Disaster Risk Reduction Measures Based on Drought Indices over Pakistan

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DEDICATION

I dedicated this humble effort to my parents and teachers whose love and encouragement enabled me to achieve so much of success.

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ABBREVIATIONS

DRR	Disaster Risk Reduction
SPEI	Standardized Precipitation Evapotranspiration Index
DDI	Decile Drought Index
PDSI	Palmer Drought Index
WASPI	Weighted anomaly standardized precipitation index
PNPI	Percent of Normal Precipitation Index
CRED	Centre for Research on the Epidemiology of Disasters
CODREX	Coordinated Regional Climate Downscaling Experiment
WMO	World meteorological organization
IPCC	International Panel for Climate Change
DRM	Disaster Risk Management
RVI	Rainfall Variability Index
PDSI	Palmer Drought Severity Index
PAWD	Percentage Area Weighted Departure
SPI	Standard Precipitation Index
ECMWF	European Centre for Medium Range Weather Forecasting
ERA 5	ECMWF Reanalysis version 5
AMD	Annual Maximum Duration
PET	Potential Evapotranspiration

CC	Correlation Coefficient
MBE	Mean Bais Error
MAE	Mean Absolute Error
UNDRR	United Nations office for Disaster Risk Reduction
NSE	Nash-Sutcliffe Efficiency

ABSTRACT

Pakistan, a predominantly arid country with a warm temperate climate, faces increasing drought vulnerability due to declining rainfall and groundwater depletion. This study analyzes historical data of ERA5-Land dataset from 1950 – 2022 and future projections from CORDEX under the RCP 8.5 scenario for 2023 – 2072, using ten drought indices, including Standard Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Standard Precipitation and Temperature Index (SPTI), Decile Drought Index (DDI), Palmer Drought Severity Index (PDSI), Weighted Anomaly Standardized Precipitation Index (WASPI), Percent of Normal Precipitation Index (PNPI), Rainfall Variability Index (RVI), Percentage Area Weighted Departure (PAWD), and Z-Index. The analysis identified eight historical drought events, with two severe episodes, Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002), selected for detailed examination. The analysis identified SPI, SPEI, and Z-Index are the best and most effective indices for drought monitoring, validated through performance metrics such as Mean Bias Error (MBE), Mean Absolute Error (MAE), and Correlation Coefficient (CC). Ziarat district, has been identified as a hotspot, or the most vulnerable region in Pakistan for drought. Projected data indicate that 2030 – 2031, 2036 – 2037, 2061 – 2063, and 2069 – 2070 are extremely vulnerable years to severe droughts. Disaster risk reduction (DRR) measures for district ziarat include rainwater harvesting, early warning systems, water management technologies, and the adoption of drought-resistant crops.

Keywords: Disaster Risk Reduction, Drought Indices, SPI, SPEI, Z-Index, CORDEX, Historical droughts.

CHAPTER 1: INTRODUCTION

Pakistan is primarily a dry country located in the warm temperate zone (Abbasi, 2016) (Raza, 2015). Over the past two years (2020-2022), the United Nations has included Pakistan among the 23 countries facing drought-related emergencies. While there are climatic differences from the northern mountains to the southern coastline, the country is predominantly characterized by aridity. Annual precipitation, apart from the northern highlands, averages less than 250 mm and decreases from north to south. Additionally, declining groundwater levels have contributed to the onset of drought conditions (Khan M. A., 2011).

The sharp decline in rainfall across most upland areas has resulted in the complete drying up of surface drinking water sources and reduced water output from springs and tube wells (Raza, 2015). This has caused the water table to drop in many valleys and low-lying regions. The extended drought period has severely impacted food production systems. During severe droughts, the scarcity of nutritious food and potable water has led to the spread of water-borne diseases. Recent droughts, driven by below-average and erratic rainfall and prolonged dry spells, have forced rural populations to migrate to barrage areas in search of food, water, and employment (Zubair, 2017).

Drought indices are commonly used to monitor drought conditions and aid in risk management. Precipitation, temperature, and other hydrometeorological parameters which play a crucial role in identifying droughts. To address this, numerous drought indices have been developed and are utilized globally. Since climatic conditions vary across regions, relying on a single drought index often fails to provide comprehensive information. These indices help determine the severity of drought and its spatial-temporal extent (Hayes, 2000). According to (Mendicino G, 2008), drought indices offer a thorough understanding of drought, making them invaluable for monitoring purposes. The selection of an appropriate drought index is vital for effective drought monitoring in any region. Some of the drought indices employed by national hydrometeorological organizations include SPEI and PDSI (Palmer, 1968) in the United States, Z-Index by the Meteorological Centre of

China (Wu H, 2001), DI by the National Meteorological Centre of Australia (Gibbs, 1967), RVI, widely used in regions like East Africa and Australia to assess rainfall variability and its impact on agriculture and water management (Mwale, 2004) (Meteorology, 2010), and SPI (McKee TB, 1993), which is the most widely used indicator for monitoring drought globally, as recommended by the World Meteorological Organization (M Svoboda, 2012) (WMO, 2012)(Hayes, 2011).

The Standard Precipitation Index (SPI) is a drought index that relies solely on precipitation data. It was developed by Tom McKee, Nolan Doesken, and John Kleist at the Colorado Climate Center in 1993. The SPI assigns a single numeric value to precipitation levels, allowing for comparisons across regions with significantly different climates. Its standardization enables the SPI to assess the rarity of current drought conditions.

The Standardized Precipitation Evapotranspiration Index (SPEI) builds on the widely used SPI by incorporating both precipitation and potential evapotranspiration (PET) into its calculations. Unlike the SPI, the SPEI accounts for the effects of increased temperatures on water demand, providing a more comprehensive measure of drought.

The Decile Index (DI) is commonly used in Australia for drought monitoring (Coughlan, 1987). It involves ranking long-term monthly precipitation data in descending order to create a cumulative frequency distribution (Gibbs, 1967).

The Weighted Anomaly Standardized Precipitation Index (WASPI) was developed by Lyon in 2004 to monitor precipitation in tropical regions. It uses monthly precipitation data to calculate WASPI, with values ranging from most severe dryness (-2) to severe wetness (2), and it correlates well with other drought indices (Lyon, 2004).

Percentage Area Weighted Departure (PAWD) is frequently employed in meteorology and hydrology and serves as an effective tool for monitoring drought conditions.

The Palmer Drought Severity Index (PDSI) is a key meteorological index used in the United States for drought monitoring (Heim, 2002). It was introduced by Palmer in 1965 and takes into account precipitation, temperature, and soil moisture content to calculate the PDSI. The Standardized Precipitation Temperature Index (SPTI), also known as the

Dryness Index (SI), considers both precipitation and temperature, as proposed by (Ped, 1975).

The Z-Index, as described by (Triola, 1995a), is calculated using the equation of the CZI. Unlike the SPI, the Z-Score does not require data fitting adjustments for Pearson Type III or Gamma distribution, but it may not be as effective for shorter durations (Edwards DC, 1997).

Disaster Risk Reduction (DRR) refers to the concept and practice of minimizing disaster risks through systematic efforts to analyze and manage the underlying causes of disasters. This includes reducing exposure to hazards, lowering the vulnerability of people and property, managing land and the environment wisely, and improving preparedness for adverse events ((UNDRR)., 2015).

To assess future drought conditions in Pakistan, the study incorporates projected data from the Coordinated Regional Climate Downscaling Experiment (CORDEX) under the RCP 8.5 climate scenario, covering the period from 2023 to 2072. This projection data, along with historical records from 1950 – 2022, was used to compute drought indices such as SPI6, SPEI6, and the Z-Index, specifically focusing on identified hotspot regions. Time series analyses were performed on these indices to understand historical and future drought patterns, with particular attention to severe drought episodes, including those from 1987 – 1988 and 1999 – 2002. The return time periods for extreme climatic event is calculated using the Weibull method in MS Excel, providing valuable insights into the frequency and severity of future drought events

1.1 Problem statement

Pakistan, being an agro-based economy, is highly vulnerable to the impacts of global climate change. According to the Intergovernmental Panel on Climate Change (IPCC), Pakistan ranks 12th among countries expected to be severely affected by climate change. The country is particularly sensitive to increase in temperature and changes in precipitation patterns. These climatic changes significantly increase vulnerabilities for agriculture, forests, and water resources, which are crucial for the economy and the livelihoods of many people.

The increase in temperature due to climate change could alter bio-physical relationships for crops, livestock, fisheries, and forests. These alterations include the shortening of growing periods, changes in species patterns, increased thermal and moisture stresses, changes in water requirements, alteration of soil characteristics, and increased risks of pests and diseases. Such changes pose substantial challenges for maintaining agricultural productivity and food security in Pakistan.

Globally, the mean annual temperature is rising, leading to variations in rainfall distribution, trends, and magnitudes. These variations have significant impacts on the hydrological cycle, affecting water availability and distribution. According to the World Economic Forum, extreme weather events and natural disasters are among the likeliest global risks with the largest impacts. Droughts, in particular, have affected more people globally than other hazards or disasters. The Food and Agriculture Organization (FAO) reports a general increase in the incidence and severity of droughts, which have caused the deaths of over 11 million people and affected more than 2 billion people worldwide, a substantial loss compared to other natural hazards (FAO, 2020).

Despite these challenges, Pakistan lacks proper monitoring networks for hydrometeorological parameters such as temperature, precipitation, and droughts. There is also a lack of resources and awareness regarding drought and climate change, as well as DRR. Addressing these issues is crucial for building resilience and ensuring sustainable development in the face of climate change.

1.2 Literature Gap

- Previously researchers have only focused on comparison of drought indices, and mostly used gauges data to calculate drought indices, while gridded (continuous) data could give better insight into spatial variation of indices.
- Most studies focused on investigation of drought indices over smaller study areas (i.e., districts or provinces) of Pakistan.

- Lack of studies suggesting DRR measures based on technical analysis / drought indices.

1.3 Objectives

- To identify best drought indices.
- To identify/detect regions highly vulnerable to historical droughts.
- Projection of droughts on the bases of drought indices.
- To suggest DRR measures based on technical findings.

1.4 Scope of Study

- Identification of vulnerable areas to drought hazard across Pakistan.
- Ensuring of continual spatial data helps in forecast / future trends of drought in hot regions.
- Suggestions for disaster risk reduction measures on the basis of technical findings of the study
- Targeted benefit sectors of research are Disaster Risk Management, Water Management, and Decision makers across the Pakistan.

CHAPTER 2: LITERATURE REVIEW

This chapter reviews previous research conducted by various researchers, organizations, and government departments on drought, drought indices (such as SPI, SPEI, RVI, CI, WASPI, PNPI, PAWD, PDSI, and Z-Index), disaster risk reduction measures for drought-affected areas.

Drought is recognized as one of the most severe hydro-meteorological hazards (Mishra AK, 2005). It is a temporary event that can last from months to years. According to (Wilhite D. , 2000), droughts can occur in any region of the world, regardless of the environment (arid, semi-arid, or humid) or whether. The inter-annual variability in precipitation makes arid regions particularly vulnerable to drought due to a higher likelihood of below-average precipitation (Smakhtin VU, 2008). The Centre for Research on the Epidemiology of Disasters (CRED) has found that droughts cause large-scale economic losses and increase vulnerability to other hydro-meteorological disasters (Guha-Sapir D, 2014). (Obasi, 1994) reported that extreme meteorological events contribute to approximately 85% of natural disasters. Droughts typically occur due to below-normal precipitation over a region and intensify over time (Rossi, 2000). Timely information about the onset and progression of drought is crucial for preparedness and mitigation efforts. Therefore, data obtained through various drought indices can be instrumental in monitoring drought conditions. Drought frequency and intensity provide valuable insights for policymakers to develop timely contingency plans (Morid et al., 2006).

Many drought indices are in use because a single index often fails to provide comprehensive drought information, given the varying climatic conditions across regions. These indices help determine the severity and spatio-temporal extent of drought (Hayes, 2000). According to (Mendicino G, 2008), drought indices offer a thorough understanding of drought and are essential for monitoring purposes. The selection of an appropriate drought index is critical for effective drought monitoring in any region. For instance, some of the indices used by national hydro-meteorological organizations include SPEI and PDSI (Palmer, 1968) in the United States, Z-Index by the Meteorological Centre of China (Wu H, 2001), DI by the National Meteorological Centre of Australia (Gibbs, 1967), and SPI

(McKee TB, 1993), which is the most widely used indicator globally, as recommended by the World Meteorological Organization (WMO, 2012; Hayes, 2011). A recent study by Adnan et al. (2015) on drought in Pakistan showed promising results using SPI alone. However, to the best of our knowledge, no other indices have been utilized to verify their effectiveness in drought monitoring in Pakistan. This study focuses on comparing various drought indices and evaluating their applicability and performance in Pakistan. The findings will be beneficial to national hydro-meteorological services for drought monitoring and early warning, water resource management, and climate change adaptation in the region.

Amin et al. (2022) reviewed 74 operational and proposed drought indices, emphasizing the critical role of drought characterization for both retrospective analysis and forward planning. Their review highlighted the wide array of available drought indices, reflecting the absence of a universal definition and diverse operational requirements. This variety underscores the need for comprehensive drought indices that encompass multiple aspects and applications (Amin Zargar, 2022).

Drought indices are essential in drought management as they convert extensive data into quantitative information for various applications, including drought forecasting, declaring drought levels, contingency planning, and impact assessment.

Sergio et al. (2010) introduced the Standardized Precipitation Evapotranspiration Index (SPEI), a new multi-scalar drought index that integrates temperature data to enhance drought assessment. SPEI outperforms traditional indices such as the Self-Calibrated Palmer Drought Severity Index and the Standardized Precipitation Index (SPI) under global warming conditions, making it a valuable tool for multi-scalar drought analysis and monitoring (Sergio m. Vicente-serrano, 2010).

Adnan et al. (2017) compared various drought indices to monitor drought status in Pakistan using long-term data from 58 meteorological stations for the period 1951 – 2014. This study evaluated indices like SPI, SPEI, RDI, CI, and others, demonstrating their effectiveness in identifying historical drought years and the prolonged drought episode from 1999 to 2002. The results indicated a positive trend toward increased wetness at a 95% confidence level, underscoring the importance of drought monitoring in Pakistan, particularly in southern regions vulnerable to decreased precipitation. The study highlights the utility of multiple drought indices for comprehensive drought monitoring and management in Pakistan (Shahzada Adnan, 2017).

Ali et al. (2020) analyzed meteorological drought in Ankara, Turkey, using SPI and SPEI under different greenhouse gas scenarios. Their research aimed to provide insights for sustainable water resource management in the region by employing regionally downscaled climate models and emphasizing the importance of accurately adjusting model outputs to match historical observations for reliable drought projections (Ali Danandeh Mehr, 2020).

Li et al. (2022) explored the effectiveness of drought indices in assessing and managing various types of droughts to mitigate their impacts. Their study highlighted the importance of innovative methods for drought monitoring and prediction to address challenges posed by droughts on ecosystems, including flash droughts. The paper advocates for natural drought mitigation strategies that prioritize environmental protection over engineering projects to prevent ecosystem degradation and underscores the need for sustainable approaches to manage drought risks and protect natural resources (Li, 2022).

Alex et al. (2021) discussed Pakistan's vulnerability to climate change, focusing on the significant impact of flooding and drought in recent years. The paper provides an overview of the country's climatology, detailing its diverse climate zones and potential future climate scenarios based on different emissions pathways. It emphasizes the urgent need for long-term risk management strategies in Pakistan to mitigate the adverse effects of climate change and natural disasters (Alex Chapman, 2021).

Zhou et al. (2016) analyzed the spatial and temporal characteristics of drought in Pu'er City, Yunnan Province, using remote sensing data, meteorological information, and Geographic Information (GI) technology. By studying precipitation observations from 10 meteorological stations over a 50-year period, the study identified trends in precipitation levels using statistical methods such as the Mann-Kendall test. The results revealed that factors like temperature, altitude, and vegetation cover influence rainfall distribution in the area (Zhou, 2016).

F. Tosunoglu et al. (2016) examined trends in maximum hydrologic drought variables, specifically annual maximum duration (AMD) and annual maximum severity (AM), using Mann-Kendall and Sen's Innovative Trend Analysis (ITA) methods in the Coruh River Basin, Turkey. They compared results from these methods applied to nine different stations in the basin, highlighting the importance of identifying drought trends for effective water resource management. While the basic Mann-Kendall test showed no trend in most stations, the modified Mann-Kendall and ITA methods revealed decreasing trends in AMD and increasing trends in drought severity for certain stations. Sen's ITA method proved valuable for detecting trends without relying on specific assumptions. The study emphasizes the significance of using innovative trend analysis methods like ITA for identifying drought patterns and aiding water resource management (F. TOSUNOGLU, 2016).

Research on assessing the costs of droughts focuses on damage costs and costs related to mitigation and adaptation policies. It categorizes drought costs into direct, indirect, and non-market costs, highlighting the lack of standardized terminology in existing literature. Various methods for estimating different types of drought costs are discussed, emphasizing the precision, data requirements, and resource needs. The paper also addresses policies for drought mitigation and adaptation, outlining challenges due to limited information on costs and benefits, and provides recommendations for best practices in assessing and managing drought impacts.

Zuliqar Ali et al. (2017) introduced the Standardized Precipitation Temperature Index (SPTI), a new drought monitoring index designed to address limitations of existing indices like SPI and SPEI in low-temperature regions. By incorporating temperature data, SPTI demonstrates strong correlations with SPI and outperforms SPEI in detecting drought conditions. The study compared the performance of these indices across different time scales and meteorological stations in Khyber Pakhtunkhwa, Pakistan, highlighting SPTI's effectiveness in monitoring drought. The SPTI's multi-scaling capability and consideration of temperature make it a recommended tool for detecting and monitoring drought conditions over various time scales (Zubair, 2017).

Shah et al. (2019) examined the disaster preparedness and capacity-building needs of local institutions in Khyber Pakhtunkhwa Province, Pakistan, to enhance disaster risk reduction (DRR). Through interviews with key informants from 19 institutions, the study found that most local institutions lacked preparedness in terms of awareness, training, human resources, financial resources, infrastructure, and coordination. The findings emphasize the need for capacity building through training, technical support, and infrastructure development. The study highlights the importance of direct linkages among institutions involved in DRR/DRM and the need for a proactive approach by local institutions to strengthen governance systems for effective disaster risk management in Pakistan (Ashfaq Ahmad Shah, 2019).

Lubna Rafiq et al. (2012) focused on assessing hazards in Pakistan based on frequency and severity, considering the increasing population and vulnerability to natural and man-made disasters. They analyzed hazard potential and vulnerability factors to create an integrated risk assessment map for districts in Pakistan, helping decision-makers understand damage potential and coping capacity. The study emphasizes a multi-risk approach that integrates socio-economic, environmental, and physical dimensions of vulnerability to estimate damage potential and coping capacity, covering 107 districts in Pakistan excluding some due data unavailability, and provides valuable insights for local authorities (Lubna Rafiq, 2012).

Tsun-Hua Yang et al. (2020) reviewed risk reduction strategies for floods and droughts, stressing the importance of efficient water resource management given the limited availability of freshwater on Earth. The study discusses various risk reduction techniques, including prediction, monitoring, and impact assessment, highlighting the need for interdisciplinary cooperation and advanced technologies like artificial intelligence and the Internet of Things for effective disaster management. It also addresses the socioeconomic impacts of droughts and floods and emphasizes the need for sustainable water management practices to mitigate these risks and enhance resilience in the face of climate extremes. The paper underscores the necessity for professionals to plan and manage water resources effectively to improve quality of life now and in the future (Tsun-Hua Yang, 2020).

Yilmaz (2019) analyzed hydrological drought trends in the GAP region of Southeastern Turkey using SPI over a 48-year period from 1970 to 2017 at nine selected stations. The study employed the Mann-Kendall trend test and the Innovative Sen Method (ISM) to identify trends in drought severity, duration, and frequency. The ISM method, known for its flexibility and ability to provide qualitative information on drought trends, showed potential for effective water resource management in arid regions like the GAP area (YILMAZ, 2019).

X.H. Xu et al. (2016) focused on drought prediction and sustainable ecological development in Pu'er City, Yunnan Province, China, which has been severely affected by drought since 2009. The study utilized Geographic Information Technology, the Mann-Kendall test for trend analysis, and examined precipitation anomalies to understand drought characteristics in the region. By analyzing the correlation between precipitation and vegetation cover, the research aimed to provide a theoretical basis and technological methods for government decision-making and early warning ecology research. The findings indicated a decreasing trend in overall rainfall, with a slight increase in spring precipitation, emphasizing the need for an ecological security early warning system and sustainable development strategy in arid areas (X. H. Xu, 2016).

Donald A. Wilhite et al. (2000) discuss drought as a widespread climate phenomenon affecting regions globally, with particular emphasis on the United States' vulnerability to extended periods of low precipitation. They highlight the growing importance of drought preparedness planning, with various government levels in the U.S. implementing strategies to mitigate drought risks. Key components of these drought plans include monitoring and early warning systems, risk assessment, and mitigation strategies. The authors stress the need for accurate and timely monitoring to trigger effective mitigation and emergency response measures (Donald A. Wilhite M. S., 2000).

Shahid Ahmad et al. (2004) emphasizes the necessity of revising existing policies for infrastructure development in drought-prone areas. They highlight the importance of enhancing mobility, such as using helicopters for rescue and relief operations in these regions. The study points out the challenges of drought monitoring due to the lack of integration among hydrological, meteorological, and socioeconomic information and the absence of a single institution responsible for drought monitoring in the country. They also mention the establishment of institutional arrangements in Baluchistan, including the Relief Commission and the Quetta Drought Crisis Control Center, to effectively address drought crises. Additionally, the paper discusses the potential for improving water distribution and efficiency within the Karez irrigation systems in Pakistan, aiming to irrigate large areas through the rod-kohli system, which channels water from hills to torrents (Shahid Ahmad, 2004).

According to M.S. Pomee et al. (2005), drought is a recurring climatic challenge that has historically caused significant distress, with varying intensity and frequency across different regions and times. Pakistan lacks a comprehensive drought management infrastructure and relies on ad-hoc crisis management rather than proactive disaster preparedness. The study highlights the need for effective drought management strategies, noting the absence of crucial elements such as early warning systems and mitigation measures. It explores options like artificial glacier melting, rainwater harvesting, and crop-based water management to enhance water resources and mitigate drought impacts. The authors emphasize the importance of evaluating the practicality, cost-effectiveness, environmental impacts, and sustainability of measures like controlled glacier melting before implementation (M.S. Pomee, 2005).

Donald A. Wilhite et al. (2014) argue for a shift towards national drought policies that prioritize risk reduction over crisis management to effectively address drought impacts. They emphasize the need for proactive mitigation and planning, risk management, public outreach, and resource stewardship as central elements of national drought policies (Donald A. Wilhite R. P., 2014).

The paper by Ashfaq et al. (2009) investigates the impact of climate change on extreme weather events in Pakistan using regional climate models. The study emphasizes the significance of localized climate projections, revealing that climate change is likely to increase the frequency and intensity of extreme weather events. These changes pose serious risks to agriculture, water resources, and overall socio-economic stability in the region.

The findings underscore the necessity for adaptive strategies to mitigate the adverse effects of these projected climate extremes. By providing detailed insights into future climate scenarios, the research aims to inform policymakers and stakeholders about the potential challenges posed by climate change in Pakistan, thereby facilitating better preparedness and response strategies (Ashfaq, 2009).

Anjum et al. (2021) assess the impact of climate change on Pakistan's water resources using CORDEX South Asia simulations under the RCP 8.5 scenario. Their study highlighted that climate change is expected to significantly changed precipitation patterns and increase temperatures, leading to profound effects on water availability and distribution across the country (Pakistan). The findings suggest a potential increase in the frequency and severity of extreme weather events, such as floods and droughts, which could intensify existing water management challenges and threaten agricultural productivity. Furthermore, the research emphasizes the urgent need for adaptive water resource management strategies to mitigate the anticipated effects of climate change. By offering detailed projections and insights into future climate scenarios, the paper aims to guide policymakers and stakeholders on the critical need for proactive measures to strengthen resilience against climate-related challenges. This approach is crucial for ensuring sustainable water management and protecting the livelihoods that rely on these essential resources in Pakistan (Anjum, 2021).

Zahid et al. (2011) projected changes in temperature and precipitation across Pakistan using both global and regional climate models. The study underscores the expectation of significant temperature increases, with projections suggesting potential impacts on various sectors, including agriculture and water resources. Additionally, the analysis indicates shifts in precipitation patterns, with some regions likely to see increased rainfall, while others may experience decreased precipitation, posing potential challenges for water management and agricultural productivity. By combining global and regional models, the study offers a comprehensive overview of potential climate scenarios for Pakistan. This information is vital for policymakers and stakeholders to craft strategies that mitigate the adverse effects of climate change, ensuring sustainable development and resilience in response to evolving climatic conditions (Zahid, 2011).

Hussain et al. (2017) evaluate precipitation simulations from the CORDEX South Asia initiative, focusing on their performance for Pakistan. The authors compare these simulations with gauge-based observations to assess their accuracy and reliability. Through hydrological modeling, the study examines how well the simulated precipitation data matches the actual observations, revealing discrepancies in certain regions. This evaluation is essential for understanding the limitations of climate models and their implications for hydrological forecasting and water resource management in Pakistan. The findings emphasize the need to improve precipitation simulations to enhance their effectiveness in hydrological applications. The accurate precipitation data is crucial for effective water management, particularly in a country like Pakistan, which is susceptible to climate variability and extremes. By pinpointing areas where models may fall short, the study provides valuable insights for future research and model development, ultimately aiming to support better decision-making in the context of climate change adaptation and water resource planning in Pakistan (Hussain, 2017).

Bonaccorso et al. (2003) investigate the spatial variability of drought in Sicily by analyzing the Standardized Precipitation Index (SPI). The study uses SPI to assess drought conditions across various regions of Sicily, revealing significant differences in drought intensity and frequency. Through the examination of historical precipitation data, the research identifies areas more prone to drought, offering insights into the spatial distribution of water scarcity in the region. The findings also highlight the importance of understanding drought patterns for effective water resource management and agricultural planning in Sicily. The authors suggest that recognizing the spatial variability of drought can help in developing targeted strategies to mitigate its impacts. This research enhances the broader understanding of drought dynamics and underscores the need for continuous monitoring and assessment to build resilience against future drought events in the region (Bonaccorso, 2003).

Mishra and Singh (2010) provide a comprehensive review of various drought concepts, emphasizing the complexity and multifaceted nature of drought. The authors categorize drought into different types, including meteorological, agricultural, hydrological, and socio-economic droughts, each defined by specific criteria and impacts. By synthesizing existing literature, the paper highlights the importance of understanding these distinctions to effectively assess and manage drought conditions. Furthermore, the review discusses the methodologies used for drought assessment, including indices like the Standardized

Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI). The authors argue that a clear understanding of drought concepts is essential for developing effective mitigation strategies and policies. They also emphasize the need for interdisciplinary approaches to address the challenges posed by drought, particularly in the context of climate change and increasing water scarcity (Mishra, 2010).

CHAPTER 3: METHODOLOGY

3.1 Study Area

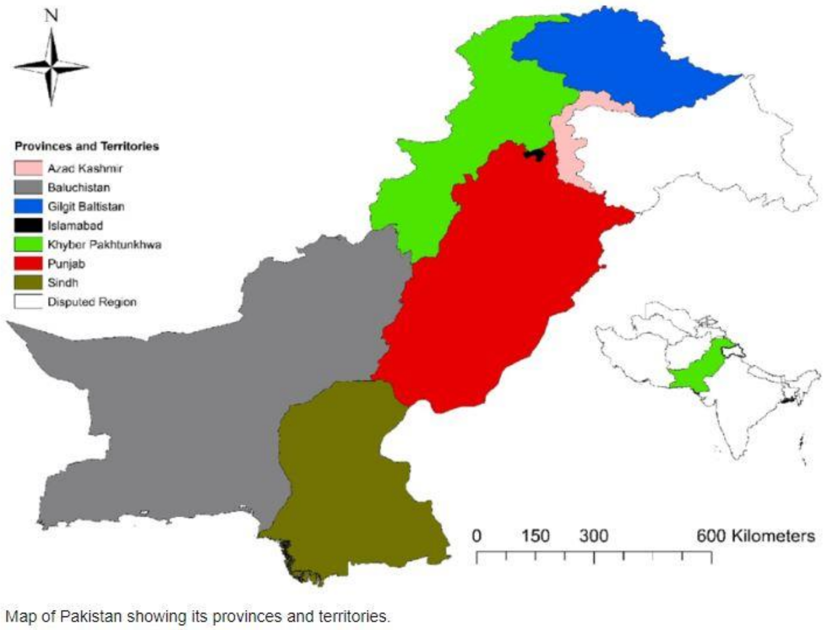


Figure 1 Map of Pakistan showing it provinces and territories.

Pakistan, situated in South Asia, is bordered by India to the east, Afghanistan and Iran to the west, China to the north, and the Arabian Sea to the south. Its geographical coordinates range from approximately 24° to 37° N latitude and 60° to 77° E longitude. The country boasts diverse landscapes, including the towering Himalayan and Karakoram Mountain ranges in the north, home to some of the world's highest peaks like K2. In contrast, the southern regions are characterized by the Thar Desert and the flat Indus River plain, which is crucial for agriculture.

Pakistan's population exceeds 230 million, making it the 5th most populous country globally. The population is a mix of ethnic groups, including Punjabis, Sindhis, Pashtuns, and Baloch. Urdu is the official language. Islam is the state religion, and the population is mainly Muslim.

The country experiences a wide range of weather patterns due to its diverse topography. Generally, Pakistan has an arid climate with hot summers and cool winters. The northern and northwestern regions receive snowfall in winter, whereas the southern regions remain mild. The monsoon season, from July to September, brings heavy rains primarily to the eastern and northeastern regions, while the western parts stay dry. This climate variability presents challenges for water resource management and agriculture. Additionally, Pakistan is vulnerable to climate change, which can increase the frequency of extreme weather events, i-e droughts and floods.

Pakistan's economy is predominantly agrarian, with the Indus River basin playing a central role in agriculture and contributing significantly to the national GDP. Major crops include wheat, rice, cotton, and sugarcane. Pakistan is facing challenges such as political instability, energy shortages, and susceptibility to climate-related impacts like droughts and floods, highlighting the need for sustainable development and effective disaster risk management.

3.2 Data

Monthly averaged temperature and precipitation datasets were obtained from the ERA5-Land dataset, with a spatial resolution of $0.1^0 * 0.1^0$; native resolution of 9 * 9 km, spanning 72 years (1950 - 2022). Projection data of 50 years (2023 – 2072) was obtained from CODREX. Additionally, secondary data from various sources, including articles, books, and survey reports, supplemented our analysis.

3.3 Methods

This study utilized monthly averaged precipitation and temperature data from the ERA5 Land dataset, renowned for its high temporal and spatial resolution, to analyze drought conditions across Pakistan. The dataset, covering a period from 1950 – 2022, offers a spatial resolution of 0.1° × 0.1° (approximately 9 × 9 km). This extensive dataset provided the necessary meteorological variables for accurately extracting monthly precipitation and temperature values, which are crucial for detailed climatic analysis.

All data processing and analysis were conducted using the R statistical software. The study began by calculating various drought indices, including the SPI, PDSI, PNPI, SPEI, Z-Index, WASPI, DDI, PAWD, SPTI, and RVI. The calculation of these indices involved aggregating and normalizing the precipitation and temperature data, providing a quantitative measure of drought conditions over different timescales. R's extensive packages and functions enabled precise data manipulation, visualization, and analysis, ensuring accurate calculation of the indices.

Key statistics, such as Mean, Standard Deviation (SD), Mean Bias Error (MBE), Mean Absolute Error (MAE), Correlation Coefficient (CC), and Nash-Sutcliffe Efficiency (NSE) were computed for each index to aid in the selection of the most effective drought indices and hotspot identification within the study area. Spatial analysis and visualization were performed using R to identify the most effective drought indices and locate problematic regions within Pakistan. The selection of hotspots, or the most extremely vulnerable areas, was based on evaluating MBE, MAE, CC, and NSE. These statistical measures helped in pinpointing regions where the drought indices showed the highest discrepancies or strongest correlations with observed drought events.

Drought maps were generated for each index, offering a clear spatial representation of drought conditions throughout the study period. Maps of historical drought episodes were drawn for two significant episodes: Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002). These visualizations highlighted areas particularly vulnerable to drought, guiding further analysis and policy recommendations.

Time series analyses were conducted on specific grid location based on the averaged top three indices, providing insights into historical drought patterns, such as those observed from 1987 – 1988 and the famous drought of 1999 – 2002.

Projected data from CORDEX under the RCP 8.5 climate scenario (2023 – 2072) were evaluated. SPI6, SPEI6, and Z-Index were computed for both historical and projected datasets to assess drought conditions at hotspots across these periods.

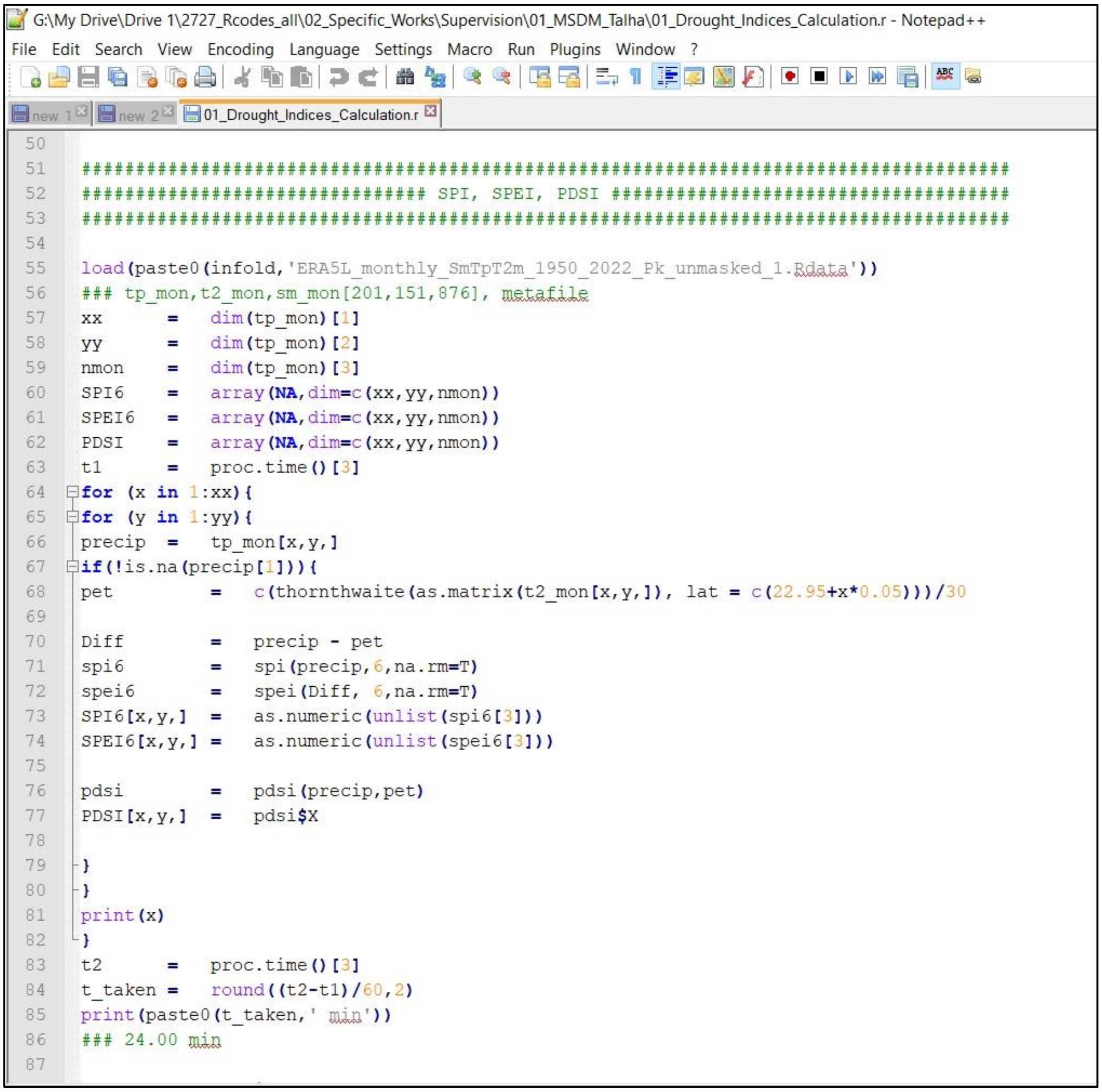
The technical findings emphasized the need for targeted DRR strategies, including improved water management practices, the adoption of drought-resistant crop varieties, and the enhancement of early warning systems to mitigate the impact of future droughts. These recommendations aim to increase resilience, ensure sustainable resource management, and reduce the vulnerability of communities in drought-prone regions.

Sr.	Drought Indices	Equations	Explanation
1	SPI	Used R packages for analysis.	
2	SPEI		
3	PDSI		
4	Z-Index		
5	WASPI	$WASP_N = \frac{1}{\sigma_{WASP_N}} \cdot \sum_{i=1}^{N} \left(\frac{P_i - \bar{P}_i}{\sigma_i} \cdot \frac{\bar{P}_i}{\bar{P}_A} \right)$	Where P_i, P_A is the monthly and annual rainfall, $\bar{P}_l$ and $\bar{P}_a$ is the monthly and annual rainfall climatology, σ_i is the standard deviation of monthly rainfall where $WASP_N$ is the standard deviation of WASPI.
6	SPTI	$Si = \frac{Ds}{VDT} - \frac{DQ}{VDQ}$	Where Si is SPTI, D_s and D_Q are the Precipitation and temperature anomalies; VDT and VDQ are respective standard deviations.
7	RVI	$\delta i = {(pi - \mu)}/{\sigma}$	Where Si represents RVI, Pi is annual rainfall for i^{th} year, μ and σ are the annual mean and standard deviation of rainfall.
8	PNPI	$\mathrm{PNPI} = \frac{P_i}{P} \times 100$	Where Pi is the total precipitation of each year, P is the average climatology for a period (study time period).
9	PAWD	$\mathrm{PAWD} = \left[\frac{(X_i - \bar{X})}{\bar{X}} \right] \times 100$	Where Xi is the precipitation of i^{th} month, $\bar{X}$ is the normal precipitation.
10	DDI		Long term monthly precipitation data is ranked in descending order to make cumulative frequency distribution. The first decile precipitation amount should not exceed by the lowest 10% of the total. The second decile is the amount between 10 and 20% of the total and so on. The severity of the drought can be assessed by comparing the amount of precipitation in a month or over a period of several months with the cumulative distribution of precipitation over a long-term period. The 20% of lowest precipitation falls is termed to be much below normal (decile 1 and 2). Decile 3 and 4 (20–40%) shows below normal, decile 5 and 6 (40–60%) indicate near normal and so on.

Table 1 Drought indices equations for analysis.

Sr.	Errors	Equations	Explanation
1	Mean Absolute Error	$\text{MAE} = \frac{1}{N}\sum_{i=1}^{N} \lvert y_i - \hat{y}_i \rvert$	Where N is the number of data points, $y^{\wedge}_i$ is the predicted value for data point i, y_i is the actual value for data point i,$\lvert yi - y^{\wedge}_i \rvert$ is the bias (or error) for each data point.
2	Mean Bais Error	$\text{MBE} = \frac{1}{N}\sum_{i=1}^{N} (\hat{y}_i - y_i)$	
3	Correlational Coefficient	$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}}$	Where r is correlational coefficient x_i is values of the x-variable in a sample, x^- is mean of the values of the x-variable; y_i is values of the y-variable in a sample; and y^- is the mean of the values of the y-variable.
4	Standard Deviation	$\sigma = \sqrt{\frac{\sum (x_i - \mu)^2}{N}}$	Where σ is the population standard deviation; N is the the size of the population; x_i is the value from the population, and μ is the population mean.
5	Nash-Sutcliffe Efficiency	$NSE = 1 - \frac{\sum_{i=1}^{n} (Q_o(i) - Q_m(i))^2}{\sum_{i=1}^{n} (Q_o(i) - \overline{Q_o})^2}$	Where $Q_o(i)$ is the observed value at time step i, $Q_m(i)$ is the modelled (predicted) value at time step i, Q_o^- is the mean of the observed values and n is the number of time steps.

Table 2 Errors equations for analysis




```r

########################################################################################
################################ SPI, SPEI, PDSI #####################################
########################################################################################

load(paste0(infold,'ERA5L_monthly_SmTpT2m_1950_2022_Pk_unmasked_1.Rdata'))
### tp_mon,t2_mon,sm_mon[201,151,876], metafile
xx      =   dim(tp_mon)[1]
yy      =   dim(tp_mon)[2]
nmon    =   dim(tp_mon)[3]
SPI6    =   array(NA,dim=c(xx,yy,nmon))
SPEI6   =   array(NA,dim=c(xx,yy,nmon))
PDSI    =   array(NA,dim=c(xx,yy,nmon))
t1      =   proc.time()[3]
for (x in 1:xx){
for (y in 1:yy){
precip  =   tp_mon[x,y,]
if(!is.na(precip[1])){
pet         =   c(thornthwaite(as.matrix(t2_mon[x,y,]), lat = c(22.95+x*0.05)))/30

Diff        =   precip - pet
spi6        =   spi(precip,6,na.rm=T)
spei6       =   spei(Diff, 6,na.rm=T)
SPI6[x,y,]  =   as.numeric(unlist(spi6[3]))
SPEI6[x,y,] =   as.numeric(unlist(spei6[3]))

pdsi        =   pdsi(precip,pet)
PDSI[x,y,]  =   pdsi$X

}
}
print(x)
}
t2      =   proc.time()[3]
t_taken =   round((t2-t1)/60,2)
print(paste0(t_taken,' min'))
### 24.00 min

```

Figure 2 Sample code for calculation of drought indices

CHAPTER 4: RESULTS AND DISCUSSIONS

This chapter consists of results obtain from analysis of ERA5-land dataset of monthly averaged precipitation and temperature in R statistical software over 10 different drought indices over Pakistan.

4.1 Standardized Precipitation Index Results

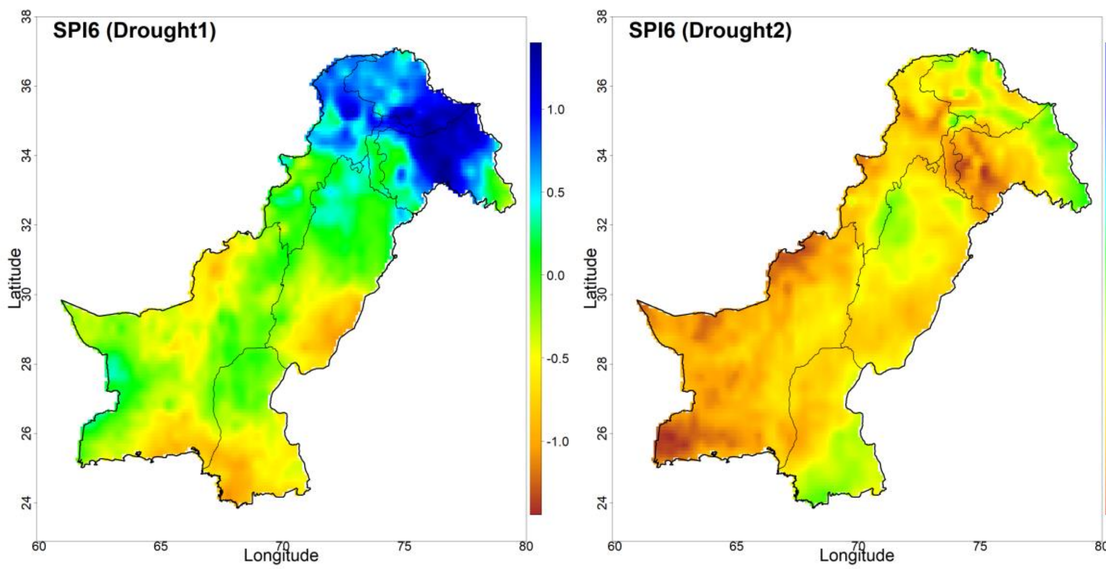


Figure 3 SPI monthly drought index values averaged over Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002).

The SPI maps (figure 2), covering the periods 1987 – 1988 and 1999 – 2002, are part of a broader analysis that spans from 1950 – 2022. Within this extensive study period, these two historical episodes of drought were identified as significant events. The maps provide a detailed visual assessment of drought conditions across the region during these critical years, revealing varying levels of severity.

In both maps, the brown-highlighted areas represent regions of extreme drought vulnerability. These areas experienced significantly below-average precipitation, leading to severe consequences such as water shortages and environmental stress. The extreme drought conditions observed during 1987 – 1988 and 1999 – 2002 highlighted the urgent need for intervention and long-term planning to mitigate the socio-economic impacts.

The yellow-highlighted areas indicate regions that faced severe drought during these periods. Although these areas were less critical than the brown zones, the insufficient rainfall posed significant risks to agricultural activities, water resources, and community well-being. In contrast, the both maps of SPI6, the green and blue areas show regions with moderate wet and extremely wet conditions.

The right-side map of episode 2 shows that during drought 2, majority regions of Pakistan were under server drought conditions.

This analysis underscores the importance of targeted drought management strategies, focusing on the most vulnerable regions while sustaining the resilience of areas that remained drought-free during these historical episodes.

4.2 Standardized Precipitation Evapotranspiration Index Results

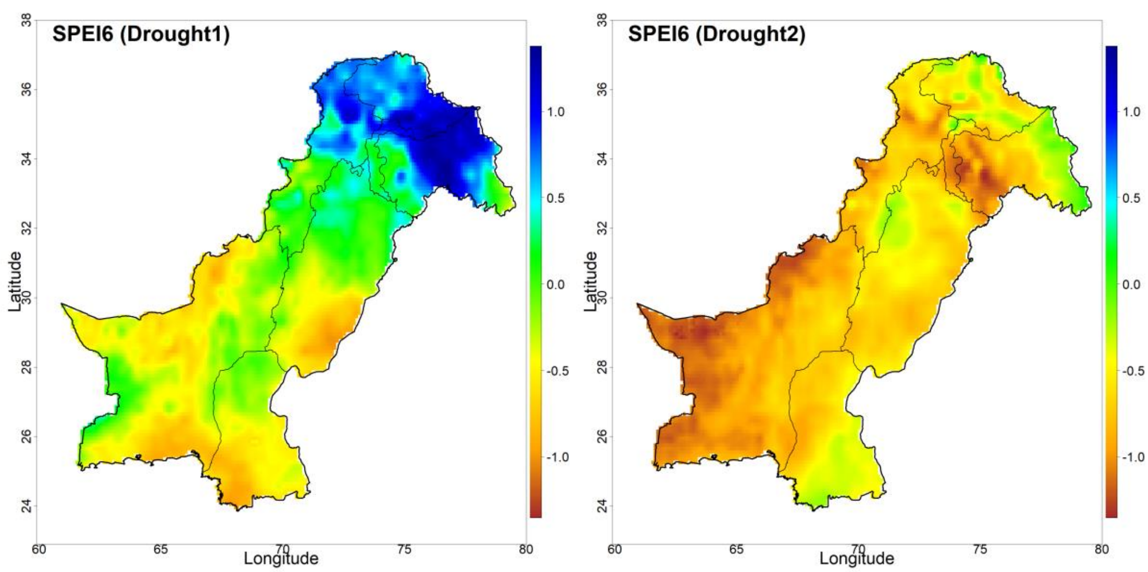


Figure 4 SPEI monthly drought index values averaged over Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002).

The SPEI maps, covering the periods 1987 – 1988 and 1999 – 2002, are resulting from a comprehensive analysis of drought conditions over the study period from 1950 – 2022. These maps show critical insights into the intensity and spread of drought across the region, with a particular focus on how changes in both precipitation and evapotranspiration affected water availability during these years.

In both periods, the brown-highlighted areas on the SPEI maps indicate regions experiencing extreme drought conditions. These areas were significantly impacted by a combination of low precipitation and high evapotranspiration rates, leading to severe water deficits. The extreme drought observed in these regions during 1987 – 1988 and 1999 – 2002 underscored the critical need for immediate and sustained drought mitigation efforts.

The yellow-highlighted regions of left side map reflect areas of severe drought conditions but on the other hand, right side map reflected severe drought during the historical episodes 2. This zone from substantial water stress due to the imbalance between precipitation and evapotranspiration.

Conversely, the green and blue areas on SPEI maps depict regions with no drought or the wet period, where the balance between precipitation and evapotranspiration was slightly negative, leading to some level of water stress. Continuous monitoring and adaptive management were essential in these areas to prevent the situation from worsening.

4.3 Z-Index Results

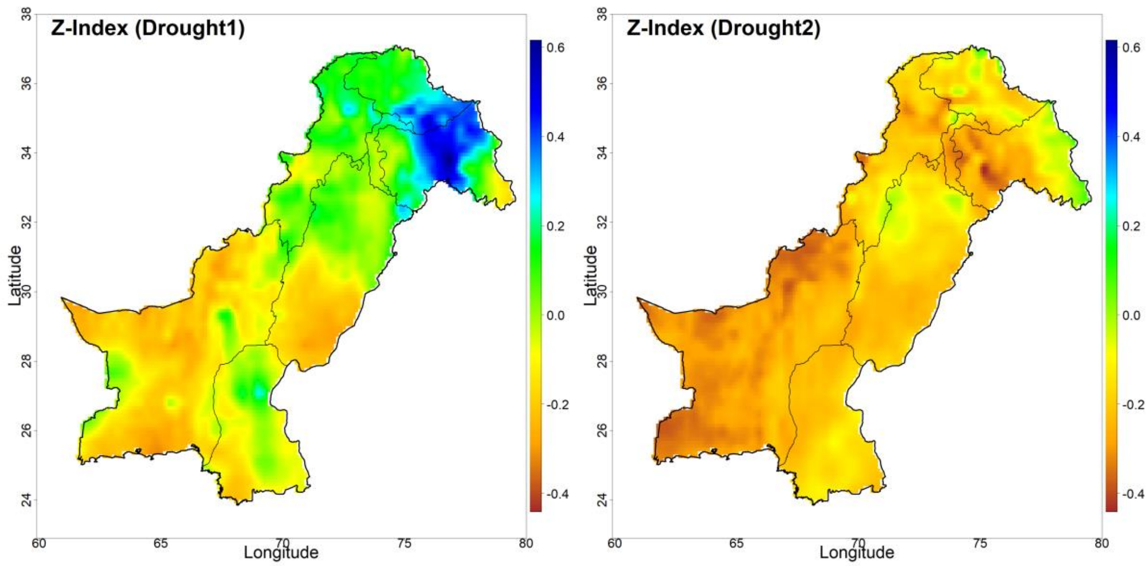


Figure 5 Z-Index monthly drought index values averaged over Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002).

The Z-Index maps, representing the periods 1987 – 1988 and 1999 – 2002, are part of a detailed drought analysis conducted over the broader study period from 1950 – 2022. The Z-Index specifically measures the departure of precipitation from the long-term average, offering a focused view on how much these specific years deviated from typical conditions.

In both drought episodes, the brown-highlighted areas on the Z-Index maps indicate regions that experienced severe drought conditions. These areas saw significantly lower precipitation than the long-term average, resulting in severe drought stress. The extreme deficits in rainfall during these periods led to critical impacts.

The yellow-highlighted areas correspond to regions that faced moderate drought during episodes 2 and wet condition during episode 1. While green color on right-side which covers the area of almost all Pakistan faces mild drought during the episode 2 of the historical drought.

4.4 Standard Precipitation Temperature Index Results

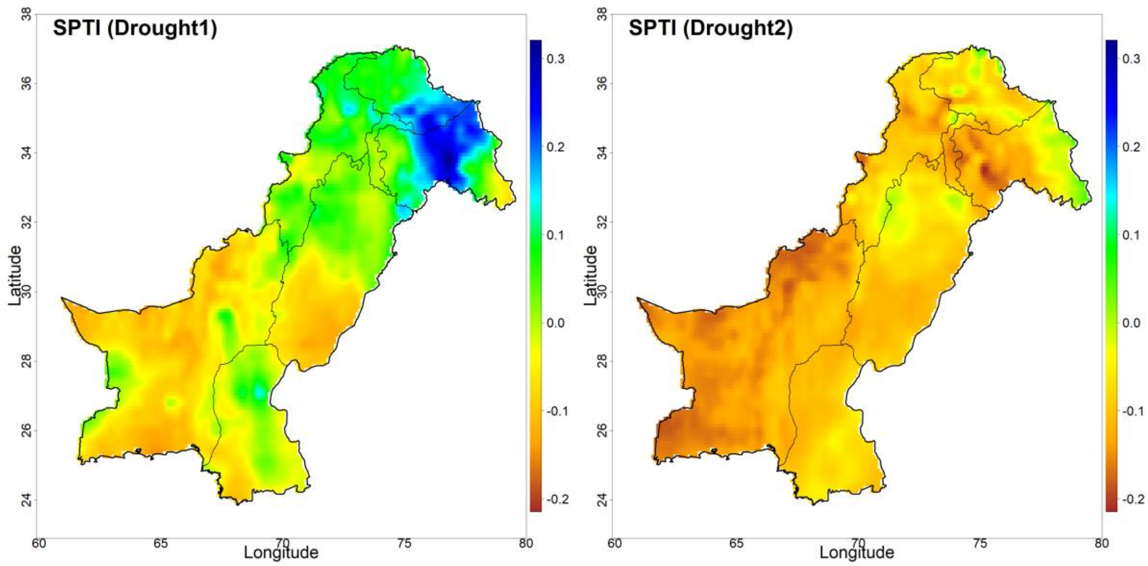


Figure 6 SPTI monthly drought index values averaged over Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002).

The SPTI (Standardized Precipitation Temperature Index) maps for the periods 1987 – 1988 and 1999 – 2002 offer a comprehensive view of drought conditions by integrating both precipitation and temperature anomalies. This index provides insight into how deviations in these variables combined to affect drought severity over the study period.

The brown-highlighted areas on the SPTI maps indicate regions experiencing moderate drought during these historical episodes. These areas were marked by significant negative deviations in both precipitation and temperature.

The yellow and green highlighted regions represent mild drought conditions in both drought episodes. Although these areas did not experience the extreme anomalies, they faced significant water stress due to below-average precipitation combined with elevated temperatures.

In contrast, blue areas on both SPTI maps show regions with no drought. However, drought-free regions, characterized by adequate precipitation and more favorable temperature conditions. These wet areas supported healthy water resources and agricultural activities, contrasting sharply with the more affected regions. This spatial variability underscores the need for tailored drought management strategies to address the diverse conditions across different regions

4.5 Weighted Anomaly Standard Precipitation Index Results

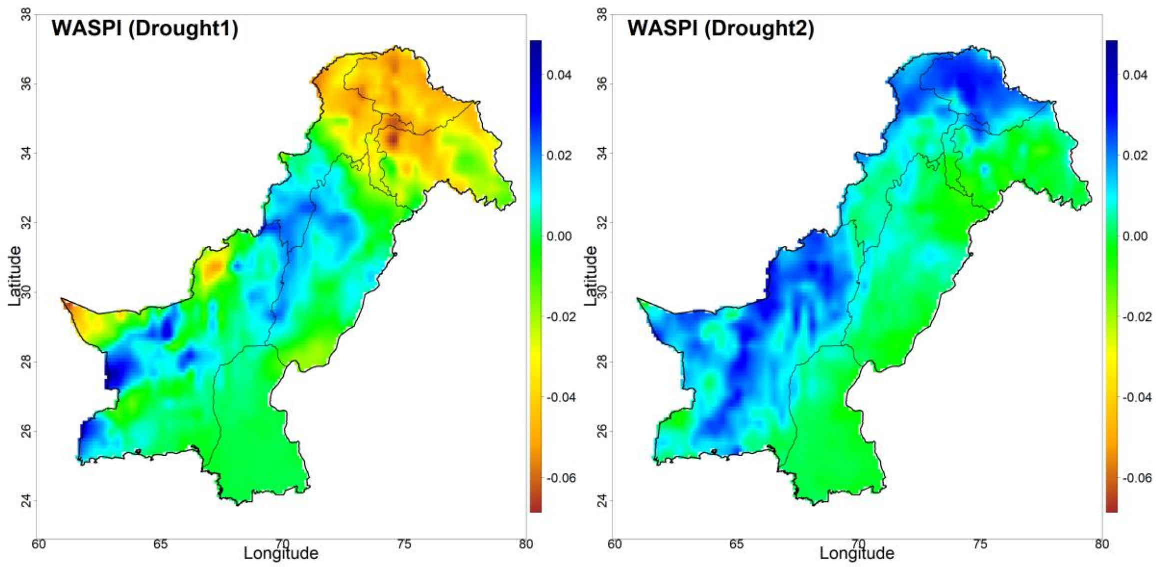


Figure 7 WASPI monthly drought index values averaged over Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002).

The WASPI maps for the periods 1987 – 1988 and 1999 – 2002 provide a detailed analysis of drought conditions by emphasizing the weighted impact of precipitation anomalies. This index is particularly useful for understanding how deviations from normal precipitation, when weighted by their significance, affect drought severity over the study period.

The brown, yellow and green highlighted areas on the WASPI maps indicate regions experiencing mild drought during both historical episodes. These areas showed significant negative anomalies in precipitation, with a high weighting reflecting the severity of the deficits.

Conversely, blue areas on the WASPI maps show regions with no drought. The contrast between these wet and drought-affected regions highlights the importance of tailored drought management strategies that address the specific needs of each area based on the weighted impact of precipitation anomalies.

4.6 Percent of Normal Precipitation Index Results

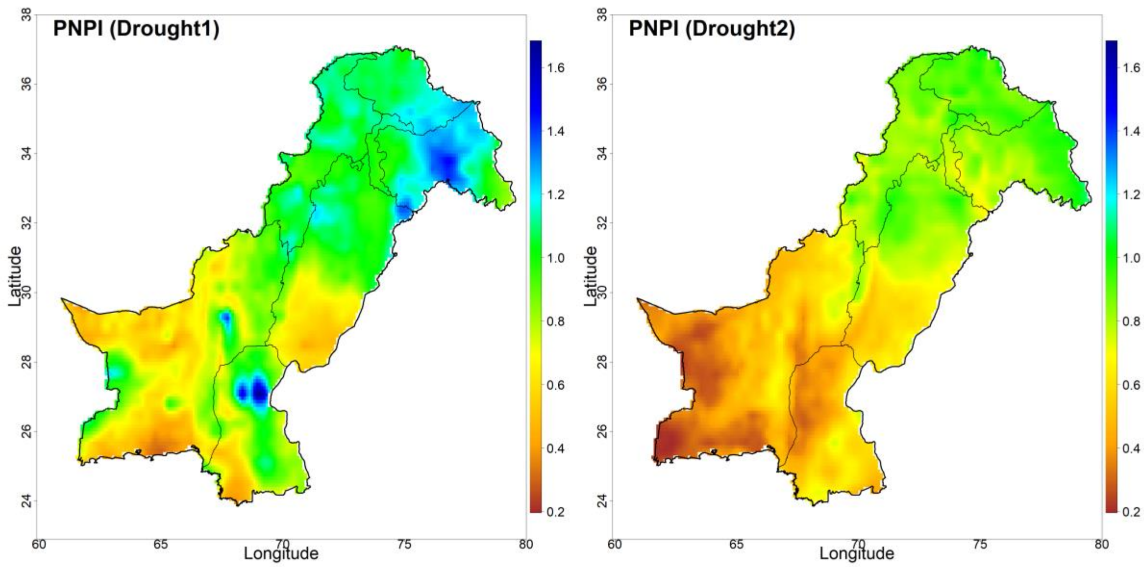


Figure 8 PNPI monthly drought index values averaged over Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002).

The PNPI maps for the periods 1987 – 1988 and 1999 – 2002 offer valuable insights into drought conditions by illustrating how precipitation during these years deviated from normal levels. This index measures the percentage of normal precipitation, helping to understand the severity of drought based on how much precipitation was above or below average over the study time period.

The brown-highlighted areas on the PNPI maps represent regions experiencing moderate drought during both historical episodes. These areas showed a significant reduction in precipitation compared to the normal levels, with percentages well below average.

The green areas on the PNPI maps depict regions with mild drought, with precipitation percentages below normal but not as critically low as in other drought zones. These regions faced some level of water stress, requiring ongoing monitoring to prevent worsening conditions. The blue-highlighted areas were out of drought, with precipitation percentages above normal levels. These wet areas benefited from favorable water availability and robust agricultural conditions, contrasting sharply with the drought-affected regions. This spatial variability highlights the need for targeted drought management strategies that address the specific conditions and needs of different regions based on their precipitation levels relative to normal.

4.7 Palmer Drought Severity Index Results.

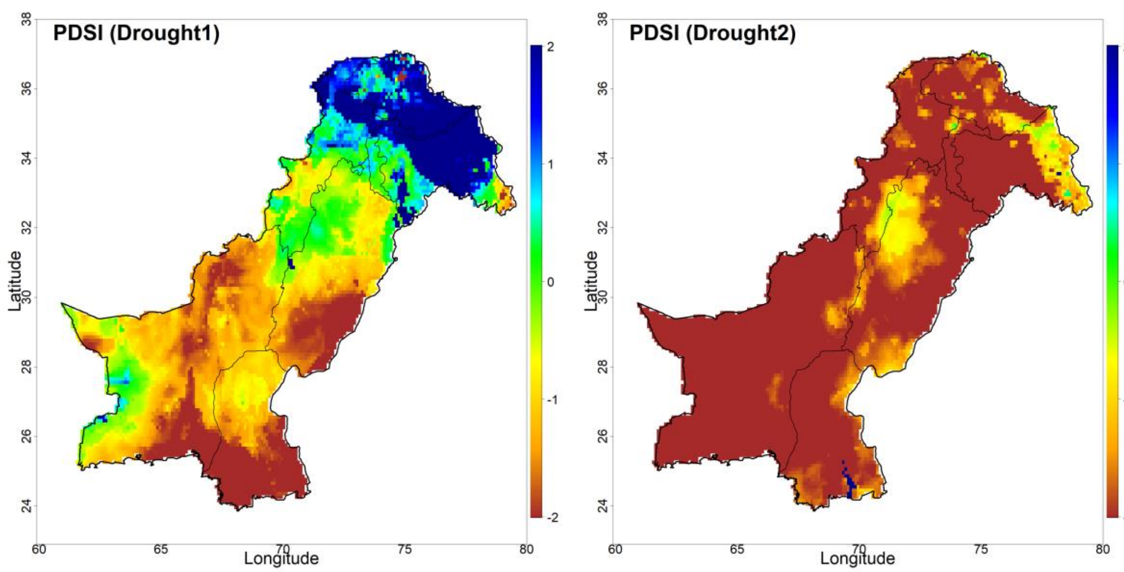


Figure 9 PDSI monthly drought index values averaged over Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002).

The PDSI maps for the periods 1987 – 1988 and 1999 – 2002 provide a comprehensive analysis of drought conditions by assessing the severity of drought based on long-term precipitation and temperature data. This index offers a nuanced view of how drought conditions evolved over the study time period, focusing on the balance between precipitation and evaporation.

The brown-highlighted areas on the PDSI maps indicate regions experiencing extreme drought during both historical episodes. These areas displayed significantly negative PDSI values, reflecting severe imbalances between precipitation and evapotranspiration.

The yellow-highlighted regions represent severe drought conditions, with PDSI values that were notably negative but less extreme than those in the brown-highlighted areas. While these regions experienced considerable drought stress during 1987 – 1988 and 1999 – 2002, the impact was somewhat less severe compared to the extreme drought zones. The challenges faced by these areas, including impacts on agriculture and water resources, required targeted drought management and mitigation efforts to address the significant water deficits.

In contrast, the green areas on the PDSI maps show regions with mild drought. The areas experienced mild drought, with PDSI values that were negative but not critically low. These regions faced some level of water stress, necessitating ongoing monitoring to ensure that conditions did not worsen. The blue-highlighted areas were free from drought, characterized by PDSI values that were above average. These wet areas benefited from favorable water availability, supporting robust agricultural conditions and contrasting sharply with the more drought-affected regions. The spatial variability depicted in the PDSI maps highlights the importance of tailored drought management strategies to address the diverse needs of regions based on their drought severity.

4.8 Rainfall Variability Index Results

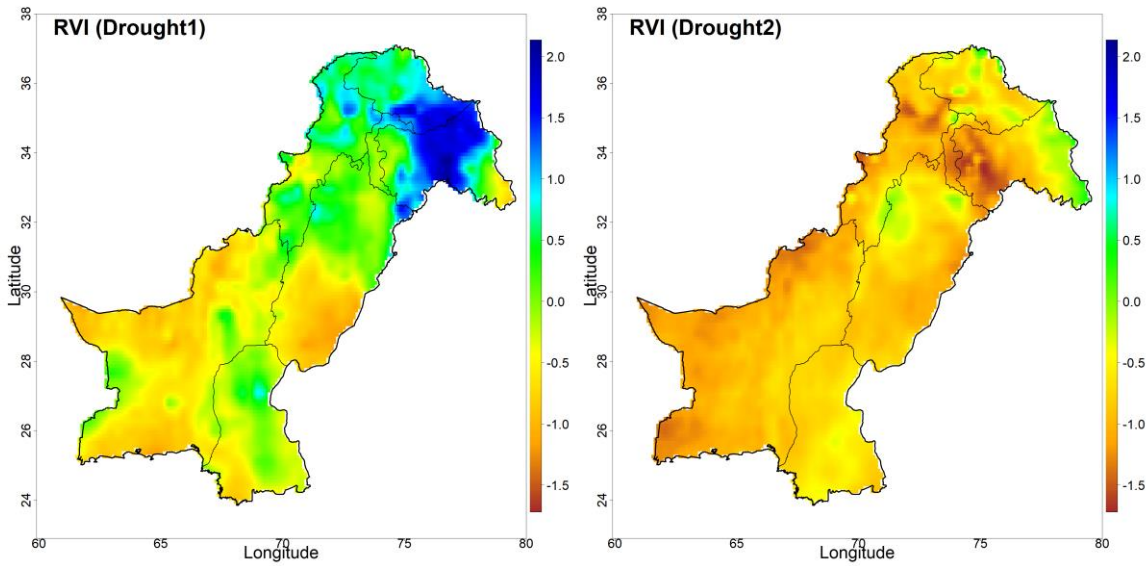


Figure 10 RVI monthly drought index values averaged over Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002).

The RVI (Rainfall Variability Index) maps for the periods 1987 – 1988 and 1999 – 2002 provide a detailed assessment of drought conditions by highlighting the variability in rainfall during these years. This index helps to understand how deviations in rainfall from the norm contribute to drought severity over the study period from 1950 – 2022.

The brown-highlighted areas on the RVI left-side maps indicate regions experiencing severe drought during episode 1 (1987 – 1988) while on right-side map of RVI shows areas experiencing extreme drought during episode 2 (1999 – 2002). These areas were characterized by high rainfall variability, with significant negative deviations from average rainfall levels. The high variability in rainfall during these periods emphasizes the critical need for effective drought management and intervention strategies to address the severe water deficits.

The yellow-highlighted regions on left-side map represent mild drought condition during episode1, while right-side map shows, severe drought conditions with notable rainfall variability but less extreme compared to the brown areas. These regions experienced significant deviations from normal rainfall levels, resulting in considerable water stress and challenges for agriculture and water resource management. Although not as severe as the extreme drought zones, the high variability still necessitated targeted measures to manage and mitigate the impacts of these conditions.

Conversely, the green areas on the RVI left-side maps depict regions with mild wet condition during episode 1; while, during episode 2 identified mild drought.

4.9 P Percentage Area Weighted Departure Results

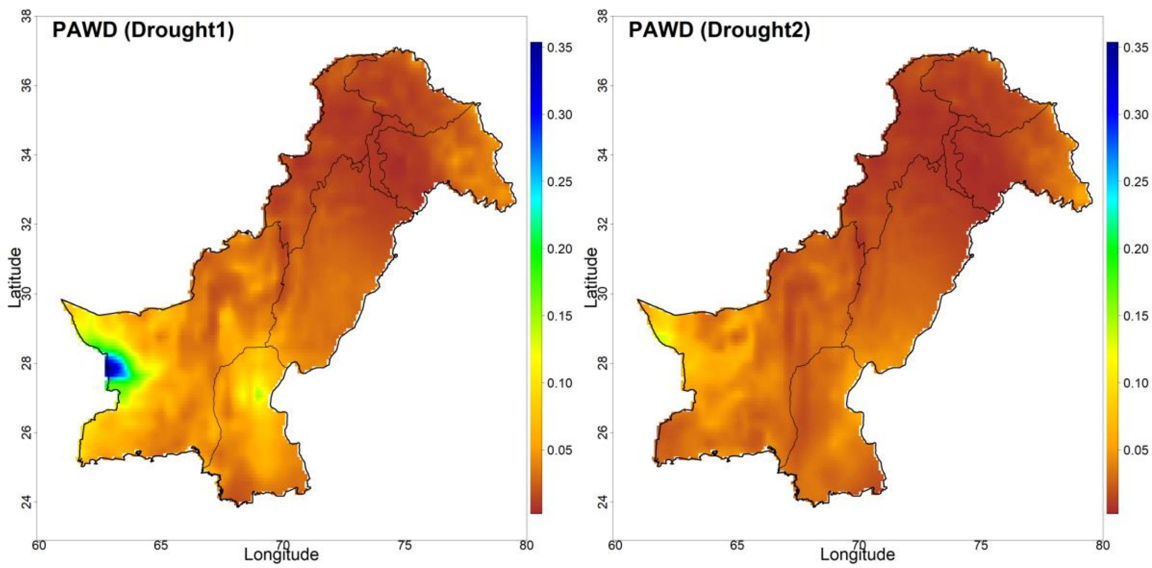


Figure 11 PAWD monthly drought index values averaged over Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002).

The Percentage Area Weighted Departure (PAWD) index maps for the periods 1987 – 1988 and 1999 – 2002 provide an insightful analysis of drought conditions by focusing on the percentage deviation of precipitation from normal levels, weighted by the area affected. This index helps to understand how widespread deviations from average precipitation contribute to drought severity over the study period.

The brown-highlighted areas on the PAWD maps represent regions experiencing severe drought during both historical episodes. These areas showed significant negative departures in precipitation, with a large percentage of the affected area experiencing severe reductions from normal levels. The high percentage area weighted departure underscores the urgent need for effective drought management strategies and interventions in these regions.

The yellow-highlighted regions indicate moderate drought conditions, with substantial but slightly less extreme departures from normal precipitation levels compared to the brown areas. Although these regions faced significant water stress and impacts on agriculture and water resources, the percentage area affected by severe reductions in precipitation was somewhat lower than in the extreme drought zones.

The blue areas on the PAWD maps show regions with mild drought, with percentage area weighted departures that were below normal but less severe compared to the more critical zones. The variability depicted in the PAWD maps highlights the importance of localized drought management strategies to address the diverse impacts of precipitation deviations across different areas.

4.10 Decile Drought Index Results.

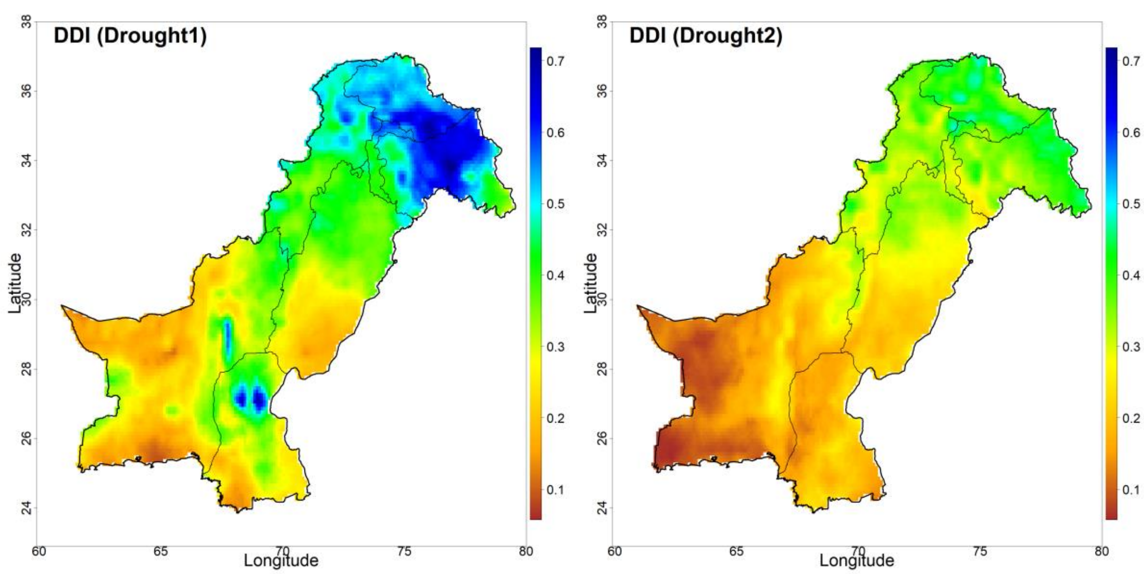


Figure 12 DDI monthly drought index values averaged over Drought 1 (1987 – 1988) and Drought 2 (1999 – 2002).

The Decile Drought Index maps for the periods 1987 – 1988 and 1999 – 2002 provide a detailed assessment of drought conditions by categorizing precipitation levels into deciles, or percentiles, relative to historical data. This index helps to understand how precipitation during these periods compares to historical norms, offering a perspective on the severity of drought based on decile rankings over the study period from 1950 – 2022.

The brown-highlighted areas on the Decile Drought Index maps indicate regions experiencing extreme drought during both historical episodes. These areas fall into the lowest deciles of precipitation, meaning they received significantly below-average rainfall compared to historical records. The extreme decile rankings in these regions highlight the critical need for urgent drought management and intervention strategies.

Green and blue areas on the Decile Drought Index maps depict regions with moderate drought or no drought. The green-highlighted areas experienced moderate drought, categorized in deciles higher than the severe zones but still below average. These regions faced some water stress but were less critically affected, requiring ongoing monitoring to prevent further decline. The blue-highlighted areas were drought-free, with precipitation levels falling into the higher deciles, indicating above-average rainfall compared to historical norms. These wet areas benefited from favorable precipitation conditions, supporting healthy water resources and agricultural activities, and providing a positive contrast to the more drought-affected regions. The decile rankings illustrated by the maps emphasize the importance of targeted drought management strategies to address the diverse impacts of precipitation deviations across different regions.

Conclusion

The historical droughts of 1987 – 1988 and 1999 – 2002 were significant events identified by all ten drought indices analyzed in this study using R statistical software. The analysis was conducted using data from the ERA5-Land dataset, which provided detailed climate information for the study period. Among the indices, SPI, SPEI, and Z-Index proved to be the most reliable indicators.

These indices demonstrated superior performance based on key statistical measures:

- **Mean Bias Error (MBE)**: The SPI, SPEI, and Z-Index showed minimal bias, closely aligning with the observed data from the ERA5-Land dataset. This highlights their accuracy in reflecting the actual drought conditions during these periods.
- **Mean Absolute Error (MAE)**: The low MAE values for these indices indicate minimal discrepancies between the predicted and observed values, underscoring their reliability in estimating drought severity.
- **Correlation Coefficient (CC)**: High correlation coefficients for the SPI, SPEI, and Z-Index reflect a strong alignment with observed drought conditions, effectively capturing the temporal dynamics of these events.
- **Nash-Sutcliffe Efficiency (NSE)**: The high NSE values for SPI, SPEI, and Z-Index demonstrate their excellent predictive capability, showing that these indices performed well in replicating observed drought events and minimizing errors over the study period.

4.11 Performance Comparison of Indices

The performance of various drought indices, including SPI, SPEI, Z-Index, PDSI, and others, was thoroughly compared using key statistical measures such as MBE, MAE, CC, and NSE. The analysis revealed that SPI, SPEI, and Z-Index consistently outperformed the other indices across multiple drought events, including the significant drought periods of 1987 – 1988 and 1999 – 2002. SPI demonstrated strong reliability in capturing drought patterns related to precipitation, while SPEI's inclusion of evapotranspiration factors made it particularly effective in assessing the intensity and duration of droughts. Z-Index also showed remarkable alignment with observed data, reflecting its ability to monitor drought conditions by measuring deviations from normal conditions. These indices exhibited minimal bias and discrepancies when compared to observed ERA5-Land data. Importantly, all these performance evaluations were conducted on the same scale, ensuring a uniform comparison of the indices' effectiveness.

On the other hand, indices like PDSI and PNPI, while still useful, showed relatively higher discrepancies in some regions and time periods. PDSI's reliance on complex water balance models sometimes led to overestimation or underestimation of drought severity in arid regions. Similarly, PNPI, which focuses on percent of normal precipitation, tended to underperform in capturing multi-dimensional drought impacts, such as those influenced by temperature fluctuations. The incorporation of NSE into the comparison further confirmed the superior predictive capacity of SPI, SPEI, and Z-Index, as they consistently achieved higher NSE values, indicating their effectiveness in reproducing observed drought patterns. This comprehensive comparison, conducted on a uniform scale, highlights the suitability of SPI, SPEI, and Z-Index as the most reliable drought indices for drought monitoring and hotspot identification within Pakistan.

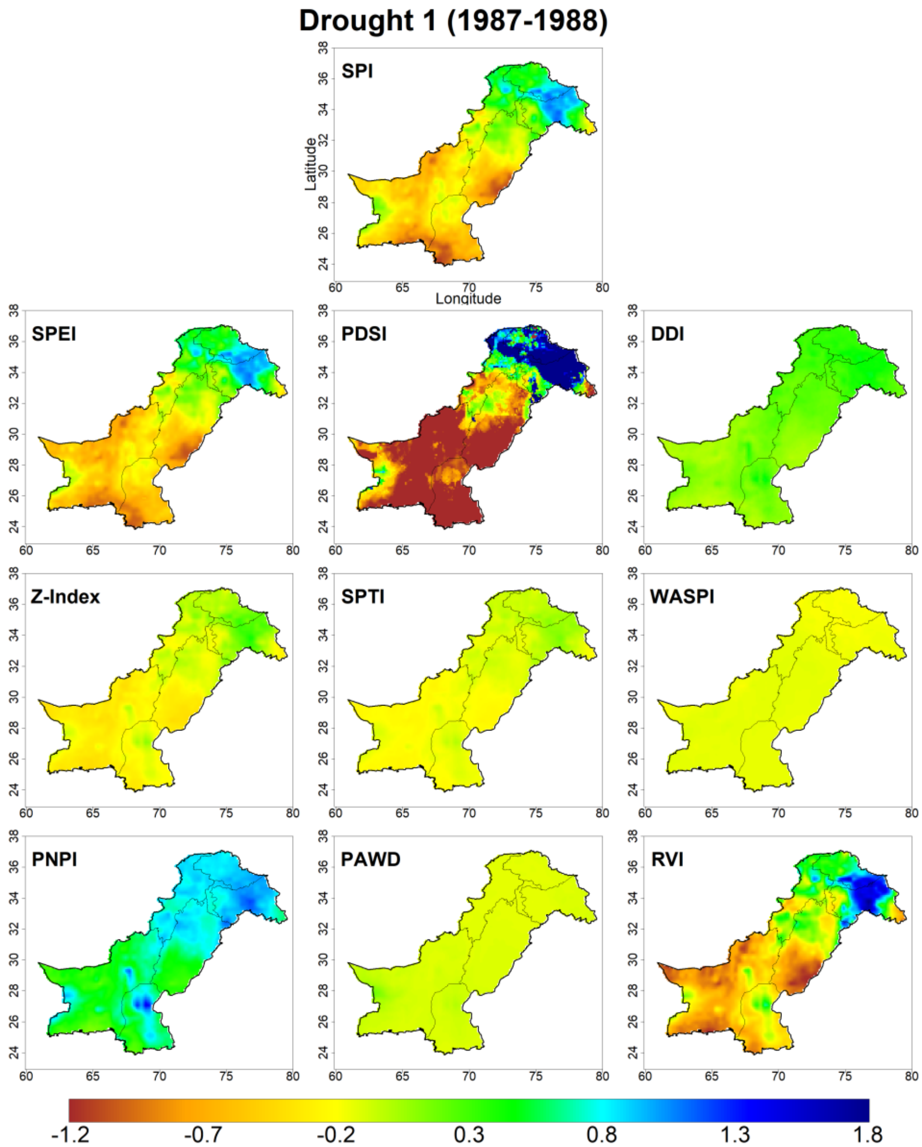


Figure 13 Maps showing performance comparison of indices at same scale for drought episode 1(1987 – 1988).

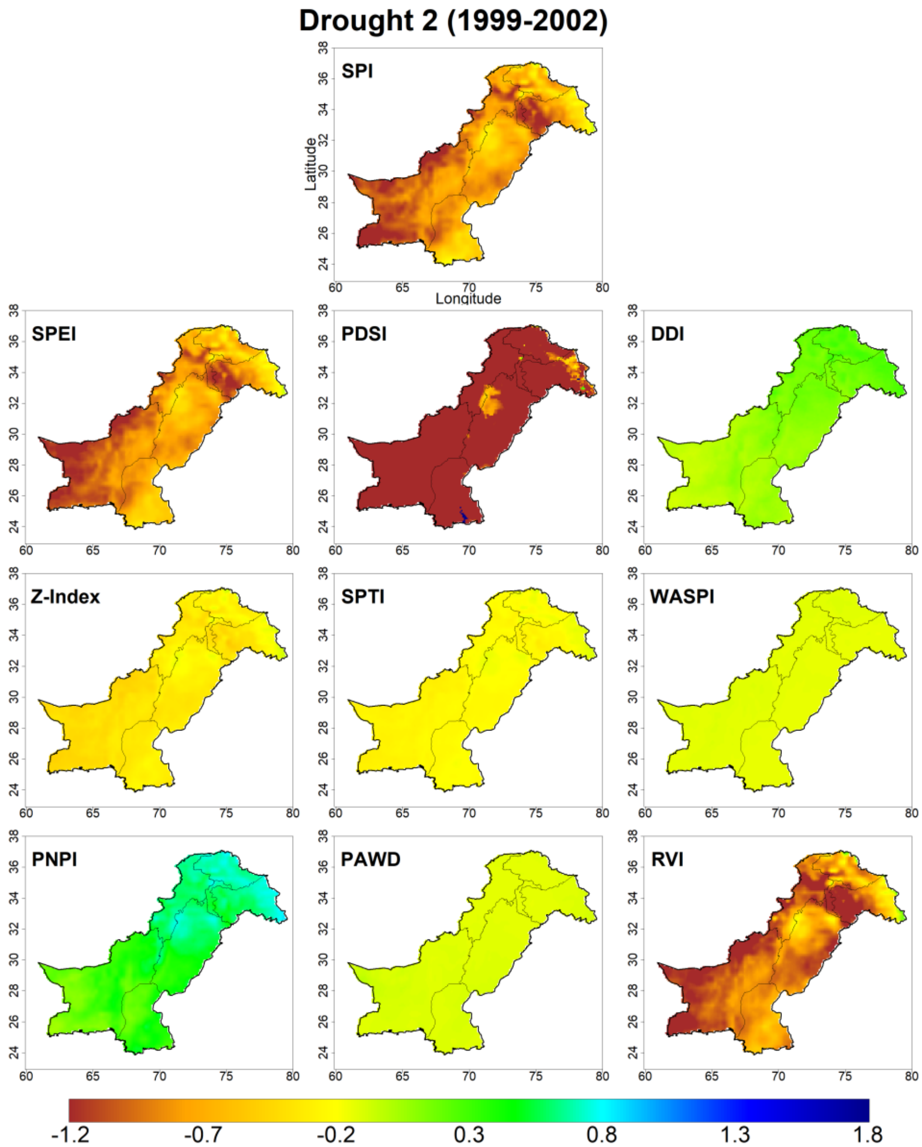


Figure 14 Maps showing performance comparison of indices at same scale for drought episode 2 (1999 – 2002).

4.12 Statistical analysis

Drought 1 (1987 – 1988)						
Index	**Statistics**					
	Mean	**SD**	**MBE**	**MAE**	**CC**	**NSE**
SPI	-0.136	0.872	0	0	1	1
SPEI	-0.136	0.842	-0.0005	0.124	0.978	0.920
PDSI	-0.858	1.033	-0.722	1.417	0.579	-3.699
DDI	0.327	0.484	0.463	0.830	0.298	-0.669
Z-Index	-0.039	0.949	0.096	0.924	0.298	-1.325
SPTI	-0.007	0.726	0.129	0.821	0.352	-0.753
WASPI	-0.009	0.787	0.126	0.931	0.235	-1.221
PNPI	0.892	1.328	1.028	1.269	0.298	-4.491
PAWD	0.040	0.067	0.176	0.812	0.298	-0.522

Table 3 Showing statistical analysis for drought episode 1(1987 – 1988).

During the 1987-1988 drought, various drought indices were analyzed to assess the drought conditions in the region. The analysis includes key statistics such as Mean, Standard Deviation (SD), Mean Bias Error (MBE), Mean Absolute Error (MAE), and Correlation Coefficient (CC) for each index. The SPI index, serving as a reference point, showed a mean of -0.136 with an SD of 0.872, indicating mild drought conditions with moderate variability. However, other indices like SPEI, PDSI, DDI, Z-Index, SPTI, WASPI, PNPI, and PAWD provided more detailed insights. For instance, the SPEI had a mean of -0.136 and a high CC of 0.978, indicating strong agreement with the reference SPI index. The PDSI showed a mean of -0.858, suggesting more severe drought conditions, but with a lower CC of 0.579. The DDI and Z-Index presented positive mean values (0.327 and -0.039, respectively) with moderate to low correlation with SPI. Similarly, indices like SPTI, WASPI, PNPI, and PAWD exhibited varying degrees of error and correlation, with PNPI showing the highest mean (0.892) and SD (1.328), indicating significant variability. This comprehensive analysis highlights the different characteristics of each drought index during the 1987 – 1988 drought, offering a multi-faceted view of the drought conditions.

Drought 2 (1999 – 2002)						
Index	**Statistics**					
	Mean	**SD**	**MBE**	**MAE**	**CC**	**NSE**
SPI	-0.633	0.931	0	0	1	1
SPEI	-0.618	0.844	0.014	0.138	0.974	0.932
PDSI	-1.986	1.377	-1.353	1.760	0.636	-4.928
DDI	0.255	0.367	0.889	1.074	0.306	-1.183
Z-Index	-0.180	0.735	0.452	0.922	0.305	-0.641
SPTI	-0.084	0.609	0.548	0.992	0.107	-0.928
WASPI	0.008	0.584	0.641	1.017	0.196	-1.004
PNPI	0.714	1.014	1.347	1.467	0.305	-3.216
PAWD	0.029	0.049	0.662	0.969	0.305	-0.820

Table 4 Showing statistical analysis for drought episode 2 (1999 – 2000).

During the 1999 – 2002 drought, various drought indices were analyzed to assess the severity and characteristics of drought conditions in the region. The SPI served as the reference point, showing a mean value of -0.633 and a SD of 0.931, indicating moderate to severe drought conditions with moderate variability.

The SPEI closely aligned with the SPI, with a mean of -0.618 and a high CC of 0.974, indicating strong agreement with the SPI. It also had a low MBE of 0.014, suggesting minimal bias in its drought severity estimation. The PDSI showed a more severe drought condition with a mean of -1.986, reflecting a significant moisture deficit. However, it had a lower CC of 0.636, indicating moderate agreement with the SPI, and a substantial MBE of -1.353, which suggests an underestimation of the drought severity.

The DDI and Z-Index presented positive mean values of 0.256 and -0.180, respectively, with moderate to low correlation with SPI, indicating that these indices capture different aspects of drought. The DDI had a relatively high MBE of 0.889, reflecting an overestimation of drought duration, while the Z-Index showed a positive MBE of 0.453, indicating some bias in its assessment.

The SPTI and WASPI exhibited low mean values of -0.084 and 0.008, respectively, with low CCs, suggesting less consistency in comparison to SPI. Both indices had relatively high MAEs, indicating greater errors in their drought assessments.

The PNPI had a mean of 0.715 and an SD of 1.014, indicating variability in precipitation conditions. It also had a high MBE of 1.348, suggesting a significant overestimation of precipitation during the drought. The PAWD had a mean of 0.029, with moderate errors, reflecting its sensitivity to water deficit conditions.

This analysis highlights the differences in how each index represents the 1999 – 2002 drought, with some indices like PDSI showing more severe conditions and others like PNPI indicating substantial variability. The varying degrees of bias, error, and correlation with SPI across these indices provide a comprehensive view of the drought's impact, emphasizing the need for a multi-index approach in drought assessment.

Average Drought 1 and 2 (1987 – 1988 and 1999 – 2002)						
Index	**Statistics**					
	Mean	**SD**	**MBE**	**MAE**	**CC**	**NSE**
SPI	-0.467	0.998	0	0	1	1
SPEI	-0.457	0.922	0.009	0.134	0.976	***0.942***
PDSI	-1.610	1.670	-1.142	1.646	0.670	-3.405
DDI	0.279	0.416	0.747	0.993	0.322	-0.637
Z-Index	-0.133	0.823	0.334	0.923	0.321	***-0.404***
SPTI	-0.058	0.649	0.408	0.935	0.209	-0.483
WASPI	0.002	0.664	0.469	0.988	0.184	-0.625
PNPI	0.774	1.145	1.241	1.401	0.321	-2.503
PAWD	0.032	0.057	0.5003	0.916	0.321	-0.412

Table 5 Showing statistical analysis average of drought 1 (1987 – 1988) and drought 2 (1999 – 2002).

During the analysis of the average drought conditions across the two drought events, various drought indices were examined to provide a detailed understanding of drought severity. The SPI served as a reference point, showing a mean value of -0.467 and a SD of 0.998, indicating moderate drought conditions with moderate variability. In comparison, the SPEI had a mean of -0.457, closely aligning with the SPI, and a high (CC) of 0.976, suggesting strong agreement with the SPI in representing drought conditions.

The PDSI exhibited a mean of -1.610, indicating more severe drought conditions, but with a lower CC of 0.670, reflecting a moderate agreement with SPI. It also had a significant

MBE of -1.142, suggesting an underestimation of drought severity. The DDI and Z-Index presented positive mean values of 0.279 and -0.133, respectively, with moderate to low correlation with SPI, indicating that they capture different aspects of drought.

The SPTI and WASPI showed mean values of -0.058 and 0.002, respectively, with low CCs, indicating less consistency in comparison to SPI. The PNPI had the highest mean value of 0.774 and an SD of 1.145, suggesting significant variability in precipitation conditions. Lastly, the PAWD had a mean of 0.032, with moderate errors, reflecting its sensitivity to water deficit conditions.

This analysis highlights the varying characteristics and reliability of each drought index, offering a nuanced understanding of the drought conditions across the two events. The indices differ in their sensitivity and agreement with SPI, providing a multi-faceted view of drought severity and variability.

4.13 Identification of Hotspot in study area

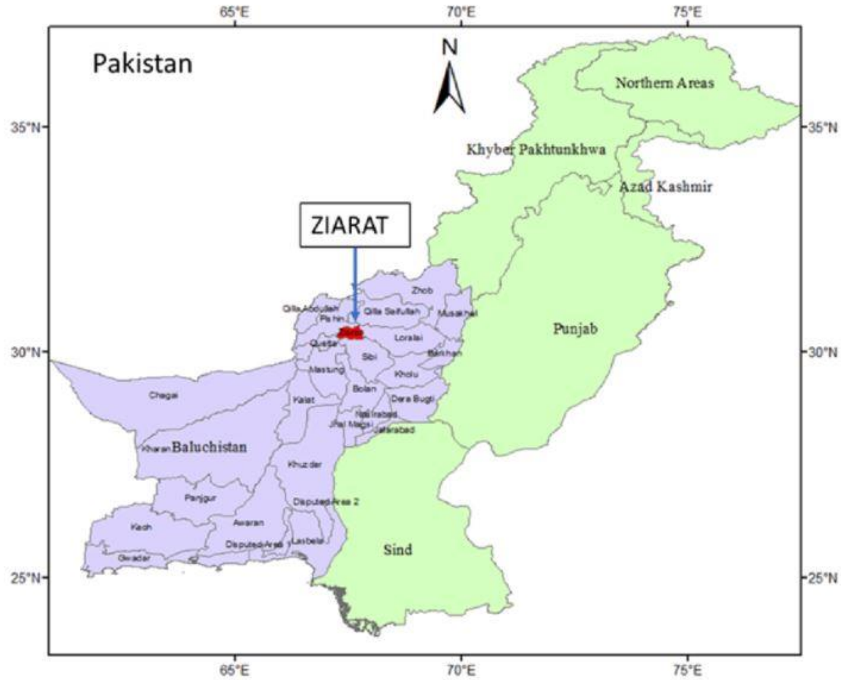


Figure 15. Map showing hotspot (Ziarat) in the study area.

The analysis of drought vulnerability in the study area highlights a critical hotspot centered around 67.5° East and 30.5° North, covering Gogai, district Ziarat in Balochistan province. This region arid climate and scarce rainfall makes it highly vulnerable to drought. Historical records reveal significant drought events, particularly in 1987 – 1988 and 1999 – 2002, which severely affected agriculture, water resources, and the local communities.

Using the best drought indices such as the SPI, SPEI, and Z-Index, the study consistently identified this area as highly vulnerable. The high values of MBE, MAE, and CC confirm a strong correlation between observed and predicted drought conditions, underscoring the region's susceptibility. The vulnerability is further compounded by irregular precipitation patterns, high evapotranspiration rates, and temperature fluctuations, leading to extended drought periods.

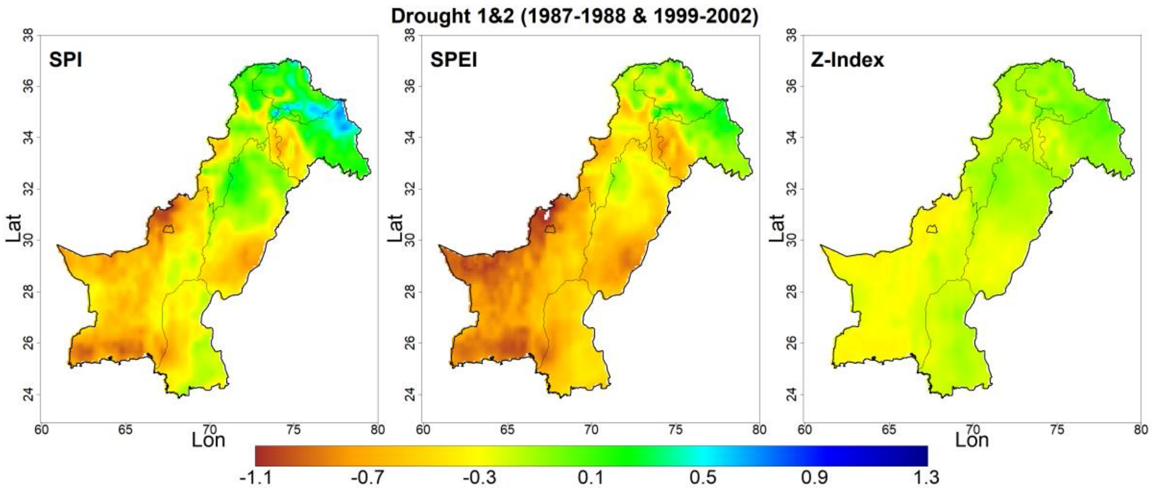


Figure 16 Maps of best drought indices showing hotspot for both episodes of droughts (1987 – 1988 and 1999 – 2002).

4.14 Projection of drought on the bases of drought indices.

In this part of analysis, historical data from the ERA5 Land dataset (1950 – 2022) and projected data from CORDEX under the RCP 8.5 climate scenario (2023 – 2072) were evaluated. SPI6, SPEI6, and Z-Index were computed for both datasets to assess drought conditions on hotspot across these periods. This approach provided a detail comparison of historical and future climate extremes, offering valuable insights into potential changes in drought frequency and intensity under future climate scenarios.

4.14.1 Time series for projected data on hotspot

The graph (figure. 17) represents the Standardized Precipitation Index (SPI) time series for historical data at a hotspot location. The SPI is used to measure the intensity and duration of droughts, where negative values indicate drought conditions and positive values represent wetter periods.

The SPI time series shows significant variability, with frequent shifts between positive and negative values, indicating alternating periods of above-average rainfall and drought. This suggests that the region experiences a high degree of variability in precipitation, which could lead to unpredictable agricultural and water resource management challenges.

The negative SPI values, especially those below -2, highlight severe drought periods. The most extreme drought event observed in the series was on 1999 – 2002 with an SPI value greater then -3, indicating a very intense drought. Such extreme events are critical for understanding the vulnerability of the region and for planning mitigation strategies. Moreover, the trend appears to be moving towards increasing droughts, as indicated by more frequent and severe negative SPI values over time. This suggests a growing vulnerability to drought in the region, which could have significant implications for water resources, agriculture, and local communities.

The overall trend in the SPI time series suggests a gradual increase in the frequency and intensity of droughts. This increasing trend towards more severe droughts is alarming and underscores the urgent need for proactive measures to manage water resources and mitigate the impacts of drought. The region is likely becoming more susceptible to prolonged dry spells, which can exacerbate the effects of climate change and strain local resources.

Given that this data is from a hotspot, the repeated occurrences of severe droughts, as seen in the SPI values, reinforce the area's growing vulnerability to drought. This highlights the necessity for targeted drought risk reduction measures and the development of early warning systems to mitigate the impact on local communities and ecosystems.

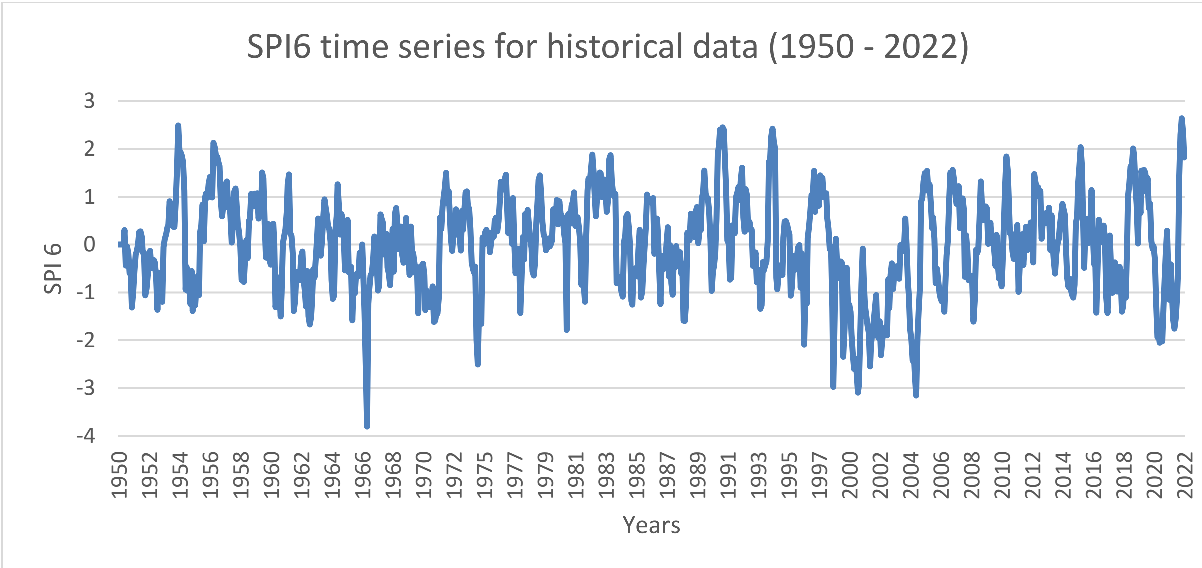


Figure 17 Time series of SPI for historical data (1950 – 2022) at hotspot.

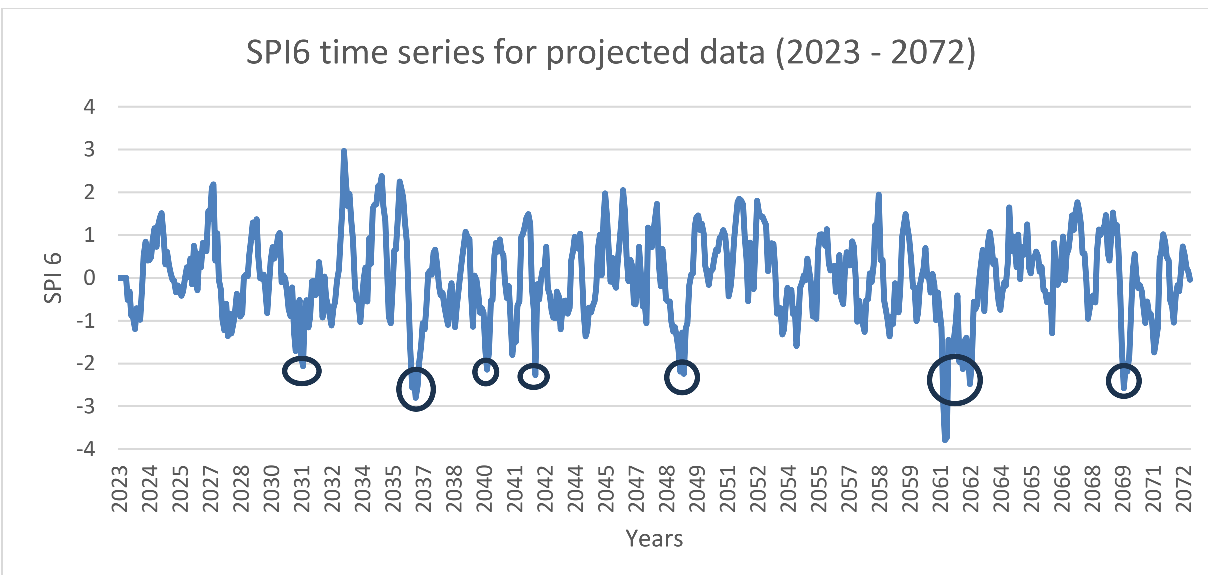


Figure 18 Time series of SPI for projected data (2023 – 2072) at hotspot

The graph (figure 18) presents the SPI6 time series from 2023 – 2072, offering a visual representation of projected drought and wet conditions. Along the x-axis, the years span from 2023 to 2072, while the y-axis shows the SPEI6 values, ranging from -4 to +4. Positive values above 0 indicate periods of wetter-than-normal conditions, whereas negative values below 0 represent drier-than-normal conditions, signifying potential droughts.

The circled areas in the graph highlight specific years where the SPEI6 values drop below -2, indicating severe to extreme severe drought conditions. These drought years are projected to occur several times, with the most significant dips around 2030 – 2031, 2036 – 2037, 2040 – 2042, 2048 – 2049, 2061 – 2063, and 2069 – 2070, where SPI6 falls close to -4. Such low values suggest periods of extreme severe droughts during these years, aligning with the previously identified drought-prone years for the region of Ziarat. These projections, based on both precipitation data, provide a valuable forecast for future drought risks, helping to prepare for potential water shortages and agricultural impacts.

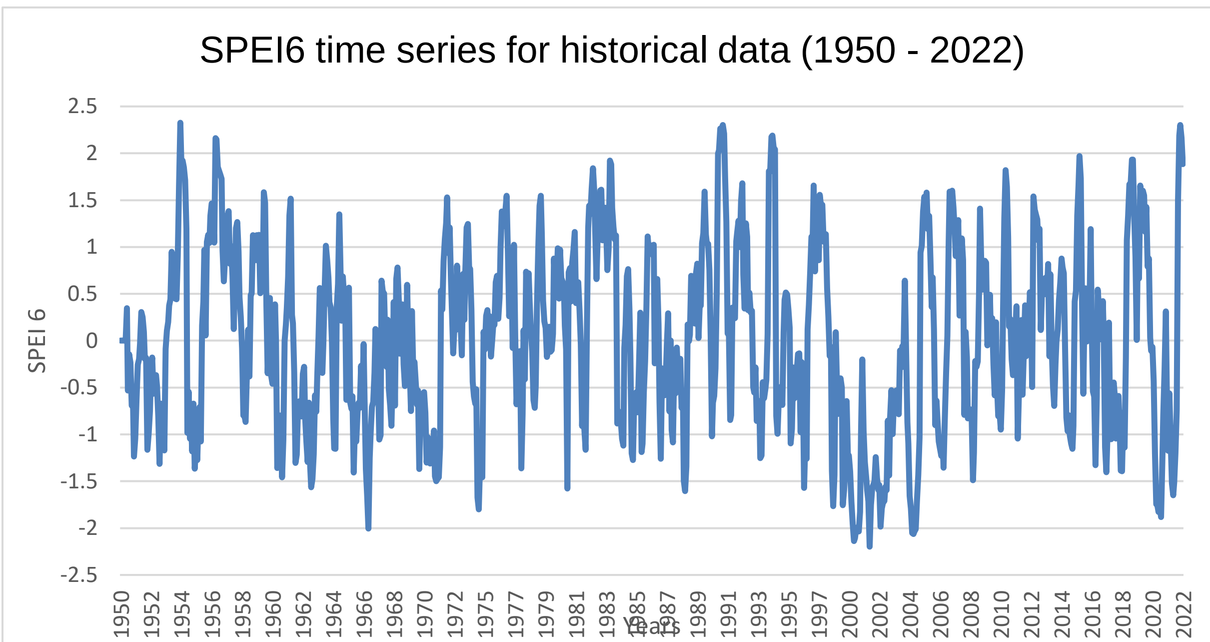


Figure 19 Time series of SPEI for historical data (1950 – 2022) at hotspot

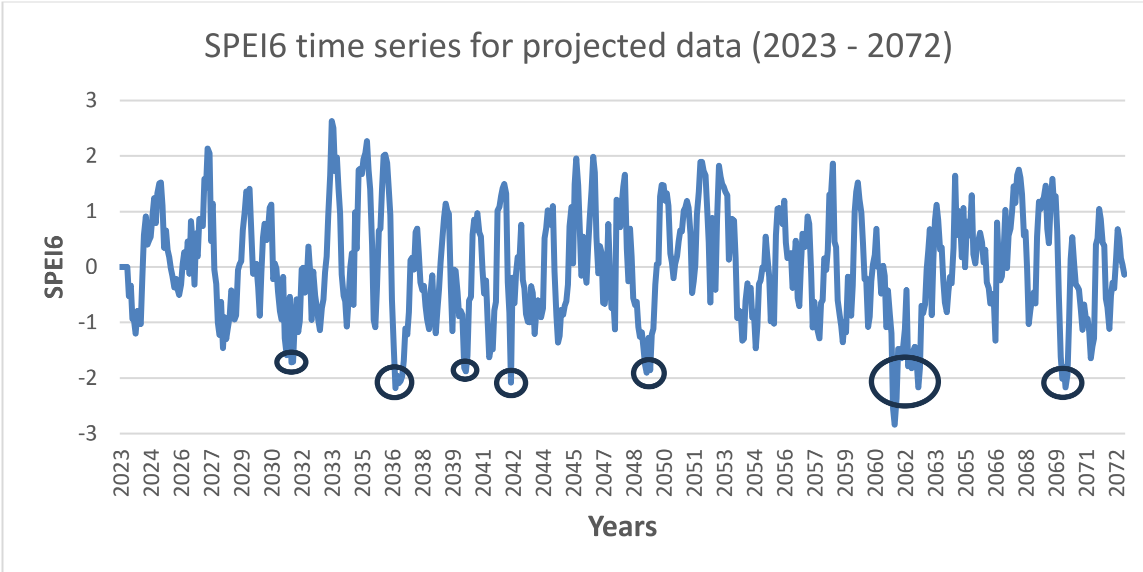


Figure 20 Time series of SPEI for projected data (2023 – 2072) at hotspot

The graph (figure 20) presents the SPEI6 time series from 2023 – 2072, offering a visual representation of projected drought and wet conditions. Along the x-axis, the years span from 2023 – 2072, while the y-axis shows the SPEI6 values, ranging from -3 to +3. Positive values above 0 indicate periods of wetter-than-normal conditions, whereas negative values below 0 represent drier-than-normal conditions, signifying potential droughts.

The circled areas in the graph highlight specific years where the SPEI6 values drop below -1, indicating moderate to severe drought conditions. These drought years are projected to occur several times, with the most significant dips around 2061 – 2063 and 2069 – 2070, where SPEI6 falls close to -2 or lower. Such low values suggest periods of extreme drought during these years, aligning with the previously identified drought-prone years for the region of Ziarat. These projections, based on both precipitation and evapotranspiration data, provide a valuable forecast for future drought risks, helping to prepare for potential water shortages and agricultural impacts.

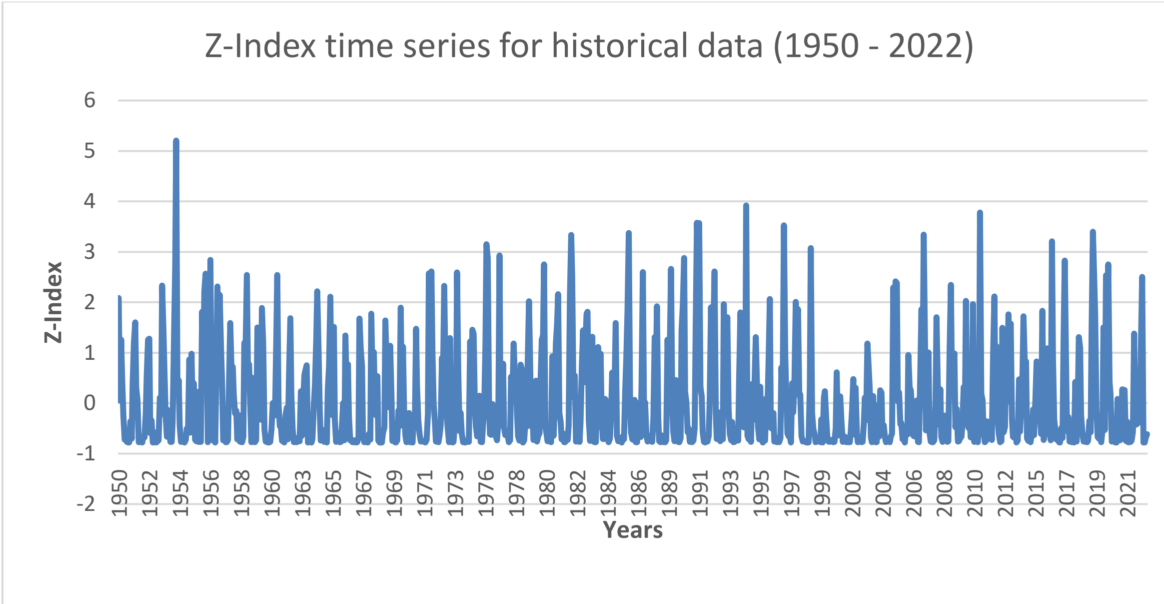


Figure 21 Time series of Z-Index for historical data (1950 – 2022) at hotspot

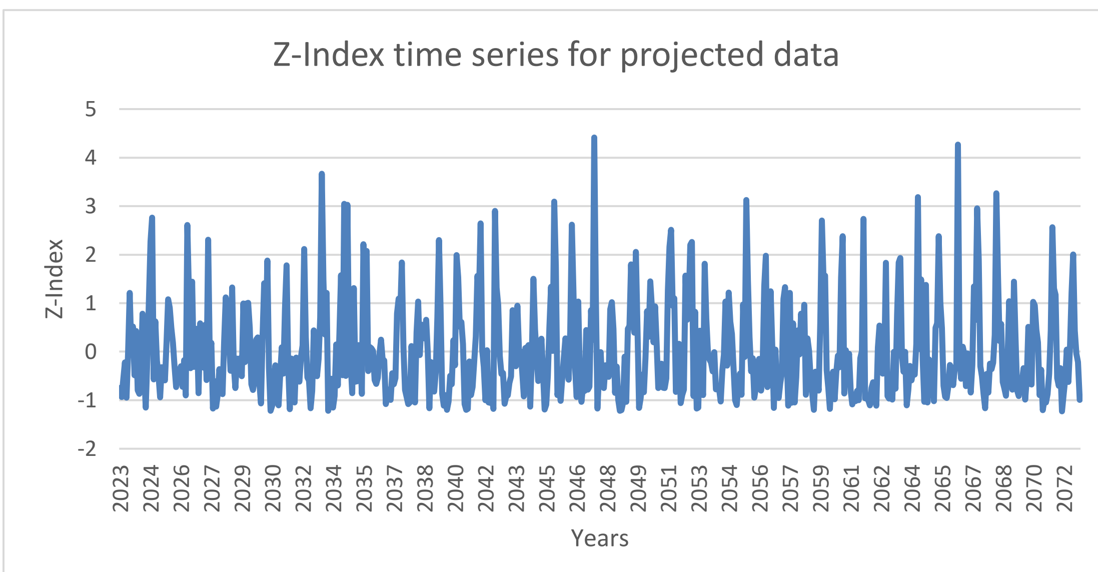


Figure 22 Time series of SPI for projected data (2023 – 2072) at hotspot

4.15 Technical DRR measures for the identified vulnerable hotspot.

Drought is a recurring natural disaster in Pakistan, particularly in regions like Balochistan. Implementing effective disaster risk reduction measures for drought requires a multi-prolong approach involving various stakeholders such as government agencies, non-governmental organizations, local communities, and international partners.

Technical disaster risk reduction measures for drought, involve a combination of technological solutions and infrastructure development aiming at mitigation the impacts of drought. Here are some technical measures:

1. **Rehabilitation and expansion of Karez system:** Restore and rehabilitate Karez systems, which are vital for water supply in balochistan as well as in ziarat district for centuries, which supports local communities in maintaining and expanding these systems to improve water access and reduces vulnerability to drought (Khan A. &., 2020).
2. **Groundwater Recharge and construction of small dams:** Enhance groundwater recharge by constructing check dams, small dams in key locations to capture rainwater, promote ground water recharge, and rehabilitating traditional systems like Karez to increase water availability during droughts (Khan A. &., 2020) (Sarfraz, 2019).
3. **Water conservation and harvesting:** promote water-efficient technologies and like drip irrigation and mulching. Install rainwater harvesting systems to capture and store water for dry periods (Qureshi, 2019).
4. **Watershed Management and Reforestation:** implement watershed management to improve groundwater recharge and prevent soil erosion, reforestation in upstream areas can increase water retention and reduce rapid runoff (Sharma, 2019).
5. **Agroforestry and Forest Management:** Expand agroforestry practices and promote the plantation of drought resistant trees in Ziarat’s juniper forests to enhance water retention, reduce soil erosion, and improve microclimates. Promote

existing juniper forests from deforestation, which is critical to local ecosystem (Shinwari, 2018).

6. **Water Harvesting and Tankas:** Encourage the construction of tankas (underground water storage systems) in rural households and public spaces to capture and store rainwater. These systems are cost effective and provide communities with water during dry spells (Baloch, 2021) .
7. **Sustainable grazing management and rangeland restoration:** introduce sustainable grazing practices, such as rotational grazing, to prevent overgrazing and preserve rangelands in drought-prone aras. Restoring degraded rangelands with native grasses and shrub will improve soil moisture retention (Niamir-Fuller, 2016).
8. **Rainwater harvesting through terracing and contour farming:** implementing contour farming and terracing in sloped areas to capture rainwater, reduce runoff and enhance soil moisture retention, especially in the hilly terrain of Ziarat (Lal, 2018).
9. **Awareness and education campaigns on water conservation:** Run educational campaigns to raise awareness among local communities about the importance of water conservation and drought preparedness. This can include training on efficient water usage, irrigation methods, and resource management (Agrawal, 2020).

By adopting these DRR measures, communities in Ziarat District can improve their resilience to drought. These strategies emphasize the importance of utilizing indigenous knowledge systems like Karez, while integrating modern technologies with careful planning, capacity building, and sustainable water management, drought risks can be reduced, ensuring better water security for both people and the environment in this drought-prone region.

4.15.1 Technical DDR measures for hotspot as well as for all Pakistan.

Some of DRR measures for droughts are mentioned below for Pakistan as well as for hotspot:

1. **Community based disaster risk management:** Engage local communities in disaster risk reduction by partnering with community-based organizations and using participatory approaches. This includes raising awareness about drought risks, organizing training sessions on drought preparedness and response, and supporting community-led initiatives such as water management committees and drought contingency planning. (Shaw, 2010).
2. **Drought Monitoring and Early Warning Systems:** Develop and improve drought monitoring and early warning systems across national, regional, and local levels. This involves combining meteorological data, hydrological indicators, and satellite imagery into integrated monitoring frameworks to detect early signs of drought and provide timely warnings to at-risk communities. (Wilhite D. A., 2014).
3. **Early warning system:** Establishing and improving early warning systems for drought is essential. This includes monitoring meteorological data, groundwater levels, soil moisture, and crop conditions to anticipate drought conditions in advance. Timely warnings can empower communities and authorities to take proactive measures. (Pulwarty, 2014).
4. **Remote Sensing and GIS:** utilize remote sensing technologies and geographic information system (GIS) for monitoring and assessing drought conditions. Remote sensing data can provide valuable information on water availability, soil moisture levels, vegetation health, enabling authorities to identify drought-prone areas and plan targeted intervention (Ahmad, 2018).
5. **Satellite based Rainfall Forecasting:** Implement satellite-based rainfall forecasting systems to enhance the accuracy of drought predictions. Satellite data can forecast rainfall patterns and identify potential drought hotspots, enabling early preparedness and response measures (Prasad, 2007).

6. **Water Management Technologies:** Implement water management technologies, such as drip irrigation, sprinkler systems, and laser land leveling, to optimize water use efficiency in agriculture. These technologies aid in conserving water resources and reducing the impact of drought on crop yields (Kang, 2009).
7. **Spring Protection and Rehabilitation:** Protect and rehabilitate natural springs by restoring catchment areas, increasing water availability during drought periods (Shah, 2021).
8. **Desalination and water recycling:** Investigate desalination and water recycling technologies to increase freshwater supplies in drought-prone areas. Desalination plants can transform seawater or brackish groundwater into drinkable water, while water recycling systems can treat wastewater for agricultural or industrial purposes, thereby reducing dependence on freshwater sources. (Fritzmann, 2007).
9. **Drought resistant crop varieties and genetic engineering:** Invest in the research and development of drought-resistant crop varieties using genetic engineering. Promote the adoption of these crops through agricultural extension services. Research institutions can develop and distribute improved seeds that are more resilient to water scarcity, while training farmers in sustainable agricultural practices can enhance water use efficiency. (Cattivelli, 2008).
10. **Reservoir management and water storage:** Enhance reservoir management and water storage infrastructure to improve water availability during droughts. This includes building new dams, reservoirs, and storage facilities, as well as upgrading existing infrastructure to increase storage capacity and optimize water flow regulation (Mahmood, 2016).
11. **Cloud seeding and rain enhancement:** Explore cloud seeding and rain enhancement technologies to induce precipitation and alleviate drought conditions. Cloud seeding involves dispersing cloud dispersing cloud seeding agents such as silver iodide or salt particles into the atmosphere to stimulate rainfall, potentially increasing precipitation in water stressed regions (Bruintjes, 1999).
12. **Climate smart infrastructure:** Design and build climate-smart infrastructure that is resilient to drought impacts. This involves creating projects like water supply systems, irrigation networks, and flood control measures that integrate climate

change adaptation principles to endure extreme weather events, including droughts. (Neumann, 2015).

13. **Capacity building and technology transfer:** Strengthen local capacity and support technology transfer through training programs, knowledge exchange initiatives, and partnerships with research institutions and technology providers. Equipping local communities with the skills and tools necessary to implement technical drought risk reduction measures will enhance their resilience and adaptive capacity (Anderson, 1989).
14. **Water resource management:** Implementing sustainable water resource management practices is crucial. This includes constructing small-scale water reservoirs, establishing rainwater harvesting systems, and adopting water conservation measures. Effective management of rivers, canals, and aquifers is also vital to ensure water availability during droughts (Gleick, 2003).
15. **Policy and institutional frameworks:** Enhance policy and institutional frameworks for drought risk reduction at national, provincial, and local levels. This involves creating comprehensive drought management plans, allocating adequate budgetary resources, and establishing coordination mechanisms among government departments, NGOs, and international agencies (Sowers, 2011).
16. **Livestock management:** provide support and training to livestock farmers for better management practices during droughts. This may include livestock vaccination programs, supplementary feeding, and establishing feed banks to ensure the availability of fodder during dry spells (Thornton, 2009).
17. **Diversification of livelihoods:** encourage diversification of livelihoods to reduce dependency on rainfed agriculture. This could involve promoting alternative income generating activities such as small-scale businesses, agroforestry, and eco-tourism (Ellis, 2000).
18. **Climate change adaptation:** Integrate drought risk reduction measures into broader climate change adaptation strategies. This involves identifying climate resilient infrastructure projects, mainstreaming climate smart agriculture practices, and enhancing ecosystem resilience to mitigate the impacts of droughts exacerbated by climate change (Adger, 2005).

19. **International Cooperation:** foster collaboration with international organizations and donor agencies to access technical expertise, financial assistance, and best practices in drought risk reduction. Engaging in regional initiatives and sharing knowledge with neighboring countries facing similar challenges can also enhance collective resilience to drought (Young, 2002).

By implementing these disaster risk reduction measures for drought in hotspot and Pakistan requires collaborative efforts among government research institutions, private sector stakeholders, and development agencies. By leveraging technological innovations and investing in resilient infrastructure, can effectively mitigate the impacts of drought and build climate resilience for the future. And Pakistan can enhance its resilience to droughts and minimize the socio-economic and environmental impacts on vulnerable communities.

4.16 Discussion

The analysis of drought indices in this study provides valuable insights into their performance across different time periods and regions within Pakistan. Historical drought events, such as those from 1987 – 1988 and 1999 – 2002, served as benchmarks for evaluating the reliability of indices like SPI, SPEI, and Z-Index. These indices consistently outperformed others, such as PDSI and PNPI, which exhibited higher error margins, particularly in arid regions. SPI's strength in capturing precipitation-driven droughts, SPEI's sensitivity to both precipitation and evapotranspiration, and Z-Index's ability to detect climate anomalies made them the most effective tools for tracking and forecasting droughts. The uniform scale used for evaluating performance enhanced the comparability of these indices, providing a clearer understanding of their strengths and limitations.

The findings also underscore the need to select appropriate drought indices based on the climatic characteristics of the study area. While SPI, SPEI, and Z-Index performed well in Pakistan's diverse climate, indices like PDSI, which depend heavily on soil moisture data, were less reliable in areas with limited soil moisture information. Additionally, the Percent of Normal Precipitation Index (PNPI) struggled to account for the complex interaction between precipitation and temperature, leading to lower performance in multi-dimensional drought scenarios. These differences highlight the importance of tailoring the choice of indices to specific regional and climatic conditions.

Future projections under the RCP 8.5 scenario, which predict more frequent and severe droughts, further emphasize the need for accurate drought monitoring tools. The identification of Gogai, in Ziarat district, as a drought hotspot demonstrates the necessity of proactive disaster risk reduction (DRR) strategies in vulnerable regions. With the expected rise in drought severity, the study's findings suggest that SPI, SPEI, and Z-Index are best suited for future drought monitoring and forecasting in Pakistan. Integrating these indices into early warning systems and policy frameworks can significantly enhance preparedness and resilience, particularly in drought-prone areas. The discussion reinforces the need for ongoing refinement of drought indices to address the increasing complexities of climate change impacts.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This research provides a comprehensive analysis of drought conditions in Pakistan, highlighting the significant impacts of climatic variability on drought severity. Historical droughts, such as those from 1987 – 1988 and 1999 – 2002, demonstrate the varying effectiveness of drought indices, with SPI, SPEI, and Z-Index consistently proving the most reliable. Through key statistical measures like MBE, MAE, CC, and NSE, these indices showed strong accuracy in capturing drought patterns, both historically and in future projections.

Under the RCP 8.5 climate scenario, projections forecast a trend toward more severe droughts, particularly over longer return periods, indicating increasing challenges in managing future drought events. The study identifies Gogai, district Ziarat, as a critical hotspot, where drought conditions are expected to intensify, emphasizing the urgent need for targeted interventions in this region. The use of reliable indices in such areas is essential for accurate monitoring and mitigation planning.

The results underscore the importance of selecting appropriate drought indices, such as SPI, SPEI, and Z-Index, for accurate drought assessment and forecasting. These findings not only inform future disaster risk reduction strategies but also highlight the need for proactive policy development to enhance resilience in vulnerable regions. Accurate drought forecasting, supported by reliable indices, is key to minimizing the impact of future climate variability on Pakistan's drought-prone areas.

5.2 Key Findings

1. SPEI and Z-Index are identified as a best drought indices (along with SPI) to monitor droughts in the study area.

2. All 10 drought indices detected Punjab province as its faced drought conditions.

3. Based on 2 selected drought, Ziarat district was Identified as a highly vulnerable area to drought across Pakistan.

4. Projected 2030 – 2031, 2036 – 2037, 2040 – 2042, 2061 – 2063, and 2069 – 2070 as highly vulnerable years to experience extreme severe droughts.

5.3 Recommendations

1. It is recommended to conduct more research studies related to drought indices, considering other types of droughts (agricultural and hydrological droughts) as well.
2. It is recommended to conduct further research studies on droughts in Punjab province as maximum research's focuses on the Sindh and balochistan as a study area, while in finds Punjab is also identified as vulnerable area to drought.
3. It is recommended to conduct research studies related to forecasting of droughts based on drought indices over Pakistan.
4. Invest in advanced statistical and machine learning techniques, alongside expanding data collection, will provide valuable insights into drought patterns and impacts.
5. There is a need to develop and implement drought related policies.
6. It is recommended to increase public awareness on drought preparedness and response.
7. There is need to shifting from a reactive to a proactive approach in drought management. Implementing and reinforcing early warning systems which can offer timely alerts, allowing communities to take preventive actions before drought conditions worsen.

8. k

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