International Journal of Scientific Research & Engineering Trends
Volume 12, Issue 3, May-Jun-2026, ISSN (Online): 2395-566X

Temporal Dynamics of Distribution of Rainfall in Monrovia, Liberia (1981-2024)

SAM, Fredrick P[1], ALABI, Omowumi[2], MD, Tawey[3], MORRIS, Susannah D[4],
UGBALA, E.N[5], Nimely, DENNIS R[6]
[1,6]College of Science & Technology School of Environmental Studies & Climate Change (CoSTECC), University of Liberia
[2]United Nations affiliated African Regional Centre for Space Science and Technology Education in English (UN-ARCSSTEE), Ile-Ife, NIGERIA
[3,5]National Water Resources Institute, Mando Road, Kaduna, Nigeria
[4]Central Agriculture Research Institute (CARI), Monrovia, Liberia

Abstract- This paper investigated the spatial and temporal dynamic pattern of rainfall over four decades (1981-2024) in Monrovia, Liberia. These rainfall data were used, a combined rainfall data that combines surface observations of the Liberia Meteorological Services (LMS) and the satellite-based Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) estimates. The presence of variability, anomalies, and extremes has been measured using the Mann-Kendall trend test and Sen's slope estimator and rainfall indices like the Precipitation Concentration Index PCI), Standardized Precipitation Index (SPI), and Rainfall Anomaly Index (RAI). Analysis showed that there is no statistically significant long-term trend in annual rainfall totals (Mann-Kendall, $p > 0.05$), but there are significant intra-seasonal changes. Drying patterns as identified in the early rainy season (April-May) with slope of Sen's values between -2.1 mm/yr and -3.7 mm/yr. Conversely, late rainy season months (August-September) showed an increasing part of rainfall with the slope between 1.456 mm/year and 1.966 mm/year, indicating redistribution in the seasonal rainfall time. Moderate rainfall concentration and non-equal seasonal distribution were characterized by PCI values (12.93 to 16.34). The SPI analysis found repeat drought and extreme wet years (1982, 1994, 2009, 2015, 2020, 2022, and 2024) and extreme wet years (1995, 1996, 2006, 2007, 2008, and 2010). The Aggregate outcome of RAI indicated that a greater proportion of the years were in the negative anomaly as opposed to the wet years; this translates to prevalent dry years with high inter-annual variability. The redistribution and increment of extremes, although resulting in no notable reductions in total rainfalls, make it impossible to reinstate only significant declines in the whole annual rainfalls. Water resources management, agriculture, irrigation, and urban flooding control in Monrovia have very significant implications under such circumstances. The implications of the findings reflect evidence-based knowledge in consonance with Sustainable Development Goals (SDG 6: Clean Water and Sanitation, SDG 11: Sustainable Cities and Communities, and SDG 13: Climate Action), the urgency of which relates to adaptive climate strategies of the urban environment in Monrovia.

Keywords- Rainfall anomalies, Rainfall variation, Intra-seasonal, West Africa, CHIRPS, Liberia Meteorological Services (LMS); Liberia, Standardized Precipitation Index (SPI), Precipitation Concentration Index (PCI), Rainfall anomaly index (RAI); Urban flooding, Monrovia, Mann-Kendall trend test, Sen's slope.

I. INTRODUCTION

The most critical climate parameter is precipitation, which has great power over the hydrological systems, ecosystems, agricultural, and socioeconomic progressions. It is regarded as one of the key indicators in fields of water resources productivity, agricultural productivity, and urbanization, risk of floods, human health, and quality. In West Africa, the significant source of fresh water and especially in Sierra Leone and Liberia, rainfall is the major source of fresh water. Thus, it is important to recognize the time and space pattern of rainfall to have sustainable planning, disaster risk reduction and climate resilience.

Liberia, located on the West African coast, receives a lot of rain because of the West African Monsoon (WAM) that is caused by land-ocean temperature contrasts and complicated atmospheric dynamics (Nicholson, 2018; Cook, 2015). The duration of the rainy season is May through October, with the heaviest rainfall in July and August in the capital city, namely Monrovia (Charles et al., 2020). Under the Köppen-Geiger system, the climate in Monrovia can easily be categorized as tropical monsoon due to the very high humidity as well as the abundant rainfall that falls during the rainy seasons. It is among the rainiest capitals in the world. An average of more than 4,600 mm of rain falls annually at Monrovia, although not evenly distributed during the year (World Bank, 2021). Rain of this magnitude not only affects the agricultural sector; it also influences water sources, infrastructure strength, and spread of diseases, flooding potential and long-term sustainability of cities. Unstable and even excessive rainfall has played a relatively bigger role in the last few years in triggering flash floods, destruction of infrastructure, and displacement of citizens within Monrovia (UNDP, 2022; EPA Liberia, 2019).

Even though weather studies and tracking in Liberia have remained underrated, the issue of the variation in rainfall and the intensity of rain is of great concern. Liberia still has limited technical capacity, no comprehensive long-term ground-based data, and a low level of integration of climate science into national planning for studies and monitoring. In the absence of high-quality, sustained in-situ rainfall measurements, satellite-based methods have become alternative solutions for addressing data gaps at such. This study utilized the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and Liberia Meteorological Service (LMS) data to determine the rainfall variability in Monrovia, Liberia. CHIRPS are an almost-global precipitation product, consisting of a blend of satellite (and in-situ station) data that provides high resolution (both spatial and time) dataset of precipitation (Funk et al., 2015). The effectiveness of the CHIRPS dataset for monitoring rainfall, drought detection, and hydrological modeling has been confirmed in various studies within the Sub-Saharan region (Dinku et al., 2018).

One of the most important parameters that have been adopted in this research is the Precipitation Concentration Index (PCI), pioneered by Oliver (1980), since it is a strong measure of the rainfall magnitude and irregularity in the course of time. The PCI indicates how concentrated the rain falls in any given month of the year. High PCI values signal that a large part of annual precipitation is brought together in several months of the year, which signals temporal irregularity and greater chances of hydrological extreme events, whether floods or drier periods. On the contrary, low PCI values imply an even monthly distribution of rainfall, which is beneficial to farming and water supply (Oliver, 1980; De Luis et al., 2011).

The evaluation of the PCI over Monrovia is especially diplomatic in the climate Adaptation planning in Liberia. An increase in rain in small windows increases the challenge of water absorption and storage, surface runoff, and, on many occasions, causes urban flooding. Monrovia and other urban areas across Liberia can usually only handle such climatic stresses with difficulty, since unregulated urbanization, inadequate drainage, and poor disaster management systems plague the country (UN-Habitat, 2016; GIZ, 2020). The Environmental Protection Agency of Liberia (EPA) stated that over 65 percent of the Monrovia population resides in informal settlements that are most frequently prone to seasonal floods and erosion, which is partly attributed to dense precipitation events in short time (EPA Liberia, 2019).

Severe weather emergencies in the West African region have been on the rise over the last four decades, partly through climate change, which is global (Niang et al., 2014). This is not the exception in Liberia. There is a suggestion that rainfall events are increasingly becoming sporadic, showers, and especially unevenly distributed (Sylla et al., 2016). This is more pronounced in Monrovia, whereby anecdotal reports and meager data on hydro-meteorological basis indicate a progressive rise in seasonal floods occurring mainly during July- September. PCI may give useful insights to policymakers regarding adaptation to the climate-sensitive sectors of Liberia, especially agriculture, urbanization, and disaster risk reduction with respect to the nature of rainfall concentration, inter-annual variability, and trends.

In many studies around the world, the methodology of PCI has been proven to provide an assessment of inconsistencies in rainfall and find vulnerable times in terms of water crisis and the risk of floods. To understand the rainfall pattern across Saudi Arabia, Alharbi et al. (2014) used PCI to find that it is very concentrated in arid areas. Equally, research has been conducted on Mediterranean climate (De Luis et al., 2011) and East Africa (Kizza et al., 2009) regions to exhibit the success of PCI in providing explanations for any sort of change in rainfall patterns associated with the changing climatic system. Although it can be considered relevant, the use of such indices has a conspicuous gap in Liberia, Monrovia in particular. Such a disparity collides with evidence-based preparations and planning of weather-related disasters.

Additionally, rain concentration has an impact on food security, water quality, and soil erosion. The sudden rise in rainfall over a short period may lead to reduced infiltration, increased surface runoff, and river sedimentation, as well as the leaching of productive upper topsoil, all of which are detrimental to sustainable agriculture and the human population (FAO, 2017). Another example was the country of Liberia, whose population is barely 70 percent who get their livelihood through agriculture and in the planning of the issue of food security in the nation, the knowledge of the variability of rainfall is crucial (World Bank, 2021). The inter-tropical convergence zone (ITCZ), which is a band of low pressure, is one of the important parameters that influence the rainfall distribution, in that the ITCZ moves to the north and south as the sun appears to move. With the movement of the ITCZ comes a rain-bearing system to various parts of Liberia. Its oscillatory nature contributes to the seasonality of rainfall, with coastal areas receiving more consistent rainfall due to proximity to the Atlantic, while inland regions experience more pronounced seasonality and variability (Camberlin et al., 2022).

This research is sensitive and policy-relevant, and it is in line with international demands for local climate information on the design of the national development strategies. Specifically, it is noted that the SDGs and goal 11 (Sustainable Cities and Communities) and 13 (Climate Action) also emphasize the need to have a focus on climate-resilient urban development and disaster risk mitigation policy agendas in vulnerable states, where Liberia can be included. Urban planning through climate-based data requires effective data and powerful indices like PCI to predict any risk possibility in the future and offer resilience to the urban infrastructure, land use, and planning governance procedures.

Moreover, the Nationally Determined Contributions (NDCs) developed by Liberia as a part of the Paris Agreement in 2021-2025 put stress on the inclusion of scientific studies in mitigation measures and adaptation to climate change (EPA Liberia, 2021). This research lends credence to the objectives of Agenda 2063 of the African Union, whose vision is to achieve climate resilience and limit disaster risk by developing sound environmental governance and spatial planning.

Methodologically, the research makes a contrast between the rainfall reports by LMS on the ground and CHIRPS precipitation products made up based on satellite data in a span of 38 years. Such a dual-source method not only gives an increased strength of the results, but it also affirms the applicability of satellite data to countries where observational infrastructure is paltry in number. Some recent studies in West Africa Sahel, and coastal West Africa used CHIRPS to understand the seasonal variability of rainfall, including the ENSO/Atlantic Niño-related anomalies (Tamoffo et al., 2019; Dinku et al., 2018). On the other hand, La Niña phases can enhance precipitation, sometimes leading to flooding events, particularly during the monsoon season (Jury, 2015). Additionally, the Gulf of Guinea sea surface temperature anomalies affect the amount of rainfall as well as its distribution. Other aspects where warmer anomalies favor the late weather of the rainy season beginning and low rainfall levels in comparison to cooler sea surface temperatures that create a favorable environment by causing early rainfall and an increase in the precipitation levels (Tokinaga & Xie, 2011). Such variations have a direct impact on agricultural production, the generation of power using hydropower stations, and water resources management.

The survey focuses on the infrastructural relevant and heavily populated urban hub of Monrovia, the epicenter of interest in Liberia, hence providing critical local information.

The results will be used in advising early warning systems, in water resource management, in urban drainage infrastructure planning, and the longer-term climate resilience of Liberia.

To sum up, the study of the Precipitation Concentration Index over Monrovia during 1981-2018 should be carried out due to a couple of reasons. It addresses an urgent knowledge gap in Liberian climate science; it makes use of sound and tested, and proven data sources; and it is linked to national and international climate policy goals. Since Liberia is increasingly experiencing climatic instability and urban at-risk conditions, the evidence-based evaluations like this will save lives by making informed decisions, fostering institutional resilience, and enhancing the lives of Monrovia residents.

Statement of the Problem

Monrovia is the capital city that is more susceptible to the effects of changing and severe rainfall patterns. In recent decades, the yet more frequent and more severely profound flood events have become visible in the city, displacing such basic infrastructural amenities as water supply, causing substantial structural damage, interrupting other basic services and activities, and increasing human health and safety risks (EPA Liberia, 2021). Such problems are commonly associated with the heavy rainfall events that cannot cope with current drainage systems, a scenario that is even aggravated through rapid urbanization, inefficient waste management, and failing infrastructure (UN-Habitat, 2020).

The inaccurate information about time- and location-specific data on rainfall and their high-resolution are one of the most current problems because such data could be helpful in evidence-based city planning and disaster prevention plans. Although the Liberia Meteorological Service (LMS) has observational records, the spatial documentation and temporal durability of the data have not been sufficient because of institutional constraints, shortage of skilled staff, and the inefficiency of the existing instruments (LMS, 2022). This impedes the efforts of urban planners, environmental agencies, and the local governments to associate changes in the rainfall patterns with the challenges of development pressures and flood hazards in and around Monrovia.

Despite the significant advances in the regional climate studies in West Africa, those efforts tend to overlook the scale of city-driven research on the rainfall behaviour and/or trends in precipitation concentration (Chadwick et al., 2021; IPCC, 2023). This has led to the fact that there are severe knowledge gaps when it comes to the spatial and temporal variation of rainfall in coastal cities such as Monrovia, which is highly vulnerable to climate-related risks.

Furthermore, the majority of such previous studies are prone to using the observational stations' data or results of modeling, any of which can seem to be sufficient to characterize rainfall in non-data-rich areas. A possible solution to the latter is the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) data product that interpolates satellite estimates of precipitation with station information, thus offering a more spatially comprehensive precipitation signal over low-observation regions such as Liberia to be used in climate trend analysis.

That being the case, the research will overcome the data and knowledge gap by analyzing rainfall patterns and concentration of precipitation index (PCI) over Monrovia between 1981 and 2024 in both LMS observational data and the CHIRPS space-based estimates. The result of this study will be useful in climate-sensitive planning and in coming up with early warning systems and sustainability development strategies that best fit the climatic and socio-environmental situation in Monrovia.

Aim and Objectives

Aim: To evaluate the dynamic changes in the rainfall distribution temporally in Monrovia from1981 to 2024.

The Specific Objectives are to:

(i) analyse temporal trends in monthly and annual rainfall totals.

(ii) assess rainfall irregularity and drought/wet event patterns.

(iii) analyse rainfall distribution in Monrovia

Research Questions

The research question used to guide the study to achieve the objectives will be as follows:

1. What are the trends of such temporal changes in total monthly and annual precipitation in Monrovia in 1981-2024 in the long term?
2. How has the rainfall been distributed in the course of the study, particularly on irregularities, dry and wet spells, and the occurrence of extreme rainfalls?
3. What are some of the inter-annual variability trends, anomalies in rainfall that can be viewed on the Monrovia rainfall observations between the years 1981-2024?

Significance of the Study

Rainfall distribution and its temporal variability are important aspects that must be understood comprehensively in formulating policy and making decisions in the most urbanized and population-dense region in Liberia, Monrovia. Prediction and interpretation ability of the extremes in rainfall are central to planning the developmental activities of the nations, particularly where the variation directly impacts the sustainability of built-up areas, water and food supply, hydro-meteorological infrastructure, and livelihood of the people (Liberia Meteorological Service [LMS], 2020).

With the current growth in vulnerability, Monrovia experiences seasonal floods due to an interaction of high rates of urban expansion, inadequacy of urban drainage infrastructure, and the lack of proper urban planning. The study is very timely and specifically applied to the research on rainfall variability trends that would transpire between 1981 and 2024. A multi-year study to acquire information on rainfall parameters at the city scale should be done to evaluate the degree of vulnerability, propose drainage and infrastructure construction, land management, and resource allocation more efficiently, depending on the empirical data on climatic conditions.

Past endeavors in research have mostly focused on either national or regional levels, whereby the microclimatic and time-specific conditions of cities have been overlooked; this is an attribute that plays a crucial role in urban planning and disaster preparedness (United Nations Development Programme [UNDP], 2021). As such, the research paper will address one of the current research gaps, since the research will be done on rainfall patterns in the city of Monrovia, and this will supplement the localized adaptation of climate change in the cities that are considered to be highly vulnerable. Secondly, the findings of the study will promote the National Adaptation Plans (NAPs) not only in Liberia but also the compliance with the United Nations Sustainable Development Goals (SDGs).

In particular, the research is in line with:

- SDG 11 -Sustainable Cities and Communities through the encouragement of climate-resilient urban plans.
- SDG 13- Climate Action, through making efforts towards preparation and resistance to the hazards of climate change.
- SDG 6- Clean Water and Sanitation, through better management of water resources in flood hazard urban areas (United Nations [UN], 2015).

In terms of methodology, this study is relevant in that it incorporates satellite Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) along with terrestrial Liberia Meteorological Service rainfall into the study. This combination helps improve the reliability of data and the spatial resolution in an area where data gaps are frequent as a result of institutional, financial, or technical shortages. Such hybrid solutions are promoted by many climate monitoring organizations that need to compensate for the data shortages in the regions where the number of observations is limited (Funk et al., 2015; Knapp et al., 2011).

Finally, the research has scientific relevance in the cross-sectorial contexts of cross-sectorial applications through climate-smart agriculture, disaster risk reduction, environmental management, and meteorological early warning systems. Its findings would provide insight to Monrovia and other urban policy makers, planners, and development partners to make an informed, evidence-based decision on climate-resilient policies that can boost sustainability and protect its infrastructure, hence unable to protect the vulnerable population.

The Scope and Limitations of the Study

This paper takes a close examination of 44 years (1981-2024) of rainfall in Monrovia, Liberia. The basis of the research findings is an evaluation of inter-annual and intra-annual variability of precipitation, and the particular analysis that was carried out relates to finding trends, anomalies, seasonality, monthly maxima, and the extreme events of rainfall. Such analyses are achieved by using commonly accepted climate indices like the Precipitation Concentration Index (PCI), Standardized Precipitation Index (SPI), and their statistical methods proposed in climate research structures across the world (McKee et al., 1993; WMO, 2012).

Towards a robust and reliable result, the study combines two of the most important sets of data; satellite-based rainfall sequences, presented by Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) that possess high spatial resolution and quasi-global coverage (Funk et al., 2015), and localized rainfall data, which are provided by ground-based observations of the Liberia Meteorological Service (LMS). The cross-validation of the results and minimization of biases that arise when only one of the datasets is used is made possible by the utilization of the two datasets. This two-source technique increases the spatial and temporal accuracy in the analysis of the rainfall pattern of Monrovia.

The research is physically restricted to the city of Monrovia and its immediate surroundings within Montserrado County. The selection of that region was based on a large population, socioeconomic value, along sensitivity to negative weather fluctuations in that region in the past, such as flooding and shoreline erosion (EPA Liberia, 2021). The urban environment in Monrovia may also be viewed as an urban microcosm to look into the problem of climate resilience within urban West African settings on a larger scale. Although the results could be useful as indicative trends, the spatial results should not be applied to all regions that are of considerably different topographies or microclimatic conditions without first ensuring and validating them locally.

In time, the period discussed by the paper begins with January 1981 and ends with December 2024. This widened length of time allows one to measure not only a short-term variation but also at least an extended trade-wind tendency.

The use of this period is because of the high-quality CHIRPS data beginning in the year 1981, and it harmonizes with the available archival data at the LMS station at the Roberts International Airport and other auxiliary locations. Such a window of analysis also comprises significant decades of climate variability over the whole world, such as those tied to ENSO phases, the West African Monsoon oscillations, and the impact of anthropogenic climate change (IPCC, 2021).

The study has a number of limitations, even though it is very broad. One is the link to completeness and continuity of the LMS ground station data. Data acquisition and archival in Liberia have been affected by political orientation, civil conflict (1989-2003), as well as institutional backwardness in the last few decades. Therefore, missing data could be spread over a specific period in the ground-based dataset, or there could be inconsistent data (LMS, 2022). This can interfere with the consistency of year-on-year comparison and can provide bias to the trend, except that it is sufficiently compensated during preprocessing.

On the second hand, despite its extensive application in climate research in data scarce areas, CHIRPS satellite-derived data may be restricted by retrieval uncertainties, particularly in highly clouded tropical areas where satellite sensing alone cannot locate or interpret cloudy areas due to extensive cloud cover, or they fail to correctly interpret maritime precipitation conditions (Knapp et al., 2011; Dinku et al., 2018). In addition to this, CHIRPS is calibrated to in-situ stations and in places where these stations are lacking, like in Liberia, the calibration errors might still be present- this is especially true when it comes to smaller-scale convective systems, which occur mainly in the West African Monsoon region.

Moreover, the study is purely climatological and does not entail the involvement of hydrological modeling as well as socio-economic impact estimations. Even though the variability in rainfall patterns can have major impacts on water resources, agriculture, urban drainage, and disaster risk, the paper does not use any modeling techniques as Soil and Water Assessment Tool (SWAT), Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS), or urban flood simulation tools, because of limitations in data and the extent of the study. A broader-based evaluation would involve inputs from different experts in hydrology, civil engineering, and urban planning (World Bank, 2022).

Besides, there is a socio-economic implication (the impact of rainfall variations on health, infrastructure, and forced migration, or food crisis), which was only mentioned but not explored further. The dimensions require quantitative and qualitative data that go beyond the sphere of climatology and include stakeholders, surveys, and policy papers (UN-Habitat, 2020; UNDP, 2021). Despite such shortcomings, the methodological quality and use of tested and validated climate indices and data sets allow the study to have significant insights concerning rainfall variability in Monrovia. The results will build on scientific debate and provide a practical foundation for the inclusion of climate data into planning, disaster risk reduction, and climate adaptation strategies of Montserrado County and other areas.

II. LITERATURE REVIEW

Concept of Rainfall Variability

Rainfall variations can be seen as changes in volumes of precipitation at the various temporal and spatial ranges. These fluctuations may happen daily, seasonally, annually, or decadal, and they are affected by numerous natural and man-made activities. Within the scope of climate science and meteorology, rainfall variability constitutes an essential element in the knowledge of hydrological activities, agricultural feasibility, water resources management, and the strategizing of socio-economic development, urban, and rural (Nicholson, 2000).

The variability in rainfall may occur in many ways, such as rainfall variability, which can be inter-annual variability (differential rainfall between years), intra-seasonal variability (variability during the rainy season), and also spatial variability (differential rainfall amounts across regions). The problem of rainfall variability has severe impacts on the livelihood of communities in areas such as West Africa, and in particular, in Monrovia, Liberia, because of crops depending on rain-fed agriculture and the vulnerability of urban centers to floods (Tarhule & Woo, 1998).

Around the world, the variations in rainfall patterns are claimed to be linked to climate change, which interferes with the traditional weather patterns, augmenting the occurrence of outrageous weather conditions, advancing the dates of rainfall start and stop, as well as decreasing the number of days per year classification (IPCC, 2021). Large-scale climate patterns like the El Niño-Southern Oscillation (ENSO), the Inter-tropical

Convergence Zone (ITCZ), and the West African Monsoon (WAM) are additional factors that influence the variability due to rainfall distribution in sub-Saharan Africa. Indeed, rainfall variability in Liberia is high because it is a coastal state located under the weather impact of the monsoons (LMS, 2022). This has made it difficult to project and plan agricultural rotations, water availability, and flood control. It is worth noting that local-scale rainfall variability is critical in defining the approach to adaptation to climate, particularly in localities where there is limited accessibility of data and the ability to forecast the climate (Owusu and Waylen 2009).

Statistical methods and climate indices (e.g., Precipitation Concentration Index (PCI), Standardized Precipitation Index (SPI), and Coefficient of Variation (CV)) are normally used to measure rainfall variability. The indices form a quantitative way of knowing when things are not right, the extremes, and the level of concentration or dispersion of rainfall at a particular given period (Oliver, 1980; McKee et al., 1993).

To conclude, the variability of rainfall is not only a meteorological issue but also a socio-economic issue, which impacts various spheres. Its analysis is crucial in facilitating the establishment of sustainable climatic policies, infrastructural development, and agricultural policies, especially in the areas that are vulnerable, such as Monrovia, Liberia.

Theoretical Framework

The theoretical basis of explicating rainfall variability is based on climatological, hydrological, and statistical. It is this framework that gives the foundation for making an interpretation of observed trends in precipitation and forecasting future scenarios under different climatic conditions. To address the forces and dynamics of the variations in rainfall, especially in West African tropical regions, various significant theories and models have been formulated.

Climate Variability and Change Theory

Rainfall variability is centered on a wider-ranging concept, that of climate variability and change. Climate variability is a natural fluctuation of the parameters of the climate over the months, years, or decades. Conversely, climate change entails a timescale of change in climate patterns that in many instances are associated with human activities such as greenhouse gases and land change (IPCC, 2021).

This theory points out that natural factors such as volcanic activities, solar deviations are some of the factors, as well as human-induced activities such as urbanization, deforestation, and burning of fossil fuels, that influence the processes within the atmosphere that determine rainfall. Within the Liberian context, evolutions in rainfall height of onset, intensity, and duration fall within this theory framework of being both happening in response to natural atmospheric circulation and climate change tendencies in general (UNDP, 2019).

Monsoon Dynamics and ITCZ Theory

One more important theoretical aspect is the interaction of the process of the Inter-tropical Convergence Zone (ITCZ) and the West African Monsoon (WAM) system. ITCZ is a region in the equatorial regions with a combination of the northeast and southeast winds that result in ascending movement of air and precipitation. It seasonally migrates north-south across tropical Africa, hence affecting the spatial and temporal rainfall distribution across its range (Nicholson, 2013).

Liberia receives most of its rainfall annually through the West African Monsoon, which is caused by the disparity between heating rates on the land and the ocean. The monsoon variations in terms of their advancing, intensity, and withdrawal are associated with marked rainfall variations owing to delays or anomalies in these patterns. The movement of the ITCZ in correlation with the monsoon system gives some theoretical answers to how and why some years are subject to above and below normal rains in Monrovia and the West African region in general (Cook, 1999).

Atmospheric Teleconnection Theory

Atmospheric teleconnections are large-scale features of pressure and circulation anomalies that affect weather and when weather scales to climate. Among these are the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Atlantic Multidecadal Oscillation (AMO). Specifically, ENSO has been associated with rainfall anomalies in West Africa that have mainly caused droughts or floods about its phase (Janicot et al., 2001).

Such patterns of teleconnection provide the theoretical explanation for the inter-annual variability of rainfall in Liberia. As an example, El Niño events may have resulted in both reducing rainfall through suppression of convection over West Africa and increasing rainfall through increased convection over La Niña episodes. Teleconnection theory offers an opportunity to implement it in the study of rainfall variability that can increase its predictive capabilities and help in climate-informed decision-making.

Hydrological Cycle Theory

The hydrological cycle just represents how water travels through the atmosphere, land, and oceans through processes like evaporation, condensation, precipitation, infiltration, and runoff. One of the fundamental elements of this cycle is rainfall. The theory establishes that cascading effects of any variations in the cycle, either due to climate forcing, land-use changes, or aspects in the atmosphere, will influence the quantity and spatial extent of precipitation (Chahine, 1992).

An example is that urbanization in Monrovia determines the surface albedo, the evapotranspiration rates, and the water balance, which can be involved in localized rainfall patterns. From a hydrological point of view, the variation of rainfall is not only dependent on the process of atmospheric dynamics but also on the processes of the Earth and the ocean.

Statistical Theory of Variability

Statistical models are used in the analysis of data concerning randomness and trends of rainfall using this theory. Patterns in rainfall records are interpreted using a combination of time-series methods, regression models, methods of detecting trends (e.g., Mann-Kendall test), and measures of variability (e.g., PCI, SPI) (Kendall, 1975; McKee et al., 1993).

Empirical approaches to understanding the variability of rainfall are based on statistical theory. By enabling the researcher to measure variability, generate meaningful trends or change, and associate these changes with output to the environment and socio-economic environment, it enables researchers to analyze. In the following paper about Monrovia, Liberia, the statistical framework gives the foundation to examine long-term values of rainfall and determine the level and consequences of variability.

Rainfall Variability in West Africa

Variability in rainfall in West Africa has attracted the attention of scientists because variable rainfall has a strong influence on agriculture, water, food security, ecosystem stability, and socioeconomic growth. The use of rain-fed agricultural practices and the risk of being exposed to the extremes of climatic conditions make the dynamics of rainfall crucial to the region. The fluctuation of rainfall has a direct impact not only on farming, pastoral activities, but also on the general means of communities to survive in the area.

West African Monsoon System

The West African Monsoon (WAM) system is the major factor contributing to seasonal rains over West Africa as it carries moisture inland during the period between May and October over the Gulf of Guinea. The intensity, occurrence, lifetime, and termination of the WAM depend on a number of large-scale atmospheric and oceanic processes such as sea surface temperature (SST) anomalies in the Atlantic, Indian, and Pacific Oceans, land processes, and feedback (Nicholson, 2013). Such teleconnections dictate the inter-annual variability that is especially sharp in the Sahelian zone.

The WAM is also marked by the movement of the Inter-Tropical Convergence Zone (ITCZ) northwards towards the convergence of wet southwesterly winds with dry northeasterly Harmattan winds. The northward limit of the ITCZ influences the pattern of the rainfall, such that southern coastal areas get good early and more uniform rainfall; meanwhile, the northern semi-arid areas, such as the Sahel, receive shorter, much more variable wet seasons.

There are two large-scale features of the atmosphere that are involved in the modulation of West African rainfall:

1. **African Easterly Jet (AEJ):** A jet stream in the middle levels of the atmosphere, which causes the emergence and vicinity of the African Easterly Waves (AEWs) that may increase convective phenomena and lead to rainfall.
2. **Tropical Easterly Jet (TEJ):** present at higher altitudes and of the upper-level divergence suppression and influencing the vertical profile of convection.

Spatial and Temporal Variability

The trend of rainfall in West Africa is highly variable on many timescales, both intra-seasonal, inter-annual, and decade time scale. The inter-seasonal variation encompasses events like dry periods and rainy season breaks that have an immense influence on the production in the fields and the quantity of water. Inter-annual activity is mainly linked to interaction between ocean and atmosphere, like El Niño -Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), and Atlantic Niño output.

On the spatial scale, the coastal regions, including Liberia, the South of Nigeria, and some areas of Sierra Leone, experience annual precipitation that surpasses 2,000 mm, although semi-arid zones within the Sahel might experience less than 600 mm per year. The slope of rainfall distribution between the south and the north can be described as seismic, and its annual variation can be said to be wide.

Historical Trends and the Sahel Droughts

The period between the 1970s and the 80s was characterized by massive and dramatic droughts in the Sahel region that caused a humanitarian crisis, crop failures, famine, and an exodus of people. Such droughts resulted in negative SST anomalies in the tropical Atlantic and changes in the global-scale atmospheric circulation (Giannini et al., 2008). The common decrease in rainfall during this time drew the issues of vulnerability of the climate in West Africa and the importance of gaining better insights regarding climatic drivers.

Partial recovery of rainfall in the Sahel has been witnessed since the late 90s. Such recovery has not been synchronized spatially or over time, however. According to Biasutti (2019), we have some areas that have seen an increase in the levels of rainfall and some areas that are still not above the historical amounts of rainfall in the 1950s and 1960s. Furthermore, higher rainfall cannot automatically be taken as a sign of better things since the type of rain has also evolved to shorter, more intense precipitations that present a higher chance of a flash flood and the occurrence of erosion.

Climate Change and Future Projections

In the West African region, changes in rainfall variability are expected to be greater in future climates. IPCC Sixth Assessment Report (2021), powered by climate models, indicates that the area can experience more extreme and frequent intense rainfall rates as well as extended dry intervals. Variability in rainfall may strain its policies of adaptation, especially in the farming sector and water management.

The models further suggest a possible shift of the beginning and end of the rainy season forward in time and vice versa, effectively reducing the growing season. These changes would adversely affect food production and food security, especially in some of the countries such as Burkina Faso, Mali, and Niger, where subsistence agriculture is very common.

Such large-scale regional climatic drivers affect the rainfall regime in Liberia and its capital, Monrovia. Despite rainfall being quite high along the Liberian coast (usually over 3,000 mm/year), variations within the season, shifts in the timing of the start and end of rainfall, and a growing number of extreme weather events (including floods in urban settings) are already being felt. The infrastructure development, disaster preparedness, and agricultural plans have to face challenges of such changes (World Bank, 2022).

Socioeconomic Impacts of Rainfall Variability

Variability in rainfall is among the key limiting factors on economic growth and development in West Africa. Variability of rain causes uncertainties in agricultural productivity both in subsistence and commercial farming systems. This has implications to food availability, prices in the markets, as well as household income. Under variable conditions, water resource management is made ever more complex and applies to drinking water supply, irrigation, and the production of hydroelectric power.

Health risks are further escalated by droughts and floods; these diseases are caused by malnutrition, water-borne diseases, and the diseases that are spread by vectors (such as malaria). The overloading of the drainage system due to heavy rainfall is a common burden that causes flooding in urban areas, especially in fast-growing cities such as Monrovia, causing destruction of property, food and labor loss, as well as the loss of lives due to urban flooding.

There are also political, and security issues related to rainfall variability. Droughts have been associated with the scarcity of resources, leading to the escalation of interventions over land and water resources. It also affects migration patterns because people relocate in pursuit of more stable environmental factors and economic prospects.

Adaptation and Resilience Strategies

With the inconsistency in rainfall, there has been an emergence of diverse strategies to adapt to it on a local, national, and regional scale. These include:

- Good season forecast and warning systems.
- Climate-smart farming (e.g., drought-resistant crops, agroforestry, water harvesting).
- Development of infrastructures, most notably the flood defenses and the irrigation systems.
- Public awareness camps and capacity-building.

The assimilation of climate data into national developmental policy.

Local projects, including the West African Climate Services Center and the African Monsoon Multidisciplinary Analysis (AMMA), are important to generate advances in science, operational monitoring, and responses to the variability of rainfall.

Urbanization and Rainfall Dynamics in Monrovia

Urbanization has the capability of transforming both the natural landscape and the local climate system, especially the precipitation cycle and the rainfall-runoff process. At the Liberian capital, Monrovia, which is the most urbanized area of the country, the high rate of built-up land development has caused further anxieties relative to rainfall processes and urban hydrology. Urbanization affects the surface energy balance, land cover, and natural processes in the hydrological cycle, which all impact variability in rainfall, surface runoff, and risks related to flooding in urban areas (Zhou et al., 2017).

Urban Expansion and Land Use Change

Land cover in Monrovia has been changing immensely over the past years. There has been a rising number of impervious surfaces, which include roads, buildings, and plotted lands taken over by agricultural and forested land. This expansion has mostly been uncontrolled and caused by population rise, rural-urban drift, and centralization of the economy. The urban realm of Monrovia has almost tripled in size between 2000 and 2020, with serious encroachment into flood-prone wetlands and coastal areas (World Bank, 2021).

Such land use patterns have violated the apparent absorption attributes of soils and lowered the evapotranspiration rates in addition to aggravating the near-surface runoff upon precipitation (Liu & Weng, 2008). The flow on the impermeable surfaces leads to precipitation, whereby the rainwater collects and moves swiftly towards the drainage channels that are, in most cases, poorly designed or blocked. Thus, low-level rainfalls may cause devastating floods, impacting urban environments, livelihood, and causing illness to public health (UN-Habitat, 2019).

Influence of Urban Heat Island Effect on Rainfall

Another important feature of urbanization that has been the focus of the study of rainfall in Monrovia is the Urban Heat Island (UHI) effect. The amount of solar radiation that reaches urban cores is greater than that in rural areas due to the absorption of the former. Such a heat accumulation is capable of causing convective upraise and triggering the instability of the atmosphere that leads to localized rainfall in the urban areas (Oke, 1987; Shepherd, 2005). The warming trend between urban and peri-urban areas has been linked to the enhancement of thunderstorms in the afternoon and the changed diurnal rainfall pattern in Monrovia.

Satellite data-based and ground-based studies have additionally confirmed that urbanized areas are more likely to be affected by the high frequency and intensity of rainfall when compared to their rural catchments (Jin et al., 2005). This peculiarity is explained by the strengthening of the vertical convection and a rise in the convergence of the wetness in the atmosphere as a result of the UHI effect. Even though there is little data specifically on the local scale and the city of Monrovia, regional levels of city-based climatological data have been shown to confirm these trends and point to the relevance of city-specific studies (Lawal et al., 2020).

Urbanization and Drainage Challenges

The other effect of a high rate of urbanization is that there is pressure on drainage infrastructure. Monrovia has poor and old storm-water drainage systems, with most of its drainage constructed during colonial times or early independence. These infrastructures did not factor in the existing population density, higher rainfall intensities caused by changing climates and urban development. Moreover, loose urban management and waste policies often result in most of the drainage channels being littered with solid waste (EPA Liberia, 2020).

This makes urban regions and especially informal settlements such as West Point, Clara Town, and Paynesville, part of the areas at high risk of flash floods. The floods affect such activities as transport and the economy, besides causing waterborne diseases like cholera, dysentery, and typhoid fever. When there is a flood, it usually drives families out of their homes during seasons of rainy weather, leading to social and economic dislocation (UNDP, 2021).

Feedback Loops Between Urbanization and Rainfall

A two-way linkage exists between rainfall and urbanization. Although the influences of urbanization change the characteristics of rainfall, the resilient strategies in an urban setting are also influenced by the resultant changes in rainfall patterns. With more volatile rainfall and more frequent extreme weather events, Monrovia's city design, land planning, and housing construction are being affected. Sadly, the majority of urban growth is still referred to as reactive as opposed to proactive and has minimal consideration of climate adaptation policies within the planning systems (LISGIS, 2022).

The feedback loops are also seen to aggravate the socio-economic inequalities. The upper classes may display flood-resistant buildings and houses raised above the ground, whereas the low-income groups stay in areas that are prone to floods with no proper shelter. With the forecast on climate requiring a higher frequency and intensity of rain patterns experienced in Liberia, particularly in metropolitan areas such as Monrovia, there is a need to ensure that urban planning will shift gears to focus on the causes and the effects of the urban rainfall reality (IPCC, 2021).

Integrating Urban Climatology into Policy

Based on the above findings, it can be recommended that the urban management of rainfall variability in Monrovia needs to integrate urban climatology into urban planning, environmental regulation, and physical infrastructure design. This comprises the implementation of green infrastructure, e.g., bioswales, rain gardens, and permeable pavements in order to increase infiltration and minimize runoff (Gill et al., 2007). The city should also integrate early warning systems, hydro-meteorological modeling, and construction codes that would be climate-resilient; this will enhance the adaptive capacity of the city.

In addition, the urban policy should advocate decentralization so that the urban core of Monrovia is not overly strained and so as to ensure robust city structuring in emerging towns. Afforestation policies, wetlands conservation, and stabilizing a river bank are crucial to reshaping the earth science balance that has been shifted out of harmony due to the uncontrolled population growth (FAO, 2019).

Impacts of Rainfall Variability on Livelihoods in Liberia

Climatic variability Rainfall in Liberia has wide-reaching implications for several components of human and environmental well-being. Since Liberia is a country in the tropics' monsoon climatic zone, most of its economy and socially related structures rely on the stability and predictability of rainfall seasons. But owing to climate change, natural fluctuations, and human activities, rainfall in the region is now even more erratic, and its effects have resulted in significant impacts on agriculture, water, health, infrastructure, and socio-economic development (UNDP, 2021; World Bank, 2022).

Agriculture and Food Security

Liberia has an economy based largely on agriculture, which directly represents more than 70 percent of the population and also contributes extensively to the country's GDP (FAO, 2023). Major agriculture in the country is subsistence rain-fed farming on crops such as rice, cassava, maize, and vegetables. Adverse weather patterns such as variable rainfall characterized by late or delayed rain, early stopping of rains, as well as heavy precipitation events, cause variations in the time of planting crops and collecting the harvest, which directly affects yield. An example is that excess rain will cause waterlogging and crop rot, whereas droughts can prevent germination and development. The two conditions pose a threat to food supplies; intensify hunger, as well as poverty within the rural areas (WFP, 2022).

Moreover, the fluctuations of rainfall restrict the level of use of historic farming calendars, which rely on the past climatic expertise. Consequently, the timing and amount of rainfall can be otherwise unpredictable to the farmers, creating instances of discrepancies between the anticipation of seasons and reality in terms of the current weather. Such a state of affairs is additionally complicated by the fact that access to meteorological information and modern farming inputs is scarce, which makes smallholder farmers extremely vulnerable (USAID, 2020).

Water Resources and Hydropower

Hydropower and Freshwater are also optimized in the river systems and watersheds of Liberia. Variability in rainfall also causes variations in the recharge of surface and groundwater supplies, which in turn affects accessibility and quality of water used by people in domestic, irrigation, and industrial purposes. During times when rainfall is scarce, there is a scarcity of water in the communities, particularly in rural and peri-urban regions. On the other hand, heavy rain may also cause pollution of any drinking water sources through water runoffs and floods, thus washing away sediments and wastes into wells, rivers, and boreholes (WHO, 2021).

A major stake in the renewable energy offered by Liberia in terms of hydropower generated using the Mount Coffee Hydropower Plant also relies on the consistent river flows that are supported by the rain. Energy production may decrease as a result of deficit rainfall in the dry season or imbalance in the shifting of seasons, leading to a shorter supply of electricity to the households, hospitals, schools, industries, etc. (Manneh et al., 2021). This may hamper economic growth and development processes, more so in an urban area like Monrovia.

Public Health and Disease Burden

The issue of rainfall variability affects the health of the population significantly in Liberia. Among the most serious impacts is the spread of water-borne and vector-borne diseases. Floods and overwhelming rainfall provide favorable conditions to mosquitoes and enhance the number of malaria cases, as it is already a prominent disease in the country in terms of public health (MOH, 2022). Analogously, the cases of cholera and diarrhea epidemics also increase in cases where flood waters mix with human and animal wastes, which contaminate the drinking water supply.

Moreover, droughts usually lead to a lack of sanitation and hygiene because of the lack of water. This has been pushing societies to utilize excessive water sources, leading to increased chances of diseases and infections. The children and elderly are especially vulnerable to such occurrences, and as a result, they carry high morbidity and mortality rates. It adds pressure to the already weak healthcare system and displaces it at the expense of other health needs and initiatives (UNICEF, 2021).

Infrastructure and Urban Settlements

The extreme rain has a strong impact on the infrastructure in Liberia, whether as downpours or long dry spells. Floods regularly occur when washouts fall in major cities such as Monrovia; this is attributed to low low-quality drainage network and the uncontrolled construction in cities. Transportation, education, and administrative activities are usually disrupted because roads, bridges, schools, and other public buildings are usually submerged and destroyed (UN-Habitat, 2021). Repeated floods degrade the road systems, houses, and worsen the maintenance requirements of both the public and private infrastructure.

Also, the settlement of cities in wetlands and floodplains worsens the likelihood of flood disaster risks. The informal settlements in such places are quite vulnerable as they fail to equip the level of resilience as a counterattack to extreme weather events. The destruction of property, evacuation of the residents, and additional repair matter financially strain households and municipalities (UNDRR, 2022).

Economic and Social Vulnerability

The overall implications of rainfall variability to the agricultural sectors, as well as to water, health, and infrastructure, provide the economic frailty and social vulnerability. The crop failure and water shortage in rural places cause diminishing revenues, food crisis, and population movement. City dwellers, instead, are greeted by increased food prices, displacement in climate-sensitive industries, and the added vulnerability to illness. One of the threats to vulnerable populations most affected by these impacts is the lack of access to resources, healthcare, and adaptive infrastructure that includes women, children, and elderly citizens (ILO, 2021).

The performance and school attendance are also influenced by the variability of rainfall. Such things as flooded roads and buildings, and disease outbreaks usually lead to long-term closures of schools. Schools are, in other instances, transformed into camps during extreme events to the point that teaching is disrupted over a long period. This also discourages the human capital development and resilience levels long term of the country (World Bank, 2023).

Psychological and Cultural Effects

The psychological effect of climate-related stress, which is, in most cases, disregarded, may be significant, like the uncertainty of rainfall. Anxiety and fear associated with the unpredictability of weather events often emerge among farmers, students, parents, and business owners. These mental stresses are common occurrences, especially in post-conflict societies such as Liberia, because communities are already facing legacies of conflicts and inefficient economies (UNDP, 2021). Also, there is an interference with cultural practices associated with seasonal changes and agricultural holidays, which disrupts the community, its unity, and identity.

Institutional and Policy Responses

The Liberian government, the partners (regional and international), in recognition of the challenges, have looked into these and initiated several projects to deal with the variability of rainfall. These are the development of early warning systems, the incorporation of climate-smart agriculture, the widening of the meteorological network, and investment in flood-resistant infrastructure. Major players in the coordination of climate data collection and later analysis to aid in the planning of adaptation are the Liberia Meteorological

Service (LMS) and the Environmental Protection Agency (EPA) (EPA-Liberia, 2021).

In addition to that, national policies like Liberia National Adaptation Plan (NAP) and Nationally Determined Contributions (NDCs) under the Paris Agreement underline the need to develop resilience in other key areas of agriculture, water, health, and energy. The priorities of the strategies are to use climate information services, better forecasting tools, and community-based adaptation (UNFCCC, 2020).

Nevertheless, institutional capacity and technical expertise, as well as a lack of money, poses a challenge to the implementation process. Subsequently, there should also be an increase in the local knowledge incorporation, gender-sensitive planning, and the involvement of the private sector, so resilience plans could be more effective and sustainable (GCF, 2022).

III. MATERIALS AND METHODOLOGY

Introduction

The methodology, summarized by the work flowchart in figure 3.2, provides the systematic program followed to determine variation in the spatiotemporal patterns of the rainfall over Monrovia, Liberia, in the period of 1981 to 2024. In the chapter, the sources of data, preprocessing steps, statistical analyses, and tools used are described. The objective is to have some useful knowledge on the long-term behavior of rainfall based on independent ground-based data and satellite-based data. The insights hold significant relevance to comprehend hazards caused by rainfall, particularly flooding, as well as the formulation of strategies to achieve adaptation within the context of United Nations Sustainable Development Goals (SDGs), and specifically, SDG 13 (Climate Action), which focuses on enhancement of resilience and adaptive capacity to hazards of climate-sensitive nature (UN, 2015).

The given hybrid approach becomes particularly crucial in low-observation situations and can integrate sparse spaced-situ data with satellite products such as CHIRPS. Such approaches were also used in other parts of Sub-Saharan Africa to examine the drought, rainfall variability, and the effects of climate change (Dinku et al., 2011; Camberlin et al., 2022). Multisource integration enables one to mitigate the constraints of limited or unreliable data due to the absence or inconsistencies in observational data and enhances the confidence in identifying trends.

Description of the Area of Study

Monrovia, the capital of the West African country Liberia, lies in the Montserrado County of the western coast of the country that borders the Atlantic Ocean (Figure 3.1). It is located at about 6.30N and 10.80W and is the political, economic, and population heart of Liberia. The Köppen-Geiger climate classification means that Monrovia has a tropical monsoon climate (Am) with intense downpour during the rainy season (May to October) and dry season, which is short (November to April) (Peel et al., 2007). Annual rainfall averages more than 4,500 mm in Monrovia, one of the most populous West African capitals.

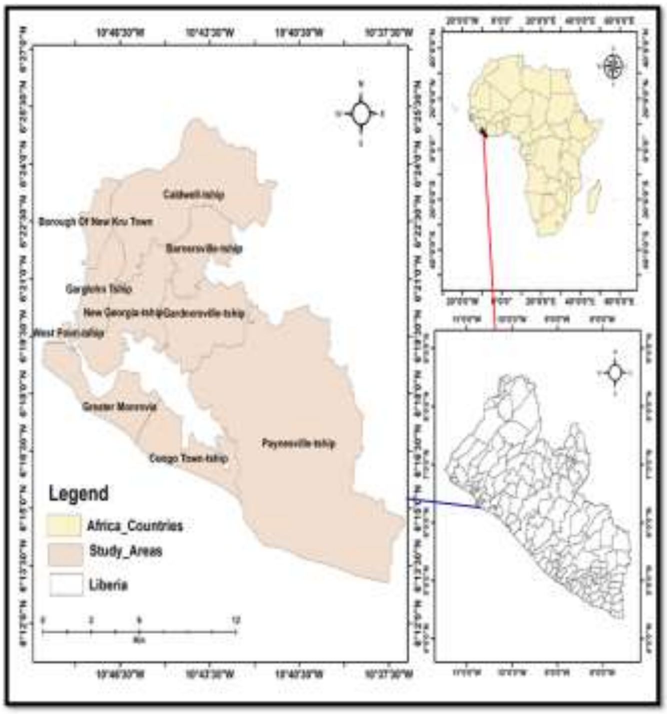

Figure 3.1: The Map of the Area of the Study

Such heavy rain has been the causal factor behind frequent cases of flooding in urban areas, which is exacerbated by unauthorized urban development and poor storm-water drainage systems (World Bank, 2020). The low coastal topography of the city also contributes to flood hazards in the event of massive rainstorms. Climate variability and change thus have direct linkages with vulnerability of urban populations to rain-related hazards (Douglas et al., 2008).

These factors come in to make Monrovia the case study necessary in exploring what rainfall patterns mean to infrastructure, health, and even urban planning.

- **Data Sources**

Satellite-Based Rainfall Data (CHIRPS)

Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) gives quasi-global estimates of rainfall since 1981. It uses a blending algorithm to combine the in-situ data with the satellite observations in such a way as to improve spatial accuracy, especially in the data-limited areas (Funk et al., 2015). The spatial resolution of CHIRPS is 0.05 (approximately 5km) with near-global coverage (500 S to 50°N) and is therefore an ideal instrument for studying the trends in long-term rainfall across a given area, such as West Africa.

CHIRPS has been demonstrated in various regions within Africa, and the results and implications tied to it are recognized to track the seasonal rainfall patterns with a reasonable degree of accuracy as compared to national weather data records (Tot et al., 2015; Dinku et al., 2018). In Liberia, its use overcomes the constraint associated with few ground measurements and provides an accessible, coherent data set to permit multi-decadal analyses.

Ground-Based Rainfall Data (Liberia Meteorological Service -LMS)

The rainfall measurements made by the Liberia Meteorological Service (LMS) give high-resolution point data on rainfall levels at Monrovia. These data were employed to determine the reliability of CHIRPS estimates as well as to perform bias correction, in case it is needed. This LMS data consists of daily and monthly cumulative rainfall, where the dataset covers the same time as CHIRPS (1981 to 2024).

The accuracy of data derived through satellite needs to be ascertained by ground observation (Klemeš, 1983). Although very low in spatial extent, station measurements assist in grounding the remote sensing statistics to the real facts and enhance the assurance with regard to the distinction of trends and characterization of anomalies.

Data Processing and Validation of Data

Data preprocessing comprised several procedures to achieve compatibility and quality among the CHIRPS and LMS datasets:

Temporal Aggregation: Seasonal totals and annual totals of rainfall data were constituted of daily and monthly data. This helped compare the year-to-year and examine trends across the 44 years in accordance with the practices applied in climatological research (Zhao et al., 2016).

Quality Control: The LMS data were reviewed on the basis of missing values, outliers, and inconsistencies. Methods like moving average smoothing, linear interpolation, threshold-based anomaly detection, and the filling of vacant spaces were used as a technique to fix and fill gaps (Wilks, 2011).

Cross-Validation: Cross-validation of the CHIRPS and LMS was done by comparing the two data sets using the Pearson correlation and RMSE as the indicators of consistency between the two data sets. Cross-validation enhances the non-reliance of findings and is essential when merging satellite and station-related data (Becker et al., 2013).

Such preprocessing procedures make data valid and allow one to determine trends, anomalies, and statistical associations in rainfall patterns effectively.

Methods of Analysis

- **Trends Analysis**

The Mann statistics and Kendall trend test and the Sen's slope estimator methods were employed to investigate the precipitation trend. These two approaches are recommended by the World Meteorological Organization to analyze the hydro-climatic variables over time (WMO, 2017).

Mann-Kendall Test: It is a non-parametric test, which identifies monotonic trends within time series data without a normality assumption. It has found a lot of applications in the fields of hydrology and climatology (Kendall, 1975; Yue & Wang, 2004). A positive or an increasing statistical trend is shown by a positive value, which is statistically significant, of the Mann-Kendall statistics. The negative and decreasing trend is revealed by a negative value, which is statistically significant, of the Mann-Kendall statistics.

Sen's Slope Estimator: This is used to compute the median of all the possible pairwise slopes in a data set so that the trend magnitude can be computed in mm/year (Sen's, 1968). It does not depend on outliers like linear regression, and it is appropriate in the circumstances of environmental data.

Rainfall Indices

Rainfall characteristics were measured with three indices:
Precipitation Concentration Index (PCI): PCI was put forward by Oliver in 1980 as a measure of the intra-annual distribution of rainfall. An index greater than 20 denotes extremely erratic rainfall patterns during the seasons, and this can be followed by flooding and soil erosion.

Standardized Precipitation Index (SPI): McKee et al. (1993) developed SPI, and this scales rainfall anomalies across time scales. It can be successfully used to classify a drought, and it has been highly implemented in sub-Saharan Africa (Ntale & Gan, 2003).

Rainfall Anomaly Index (RAI): RAI expresses annual rainfall departures in long-term mean as a standardized anomaly, which enables the classification of a year as being either dry, normal, or wet (van Rooy, 1965; Nicholson, 2001).

Descriptive and Inferential Statistics

Central Tendency: Mean, median, and standard deviation were calculated in order to have a summary of the annual and seasonal rainfall patterns. These gauges give knowledge on the amount and regularity of rain over some time (Wilks, 2011).

Coefficient of Variation (CV): This is used to show the degree of variability compared with the mean and serves to generate an understanding of predictability (Gadgil & Gadgil, 2006).
T -Test: This is applied in testing the statistically significant differences between rainfall amounts between two times (e.g., 1981-2000 and 2001-2024). This assists in identifying if there is a considerable change in the rainfall pattern over the recent years as compared to older decades (Kottegoda & Rosso, 1997).

Techniques of Visualization

- **Line Graph:** Presented long-scale rainfall patterns and inter-annual variation.
- **Histograms:** Frequency distributions of the rainfall per year, which were illustrated.
- **Heatmaps:** Depicted rampant seasonal precipitation in the form of color gradations to identify the peak and low precipitation concentration (Zhou et al., 2014).

Such visualization tools play an important role in discovering patterns and outliers and reporting on outcomes to non-technical audiences, such as policymakers.

Tools and Software

The analysis was based on an integration of statistical and geospatial programs. These digital tools enumerated below, enabled flexibility, reproducibility, and the visualization of rainfall data of high quality.

- **Microsoft Excel:** Data cleaning, basic organization, and simple plots.
- **R Programming Language:** The R Programming Language was used to identify the statistical trends employing the libraries (trend, climdex.pcic, data visualization) using ggplot2 (R core team, 2022).
- **Python:** Data could be manipulated using libraries including matplotlib, seaborn, and pandas, among others, to generate heatmaps and create custom graphics (van Rossum & Drake, 2009).
- **ArcGIS 10.7:** used to map the area of study and depict the spatial patterns of the variation of rainfall within Monrovia.

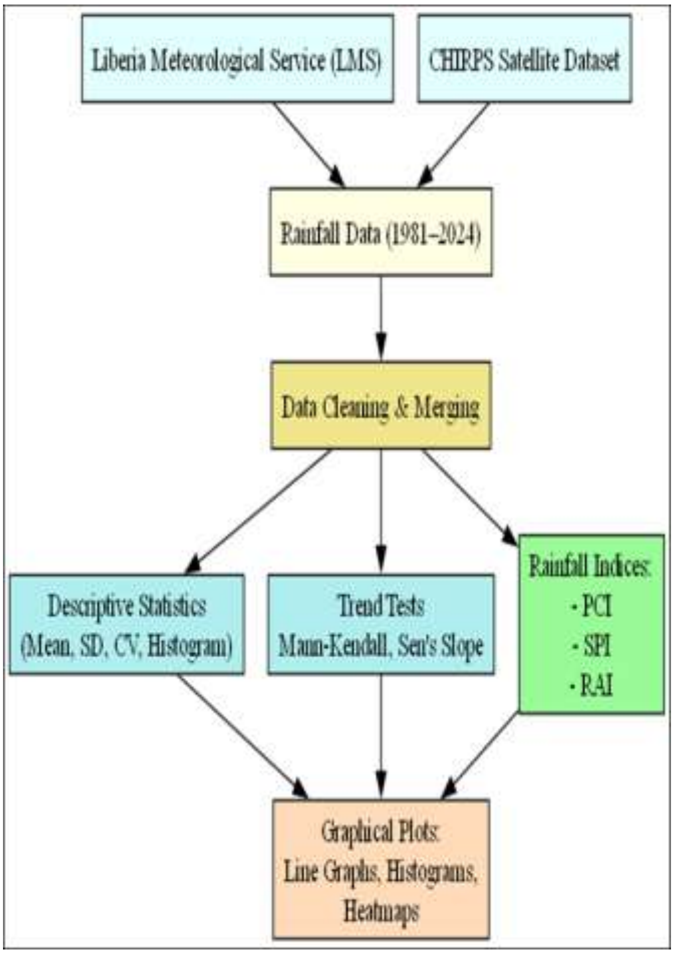

Figure 3.2: Workflow Chart for the Study

Limitation of the Methodology

Despite the advantages of this approach, several limitations can be noted:

- **Few Meteorological Variables**: The researchers single out the rainfall. Temperature, evapotranspiration, and humidity are among other variables that do not contribute to the process of hydrology. They can help to realize the rainfall effects even more (Trenberth et al., 2014).
- **Data gaps and data inconsistencies:** Data available in ground stations sometimes lack completeness because of equipment losses, political vagaries, or bad maintenance. As much as there may be doubts with CHIRPS integration, there could still be doubts (Dinku et al., 2011).
- **No Predictive Modeling:** No future forecast of rainfall is modeled, and no predictive analysis like ARIMA, ANN, or GCM-based prediction models is applied. This modeling would provide information about threats to the climate in the future (IPCC, 2021).

Nevertheless, both CHIRPS and LMS data, coupled with powerful statistical tools, are impressively good starting points for investigating past precipitation variability and variability trends in Monrovia.

IV. RESULTS AND DISCUSSION

Introduction

This chapter shows the significant results of the trend and variability analysis of rainfall in Monrovia over the years 1981-2024. Various statistical methods including the Mann-Kendall (MK) trend test and Sen's slope estimator were used to analyze the direction and intensity of trends of rainfall. Also, indices of rainfall such as Precipitation Concentration Index (PCI), Standardized Precipitation Index (SPI), and Rainfall Anomaly Index (RAI) were employed to describe the time fluctuation and deviations. The combination of these tools can give insights into long-term variability and intra-annual rainfall distribution that can be used in water resource management and agricultural planning, as well as, in flood risk mitigation.

Trends of Monthly Rainfall

The findings show that the trends over the twelve months are not statistically significant at the 5% level of confidence. There was a near significant positive trend ($p = 0.08016$) toward March with the Sen's Slope of 0.559 mm/year. This implies that there may be more rainfall early in the pre-rainy season, which would have the possible implication of agricultural activities and water availability towards the end of the dry season. Figure 4.1 indicates that the long-term trend in the March rainfall depicts a gradual and steady increasing tendency over the years.

Meanwhile, the two most crucial months on the seasonal onset of the rainy season, April and May, had a little tendency towards drying with low magnitude. These drying patterns may cause a lag to the beginning of favourable rainfall used in growing crops, thus complicating farm schedules. These adverse trends are reflected in the negative slopes of the corresponding Sen's Slope of Figure 4.2.

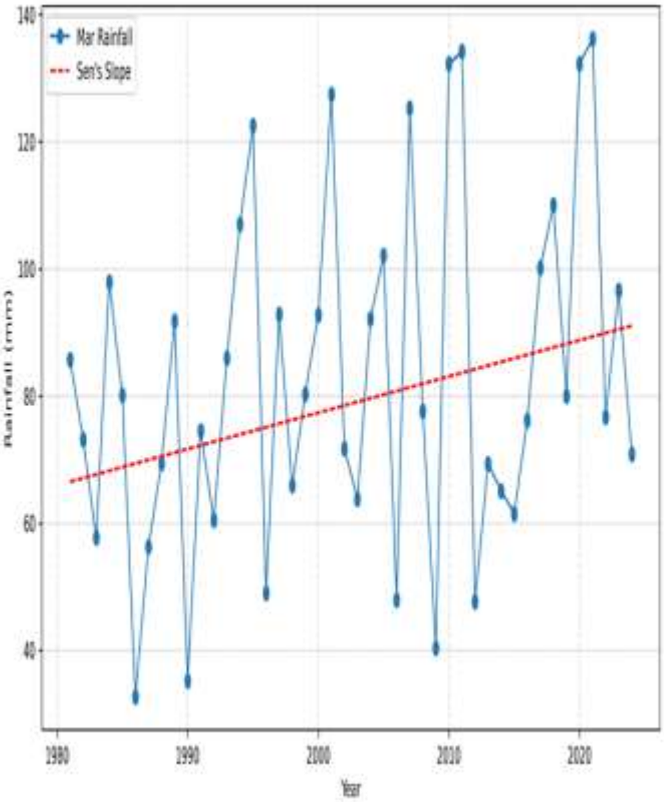

Figure 4.1: March Rainfall Trend (1981-2024) with Sen's Slope line

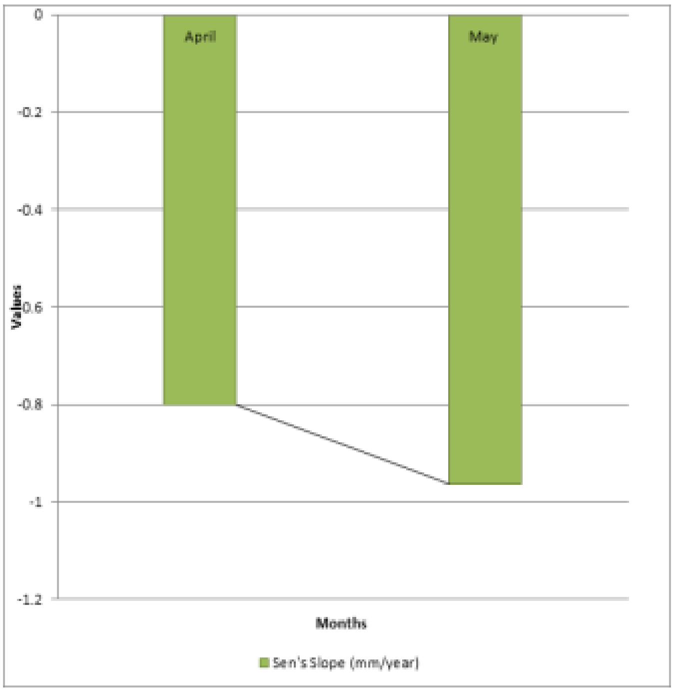

Figure 4.2: Sen’s slope values for April and May showing slight drying

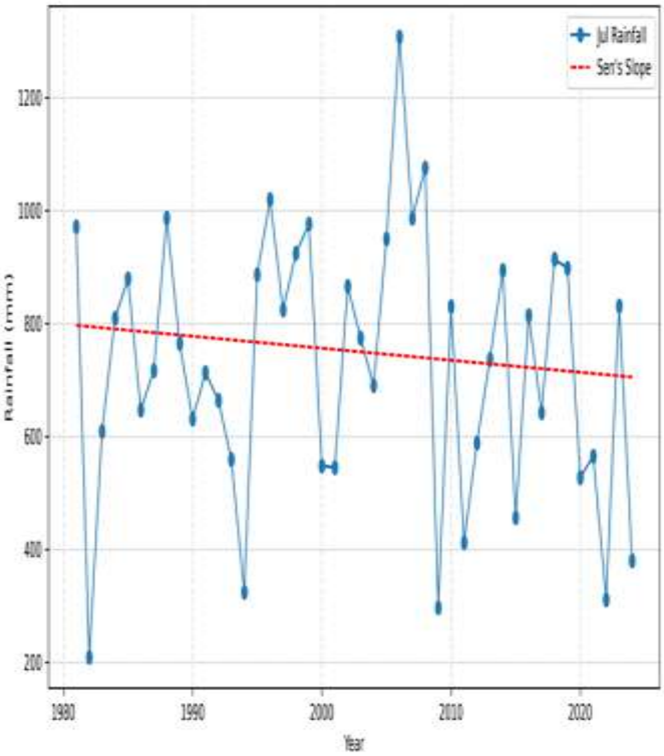

Figure 4.3: Monthly Rainfall Trend –July (1981 -2024)

July is climatologically one of the wettest months in Monrovia and recorded the strongest negative trend (2.111 mm/year). A lower rainfall in July can depress soil moisture during the primary growing season, likely to affect crop productivity, as well as recharge of the hydrological regime. This is well illustrated in Figure 4.3, where the July trend line reflects as downward trend across the period of study.

The results correspond with regional studies of heightened variance within the West African Monsoon system, typically ascribed to climatic change and broad atmospheric-oceanic mechanisms such as the Atlantic Multidecadal Oscillation (AMO) and El Niño-Southern Oscillation (ENSO) (Sylla et al., 2016; Niang et al., 2014). The evident changes indicate that the amount of rainfall in Monrovia is getting less regular, with less precipitation during early months and peak months, but the later months are recording more intense droplets. The dynamic trend necessitates the need to adopt dynamic approaches to agriculture, urban planning and disaster risk reduction.

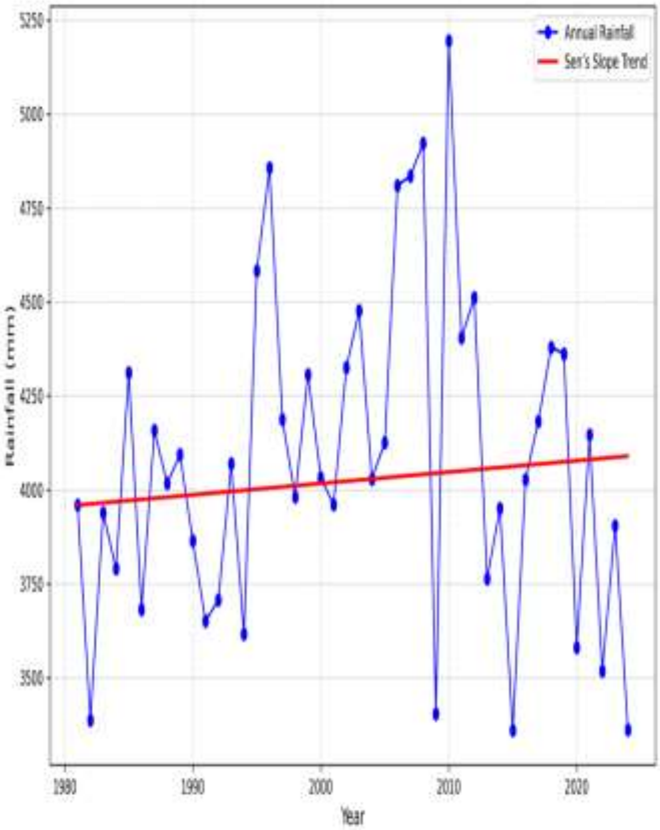

Figure 4.4: Annual rainfall (1981-2024) with Sen’s slope line

The Mann-Kendall test of annual rainfall totals at Monrovia over the period 1981-2024 has yielded a p-value of 0.59192, suggesting that there is no statistically significant overall trend in annual rainfall. The slope estimate given by Sen's slope of +3.031 mm/year gives a positive trend that is not statistically significant (Z = 0.53606). On the whole, it can be said that annual precipitation in Monrovia has not changed significantly over the past 40 years; however, it is characterized by fluctuations every year (Liberia Meteorological Service, 2020).

The trend of the rainfall series can be visualized through Figure 4.4, where the series of the annual rainfall was presented with Sen's slope line overlaid. The figure illustrates that there is no directional trend as rainfall levels go above and below the mean without the trend of continually rising or falling.

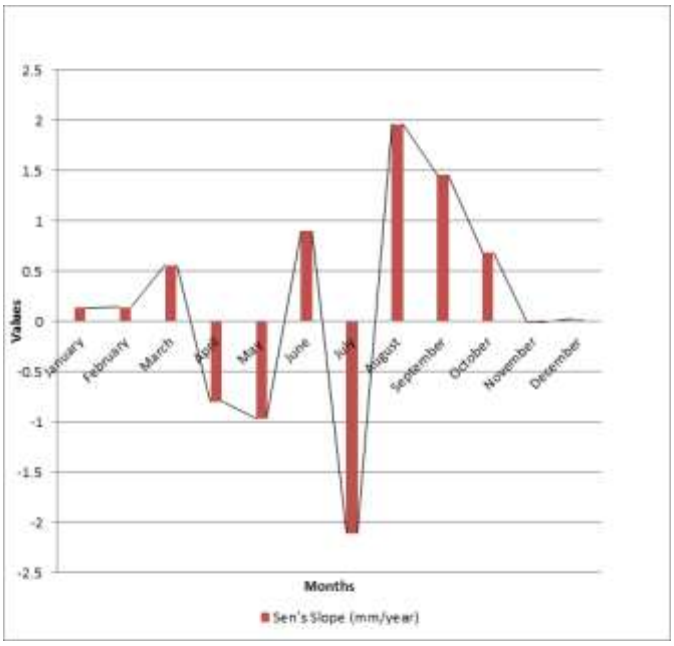

Figure 4.5: Bar chart of Sen's slope (Jan-Dec), highlighting positive /negative month (1981 -2024)

Interestingly, positive trends were observed in August and September, which may reflect the shift in seasonal precipitation distribution with more rain in the latter half of the rainy season (Nicholson et al., 2018). This time lag is illustrated in Figure 4.5, where the slope values of Sen's slope highlight the difference between mid-season desiccation and late-season wetness. This shift has both positive and negative implications; while it may compensate for the low rainfall in July, it could also lead to waterlogging, late harvests, and flooding in low-lying areas, especially in urban Monrovia.

Trend of Rainfall per Year (1981-2024)

Although the general long-term tendency is statistically not significant, one can notice some variability in time-wise terms. Periods of very high rainfall totals occurred almost every few years, sometimes related to intense monsoon activity, or other local climatic events like La Niña, whereas deficits occurred at other times, and may be related to weak monsoon circulation or strong El Niño. It is against this background that this inter-annual variation has been portrayed in Figure 4.6, showing rainfall anomalies as it relates to the 1981-2010 climatological mean. The anomaly plot further highlights the year by year alternating of wet and dry years again confirming the lack of a systematic slow but persistent decline or rise.

The lack of an overall negative trend is opposite to what was observed in certain locations in the Sahel and Western Africa where decadal plunges in rainfall have been relatively clear since the 1970s (Nicholson, 2013; Sylla et al., 2016). Monrovia, however, does not show a significant change in terms of rainfall, and its tendency is slightly wet, which is also later supported by recent reports of increased rainfall recovery in parts of West Africa, including coastal regions since 1990s (Biasutti, 2019).

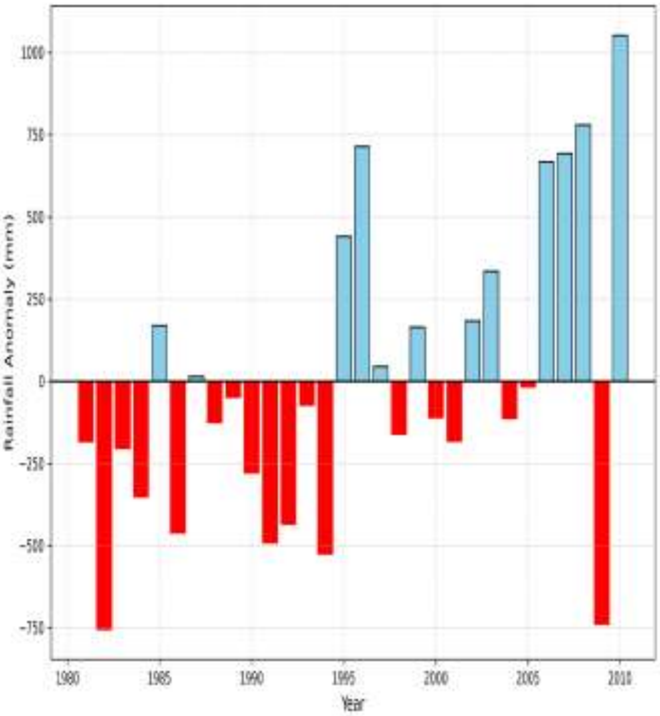

Figure 4.6: Rainfall anomaly plot (relative to 1981-2010 mean), highlighting wet and dry years

In pointing out a practical fact, the fact that there is variance in annual totals should not make us lose track of the seasonal changes mentioned in Section 4.2. Although the amount of rainfall is relatively constant annually, the temporal rearrangement of rainfall, where the drying months are April, May and July and the wet months are August and September, can be more problematic to other spheres and in particular agriculture, hydrology and flood. control in the urban centres.

Therefore, the focus of an adaptation strategy should not only be on annual amounts, but also on intra-annual distribution because this is more relevant to planting calendars, water resource planning, and flood risk in Monrovia.

Unpredictable rainfall and weather indices

Rainfall variability in Monrovia was also studied with the use of three well-known indices: the Precipitation Concentration Index (PCI), the Standardized Precipitation Index (SPI), and the Rainfall Anomaly Index (RAI). Such indices give information on rainfall irregularity, dryness and wet/dry year behaviour.

Precipitation Concentration Index (PCI)

Precipitation Concentration Index (PCI) created by Oliver (1980) determines the monthly spread of rainfall. It is estimated by:

$$\text{PCI}=\left(\frac{\sum_{i=1}^{12} P_i^{\,2}}{\left(\sum_{i=1}^{12} P_i\right)^2}\right)\times 100$$

Where Pi is the measure of rainfall in the ith month.

Interpretation of PCI values (Oliver, 1980)

< 10: uniform rainfall distribution
11-20: Moderate irregularity
21-30: Irregular distribution
> 30: Strong irregularity

Results:

The PCI values in Monrovia lie between 12.93 and 16.34, which reveals that there is a moderate amount of seasonality of rain and rainfall is fairly evenly distributed throughout the months (Boken, 2005). What this implies is that rainfall is not too focused in a few months of the year but is somewhat more balanced in the wet season. The results are given in Figure 4.7.

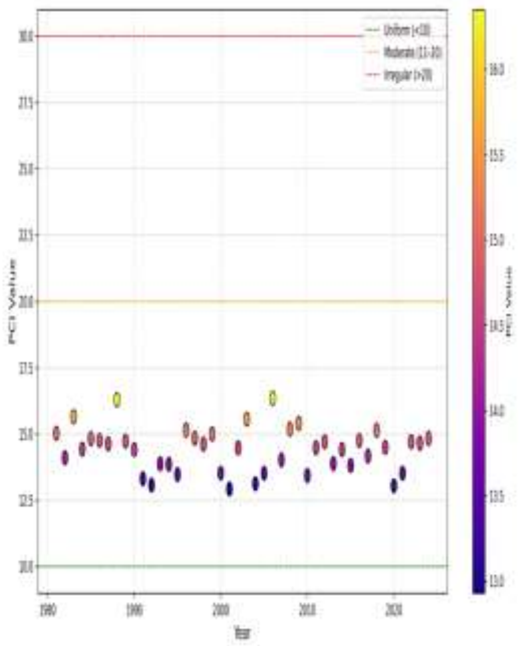

Figure 4.7: Precipitation Concentration Index (PCI) of Monrovia (1981-2024)

Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI), developed by McKee et al. (1993), is a measure of rainfall anomaly at various time-scales that are generated by the application of a gamma-distribution fit to the rainfall values and transformation of the values into a standard normal distribution. High values are wet anomalies and low are drought.

Interpretation of SPI Values:

- ≥2.0: Extremely wet
- 1.5 to 1.99: Very wet
- to 1.49: Moderately wet
- -0.99 to 0.99: Near normal
- -1.0 to-1.49: Moderately dry
- -1.5 to-1.99: Severely dry
- ≤-2.0: Extremely dry

Results:

The SPI values appeared to bounce around zero, signifying wet and dry periods. Years of significant drought existed during the early 1982, 1994, 2009, 2015, 2020, 2022, and 2024, whereas the early 1995, 1996, 2006, 2007, 2008, and 2010 were wet. The trend aligns with the variability in rainfall in the region in West Africa (Chadwick et al., 2021). Figure 4.8 shows these results.

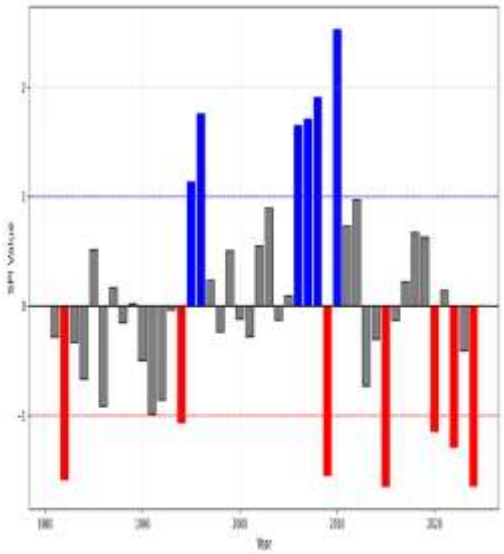

Figure 4.8: Standardized Precipitation Index (SPI) of Monrovia (1981-2024)

Rainfall Anomaly Index (RAI)
The Rainfall Anomaly Index (RAI) which has been developed by van Rooy measures absolute deviations about long-term mean making a comparison of the back excruciating of each year's rain fall by difference in 10 maximum years and 10 minimum years.

Interpretation of RAI values:

- ≥3.0 : Extremely wet
- 2.0 to 2.99: Very wet
- to 1.99: Moderately wet
- -0.99 to 0.99: Near normal
- -1.0 to-1.99: Moderately dry
- -2.0 to-2.99 : Very dry
- ≤3.0: Extremely dry

Results:
The RAI values showed that there was significant variability in them over the years of the study period Maximum anomaly of wetness was observed in the year 2010, whereas extreme dry anomaly was observed in year 2015. The total percentage of dry years (negative anomalies) was 54.55%; this is equal to 45.45% wet years (positive anomalies). This pattern implies that the possession of negative anomalies is increased in the current years which points to the drying trend in the area (Nicholson et al., 2018; IPCC, 2023). Wet, dry and near-normal years are described in Figure 4.9.

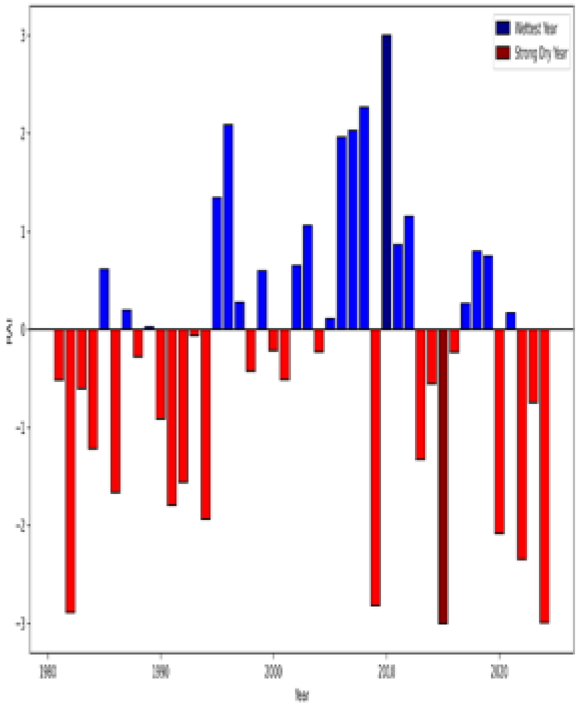

Figure 4.9: Rainfall Anomaly Index (RAI) of Monrovia (1981-2024)

Patterns of Annual Rainfall and Anomalies
The annual average rainfall at Monrovia over the study period was 4, 085.29 mm. It was observed that there were some marked fluctuations of rainfall anomalies. The wettest year was experienced in 2010 when the rainfall was above a mean value of 5,195.33 mm that is a positive anomaly of +1,110.04 mm against the mean. On the other hand, 2015 marked the average rainfall in mm to be 3,360.49 (in comparison) which is currently the driest year with negative anomaly of -724.80.

Although the overall long-term trend is not statistically significant (see Section 4.3), variability in rainfall has been growing stronger over the past few decades. The increased variance in the rainfall of Monrovia is an indication of increased uncertainty in the rainfall pattern of the region (World Bank, 2021). These variants indicate the twofold challenge of managing water shortages related to dry seasons in years and avoiding flooding risk in years of excessive precipitation. The results underline the urgency of referring to the climate-resilient procedures of urban plans, infrastructure building, and water management. Figure 4.10 shows the series in yearly rainfall with the anomalies indicated.

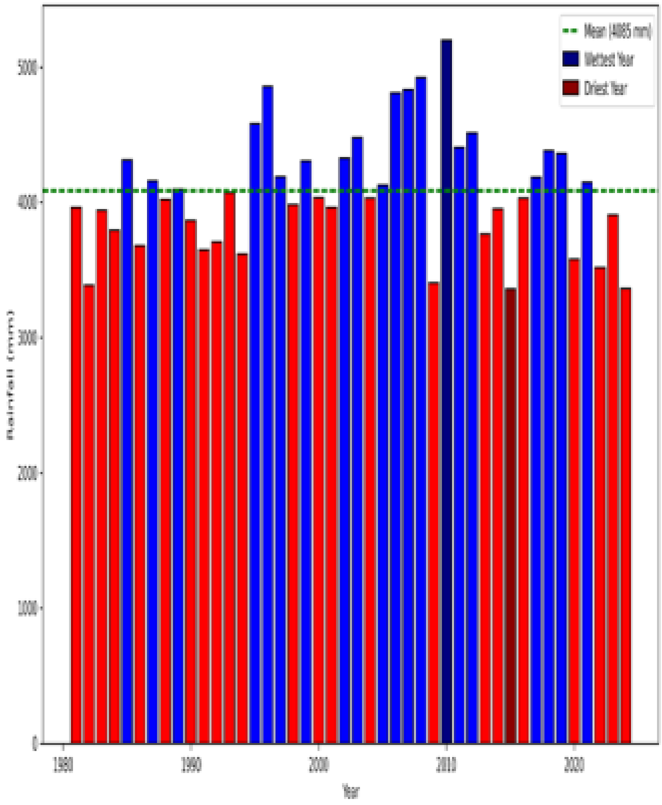

Figure 4.10: Annual Rainfall and Anomalies in Monrovia, Liberia (1981-2024)

Histogram of Rainfall Distribution in Monrovia (1981-2024)

The histogram of annual rainfall frequency of Monrovia (Figure 4.11) gives some information about the statistical characteristics of rainfall distribution within 1981-2024. The most likely ratio of extremely dry to extremely wet years is skewed toward high precipitation levels of years (skewness = 0.41) (Wilks, 2019).

The average annual precipitation amounted to 4,085.29mm and the median was marginally lower at 4,031.25mm showing resultant effects of extreme wet years on the data distribution. The vast majority of annual accumulations were within the range of 3,784-4,335 mm which concurs with IQR of 551.02 mm, whereas outliers were identified as lesser than 2,958 mm and greater than 5,162 mm or abnormally dry or wet years, respectively. For instance, the year 2010 was characterized by an exceptional wet anomaly (1,110.04 mm above the mean), and the year 2015 was the scene of an exceptional dry anomaly (724.80 mm below the mean), which confirms that the two extremes of the distribution are present (Nicholson et al., 2018; IPCC, 2023).

The coefficient of variation which is accounted as 12.6% is proof that the variation of rainfall in a year is low to moderate which is in conformity with what the Precipitation Concentration Index (PCI) calculation reveals. These observations will validate that despite the high amount of rainfall that is received in Monrovia each year, the extreme deviations of the long-term average is relatively low. However, the value of the positive skewness is an indicator of the presence of years when the precipitation level is rather high, which serves as a reminder that implementing mechanisms to address flood-related hazards in the context of climate-adaptive urban design is critical (World Bank, 2021).

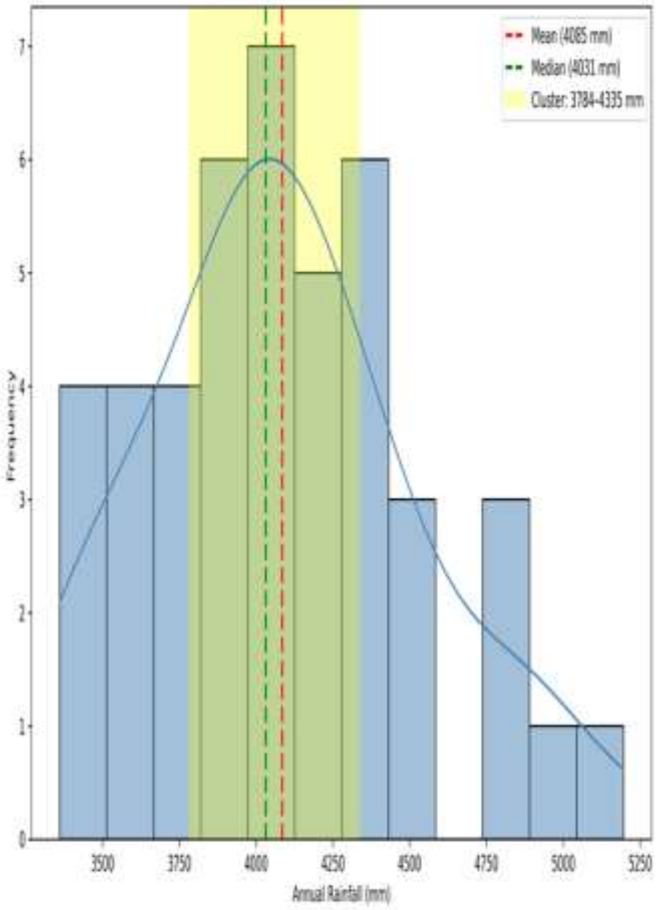

Figure 4.11: Histogram of Annual Rainfall Distribution in Monrovia, Liberia (1981-2024)

Monthly Rainfall Heatmap

The monthly rainfall heatmap (Figure 4.12) and the table of maximum monthly rainfall (Table 4.1) give a concise perspective of the intra-annual process of rainfall in Monrovia between 1981 and 2024. The table analysis reveals that the month of June and July is always dominant as the rainiest months with June and July taking the majority of the highest rainfall instances in a month.

Actually, July is the highest month in 28 out of 44 years, and annual maxima ranged between 664 mm (1992) and 1307.55 mm (2006). The most rainfall was observed in June and came to a high of 654.8 mm (2015) to 1043.55 mm (1983). There are a few outstanding years like 1986, 1990, 1993, and 2004 with highest rainfall falling in September portending rare late-season wet-season outbreaks.

There were also fluctuations in the amount of rainfall between different months with a maximum single month rainfall being recorded in July 2006 (1307.55 mm), indicating a year of severe wet season and the lowest amounts of maximum rainfall recorded in June 2015 (654.8 mm) and July 1992 (664.07 mm) indicating years of mild rainfall intensity. These extremes show how the rainfall regimes in Monrovia vary in terms of inter-annual differences, although the overall seasonal pattern at least does not change.

Based on the heatmap and table together it would appear that there are some patterns:

Seasonal Concentration: Rainfall maxima are evidently confined to the heart of the wet season (June-July) and July is typically the most intense month.

Late-Season Shifts: Maxima are occasionally derived in September, indicating that the withdrawal of the rainy season might not be consistent; indeed the late rain seasons in October and November have been prolonged to recent years.

Inter-annual Variability: The maximum monthly rainfall across years brings out the extent of variation with extremes of wetness such as July 2006 showing open contrasts in months of reduced rainfall as June 2015.

This is congruent with the PCI, SPI, and RAI results that also revealed moderate seasonality involving periodicity of wet and dry extremes. These peaks consistently in June and July and sometimes wet-season rainfall at the end of the months indicate a relatively stable patterns in terms of timing but increasing variability in magnitude, a factor that is very important in urban planning, agriculture, and water resource management (Funk et al., 2015; Nicholson et al., 2018; UN-Habitat, 2021).

Table 4.1: Maximum Monthly Rainfall in Monrovia, Liberia (1981-2024)

Year	Max Month	Max Rainfall mm
1981	Jul	971.41
1982	Jun	795.00
1983	Jun	1043.55
1984	Jul	809.17
1985	Jul	879.41
1986	Sep	806.31
1987	Jun	832.18
1988	Jul	986.88
1989	Jun	834.14
1990	Sep	782.01
1991	Jul	713.02
1992	Jul	664.07
1993	Sep	884.22
1994	Jun	729.44
1995	Jul	887.07
1996	Jul	1019.74
1997	Jun	827.13
1998	Jul	924.25
1999	Jun	985.53
2000	Jun	878.24
2001	Jun	851.31
2002	Jun	925.02
2003	Jun	1004.64
2004	Sep	759.49
2005	Jul	950.50
2006	Jul	1307.55
2007	Jul	987.31
2008	Jul	1075.31
2009	Jun	957.71
2010	Jun	956.42
2011	Jun	993.29
2012	Jun	936.17
2013	Jul	736.53
2014	Jul	894.74
2015	Jun	654.80
2016	Jul	813.80
2017	Jun	953.71
2018	Jul	913.87
2019	Jul	898.20
2020	Jun	761.34
2021	Jun	909.22
2022	Jun	802.47
2023	Jul	831.60
2024	Jun	735.90

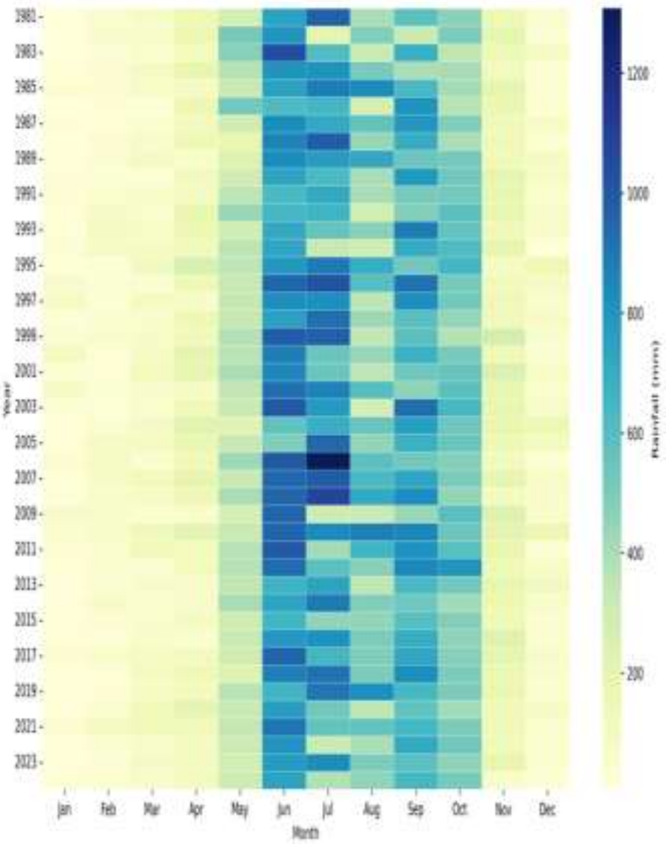

Figure 4.12: Monthly Rainfall Heatmap for Monrovia, Liberia (1981-2024)

Table 4.2: Descriptive Statistics of Monrovia, Liberia (1981-2024)

Mean Rainfall	4085.29 mm
Median Rainfall	4031.25 mm
Standard deviation	439.48 mm
Range	3360.49 mm – 5195.33 mm
Interquartile Range (IQR)	551.02 mm

Table 4.3 Inferential Statistics of Monrovia, Liberia (1981 - 2024)

T-test statistic	- 0.9494
P-value	0.3488
Result	No significant change in mean rainfall between early and recent years.

Table 4.4: Sustainable Development Goals (SDG) Linkage to Monrovia, Liberia (1981-2024)

Finding	Policy Risk	Relevant SDG	Action Pathway
Extreme wet years (+1,000 mm above mean)	Urban flooding, sanitation system overload	SDG 11 (Sustainable Cities)	Flood-resilient infrastructure, drainage upgrades, relocation from floodplains
Extreme dry years (-700 mm below mean)	Water scarcity, agricultural stress	SDG 6 (Clean Water)	Rainwater harvesting, groundwater recharge, irrigation planning
Stable long-term mean, but higher variability	Climate uncertainty, urban vulnerability	SDG 13 (Climate Action)	Early warning systems, climate adaptation strategies, green infrastructure

Descriptive and Inferential Statistics of Monrovia, Liberia (1981-2024)

The descriptive statistics of annual rainfall in Monrovia, Liberia, between the years 1981 to 2024 show that the mean rainfall was 4085.29 mm and the median 4031.25mm, which means that the distribution of rainfall is highly symmetrical around the centre. The fluctuations in the rainfall show themselves in the presence of a standard deviation of 439.48 mm and of interquartile range (IQR) of 551.02 mm, indicating that the rainfalls vary quite considerably. The lowest precipitation was 3360.49 mm and the highest was 5195.33 mm, indicating strong swings left to right in the 44-year time layout (Table 4.2).

Inferential statistics between early and recent periods were used to test significant long-term changes with a t-test. As we see, the t-statistic obtained is -0.9494 and the p-value is 0.3488, which shows that there is no significant difference between the mean rainfalls within two periods at 5% level of significance. This implies that the total average rainfall in Monrovia has not changed considerably between the periods 2001 and 2019, despite the visible fluctuations and extremes (World Bank, 2020) (Table 4.3).

Synthesis of findings

The evaluation of the analysis of rainfall dynamics in Monrovia between 1981 and 2024 shows that there is a stable long-term mean (4085 mm), although the rainfall distribution has increasingly been defined by increased inter-annual variability. Such variability is reflected in extreme wet and dry years, though no statistically significant change occurred at the mean rainfall (t-test p = 0.3488). These extremes have direct consequences on water security, infrastructure in cities, and climate resilience in general.

To contextualize these findings with other development processes, they are cross-related with the corresponding Sustainable Development Goals (SDGs). This interconnection depicts that rainfall variability is not only a climatological issue but also a development and policy issue of Monrovia.

Three key channels through which the variability of rainfall impacts the results of sustainable development have been identified in the synthesis, as shown in Table 4.4. On the one hand, exceptionally wet years (more than 1,000 mm above average) can increase urban flood risks and risk overloads in sanitation systems, which directly prejudge the achievement of SDG 11 (Sustainable Cities and Communities). Second, extreme drought periods (less than 700 mm below the mean) propagate water scarcity and agricultural stress, which undermines SDG 6 (Clean Water and Sanitation). Lastly, the continued fashion of a more stable average that is more variable highlights the uncertainty of climate influences, especially SDG 13 (Climate Action), which will form a vital part of policy responses in the future.

The results featured in Table 4.4 highlight that the major problem lies not in decreasing average rainfall but in the rise in variability, which increases risks in various sectors. Incorporating these understandings into the planning of resilient cities, water resource planning, and climate change adaptation principles will be critical in helping Liberia move towards the SDGs amidst uncertainty in rainfall.

V. RECOMMENDATIONS AND CONCLUSION

Conclusion

The paper describes the temporal evolution of the rainfall distribution in Monrovia (Liberia) in 1981-2024 based on the CHIRPS and wheat Liberia Meteorological Service (LMS) data. The statistical analyses (PCI, SPI, RAI, trend detection, and heat-maps) showed no significant long-term trend concerning yearly or monthly cumulates, and it follows that there is no significant long-term change in the overall amounts of rainfall. The analysis, however, pointed out significant changes within the year and between the years that have significant implications in the planning of a city and water resource management.

The highest precipitation months-month maxima analysis (Table 4.1, Figure 4.12) revealed that June and July had consistent monthly maxima with July as the single wettest month in 28 of the 44 years. July 2006 (1307.55) was rated as the wettest month, whereas June 2015 (654.8) and July 1992 (664.07) were the worst months (highest minima). Such changes show that the timing of rainfall maximums is fairly consistent, but rainfall levels have been increasingly changing. In exceptional years (1986, 1990, 1993 and 2004), the highest monthly rainfall was observed in September, indicating that some years may get late season precipitation surges and extended wet seasons that may continue until October and November.

These findings are consistent with those of PCI, SPI, and RAI indices, which show moderate seasonality and alternate wet and dry extremes. The results indicate that although the rainfall system of Monrovia is seasonally predictable, it is characterized by increasing levels of variability in the form of rainfall intensity, a complication in the management of floods, agricultural processes, and infrastructure durability.

Recommendations

Based on the findings, the recommendations are offered as follows:

Urban Management & Drainage systems:

The growing variable on the intensity of rainfalls, especially in the peak months (June-July), necessitates the need to improve on urban drainage, floodplain maps and storm water management to allay the chances of floods in Monrovia.

Agricultural Adaptation:
There also needs to be support for farmers to adopt climate-smart agriculture techniques that take into consideration changing rainfall patterns, especially the potential occurrence of rain later in the season in September-November.

Water-Resource Administration:
Governments need to increase rain harvesting, the capacity of reservoirs, and groundwater recharging to improve the effects of the varied intensity of rainfall.

Climatic Risk Observation
Seasonal monitoring of the PCI, SPI and RAI indices should be institutionalized so as to have early warning systems and disaster preparedness.

Policy Integration:
The findings ought to influence national adaptation measures of the climate and be consistent with SDGs (6, 11, and 13) so that Monrovia can be more resistant to rainfall fluctuations and extreme weather.

REFERENCES

1. Ahmad, U. A. (2024). Rainfall Spatio-Temporal Variability in Kano Region, Nigeria.
2. Akinsanola, A. A., & Ogunjobi, K. O. (2014). Analysis of rainfall and temperature
3. variability over Nigeria. Theoretical and Applied Climatology, 117(1), 211–219.
4. Akpoti, K., Antwi-Agyei, P., & Jalloh, A. (2019). Impacts of climate variability and change on crop production in the West African Sudano-Sahelian zone: A review. Environment, Development and Sustainability, 21(1), 1–21.
5. Alharbi, A. M., Abdel Basset, H. H., & Almazroui, M. (2014). Spatiotemporal distribution of rainfall over Saudi Arabia. Atmosphere, 5(2), 401–417.
6. Amanambu, A. C., Ololade, O., Abiye, T. A., Oyeku, O. A., & Akinlalu, A. A. (2021).
7. Armah, F. A., Yawson, D. O., Yengoh, G. T., Odoi, J. O., & Afrifa, E. K. A. (2010).
8. Impact of floods on livelihoods and vulnerability of natural resource-dependent communities in Northern Ghana. Water, 2(2), 120–139.
9. Asante, F. A., Boakye, A. A., Egyir, I. S., & Jatoe, J. B. D. (2012). Climate change and farmers' adaptive capacity to strategic innovations: The case of northern Ghana. International Journal of Development and Sustainability, 1(3), 766–784.
10. Ayanlade, A., Radeny, M., & Morton, J. F. (2017). Comparing smallholder farmers' perception of climate change with meteorological data: A case study from southwestern Nigeria. Weather and Climate Extremes, 15, 24–33.
11. Barnes, A. P., & Toma, L. (2012). A typology of dairy farmer perceptions towards climate change. Climatic Change, 112(2), 507–522.
12. Barry, B., Olaleye, A. O., & Fatondji, D. (2021). Rainfall variability and its impact on water resources in West Africa. In Water Resources and Rural Development, 18, 100-145.
13. Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Schamm, K., Schneider, U., &
14. Ziese, M. (2013). A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901 to the present. Earth System Science Data, 5(1), 71–99.
15. Biasutti, M. (2013). Forced Sahel rainfall trends in the CMIP5 archive. Journal of
16. Geophysical Research: Atmospheres, 118(4), 1613–1623.
17. Boken, V. K. (2005). Monitoring and predicting agricultural drought: A global study. Oxford University Press.
18. Camberlin, P., Moron, V., & Boyard-Micheau, J. (2022). West African rainfall variability: Role of the ITCZ and implications for agriculture. Climate Dynamics, 58(1), 145–161.
19. Chadwick, R., Boutle, I., & Stratton, R. (2021). Can regional climate models represent the West African Monsoon? A review of studies and perspectives. Climate Dynamics, 56, 127–148.
20. Charles, J. F., Ngumbu, R. S., Toe Sr, J. T., & Sangodoyin, A. Y. (2020). Evaluation of the impact of flood on groundwater quality in hand-dug wells in Monrovia, Liberia. International Journal of Energy and Water Resources, 4(2), 181-188.

21. Change, I. C. (2014). Impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental Panel on Climate Change, 1132.
22. Codjoe, S. N. A., & Owusu, G. (2011). Climate change/variability and food systems:
23. Evidence from the Afram Plains, Ghana. Regional Environmental Change, 11(4), 753–765.
24. Cook, K. H. (2015). The climate of West Africa. Progress in Physical Geography, 39(3), 397–414.
25. De Luis, M., Raventós, J., González-Hidalgo, J. C., Sánchez, J. R., & Cortina, J. (2011).
26. Climate trends and their impact on hydrological patterns in Mediterranean environments: A case study in Valencia, Spain. Climatic Change, 103(3–4), 537–553.
27. Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., & Ceccato, P.
28. (2018). Validation of the CHIRPS satellite rainfall estimates over eastern Africa. Quarterly Journal of the Royal Meteorological Society, 144(S1), 292–312.
29. Dinku, T., Ceccato, P., Grover-Kopec, E., Lemma, M., Connor, S. J., & Ropelewski, C.
30. F. (2007). Validation of satellite rainfall products over East Africa's complex topography. International Journal of Remote Sensing, 28(7), 1503–1526.
31. Douglas, I., Alam, K., Maghenda, M., McDonnell, Y., McLean, L., & Campbell, J.
32. (2008). Unjust waters: Climate change, flooding and the urban poor in Africa. Environment and Urbanization, 20(1), 187–205.
33. Dube, T., & Phiri, K. (2013). Rural livelihoods under stress: The impact of climate change on livelihoods in South Western Zimbabwe. American International Journal of Contemporary Research, 3(5), 11–25.
34. Environmental Protection Agency (EPA) Liberia. (2019). State of the Environment Report for Liberia 2019. Monrovia: EPA.
35. Environmental Protection Agency (EPA) Liberia. (2021). Liberia's Updated Nationally
36. Determined Contributions (NDCs) 2021–2025. Monrovia: EPA.
37. FAO. (2008). Climate change and food security: A framework document. Food and Agriculture Organization of the United Nations.
38. FAO. (2016). The state of food and agriculture: Climate change, agriculture and food
39. security. Food and Agriculture Organization of the United Nations.
40. FAO. (2017). The impact of disasters and crises on agriculture and food security, 2017.
41. Rome: Food and Agriculture Organization of the United Nations.
42. Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J. P., Shukla, S., ... & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—A new environmental record for monitoring extremes. Scientific Data, 2, 150066.
43. Gadgil, S., & Gadgil, S. (2006). The Indian monsoon, GDP, and agriculture. Economic and Political Weekly, 41(47), 4887–4895.
44. GIZ. (2020). Climate risk country profile: Liberia. Bonn and Eschborn: Deutsche
45. Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.
46. IPCC. (2014). Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
47. IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
48. IPCC. (2023). AR6 Synthesis Report: Climate Change 2023. Geneva: Intergovernmental Panel on Climate Change.
49. Jury, M. R. (2015). West Africa rainfall and Atlantic air-sea interactions during three extreme years. Climate Dynamics, 44(3), 979–995.
50. Kanu, I., Salami, A. O., & Numasawa, K. (2014). Climate change and agricultural production in Africa: Impact assessment and adaptation strategies. African Development Bank Group, Working Paper Series No. 154.
51. Kendall, M. G. (1975). Rank correlation methods (4th ed.). Charles Griffin.
52. Klemeš, V. (1983). Conceptualization and scale in hydrology. Journal of Hydrology, 65(1–3), 1–23.
53. Kizza, M., Nawaz, N. R., & Bauer, H. S. (2009). Analysis of rainfall variability and
54. Uganda uses PCI and SPI indices. Theoretical and Applied Climatology, 106(3–4), 347–363.

55. Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J., & Neumann, C. J. (2011).
56. The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. Bulletin of the American Meteorological Society, 91(3), 363–376.
57. Kottegoda, N. T., & Rosso, R. (1997). Statistics, probability, and reliability for civil and environmental engineers. McGraw-Hill.
58. Kumi, M. A., & Abiodun, B. J. (2018). Climate change and variability in rainfall over West Africa. Environmental Earth Sciences, 77(11), 1–14.
59. Kurukulasuriya, P., & Mendelsohn, R. (2006). Crop selection: Adapting to climate change in Africa. CEEPA Discussion Paper No. 26.
60. Lalego, B., Ayalew, T., & Kaske, D. (2019). Impact of climate variability and change on crop production and farmers' adaptation strategies in Lokka Abaya District, Southern Ethiopia. African Journal of Environmental Science and Technology, 13(3), 1-11.
61. Liberia Meteorological Service (LMS). (2020). Annual Climatological Summary Report 2020. Monrovia: LMS.
62. Liberia Meteorological Service (LMS). (2022). Technical Report on Rainfall Observations and Challenges. Monrovia: LMS.
63. Mahé, G., & Paturel, J. E. (2009). 1896–2006 Sahelian annual rainfall variability and runoff increase of Sahelian rivers. Comptes Rendus Geoscience, 341(7), 538–546.
64. McKee, T. B., Doesken, N. J., & Kleist, J. (1993, January). The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology (Vol. 17, No. 22, pp. 179-183).
65. Morton, J. F. (2007). The impact of climate change on smallholder and subsistence agriculture. Proceedings of the National Academy of Sciences, 104(50), 19680–19685.
66. Nhemachena, C., & Hassan, R. (2007). Micro-level analysis of farmers' adaptation to climate change in Southern Africa. IFPRI Discussion Paper 00714.
67. Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J., & Urquhart, P. (2014). Africa. In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Cambridge University Press.
68. Nicholson, S. E. (2013). The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. ISRN Meteorology, 2013, Article ID 453-521.
69. Nicholson, S. E. (2018). The ITCZ and the seasonal cycle over equatorial Africa. Bulletin of the American Meteorological Society, 99(2), 337–348.
70. Nicholson, S. E. (2001). Climatic and environmental change in Africa during the last two Centuries. Climate Research, 17(2), 123–144.
71. Nicholson, S. E., Funk, C., & Fink, A. H. (2018). Rainfall over the African continent from the 19th through the 21st century. Global and Planetary Change, 165, 114–127.
72. Ntale, H. K., & Gan, T. Y. (2003). Drought indices and their application to East Africa.
73. International Journal of Climatology, 23(11), 1335–1357.
74. Olawale, K. O., & Adetunji, E. O. (2024). Seasonal and Interannual Variability of
75. Precipitation in Nigeria. Journal of Science Innovation and Technology Research.
76. Oliver, J. E. (1980). Monthly precipitation distribution: A comparative index. Professional Geographer, 32(3), 300–309.
77. Ozor, N., & Cynthia, N. (2010). Difficulties in climate change adaptation in Nigeria. African Technology Policy Studies Network (ATPS) Research Paper No. 29
78. Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the
79. Köppen–Geiger climate classification. Hydrology and Earth System Sciences, 11(5), 1633–1644.
80. R Core Team. (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing.
81. Sen's, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association, 63(324), 1379–1389.
82. Sylla, M. B., Giorgi, F., Coppola, E., & Mariotti, L. (2013). Uncertainties in daily rainfall
83. over Africa: Assessment of gridded observation products and evaluation of a regional climate model simulation. International Journal of Climatology, 33(7), 1805–1817.
84. Sylla, M. B., Nikiema, P. M., Gibba, P., Kebe, I., & Klutse, N. A. B. (2016). Climate change mover West Africa: Recent trends and future projections. In Adaptation to Climate Change and Variability in Rural West Africa (pp. 25–40). Springer.
85. Tambo, J. A., & Abdoulaye, T. (2012). Climate change and agricultural technology adoption: The case of drought-tolerant maize in rural Nigeria. Mitigation and Adaptation Strategies for Global Change, 17(3), 277–292.

86. Tamoffo, A. T., Kuwano-Yoshida, A., & Sylla, M. B. (2019). Investigating rainfall variability in West Africa using CHIRPS: Teleconnection patterns and drought implications. Climate, 7(8), 92.
87. Tokinaga, H., & Xie, S. P. (2011). Weakening of the equatorial Atlantic cold tongue over the past six decades. Nature Geoscience, 4(4), 222–226.
88. Toté, C., Patricio, D., Boogaard, H., Van der Wijngaart, R., Tarnavsky, E., & Funk, C. (2015). Evaluation of satellite rainfall estimates for drought monitoring in Mozambique. Remote Sensing, 7(2), 1758–1776.
89. Trenberth, K. E., Fasullo, J. T., & Shepherd, T. G. (2014). Attribution of climate extremes events. Nature Climate Change, 5(8), 725–730.
90. Tschakert, P., Sagoe, R., Anyidoho, N. A., & Jatoe, P. (2010). Floods in the Sahel: An analysis of anomalies, memory, and anticipatory learning. Climatic Change, 103(3), 471 502.
91. UNFCCC. (2007). Climate change: Impacts, vulnerabilities and adaptation in developing countries. United Nations Framework Convention on Climate Change.
92. UN. (2015). Transforming our world: The 2030 agenda for sustainable development. United Nations.
93. UN-Habitat. (2016). Urbanization and Flood Risk in Liberia: A Policy Brief. Nairobi: UN-Habitat.
94. UN-Habitat. (2020). City Resilience Profiling Tool: Monrovia Pilot Report. Nairobi: UN-Habitat.
95. United Nations Development Programme (UNDP). (2021). Climate Information and Early Warning Systems in Liberia. Monrovia: UNDP.
96. United Nations. (2015). Transforming our world: The 2030 Agenda for Sustainable Development. New York: United Nations.
97. van Rooy, M. P. (1965). A rainfall anomaly index independent of time and space. Notos, 14, 43–48.
98. van Rossum, G., & Drake, F. L. (2009). Python 3 reference manual. Python Software Foundation.
99. Westra, S., Alexander, L. V., & Zwiers, F. W. (2013). Global increasing trends in annual maximum daily precipitation. Journal of Climate, 26(11), 3904–3918.
100. Wilks, D. S. (2011). Statistical methods in the atmospheric sciences (3rd ed.). Academic Press.
101. World Bank. (2020). Enhancing urban resilience in Liberia: Flood risk management in Monrovia. World Bank Group.
102. WMO (World Meteorological Organization). (2017). Guidelines on the analysis of extremes in a changing climate in support of informed decisions for adaptation (WMO-No. 1206).
103. World Bank. (2021). Liberia Climate Risk Country Profile. Washington, D.C.: World Bank Group.
104. World Bank. (2022). Building Urban Resilience in Africa: Country Diagnostics for Monrovia. Washington, D.C.: World Bank.
105. World Meteorological Organization (WMO). (2012). Standardized Precipitation Index User Guide (WMO-No. 1090). Geneva: WMO.
106. Yue, S., & Wang, C. Y. (2004). The Mann–Kendall test modified by the effective sample size to detect trends in serially correlated hydrological series. Water Resources Management, 18, 201–218.
107. Zhao, T., Zhang, Q., Xu, C. Y., & Li, J. (2016). Streamflow variability and its links to climate change in the Yellow River Basin. Hydrology and Earth System Sciences, 20(2), 759–773.
108. Zhou, L., Tian, Y., Myneni, R. B., Ciais, P., Saatchi, S., Liu, Y. Y., ... & Friedlingstein, P. (2014). Widespread decline of Congo rainforest greenness in the past decade. Nature, 509(7498), 86–90.