Chapter 1
INTRODUCTION

1.1 General

Changing climates necessitate the assessment of climate extremes, trends, and spatiotemporal variability analysis to evaluate climate-induced changes and encourage policymakers to implement suitable intervention measures for water resource management and agricultural and pastoral programs. Escalation of greenhouse gases due to changes in climate on temporal and spatial scales induces a significant rise in global temperature and alters the pattern of precipitation and runoff characteristics (IPCC, 2014). The climate system consists of interdependent and dynamic mechanisms that fluctuate randomly within a static envelope of variability. Quantum, geographical distribution, intensity, time, and frequency of extreme events considerably affect the management techniques that decision-makers use for water resources. Besides the availability of surface water runoff for residential, agricultural, industrial, and recreational uses, the infrastructure system that drains wastewater from the urban population is also influenced by precipitation features. However, precipitation is the meteorological term for the substance from air vapors condensing and falling under gravity. In nature, many types of precipitation occur, including drizzle, rain, sleet, snow, graupel, and hail. The major component of the water cycle is precipitation, which is responsible for accumulating most of the fresh water on the Earth. Approximately 505,000 km^3 (121,000 m^3) of water falls yearly as precipitation; roughly 398,000 km^3 (95,000 m^3) precipitates over the oceans. This amounts to a global average annual precipitation of 990 millimeters, i.e., approximately 39 inches. This huge quantum of precipitation becomes the primary basis of the survival of living species and its use.

On the other hand, the precipitation characteristics are altered by anthropogenic changes on the Earth. Thus, a dynamic interrelation exists between precipitation features and the earth's surface characteristics. These features of precipitation that alter with the changes on the Earth’s surface need to be assessed. To evolve an effective plan and implement a water policy, spatial and temporal distributions of rainfall and various extreme climatic indices are also to be estimated. Water supply and demand may be mismatched due to unequal distribution of rainfall. In such cases, new irrigation facilities must be planned and erected across rivers and streams to redistribute water in line with the needs of particular areas. Estimating extreme rainfall and its frequency of occurrence are additional factors that influence dam design, spillways, flood protection structures, and drainage networks. Thus, for the same reason, trend analysis of extreme climatic indices becomes a matter of great concern, particularly under global climate change. Trend analysis helps in understanding the changing patterns. This analysis provides a means for estimating the quantum of stream flows, soil moisture, and groundwater reserves and a framework for decision-makers who strive for sufficient water availability to various users. According to studies on rainfall patterns globally, rainfall variability is increasing on both a geographical and temporal scale. There was a substantially declining tendency in precipitation in South-Western India, and a growing trend was seen during the post-monsoon season. Increasing yearly and southwest monsoon rainfall patterns occurred in Indian areas such as Punjab, Haryana, Rajasthan, and Madhya Pradesh (Kumar et al., 2023; Madane & Waghaye, 2023; Meena et al., 2019). Research on trend analysis of precipitation based on station-scale data is still rare, especially for Jharkhand and West Bengal states. The trend analysis of extreme climatic indices is minor in the states of Jharkhand and West Bengal, where the studied region lies.

It is essential to know the overall precipitation trend for water resources planning, development, and management, as well as disaster management(Giupponi & Gain, 2017; Zhao & Boll, 2022). However, also intermediate outbursts of changed behavior, if any, on a real-time basis to mitigate urban infrastructure disasters, as evidenced by the extreme rainfall in the year 2017 in Mumbai (Parchure & Gedam, 2019) India and a high Spatio-temporal variation has been to be the reason of intense precipitation (Saha & Singh, 2017).

Climate change and anthropogenic activities play a vital role in water resources (Konapala et al., 2020; Xu et al., 2022) Moreover, it introduces abrupt changes reflected by broad drifts, shifts, or even sudden jumps in the behavior of observed precipitation (Mahato et al., 2023). In order to assess the impacts of anthropogenic changes on the climate, it is essential to analyze changes in the pattern of precipitation (Jain et al., 2023), as illustrated by the decrease in rainfall during the century as a sudden shift instead of a gradual monotonic trend of rainfall in the Indian Himalayan terrain (Swain et al., 2022). Further, precipitation data is often viewed as stationary, and a parametric/non-parametric test is applied to identify the trend as non-stationary has received limited attention (Fauer & Rust, 2023). The presumption of stationary of the dataset has also been questioned (Gupta et al., 2021).

Time series data usually do not display a monotonic behavior but instead show non-periodic alternating during an intermediate period. Thus, the traditional parametric/non-parametric tests for aggregated datasets may not unravel real-time information, which may differ in the aggregated character of the datasets. Changes in the mean precipitation, frequencies of occurrence of extremes, the magnitude of evapotranspiration, and river discharges result from non-stationary hydrologic processes. Complex interdependence and interactive mechanisms of climatic variables continuously update hydro-meteorological processes and add non-parametric to climatic variables. Anthropogenic activities (Zhang et al., 2016) also perturb the interactive mechanisms by impacting the forcing and the climate's state.

In order to capture the intermediate precipitation trend that swings during a study period, the present study proposes to apply a repeated test protocol (Zhang et al., 2016), which was implemented for the stream flow dataset of the west-branch Susquehanna River in the Bower watershed. By varying the west-branch Susquehanna River flow dataset in the Bower watershed, they repeatedly applied the M-K test to discern the river flow pattern through color variation for abrupt or gradual changes. The methodology involved different data clusters of varying sizes with changed beginning and ending times of the data series. The trend pattern of extreme climatic indices over the Damodar River basin, which is part of the Ganges River system of India, is analyzed and plotted to ascertain the consistency/monotonicity of the trend. Most of the work analyzing trends of extreme climatic indices in the Indian sub-continent accounted for spatially averaged datasets from various states or grid datasets from a large segment of India (Bhattacharyya et al., 2022) by assuming rainfall to be uniformly distributed over the large region of India. Hence, station (district) scale data was applied for a more realistic analysis of precipitation trends. Thus, rainfall and temperature data from fifteen stations of DRB, India, were considered to obtain an overall view of the trend pattern.

The approach involves repetitively applying the Mann-Kendall test with a moving window. However, the varied beginning and ending times, i.e., varying size of data cluster with the moving window, were applied to yield a 3-D pictorial representation for the easy realization of the trends of extreme climatic indices over DRB, India. As a result, the current research focuses on the Damodar River basin, India, part of the Ganges River system. It lies in the states of Jharkhand and West Bengal, rich in minerals. Drying is not new for the states of Jharkhand and West Bengal, where the DRB lies is practically often encountered. Every year, droughts of variable size and percentage occur in one or more regions within the basin area. The precipitation pattern during the monsoon period, which ends in October, does not precisely reflect well for the state, and the overall precipitation across the state may be termed deficient rainfall in plain meteorological terms. However, it may be viewed as highly deficient from an agricultural perspective, significantly affecting the basin's agricultural production. Over the last decade, annual rice, maize, jute, and other plants have declined. To determine why agricultural yields should be reduced while increasing irrigation and other agricultural inputs in the area, the changing environment, i.e., inadequate soil moisture availability due to unpredictable precipitation patterns, may provide a better explanation.

1.2 Multiple Climatic Extremes

Climate extremes refer to unusual or rare weather events that deviate significantly from the typical conditions experienced in a particular region over a specified period. These extremes can manifest as heatwaves, cold snaps, droughts, floods, severe storms, etc. Recent studies have highlighted the increased frequency and intensity of climate extremes globally. Heatwaves have become more prolonged and intense in many regions, leading to record-breaking temperatures. Similarly, precipitation patterns have changed, resulting in more frequent and severe droughts in some areas and intense rainfall events to flooding in others. Attribution studies aim to determine the extent to which human-induced climate change contributes to the occurrence and severity of specific extreme weather events. These studies utilize climate models and observational data to assess the role of anthropogenic greenhouse gas emissions in exacerbating extremes such as heatwaves, heavy rainfall, and hurricanes.

Compound events involve multiple climate extremes' simultaneous occurrence or interaction, amplifying their impacts and complexity. For example, a heatwave with drought conditions can exacerbate water shortages and increase wildlife risk. Compound events pose significant challenges for adaptation and disaster risk management, requiring integrated and interdisciplinary approaches to address their multifaceted impacts. Climate extremes exhibit significant regional variability, with some contributing to this variability due to geographic location, land use changes, and natural climate variability. Vulnerable regions, such as coastal areas and small island states, are particularly susceptible to the impacts of climate extremes due to their exposure to hazards such as sea-level rise, storm surges, and tropical cyclones. Climate extremes have significant economic and social implications, including damage to infrastructure, disruptions to agriculture production, displacement of populations, loss of livelihoods, and increased healthcare costs. Vulnerable and marginalized communities are often disproportionately affected, exacerbating existing inequalities. Practical risk assessment and management strategies are essential for resilience to climate extremes. These strategies involve identifying vulnerable populations, infrastructure, and ecosystems, assessing exposure and sensitivity to climate risks, and implementing measures to reduce vulnerability and enhance adaptive capacity. Integration of climate information into decision-making processes at various is critical for informed decision-making and effective risk management.

1.3 Problem Statement

Damodar River Basin is a rainfed, shallow, comprehensive, and flashy river part of the Ganges River System, having 10% of the total length and 2.7% of the total area of the Ganga master basin and a significant part of the basin economy relies on agriculture and industrial purposes. The climate over the basin was heterogeneous, which significantly varies spatially. The study will concentrate on the Damodar River Basin, which covers about 42.34% of agricultural land, forest 31.69%, wasteland 14.1%, and other 11.87%. At the same time, the net irrigated area is around 9.3% (0.16 million hectares) of the cultivable area. Since it is primarily rainfed all over the basin, it has cropping potential due to the availability of optimum soil moisture with good soil fertility. Most people rely on the primary sector for their survival. The basin is a major producer of wheat (28%), rice (12%), pulses (14%), and sugarcane (44%) and has significantly contribution nearly 20% of food grains to the national food basket. The agricultural output of different areas of the basin varies widely.

Rainfall has a significant role in the economy of the investigated basin, which primarily depends on agriculture and the industrial sector. There will be a deficit of rainfall in the basin most of the time, so Meteorological drought became a standard feature with a 3 to 5-year return period in the DRB. Droughts of varying severity and spatial extent occur yearly in one or more stations. The monsoon rainfall shows a downward trend over the basin from long ago. From an agricultural point of view, it causes fluctuations in water availability, such as in agricultural production. Despite the increase of irrigation and other farming inputs in the area, the fluctuating rainfall patterns and pollutants from nearby industries cause inadequate soil moisture that reduces agricultural yield, which may not be sufficient for the population around the basin. The dense population and its dependence on agriculture made it possible to study the impact of extreme climatic variables on primary crop yield in the basin.

Many studies have been conducted in different parts of the basin, India to examine the impact of anticipated climatic changes; several studies have been conducted to detect trend analyses of extreme rainfall indices. Several researchers have concentrated on understanding the dynamics and variability of rainfall patterns in the Indian basin. As a result, the rainfall patterns for the specified study area have been examined. The irregular behavior of rainfall and rising temperatures are causing a drying situation throughout the basin area, which necessitates the trend assessment of precipitation, temperature, and evapotranspiration. This study focused on assessing multiple climatic extreme indices in an Indian basin. However, no adequate literature has been conducted at the sub-regional level over the Damodar River basin that specifically examines the effects of climate change due to different extreme climatic indices and characterization of 3-D pattern trend analysis of extreme climatic indices. Understanding the pattern of extreme indices for the forthcoming time will allow us to do better state preparedness and contingency planning. This study used various extreme indices based on rainfall and temperature, such as RX1 day, RX5 day, R20mm, CDD, CWD, etc., to estimate the variability of trends in 3-D and 2-D patterns to visualize and understand clearly.

Additionally, a graphical representation has been plotted to show multiple change points. The extreme indices considered for this research across the 15 synoptic stations. As a result, this is the first study to provide a spatially explicit analysis of multiple extreme climatic indices and 3-D and 2-D pattern characterization of extreme indices taken for research on a regional scale as a foundation for any future climate change adaptation and resilience plans. Furthermore, despite significant evidence of climate change in the region, Extreme climatic events have increased over the last few decades; subsequently, these events are anticipated to become even more pronounced. The preceding research concentrated solely on multiple features of extreme events. This study aims to fill that void by addressing specific issues, such as collectively evaluating the pattern of trends of extreme indices and using VSCA, 3-D, and 2-D visualization techniques to show trends more clearly and also a representation of multiple change points detection of the observed periods in graphical format over the study region.

1.4 Research Objectives

The primary objectives of this research work are to estimate the trend pattern of multiple climatic extremes based on rainfall and temperature and their behavior toward climate change. To determine the principal cause of climate change, we need to understand the change in the behavior of climatic variables, their derived indices from rainfall and temperature, and the impacts of climate change and global warming; for this, we have to analyze the trend characteristics of climatic parameters. The results of this study will be further utilized for water conservation purposes in the studied area, which is majorly covered by the Damodar River basin.

The specific objectives of the present study are narrated hereunder:

Specific Objectives of the Present Study

1. Data Collection:

Collect precipitation and temperature data spanning 100 years from 15 stations within the Damodar River Basin, India.

2. Trend Analysis Using Statistical Methods:

Apply various statistical methods such as the non-parametric Mann-Kendall test, Modified Pettitt Mann-Whitney test, and Sen's slope estimator to determine trends in numerous climatic indices.

3. Spatiotemporal Trends Assessment:

Assess spatiotemporal trends in extreme climatic indices over the Damodar River Basin, India, at different scales (1951-2020) using the Modified Mann-Kendall test (MMK) and Sen's slope estimator.

4. 3-D Pattern Characterization and Change Point Detection:

Utilize Variable-Sized Cluster Analysis (VSCA) for 3-D pattern characterization of trends in extreme climatic indices.

Detect change points in the Damodar River Basin using the Mann-Kendall test (MK), Sen's slope estimator, and the Modified Pettit Mann-Whitney test (PMW).

5. Application of VSCA:

Apply VSCA to extreme climatic indices to enhance the understanding of trends and patterns.

These objectives aim to provide a comprehensive analysis of climatic trends and patterns within the Damodar River Basin, facilitating better preparedness and adaptive strategies for climate change impacts.

1.5 Organization of the Thesis

This thesis contains seven chapters. Chapter 1 includes a brief overview of climate change impacts and the concept of multiple climatic extremes. Chapter 2 focuses on understanding the relevant literature on climate change impact assessment, multiple climatic extremes, and its analysis. Chapter 3 details the study area with the stations concerned for research analysis. Chapter 4 describes the methodology adopted for this research. Chapter 5 Spatio-temporal variability of extreme climatic indices over the Damodar River basin. Chapter 6. discusses the 3-D pattern characterization of multiple climatic extremes. Chapter 7 summarizes significant findings from the present investigation and highlights recommendations for future studies in this field.

The chapters are outlined as follows:

Chapter 1: Introduction

Provides a brief overview of climate change impacts and the concept of multiple climatic extremes. Outlines the objectives of the present work, setting the foundation for the study.

Chapter 2: Literature Review

Offers a comprehensive review of relevant literature on climate change impact assessment, multiple climatic extremes, and their analysis. Provides background information necessary for understanding the context and significance of the study.

Chapter 3: Study Area and Data

Describes the study area, including its climate, geology, soil type, and other relevant characteristics. Details the data sources and tools employed for the research analysis, focusing on the 15 stations within the Damodar River Basin.

Chapter 4: Methodology

Outlines the statistical techniques used in the study, including the Mann-Kendall test, Sen's slope estimator, and the Modified Pettitt Mann-Whitney test. Explains the approach for detecting multiple change points and analyzing trends in climatic indices.

Chapter 5: Spatiotemporal Variability of Extreme Climatic Indices

Examines the spatiotemporal variability of extreme climatic indices for each station within the basin. Highlights the patterns of 15 indices based on rainfall and temperature as per ETCCDI (Expert Team on Climate Change Detection and Indices).

Chapter 6: 3-D Pattern Characterization of Extreme Climatic Indices

Discusses the 3-D pattern characterization of multiple climatic extremes in the Damodar River Basin. Provides graphical representations of multiple change points for each station considered in the study.

Chapter 7: Conclusions and Recommendations

Summarizes the significant findings from the present investigation. Highlights recommendations for future studies in the field of climate change and extreme climatic indices. Concludes with a list of references used for the study, ensuring a comprehensive documentation of the sources.

This organization ensures a logical flow of information, from the introduction and background to the detailed analysis and conclusions, providing a thorough understanding of the research conducted on climatic extremes in the Damodar River Basin.