CHAPTER 1

Introduction

1.1 Background

There is growing evidence of increasing events of climate extremes (drought and flood) becoming more regular due to the impact of recent warming, which significantly alters the global hydrologic cycle. A changing climate alters the frequency, severity, spatial extent, duration, and timing of weather and climatic extremes, causing unprecedented extremes. Changes in extremes can also be directly linked to changes in the mean climate, as future mean conditions for some variables are anticipated to be within the tails of the present conditions. However, variations in climatic or weather extremes are not necessarily highly related with changes in its mean; in certain instances, they may even have the opposite sign. Changes in phenomena like the monsoons and the El Nino-Southern Oscillation (ENSO) could significantly impact the frequency and intensity of climate extremes concurrently across various regions. The climate system comprises interdependent and dynamic mechanisms that fluctuate randomly within a fixed range of variability. The climate system consists of interdependent and dynamic mechanisms that fluctuate randomly within a static envelope of variability (Gupta et al. 2022). 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 anthropogenic activities have perturbed the climate system (AghaKouchak et al., 2015) and added nonstationary features to the climate variables (Bayazit, 2015), causing wide drift, shift, and a sudden jump in the behavior of meteorological processes. Water supply and demand may be incompatible due to the unequal distribution of precipitation. The alteration in rainfall distribution would change the surface runoff, soil moisture, recharge, and storage (Omar et al. 2019). Both would adversely affect India's climate and natural resources up to the 2050s (IPCC, 2007). The researchers have indicated that global warming is one factor that highly influences rainfall patterns at a regional scale and worldwide (Gupta et al., 2021). The rainfall variability analysis is crucial to decide the cropping pattern. The rise of extreme precipitation and rising temperatures leads to plant damage, excessive soil erosion, soil water reclamation, adverse surface water quality, and urban settlement disruption. Thus, a dynamic interrelation exists between the features of precipitation and temperature with the earth's surface characteristics. Spatiotemporal distributions of rainfall and temperature are also essential to evolve an effective plan and implementing a water policy (Omar et al., 2020). The trend analysis technique helps to analyze the changing rainfall and temperature pattern. 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 the all-time availability of sufficient water to various users (Gupta et al., 2021). Climate changes affect rainfall distribution all over the world.

Statistical methods, including parametric and nonparametric tests, are considered with long time data series to depict the trend (Dahmen & Hall, 1989; Dehghan et al., 2020). The assumptions of parametric tests (i.e., normally distributed datasets, zero autocorrelation, and stationarity) are violated by climatological data. Therefore, nonparametric tests, particularly the Mann-Kendall (MK) (Mann 1945; Kendall 1975), have been widely accepted among the climatological community for the analysis of hydrologic time series data (Bayazit, 2015; Hadi & Tombul, 2018; Madsen et al., 2014; Sharma et al., 2018). In addition, Sen's slope test is used to quantify the magnitude of the trend of long-term time series over the range of the climatic variable (Mahmood et al., 2019; Malik & Kumar, 2020). The Mann-Kendall (MK) test has been used widely to detect the monotonic change in long-term time-series of climatic variables (Gupta et al., 2021). Precipitation and temperature change are the determining factors for drought occurrence in any region. In order to assess the occurrence of drought events in a particular region, it is necessary to monitor the change in these hydrometeorological variables.

Drought footprint is typically large and causes serious socioeconomic threats, and it has remained one of the most complex and least-understood of all-weather and climate extremes (Wilhite & Vanyarkho, 2000). Drought is a slow-onset environmental hazard caused by rainfall deficit combined with other influencing factors. Precipitation deviation from the long-term average is regarded as a critical indicator of drought, whereas temperature, relative humidity, wind, and solar radiation are other meteorological parameters that have a significant impact on the severity of drought occurrences. It leads to serious threats in water scarcity that pose challenges to agricultural production, making ecological resources and the economic sector more vulnerable and increasing the level of socioeconomic distress. The climatological community has classified drought, based on its timescale and affected area, as meteorological, agricultural, hydrological, socioeconomic, and groundwater drought (David & Davidová, 2017; Mishra & Singh, 2010; Wilhite & Glantz, 2019).The order in which meteorological, agricultural, and hydrological droughts have an impact accentuates their distinctions even more. Agriculture is typically the first to suffer from drought due to its reliance on stored soil water. If precipitation deficits continue, people who rely on alternative water sources will be affected. Flash droughts are a new type of drought that develop when there is a rapid loss of soil moisture due to precipitation deficit, a rise in temperature, or both during a period of less than one month. Flash droughts can quickly turn favorable crop-growing conditions into catastrophic dry circumstances. Consequently, flash droughts during the crop-growing season damage agriculture and ecosystems and cause significant economic losses. Understanding flash droughts is crucial since India heavily relies on the summer monsoon and groundwater for irrigation. Hence, the likelihood of flash droughts during the crop-growth season could lead to a rise in irrigation demands (Mishra et al., 2021). Due to the anticipated rise in temperatures, there will probably be more flash droughts in India in the future. However, no extensive research has been done into changes in the frequency or characteristics of flash droughts in India. (Mahto & Mishra, 2020). Therefore, It is necessary to utilize a wide range of drought indicators to monitor a wide range of hydrologic cycles and processes due to a variety of different types of meteorological, agricultural, and hydrological droughts that have been seen in recent decades. The Palmer drought severity index (Palmer, 1965), the standardized precipitation index (SPI) (McKee et al. 1993, 1995), the vegetation drought response index (Brown et al., 2008), the self-calibrating Palmer Drought Severity Index (sc-PDSI) (Wells et al., 2004) and the multivariate standardized drought index (Hao & AghaKouchak, 2013), enlist some of the commonly used analysis tools for the quantification of drought occurrence. PDSI was developed to estimate relative dryness and wetness for longer time series over the United States (Palmer, 1965), limiting its use for other assessments of drought in different climatological conditions. Self-calibrating palmer's drought severity index (sc-PDSI) was proposed by Wells et al. (2004) to rectify this spatial compatibility and varies in accordance with the climatological regime. The SPI is a widely used drought indicator that World Meteorological Organization (WMO) recommends for drought characterization at any specified timescale (like 3, 6, 9, and 12-month), where precipitation is the only input variable required. It can be evaluated on a short timescale, which reflects seasonal variation and is thus used to estimate agricultural drought, whereas long timescale (12 and 24-months) conditions reflect annual water balance conditions and hence, are used to analyze the impact of hydrological drought conditions. The Standardized Precipitation Evapotranspiration Index (SPEI) drought index was proposed by Vicente-Serrano et al. (2010) to incorporate the effect of temperature on drought characteristics. Water balance (P-PET) is used as an input variable to estimate drought characteristics. SPEI has been increasingly popular in recent years because of its ability to better estimation of drought characteristics. Although the estimation theories of the SPI and SPEI are similar, the input variables of the SPI and SPEI are different. The SPI analyses precipitation deficit which is simple to compute, and it has excellent time and space adaptability (Mckee et al., 1993), whereas SPEI is derived using the cumulative difference between precipitation (P) and potential evapotranspiration (PET), which can accurately reflect changes in the water balance. Sensitive analysis was used to identify the dominant meteorological variable (P, PET, temperature, and total storage water) that controls the drought characteristics (Ding et al., 2008). So, sensitivity analysis can be used in order to determine the primary meteorological variable causing drought across a particular region. Wang et al. (2021) examined the sensitivity of SPEI to PET and precipitation at multiple scales over Huang-Huai-Hai Plain, China, and explained that the precipitation is the dominant driving meteorological variable which control the occurrence of drought. Noguera et al. (2022) assessed the applicability of SPEI to quantify flash drought in Spain. Kchouk et al. (2021) reviewed the 5000+ scientific studies on drought assessment and concluded that research on the effects of drought is influenced by the local context, which includes both physical and human activities. Hao & Singh. (2015) urge that interpretations and validations of the current drought indices in operational drought management and decision making are of equal importance. Hence, it is essential to give decision makers a variety of drought indices at numerous time steps that are most suitable for particular applications, as not all drought indices are optimal for all locations and all time periods (Svoboda et al., 2015). India is considered a heavily impacted drought-prone country where drought occurs at least once every three years to four years, drawing the attention of meteorologists and climatologists to develop a better understanding of this phenomenon at a regional scale (Roy & Hirway, 2007). Monsoon variabilities, such as delayed arrival and early withdrawal of monsoon and its long beaks, trigger agricultural and meteorological drought in India (Gautam & Bana, 2014). Recent studies on the Bundelkhand region examined the drought variability and highlighted the area undergoing drought stress (Thomas et al., 2016). In addition, rise in the frequency of drought events is projected in the future under different climate change scenarios (Saharwardi et al., 2021). Drought is expected to occur with higher frequency in India's west-central, peninsular, and central northeast regions in the upcoming period from 2050 to 2099 (Ojha et al., 2013). Mallya et al. (2015) summarized an increasing drought severity and frequency trend over Indo-Gangetic plains. Trend assessment of drought makes us aware of the future vulnerability of expected drought events. And it determines the variability and pattern of drought characteristics over a region. Several authors focused on the trend of changing behavior of meteorological variables and drought to anticipate future changes (Guhathakurta et al., 2017; Hadi & Tombul, 2018). The drought characteristic of the Ken River of the Bundelkhand region was studied by Moktan et al. (2021). Morphometric analysis through performed in a part of the Yamuna and Ken basins of the Bundelkhand region using remotely sensed data and GIS to deduce the nature of the basin (Kumar et al., 2018). Nonetheless, a number of studies focused on understanding the dynamics and variability of the drought in Bundelkhand, whereas drought of various categories hits in the southern and eastern part of Uttar Pradesh, India, which needs to be evaluated.

Under the context of global warming, the hydrological cycle is intensifying, resulting in changes to the regimes of extreme dry (Mishra et al., 2019) and extreme wet occurrences over India (Ali et al., 2019). India endures dry and wet extremes resulting in significant economic, social, and environmental consequences (Parida et al., 2021). Moreover, India is susceptible to hydroclimatic extremes because of its dense population and agriculture-based economy. In recent decades, India has experienced an increase in dry and wet extremes due to irregular monsoon patterns and a changing climate (Mishra et al., 2012). As reported, recent flooding in India is attributed to distinct atmospheric circulations and geomorphological conditions (Roxy et al., 2015). Extreme precipitation and beginning hydrological conditions may have had a significant influence, given that precipitation extremes are expected to increase due to India’s warming climate (Goswami et al., 2006). The observed and projected changes in the region and human population affected by these hydro-climatic extremes are poorly understood, despite the huge significance of dry and wet extremes under a changing climate (Kumar & Mishra, 2020). The past several decades has seen a significant increase in the frequency and severity of natural disasters like floods and droughts and their rapid successions (recurrent episodes).

Further, such occurrences can significantly affect water supply, agricultural output, food security, electricity generation, and natural ecosystems (He et al., 2019). During the 21st century, South Asia is likely to experience more intense and frequent heat waves and humid heat stress, while both annual and summer monsoon precipitation will increase, with enhanced inter-annual variability, according to the IPCC sixth Assessment Report (AR6) (Arias et al., 2022). Water resource management and planning usually consider wet and dry events separately. These occurrences are interrelated and influenced by the same hydrological processes and atmospheric dynamics, which may increase hydro-climatic variability under climate change (He & Sheffield, 2020). The frequent climatic extremes occurrence has highlighted the importance of a sequence of wet-dry spells in succession in the past decade. De Luca et al. (2020) investigated the concurrent occurrence of hydrologic extremes (dry and wet events) at a global scale using the monthly self-calibrated Palmer Drought Severity Index based on the Penman-Monteith model (sc_PDSI_pm). Zhao et al. (2020) used Standard Weighted Average Precipitation (SWAP) to evaluate drought, flood, and drought-flood abrupt alternation events under changing climate over China.

Climate change refers to the long-term changes in the behavior of climatic variables over a specific region/ terrain on the earth. These changes are persistent and often irreversible. The alteration in the concentration of greenhouse gases (GHGs) in the stratosphere is the prime cause of climate change; anthropogenic activities further add to the environmental adversities. AR5 report (2013) of the Intergovernmental Panel on Climate Change (IPCC) predicted a rise in mean global (ocean and land) temperature by 0.85 ºC during 1800-2012, and it is expected to increase further up to 1.4 ºC - 5.8 ºC by the end of last quarter of 21st century (Alexander, 2016). Under the current changing climate, more frequent occurrences of drought are inevitable; therefore, it is crucial to carry out drought assessments by analyzing the associated meteorological variables with adequate historical records to detect the pattern and change (Gupta et al., 2020). Prediction of the drought offers several difficulties due to its multivariate origin, so predicting the drought is the fundamental step toward evaluating disaster risk management strategies to mitigate the drought impact. Several climatic models have predicted increased aridity events in upcoming decades over Southern Europe, Africa, the Middle East, the Americas, Australia, and Southeast Asia (Dai, 2011). Prediction of drought events depends on the prediction of two meteorological covariates, precipitation and temperature. An increasing trend in positive temperature extremes over the South Asia region has also been indicated by Revadekar et al. (2012). Downscaling and prediction methods are divided into dynamical, statistical, and hybrid categories by the author in his review (Neugebauer, 1988). Data from various sources, including large-scale climate indices, baseline land conditions, and local climate variables, are used to model drought indices of interest. Climate forcing and beginning circumstances determine the predictability of dynamic meteorological drought predictions, which rely on seasonal climate forecasts from general circulation models (GCMs). GCMs can drive hydrological models for hydrological drought and agricultural drought assessment. Data series of the climatic variable at different timescales can be downscaled using linear regression, canonical correlation analysis, artificial neural network, support vector machine, stochastic weather generator Long Ashton Research Station Weather Generator (LARS-WG), non-homogeneous hidden

Markov model (NHMM), and SDSM. SDSM is a well-known statistical downscaling tool that enables the rapid and cost-effective creation of multiple single-site forecasts of daily surface climatic variables under current and future climate forcing. More precisely, predictors are linked to the local predictand by linear relationships that minimize root mean square error. Additionally, the downscaled daily data's variance is stochastically adjusted to more accurately reproduce the observed time series (Wilby & Dawson, 2007). Furthermore, compared to other statistical downscaling models, SDSM excels in capturing rainfall features as well as maximum and minimum temperatures (Hashmi et al., 2011; Hassan et al., 2014; Wilby et al., 2002). Hassan et al. (2014) used LARS-WG and SDSM for downscaling the rainfall and temperature. Both models are used to quantify the effect of climate change on a local scale. As a result, it is found that SDSM yields better performance as compared to LARS-WG. Hessami et al. (2008) and Chen et al. (2012) have also been used to assess the influence of climate change. Gulacha & Mulungu, (2017) downscaled the climatic variables (rainfall and temperature) in the Wami-Ruvu river basin using the HadCM3 model and projected the average monthly change in the maximum temperature by 0.2-7.5^{o}C for 2020-2080. Climate change consequences on the hydrology of the Tunga–Bhadra River watershed, upstream of the Tungabhadra dam, were studied using the HadCM3 GCM model (Meenu et al., 2013). Ensembles of two GCMs (CGCM3 and HadCM3) were also applied for statistical downscaling and projection of future precipitation and temperature in the middle reach of the Sutlej River basin, India (Singh et al., 2015) and Godavari River basin (Saraf & Regulwar, 2016). Pervez & Henebry (2015) analysed changes in the precipitation from 1988 to 2010 for the Ganges River basin using CGCM3.1 and CMCC-CMS, respectively. Sharma et al. (2019) have also analysed the downscaling of precipitation from 1948 to 2015 for the Ganges River basin using ten different GCM. Dehghan et al. (2020) evaluated the drought state using PDSI to assess the drought condition in the Fars Province of Iran. The output results of the general circulation model were applied in Fars Province using a statistical downscaling model (SDSM). Mesbahzadeh et al. (2020) assessed the influence of climate change on future drought using the CanESM2 of the CMIP5 model under RCP 4.5, and RCP 8.5.

1.2 Problem Statement

The Indo-Gangetic plains, which include Uttar Pradesh, contain extremely fertile crop regions with enormous potential. The climate over Uttar Pradesh is heterogenous, which significantly varies spatially. Uttar Pradesh is facing a drought-like situation due to insufficient rainfall. Droughts of varying severity and spatial extent occur yearly in one or more locations. Uttar Pradesh is one of the most densely populated states of India, and the major part of the economy relies on agriculture. It cultivates more than 70% of the total geographical area. At the same time, the net irrigated area is around 0.16 million hectares or 9.3% of the planted area. Because it is primarily rainfed, the state has a cropping intensity of 126 percent. Nearly half of the population (47%) rely on farming as their primary source of income. Although agriculture's contribution to Gross State Domestic Product (GSDP) fell to 12% in 2017-18, it provides a significant economic foundation to the country. The state is a major producer of wheat (28%), rice (12%), pulses (14%), and sugarcane (44%) and has a significant contribution of nearly 20% of food grains to the national food basket. The agricultural output of different areas of the state varies significantly. The agricultural output of different areas of the state varies widely. While Western UP contributes the most to the value of agricultural and allied activities, Bundelkhand falls far behind because of its frequent occurrence of severe drought. The monsoon season rainfall indicates a downward trend over the state. The changing environment, i.e., inadequate soil moisture availability due to unpredictable precipitation patterns, may explain why agricultural yields are reducing despite increasing irrigation and other agricultural inputs. Several researchers have concentrated on understanding the dynamics and variability of drought, specifically over the Bundelkhand region of Uttar Pradesh, whereas drought of various categories has hit the Indo-Gangetic Plain of Uttar Pradesh. As a result, the drought characteristics for the specified study area have been examined. The irregular behavior of rainfall and rising temperatures are causing a drying situation throughout Uttar Pradesh, which necessitates the trend assessment of precipitation, temperature, and evapotranspiration. This study focused on the impact of climate changes on meteorological variables and drought, as well as the trend and changes compared to previous climates. However, no adequate literature has been conducted at the sub-regional level over Uttar Pradesh that specifically examines the effects of climate change on the characteristics of future droughts under varying climate scenarios. Understanding the drought characteristics for the forthcoming time will allow us to do better state preparedness and contingency planning. Previously, drought assessment was primarily focused on the assessment of drought based on a single drought index, which could result in uncertainty in drought assessment over spatially varied climates in the research area. Most studies focused on drought evaluation based on trend assessment, severity, and duration. Over this region, no study offered a complete assessment of drought characteristics considering all of the evaluation parameters. The regional variability of the drought was measured in this study based on the intensity, duration, and frequency of three different classes (Moderate, Severe, and

Extreme). Temporal variability over a half-decade was investigated using trend analysis. The spatial extent of drought occurrence of various severity levels is assessed using station proportion. This regional assessment of drought characteristics provides a comprehensive framework for evaluating drought in any study region. The aforementioned parameters accurately quantified meteorological drought characteristics across the 18 synoptic stations. As a result, this is the first study of its sort on Uttar Pradesh (India) that provide a spatially explicit analysis of drought characterization, with a particular emphasis on drought on the sub-regional scale as a foundation for any future climate change adaptation and resilience plans. The region has experienced an increase in extreme meteorological events in recent decades, and these events are expected to become even more pronounced in the future. The study aims to examine historical patterns in the transition between dry and wet periods at a regional scale over Uttar Pradesh, identifying hotspots of dry-to-wet transitions and exploring their dynamic evolution in response to the warming climate. The study also investigates the interrelationships between characteristics of dry-to-wet transitions and variabilities at different spatial and temporal scales, aiming to improve our understanding of dry-to-wet transition mechanisms and develop effective risk mitigation strategies. The study employs the Standardized Precipitation Evapotranspiration Index (SPEI) to analyze deviations in climatic features, with shorter timescales for detecting frequent seasonal and inter-annual variations and longer timescales providing insight into the events' signature over the region. However, the study also highlights the need for further investigation into whether drier conditions are expected to continue in the future. Furthermore, this study focuses on the impact of climate change on meteorological drought characteristics over 18 synoptic locations in

Uttar Pradesh, India. The climate in this region is spatially heterogeneous and ranges from humid to semi-arid, making it difficult to use the outputs of general circulation models (GCMs) directly for sustainable water management at this divisional scale. To overcome this, the Statistical Downscaling Model (SDSM) was employed to downscale future meteorological variables, including daily precipitation, maximum temperature (Tmax), and minimum temperature (Tmin) under the climate change scenario for the future. Projected daily meteorological variables were converted into monthly data for the estimation of the standardized precipitation evapotranspiration index (SPEI), which is used to assess meteorological drought variability. Drought characteristics, such as severity, duration, and frequency, were defined based on run theory applied to SPEI time series at a selected threshold.

The specific objectives of the present study are narrated hereunder:

1. Assessment of trend variability of meteorological variables, monthly precipitation, and temperature by implementing the Mann Kendall (MK) and Sen's slope methods.
2. Spatiotemporal drought characteristics were assessed and compared based on intensity, duration, and frequency for different severity based on drought indices SPI and SPEI at different timescales for the time period of 1971 to 2018 over Uttar Pradesh (India).
3. Assessment of temporal variability of the spatial extent of drought occurrence of different severity. Furthermore, the Mann-Kendall (MK) test is used to detect the drought trend over 18 synoptic locations in Uttar Pradesh (India).
4. Assessment of concurrent occurrence of dry and wet event characteristics and their transition across Uttar Pradesh (India).

5. Assessment of future daily precipitation, maximum temperature (Tmax), and minimum temperature (Tmin) of 18 synoptic locations of Uttar Pradesh, India, was projected for the future period (2019-2050) under different scenarios (RCP 4.5 and RCP 8.5) using Statistical Downscaling Model (SDSM).
6. The assessment of projected changes in drought severity, duration, and frequency was estimated using SPEI in the near future from 2019 to 2050 under two climate change scenarios, RCP 4.5 and RCP 8.5.

1.3 Organization of the Thesis

The primary objective of this study is to evaluate the meteorological drought characterization under the observed and changing climate of Uttar Pradesh. The thesis has been organized into nine chapters.

Chapter 1 entitled 'Introduction' lays the foundation for the present work, explicitly outlining motivation and objectives.

Chapter 2 presents a comprehensive literature review that contains pertinent information to provide a background in climate change impact assessment, downscaling techniques, drought assessment, and trend assessment over meteorological variables.

Chapter 3 gives the detailed characteristics of the study area, including physiographic features, climate, and agroclimatic zones, besides the data and tools employed in this research.

Chapter 4 outlines the methodology for several statistical techniques, including the Mann-Kendall test, Sen's slope, and drought indices (SPI and SPEI), which are used to evaluate trends and drought severity. The chapter also covers statistical parameters for estimating dry and wet event characteristics and transitions and the statistical downscaling methodology (SDSM) used to project future climate scenarios using precipitation and temperature data.

Chapter 5 reflects on the results from the trend assessment of meteorological variables and theirinferences. It also portrays the evaluations made in relation to observed data to make inferences about climatic variables over Uttar Pradesh.

Chapter 6 presents the evaluation of a comparative assessment of the spatiotemporal drought characteristics based on the intensity, duration, and frequency using the standard drought indices SPI and SPEI. In addition, the result of temporal variability of the spatial extent of drought events of various categories at different timescales has been demonstrated.

Chapter 7 presents the result and discussion of an assessment of spatiotemporal dry and wet event characteristics and their transition from the wet-to-dry event or dry-to-wet event at different severity.

Chapter 8 shall describe the impact of climate change on future drought characteristics under two different climate scenarios: RCP 4.5, and RCP 8.5 that has been estimated by employing the Statistical Downscaling Model (SDSM).

Chapter 9 concludes the present investigation's major findings and highlights recommendations for future work in this direction. The last section enlists the references which were referred to for undertaking the present study.