the future [89]. By deepening our understanding of these climatic shifts, policymakers and stakeholders can develop strategies to mitigate the impacts of changing rainfall patterns and promote the resilience of local communities and ecosystems [90-91].

An analysis of decadal rainfall trends was conducted for Cherrapunji and Mawsynram using average rainfall data spanning two distinct time intervals: 1901-2022 and 1960-2022. The findings revealed contrasting trends between these periods. When considering the long-term trend from 1901 to 2022, both locations exhibited an increasing trend in rainfall over time. This suggests that over several decades, there has been a consistent rise in the amount of rainfall received in Cherrapunji and Mawsynram. However, a different pattern emerges when focusing on the more recent period from 1960 to 2022, where a declining trend in rainfall becomes evident (Figure 9). This indicates that in recent years, there has been a notable decrease in the amount of rainfall observed at both locations. These contrasting trends highlight the dynamic nature of rainfall patterns and the importance of analysing data over different time intervals to gain a comprehensive understanding of long-term climatic changes.

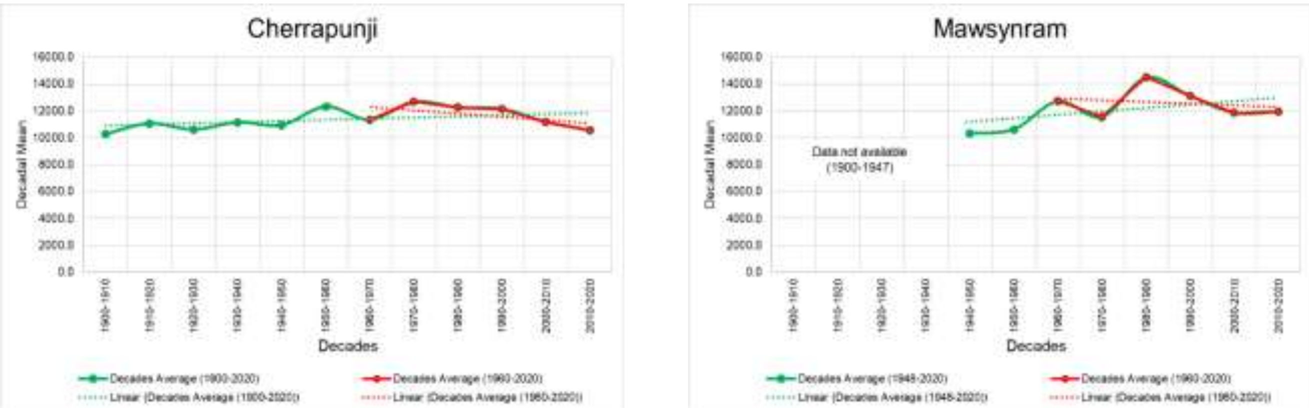

Figure 9. Trend Analysis of Annual Rainfall from 1901 to 2022, and 1960 to 2022 at Cherrapunji and Mawsynram

The findings of this study hold significant implications for comprehending the evolving precipitation patterns in Cherrapunji and Mawsynram. The observed long-term increasing trend in rainfall provides evidence of historical augmented precipitation levels, indicating a pattern of enhanced rainfall in these regions. However, the documented decreasing trend in rainfall during more recent decades raises concerns about a potential shift in precipitation patterns. The analysis of decadal rainfall trends offers valuable insights into the temporal variability of precipitation, aiding in our understanding of how rainfall patterns evolve over time. Ongoing monitoring and analysis of rainfall trends are crucial to identify and address the potential impacts of changing precipitation patterns on local ecosystems and communities.

5.3. Return Period of Maximum One-Day Rainfall

The estimation of maximum rainfall for various return periods was conducted using daily rainfall data from 1978 to 2023, utilizing the EVA (Extreme Value Analysis) tool of MIKE Zero software [92]. The maximum recorded rainfall values for a one-day duration were subjected to a frequency analysis using the GUM technique proposed by Gumbel [93]. To determine the return periods (T) of the extreme annual values, the formula T = (N + 1) / m was employed, where N represents the total number of years of record and m is the rank number of the annual series arranged in descending order. The frequency bar plots, extreme value analysis results, probability plots for rainfall, and quantiles estimates for different return periods can be found in Table 4.

Table 4. Quantiles estimate for different return periods at Cherrapunji.

Return Period (Y)	GEV / MOM	GUM / LMOM	LP3 / LMOM
2	537.121	545.68	540.225
5	749.435	758.555	752.763
10	898.575	899.497	896.738
20	1048.407	1034.691	1037.034
25	1097.372	1077.577	1082.042
50	1252.711	1209.687	1222.455
100	1413.856	**1340.822**	1364.864

*Generalized Extreme Value (GEV), Method of Moments (MOM), Gumbel (GUM) Distribution Model, L-Method of Moments (LMOM), Log-Pearson Type 3 (LP3).

The data points representing the observed one-day rainfall values and the corresponding computed straight line are depicted in Figure 10. The highest recorded one-day rainfall during the period from 1978 to 2023 was 1340.82 mm, and based on the analysis, it is estimated to have a return period of approximately 100 years. This finding indicates that such an extreme rainfall event, as observed, is relatively rare and expected to occur approximately once in a century.

Frequency analysis has been applied to predict design rainfall for Cherrapunji by utilizing observed rainfall data. This technique involves the utilization of statistical information, such as mean values, standard deviations, skewness, and recurrence intervals, calculated from the observed rainfall data. These statistical parameters are used to construct frequency distributions, which provide information on the likelihood of various rainfall intensities based on recurrence intervals or exceedance probabilities. The process of frequency analysis entails fitting a probability model to the maximum recorded rainfall data from a given observation period at a particular station (Figure 11). The established model parameters are then employed to estimate the occurrence of extreme rainfall events with large recurrence intervals.

6 Conclusion

The research paper focuses on comprehensively studying the climate and geomorphological features of Cherrapunji and Mawsynram, aiming to understand the factors behind their extreme precipitation and its implications for the environment. The study examines climatic patterns, identifies geomorphological features, and investigates factors influencing extreme rainfall, providing valuable insights into these unique regions. Northeast India, particularly the Meghalaya plateau, exhibits unique characteristics with regards to its rainfall patterns. The region experiences high rainfall with large spatio-temporal variation due to interactions with topography. Trend analysis indicates stable rainfall conditions over the past 150 years, and the interaction between large-scale circulation and local topography influences the distribution of rainfall. Previous studies on rainfall at Cherrapunji, Mawsynram and Meghalaya plateau have highlighted orography as the primary cause of their exceptionally high precipitation. Their unique climatic and geomorphological characteristics make them some of the rainiest places on Earth. The exceptionally high rainfall in Mawsynram and Cherrapunji is influenced by various factors including geographical location, local topography, human influence, rain shadow effect, and orographic lifting effects. The shift of the world's wettest place from Cherrapunji to Mawsynram in recent decades in northeast India have been affected by these factors. The geology of Cherrapunji and Mawsynram, characterized by sedimentary rocks and extensive limestone formations, contributes to the diverse landscapes, karst topography, and hydrological systems in the region. The geomorphology of Cherrapunji and Mawsynram on the Meghalaya Plateau is characterized by steep slopes and undulating terrain, which have given rise to a variety of landforms. The geological and geomorphological maps of Meghalaya state have been updated by using satellite remote sensing data, DEM data with limited field check.

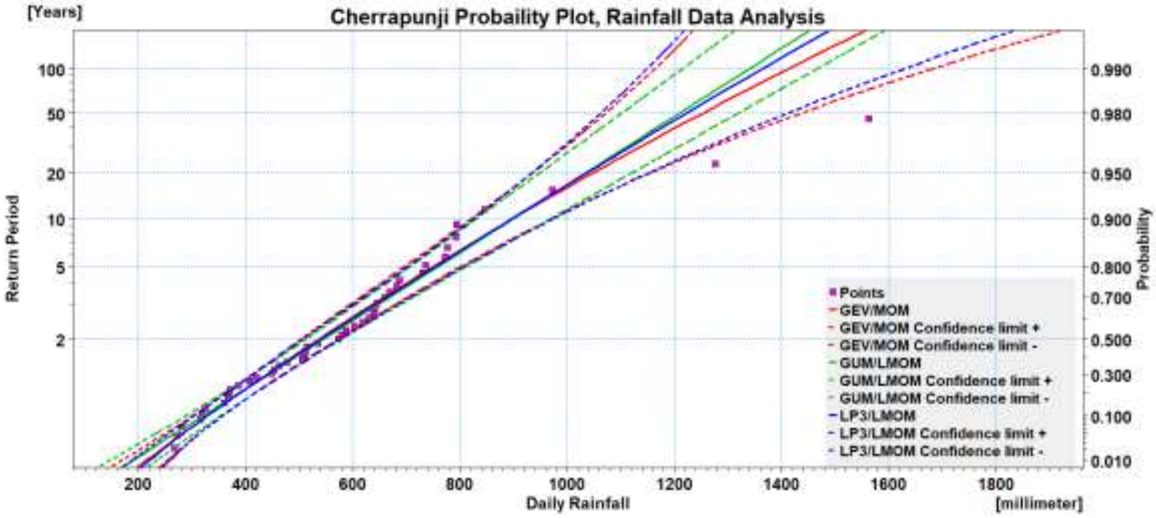

Figure 10. Extreme Value Analysis and Probability Plot for Daily Rainfall (mm) at Cherrapunji

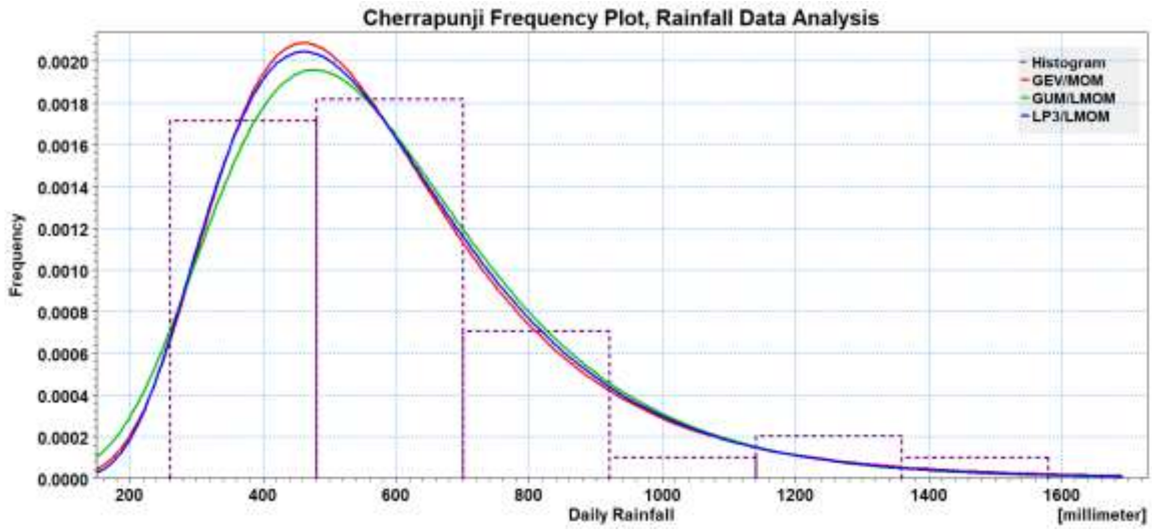

Figure 11. Frequency Bar Plot for Daily Rainfall (mm) at Cherrapunji

Studies have been conducted to analyze rainfall patterns, identify long-term trends, and understand the impact of climate change on precipitation. The rainfall disparities between Cherrapunji and Mawsynram in Meghalaya, India, have been visually represented, highlighting the consistent excess rainfall in Mawsynram since 1977. Winter precipitation is generally lower compared to pre-monsoon and summer monsoon precipitation. Pre-monsoon season experiences the highest rainfall, followed by the dominant monsoon season with heavy rainfall. There is a notable occurrence of heavy rainfall during the night in Cherrapunji, as observed in previous studies. The analysis of long-term rainfall data for Cherrapunji and Mawsynram reveals distinct dry and wet seasons over the years, with recent trends indicating a decline in rainfall for both locations. The analysis of long-term rainfall trends in Cherrapunji and Mawsynram highlights the contrasting patterns of increasing rainfall over the entire period of study (1901-2022) and a more recent decreasing trend (1960-2022). Through the application of Extreme Value Analysis (EVA) using the GUM technique, the maximum rainfall for different return periods has been estimated based on daily rainfall data from 1978 to 2023. The frequency bar plots, extreme value analysis, and probability plots provide valuable insights into the probability and quantiles estimates for various return periods, enhancing our understanding of extreme rainfall events in the region. Furthermore, the studies contribute to our understanding of climate change impacts, provide insights for sustainable development practices, and inform strategies for water resource management and erosion mitigation in similar geographic contexts. Overall, the research enhances our knowledge of these unique regions and their significance within the broader context of global climate systems.

There are also some future research options in this study, such as (i) To investigate the impact of climate change on precipitation in these regions, using historical data and climate models to guide adaptation and mitigation efforts; (ii) To develop specific hydrological models for Cherrapunji and Mawsynram, considering their specific geology, to forecast river flow, groundwater recharge and flood susceptibility; (iii) To study the causes and processes of landslides and erosion in these areas due to heavy rainfall. Emphasize early warning systems for disaster prevention; and (iv) To analyze the climate and geomorphology of Cherrapunji and Mawsynram in comparison to other global rainfall regions for similarities and differences.

Data availability:
The data used in this study is available upon request from the corresponding author. Due to confidentiality agreements and ethical considerations, some restrictions may apply to the sharing of certain data. However, reasonable requests for data will be considered and accommodated to the extent possible within the constraints of the data usage policies and regulations in India. Please contact the corresponding author for further information regarding data availability.

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