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SPATIOTEMPORAL ANALYSIS OF DROUGHT SEVERITY AND PRECIPITATION VARIABILITY IN PUNJAB'S POTHOHAR PLATEAU USING PDSI AND SPEI

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Abstract

The study investigates drought variability in the Pothohar Plateau region of Pakistan from 1983 to 2022, focusing on the Standardized Precipitation-Evapotranspiration Index (SPEI) and the Palmer Drought Severity Index (PDSI). The region, Pothohar Plateau Pothohar Zone lies from about 32.5˚N to 34.0˚N Latitude and from about 72˚E to 74˚E Longitude with area 22254 km^2, with a total area of 4% irrigated and 96% rainfed agriculture. It includes Rawalpindi, Chakwal, Attock, and Jhelum, with a semiarid to, humid. The study examines drought patterns and impacts on Pakistan's Pothohar Plateau region, focusing on the Standardized Precipitation-Evapotranspiration Index (SPEI) and Palmer Drought Severity Index (PDSI) from 1983 to 2022. The drought susceptibility map showed northern Rawalpindi and parts of Attock as highly susceptible, with Attock experiencing significant droughts including a mild drought in 1985-1986 (-1.147) and severe droughts from 1999-2000. Chakwal faced severe droughts in 1987-1988, 1999 (-1.504), and 2002 (-1.641), while Jhelum recorded severe droughts in 1999 (-1.488), 2002, and July 2012, highlighting increased drought frequency and variability across the Pothohar Plateau. Rawalpindi's SPEI12 data from 1980 to 2005 showed alternating wet and drought periods, with severe drought in 2000 (-1.436) and very wet conditions in 1983 (+1.982) and 2004 (+1.549), impacting agriculture and water resources. The PDSI data for Attock district from 1980 to 2022 showed significant variability, including drought from 1980 to 1983, severe drought in the early 2000s (PDSI below -3.0), and wet conditions in 2015-2016, with fluctuating conditions extending into the 2020s. Chakwal's PDSI data indicated severe drought in September 1985 (-3.063), with wet conditions peaking in December 1990 (4.3285) and October 2015 (6.3411), followed by a shift to drier conditions in August 2000 (-3.3574). Jhelum district experienced severe drought in 1985 (-3.4213) and a notable dry shift in 1999 (-2.605), with extreme fluctuations observed from 2000 to 2007, highlighting the region's drought sensitivity. Rawalpindi's PDSI data revealed extreme wet conditions in 1981, followed by severe drought from 1999 to 2001, with low values during this period, reflecting notable climatic extremes in the region. Overall, the PDSI data across all districts from 1980 to 2022 illustrated a pattern of alternating wet and dry conditions, emphasizing the need for effective drought management strategies to mitigate agricultural impacts. The study identified increasing drought frequency and severity in the Pothohar Plateau from 1983 to 2022, particularly affecting Chakwal and Attock districts,

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with significant implications for agriculture and water resources. It emphasized the need for effective drought mitigation strategies, including drought-resilient crops, improved water management, and community awareness programs, alongside ongoing research to address climate change impacts on drought patterns.

Keywords: Drought Variability, Pothohar Plateau, SPEI (Standardized Precipitation-Evapotranspiration Index), PDSI (Palmer Drought Severity Index), Agriculture, Water Resources, Climate Change, Drought Mitigation Strategies.

1. INTRODUCTION

Climate change, a global phenomenon, has significantly increased global surface temperature since 1861, affecting developing countries, as reported by the Intergovernmental Panel on Climate Change (IPCC). *(IPCC 2019).* The productivity of agriculture is greatly impacted by climatic factors like temperature and precipitation. Food production has been impacted by climate change in emerging nations in Asia and Africa. *(Kurukulasuriya et al. 2006; Mendelsohn 2014).* By 2050, production of wheat in South Asia is expected to fall by 50%, or around 7% of all grain production worldwide *(Ali et al. 2017).* Thus, sustainable agriculture and food security are seriously threatened by climate change.

Stochastic droughts have severe impacts on the environment and human culture, making them one of the most expensive natural disasters globally. The annual economic losses caused by drought are estimated to be between 6 and 8 billion US dollars, significantly higher than other weather-related calamities. The growth of populations and the development of agricultural, energy, and industrial sectors has increased the demand for water resources, leading to water shortages nearly yearly in many parts of the world *(Wilhite, 2000; Mishra and Singh, 2010; Sternberg, 2011; Zargar et al., 2011; Wilhite, 2016; Zhang et al., 2018)*. The frequency and intensity of extreme weather events are predicted to increase due to climatic extremes. The seventeen Sustainable Development Goals (SDGs) were established in 2015, with 17 objectives and 169 targets. Droughts worsen ecological crises, poverty, and water pollution, and pose a threat to food security. To thrive sustainably in a changing climate, it is crucial to learn more about droughts and improve human response to them *(Battisti and Naylor, 2009; Li et al., 2015; He et al., 2017; Pradhan et al., 2017; Hu et al., 2018).*

The initial step towards human adaptation and controlling drought hazards involves monitoring droughts. Several indices are available for tracking droughts, with satellite imagery and remote sensing data being the main sources. The Standardized Precipitation Index (SPI) was used in the early creation of drought indexes *(McKee et al., 1993; Zargar et al., 2011; Sun et al., 2017a)*. The Reconnaissance Drought Index (RDI) and the Standardized Precipitation Evapotranspiration Index (SPEI) are two drought monitoring tools that incorporate hydrological and meteorological factors, respectively, to better account for temperature fluctuations and incorporate evapotranspiration into drought monitoring procedures *(Tsakiris et al. 2007; Vicente-Serrano et al. 2010)*. Palmer's 1965 PDSI, based on water balance theory, considers runoff, soil moisture, precipitation, and

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potential ET. This physical basis allows for long-term drought tracking, making it a crucial tool in drought monitoring practices *(Dai et al., 2004; Dai, 2011a, 2011b, 2013; Sheffield and Wood, 2008; Sheffield et al., 2012)*.

Drought risks are expected to increase as global temperatures rise, with amplified droughts. Studies show that the warming climate is causing droughts to become more severe and affect a larger area. Penman-Monteith and Thornthwaite algorithms have been shown to impact drought monitoring results, but Dai (2011b) found little impact. The performance of PDSI and SPEI in monitoring real-world droughts is still debated, with the choice being a topic of debate. Despite these differences, the effectiveness of these methods in monitoring droughts remains a topic of debate. (*Sheffield and Wood, 2008; Briffa et al., 2009; Cai et al., 2009; Wang et al., 2010; Dai, 2011a, b; Vicente-Serrano et al., 2011; Zhang et al. 2016; Sheffield et al., 2012).* The study suggests that the Palmer Drought Severity Index (PDSI), a drought index derived from the water balance equation's supply-and-demand theory, overestimates drought severity in a warming climate. This suggests that the proper drought index is crucial for human adaptation and monitoring drought episodes. PDSI can accurately indicate water deficit/surplus situations than the standardized precipitation evapotranspiration index. The study aims to enhance PDSI, or the modified Palmer Drought Severity Index (MPDSI), by addressing the limitations of traditional drought indicators and considering irrigation in water balance. *(Palmer, 1965; Vicente-Serrano et al., 2010; Ma et al. 2014)*.

Climate change is believed to cause increased droughts, which are costly, complex, and unpredictable natural disasters, which can significantly impact the economy, particularly the agricultural sector. The length and intensity of droughts have been increasing since the 1970s, and the adverse effects and frequency are predicted to rise. Agriculture is more susceptible to severe droughts than other sectors in developing nations. Studies have assessed the impact of climate change on agriculture at various geographic scales, with China's greatest drought in recent memory damaging over 40 million hectares of its crops in 2000 *(Dilley et al. 2005; Kang et al. 2009; Li et al. 2009; Blunden et al. 2011; Walthall et al., 2013; Yu et al. 2014; Troy et al. 2015; Paull et al. 2017).* Droughts cause crop damage, revenue loss, and losses in annual or perennial crops. Certain crops, like cotton and sorghum, require less water, leading to a higher likelihood of agricultural drought. Severe droughts can significantly lower agricultural output, causing an imbalance in grain supply and demand, impacting global food security. To reduce drought effects, it is crucial to increase knowledge and predict the impact of droughts on agriculture. This will help reduce the impact of droughts on global food security *(Li et al. 2009; Hayes et al. 2012; Gurian-Sherman 2012; Kogan et al. 2013; Safdar et al., 2023).*

Pakistan is mostly situated in arid to hyper-arid areas, which are marked by high temperatures, little precipitation, and frequent droughts *(Rahman et al. 2021).* Most people are rural dwellers, and their main source of income is agriculture. Pakistan's economy is mostly reliant on the agricultural sector *(Kazmi et al. 2015).* Approximately 43% of the labor force is employed in this industry, which generates 24% of the nation's

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GDP. Pakistan's reliance on agriculture has made it very susceptible to droughts brought on by climate change. In Pakistan, droughts have occurred once every three years during the past 55 years *(Miyan 2015).* There have been severe droughts in Pakistan in Punjab province in 1899, 1920, and 1935, and in Khyber Pakhtunkhwa in 1902 and 1951. Due to their hyper-arid to arid environments, Pakistan's Baluchistan and Sindh provinces have seen severe drought episodes *(Ashraf et al. 2015).* The Standardized Precipitation Evapotranspiration Index (SPEI) was used to calculate the drought, and the results showed that from 1902 to 2015, there were considerably more negative (severe) drought occurrences in Baluchistan *(Jamro et al. 2020).* There were severe droughts in Baluchistan and Sindh in 1871, 1881, 1899, 1931, 1947, and 1999 *(Rahman et al. 2021).* Seldom has research from 1997 to 2003 mentioned the severe drought *(Ahmed et al. 2016).* In the provinces of Sindh and Baluchistan, drought is a common occurrence. In 1998–2002, Pakistan went through a protracted national drought that was the worst in the country's history *(Adnan and Ullah 2020; Shahid and Rahman 2021)*.

Rainfall and river flow decreased during this dry episode, and the water level in the main reservoir at Tarbela Dam neared zero. During dry years, the province of Baluchistan had a 60–73% decrease in winter rainfall *(Khan et al. 2020).* In a similar vein, from 1999 and 2000, the province of Sindh had a 30% drop in rainfall; this drought episode affected around 3.3 million people *(Adnan and Ullah 2020)*. Pakistan's farming industry, heavily reliant on Indus River water supplies, has been severely impacted by droughts, resulting in a decline in growth for important crops and a negative 2.6% growth in agriculture from 2000-2001. The non-agricultural sectors also suffered, and the government has implemented a relief strategy to address the situation *(Ahmad et al. (2004).* Droughts are classified into four types: hydrological, meteorological, agricultural, and socio-economic. Hydrological droughts result from decreased precipitation and surface water, meteorological droughts from precipitation deficiencies, and agricultural droughts from decreased soil moisture conditions *(Dai 2013).* The intensity of Pakistan's droughts was evaluated by several research *(Adnan et al. 2017, 2018; Haroon et al. 2016).*

The study focuses on the SPEI and PDSI drought indices for the Pothohar Plateau region from 1983 to 2022, including Rawalpindi, Chakwal, Attock, and Jhelum. The hypotheses suggest that the SPEI and PDSI indices effectively capture drought variability in the region. There will be significant differences in drought severity across the regions, impacting agricultural productivity. Seasonal droughts will have varying impacts on crop production, with different crops affecting different crops based on their water requirements and sensitivity to drought. Irrigation practices will vary across different districts, with regional differences in how drought affects strategies and water usage. Comparative analysis of drought severity using these indices will reveal distinct patterns of drought impact, providing insights into localized drought effects and guiding the development of targeted mitigation strategies. These hypotheses aim to provide insights into the relationship between the SPEI and PDSI indices and their impact on agriculture and irrigation in the Pothohar Plateau.

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2. MATERIALS AND METHODOLOGY

2.1 Study Area:

In Punjab, there are two rainfall-dependent regions i.e., the Thal desert region and the Pothohar region. In the Thal desert region, mostly chickpea crops are being cultivated. Therefore, we are taking the Pothohar plateau as our study area to check the drought impacts on crop production. Pothohar Zone lies from about 32.5˚N to 34.0˚N Latitude and from about 72˚E to 74˚E Longitude. The Pothohar Plateau is situated in the Northern part of Punjab with an elevation ranging from 350 m to 575 m above mean sea level. It includes Chakwal, Jhelum, Attock, Rawalpindi, districts and is sandwiched between Jhelum and Indus rivers. The climate varies from semiarid to humid due to topography and seasonal variations in rainfall patterns. The total area of the plateau is 22254 km^2, with 4% irrigated and 96% dependent on rainfed agriculture. The crops grown in the area include wheat, maize, barley, bajra, gram, and ground nut. With an average annual rainfall of 380-500 mm and maximum temperatures of up to 47 °C with more than 3000 hours of sunshine annually, the area is susceptible to brief droughts.

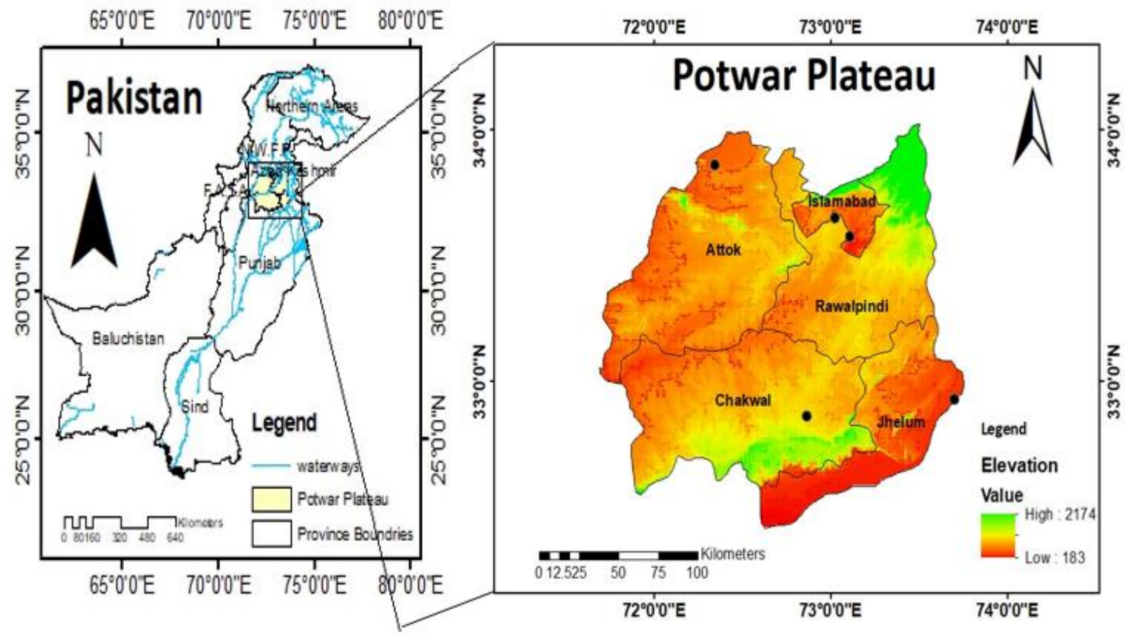

Figure 1: Study Area Elevation Map of the Pothohar Region

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2.2 Data Acquisition:

Table 1: Data Acquisition, Specifications, Duration, and Sources

Datasets	Specifications	Duration	Sources
SPEI base: Standardized Precipitation-Evapotranspiration Index	Resolution 55660 meters The Standardized Precipitation-Evapotranspiration Index (SPEI) is a global tool used to measure precipitation and evapotranspiration data over the past 12 months, based on FAO-56 Penman-Monteith estimations. The Global SPEI database provides comprehensive data on global drought conditions, with a 0.5-degree pixel size and monthly cadence, covering time scales from 1 to 48 months.	1980-2022	*(Beguería et al., 2023) (Serrano et al., 2010)*
PDSI: Palmer Drought Severity Index	Terra Climate uses a water balance model to produce monthly surface water balance datasets, including reference evapotranspiration, precipitation, temperature, and interpolated plant extractable soil water capacity, using a modified Thornthwaite-Mather model and extractable soil water storage capacity data. *Wang-Erlandsson et al. (2016).*	1980-2023	*(Abatzoglou et al., 2018)*

2.3 Google Earth Engine for Computing SPEI:

- **Data Preparation and Import**: The analysis begins by importing the SPEI (Standardized Precipitation Evapotranspiration Index) dataset from the Earth Engine repository, specifically the "CSIC/SPEI/2_9" collection, which includes SPEI data with a 12-month time scale. The dataset spans from 1980 to 2023. The relevant images are selected from this collection.
- **Defining the Study Area**: The region of interest is specified using a variable named geometry, which represents the spatial boundaries for which the drought analysis will be conducted.
- **Visualization of SPEI Data**: To visualize the SPEI data, a time series chart is created. This chart shows the mean SPEI values over time for the defined geometry. The chart uses a 55,000-meter scale to aggregate data and is displayed using the Earth Engine UI.
- **Calculation of Mean SPEI Values**: Each image in the SPEI collection is processed to calculate the mean SPEI value over the defined geometry. This is achieved using the reduce Region function with the mean reducer. The calculated mean value is then stored as a property in each image, which is useful for further analysis.
- **Classification of SPEI Values**: The mean SPEI values are classified into different drought categories. The classification is done based on the following thresholds:

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Table 2: SPEI Classification

SPEI Range	Drought/Wet Condition
SPEI > 2	Extremely Wet
1.5 ≤ SPEI < 2	Very Wet
1 ≤ SPEI < 1.5	Moderately Wet
-1 ≤ SPEI < 1	Near Normal
-1.5 ≤ SPEI < -1	Moderate Drought
-2 ≤ SPEI < -1.5	Severe Drought
SPEI < -2	Extreme Drought

This classification is applied to each image, and the drought class is stored as a property.

- **Renaming and Final Processing**: Each image in the collection is renamed based on its drought classification, making it easier to identify the drought status in the dataset. The images are also copied with their properties intact for consistency in the analysis.
- **Visualization of Drought Classes**: Finally, a scatter chart is generated to visualize the drought classifications over time. This chart illustrates the frequency and distribution of different drought classes within the defined geometry, using a 55,000-meter scale. The scatter chart is set to display with point sizes of 3 for clarity.

This methodology outlines the steps to preprocess, analyze, and visualize drought data using the SPEI dataset, providing insights into drought conditions and trends over time.

2.4 Google Earth Engine for Computing PDSI:

To assess drought conditions over the study area, we implemented the following methodology using Google Earth Engine: This methodology outlines the steps to preprocess, analyze, and visualize drought data using the PDSI dataset, providing insights into drought conditions, severity and trends over time.

Table 3: PDSI Classification

PDSI Range	Drought/Wet Condition
PDSI ≥ 4	Extremely Wet
3 ≤ PDSI < 4	Very Wet
2 ≤ PDSI < 3	Moderately Wet
1 ≤ PDSI < 2	Slightly Wet
0.5 ≤ PDSI < 1	Incipient Wet Spell
-0.5 ≤ PDSI < 0.5	Near Normal
-1 ≤ PDSI < -0.5	Incipient Dry Spell
-2 ≤ PDSI < -1	Mild Drought
-3 ≤ PDSI < -2	Moderate Drought
-4 ≤ PDSI < -3	Severe Drought
PDSI < -4	Extreme Drought

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- **Define Region of Interest (ROI):** The analysis begins by specifying the region of interest (ROI) using a predefined table or shape file that outlines the geographical area for which the drought analysis will be conducted.
- **Load and Filter Terra Climate Data:** We utilized the Terra Climate dataset, specifically focusing on Potential Evapotranspiration (PET) as a critical input for drought assessment. The dataset was filtered to include data from January 1, 1983, to December 31, 2023, and restricted to the bounds of the defined ROI. This dataset provides monthly PET values essential for understanding moisture deficits.
- **Scale PET Data:** To ensure compatibility with further calculations, the PET values were scaled. This step involved multiplying each PET value by 0.1 to adjust the data units, followed by setting the 'system property for time series analysis.
- **Calculate Drought Index:** A placeholder function was used to calculate a drought index, termed as 'drought index,' for demonstration purposes. This function currently performs a basic transformation of PET values by multiplying them by -1 to create a simplified index. In practice, a more sophisticated formula incorporating both PET and precipitation data would be employed to calculate the PDSI accurately. This step is crucial as PDSI calculations require specific formulas and additional datasets, which are not covered in this example.
- **Generate Time Series Chart:** We created a time series chart of the drought index for the ROI to visualize the temporal variation in drought conditions. The chart was generated using the ui.Chart.image.series function, plotting the mean values of the drought index over time. The chart's x-axis represents the date, while the y-axis displays the drought index values, providing a visual representation of drought trends.
- **Export Time Series Data:** Finally, the time series data of the drought index was exported as a CSV file for further analysis. This involved calculating the mean drought index values for the ROI and formatting the data with corresponding dates. The CSV file was then exported to Google Drive for accessibility and detailed examination.

3. RESULTS AND DISCUSSIONS

3.1 Spatial Distribution of Drought in Pothohar Plateau

The map you provided illustrates the spatial distribution of drought susceptibility in the Pothohar Plateau, covering the districts of Attock, Rawalpindi, Chakwal, and Jhelum. The color-coding represents varying degrees of susceptibility to drought, categorized into five levels:

1. Highly Susceptible Areas (marked in red): These regions are the most vulnerable to drought, with a higher frequency and intensity of dry periods. They are located mainly in the northern parts of Rawalpindi district and scattered sections of Attock.

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2. Medium Susceptible Areas (marked in orange): These areas experience moderate drought susceptibility. They are spread across central Attock and some areas of Rawalpindi and Jhelum.
3. Susceptible Areas (marked in light green): These regions are moderately affected by droughts but less than the previous categories. A large portion of Chakwal and Jhelum is covered by this classification.
4. Low Susceptible Areas (marked in green): These zones are less prone to drought conditions. Much of Chakwal and parts of Attock fall into this category, indicating relatively lower drought risks.
5. Least Susceptible Areas (marked in dark green): These areas are the least affected by droughts, experiencing more consistent rainfall. They are primarily located in western Chakwal and southern Attock.

Northern Rawalpindi and parts of Attock are more vulnerable to droughts, likely due to their geographical location and climatic conditions. Chakwal and Jhelum show a mix of low to moderate susceptibility, likely due to better water retention and higher rainfall. Drought susceptibility decreases from north to south, with southern Chakwal and Attock showing the least vulnerability as reported by (Khan et al., 2020). This spatial distribution suggests that targeted water management and drought mitigation strategies should prioritize highly and medium-susceptible areas in the northern and central parts of the Pothohar region as shown in **Figure (2).**

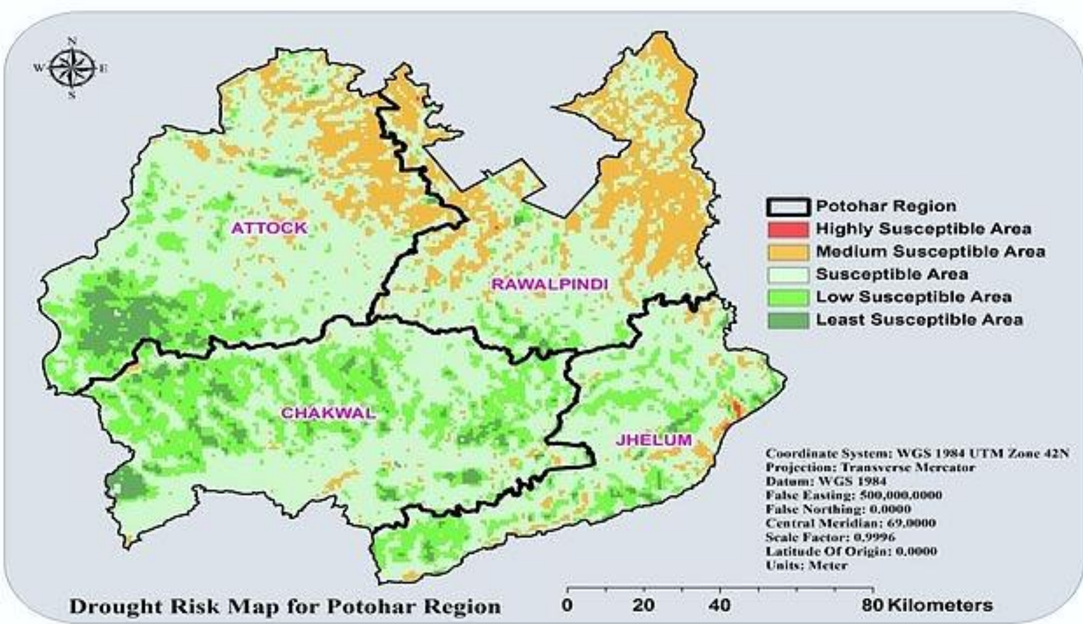

Figure 2: Drought Risk Map for Pothohar Plateau

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3.2 Temporal Distribution of Drought in Pothohar Plateau Using Standardized Precipitation Evapotranspiration Index (SPEI):

3.2.1 SPEI in Attock District:

The Standardized Precipitation Evapotranspiration Index (SPEI12) is a tool used to assess long-term droughts in the Attock district, Pakistan. It measures the balance between precipitation and potential evapotranspiration over a 12-month period. The index shows periodic shifts between drought and non-drought conditions, with significant dips in the early 1980s and 2000s, normal drought conditions in the 1990s and mid-2010s, and mixed conditions from 2015 onwards. The Attock District experienced three dry periods from 1985-1986: a moderately dry period with mild drought, a prolonged drought from 1987-1988, and a severe drought from 1999-2000. The 1985-1986 drought was marked by a low recorded value of -1.147, indicating a mild drought. The 1987-1988 drought was prolonged, characterized by significant lack of rainfall or increased evapotranspiration. The 1999-2000 drought was the most severe, with SPEI12 values consistently below -1, affecting agriculture, water resources, and livelihoods. Long-term drought periods, particularly between 1985-1986, 1987-1988, and 1999-2000, have significant impacts on agricultural productivity and water availability. These droughts likely stressed crops, affected groundwater recharge, and limited water for irrigation and drinking. The 1987-1988 drought lasted nearly two years, with continuous water deficits. The 1999-2000 drought was particularly intense, lasting over a year with substantial water shortages. These droughts likely reduced crop yields, especially for water-sensitive crops like wheat, and farmers struggled to maintain water supply for irrigation, resulting in reduced agricultural productivity. The late 2010s to early 2020s saw intermittent mild drought conditions, reflecting increasing climate variability influenced by global warming and regional climate changes. Attock, Pakistan, is facing periodic water stress events due to regional rainfall patterns and evapotranspiration rates. Droughts have significantly impacted water resources, agriculture, and livelihoods in Attock, as the district's economy relies heavily on precipitation for irrigation. Drought periods likely reduce crop yields, especially for staple crops like wheat and maize. The increasing frequency of mild to moderate droughts in recent years underscores the urgent need for drought mitigation strategies and sustainable water management practices in the face of climate change. *(Farooqi, et al., 2021; Ashraf et al., 2022).*

The moderate drought conditions in the late 1990s and early 2000s (e.g., 2001-2002 drought) correlate with significant water shortages in Pakistan, as this period marked one of the worst droughts in the country's history, affecting agriculture and water resources, particularly in Punjab, where Attock is located. The late 2010s to early 2020s again show intermittent mild drought conditions, reflecting the increasing climate variability influenced by global warming and regional climate changes. Attock, Pakistan, is facing periodic water stress events due to regional rainfall patterns and evapotranspiration rates. The early 2000s droughts were attributed to El Niño events and regional precipitation deficits, impacting Pakistan's agriculture-dependent economy. The 21st century's increase in

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drought conditions is linked to the amplification of extreme climate events due to rising global temperatures, which accelerate evapotranspiration and reduce water availability. The drying trend in recent decades reflects larger climate change impacts on semi-arid regions like Punjab, where Attock is located. Droughts have significantly impacted water resources, agriculture, and livelihoods in Attock, as the district's economy relies heavily on precipitation for irrigation. Drought periods likely reduce crop yields, especially for staple crops like wheat and maize. The increasing frequency of mild to moderate droughts in recent years underscores the urgent need for drought mitigation strategies and sustainable water management practices in the face of climate change. The Stock District experienced significant droughts from 1983 to 2022, impacting agriculture and water resources. The data from 1985-1986, 1987-1988, and 1999-2000 revealed the intensity and frequency of these droughts, emphasizing the need for monitoring and managing water resources to mitigate future drought impacts. *(IPCC, 2021; Vicente-Serrano, S.M., et al., 2020).*

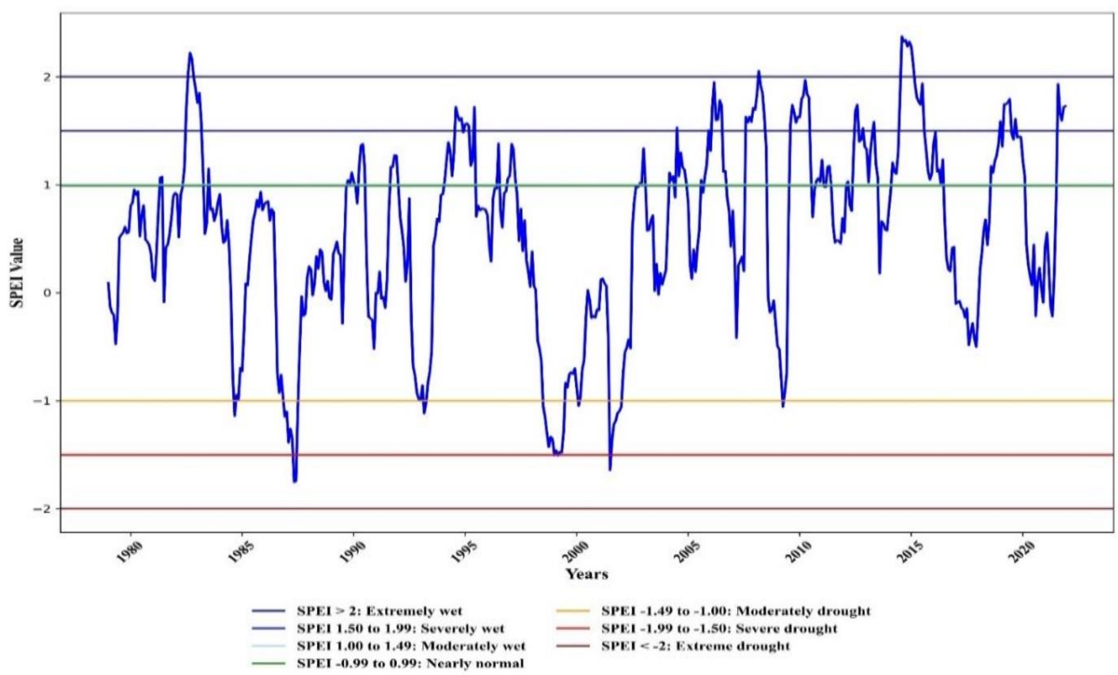

Figure 3: SPEI for Attock District of Pothohar Plateau

3.2.2 SPEI in Chakwal District:

The Standardized Precipitation-Evapotranspiration Index (SPEI12) is a tool used to assess drought intensity and frequency over a 12-month period. It categorizes droughts into mild, moderate, no, and normal. The Chakwal district experienced multiple droughts in the 1980s, with the 1987-1988 period being particularly severe. The 1990s saw near-normal conditions and moderate wet anomalies, but the 1999 drought was significant, reaching -1.504 in January 2000. This drought lasted through much of 1999, indicating the district's susceptibility to periodic dry spells with moderate-to-severe impacts. The

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early 2000s saw severe drought conditions, with January 2000 showing a -1.504 SPEI12, marking one of the most severe drought episodes. In 2002, the SPEI12 values dropped to -1.641, indicating extreme drought conditions. The 2010s saw fewer extreme drought events, but the 2018-2019 drought was notable, affecting agricultural yields and likely indicating moderate-to-severe drought conditions.

The data shows prolonged drought events in Chakwal, including a 1.5-year drought lasting from 1987-1988, with the most severe impact in mid-1988. *(Farooqi, A. et al., 2021; Ashraf, M. et al., 2022).*

The Chakwal District in Pakistan has been severely impacted by droughts, causing reduced agricultural productivity, groundwater depletion, and livestock stress. These droughts have also led to reduced household income and increased migration towards urban centers. Despite these challenges, wet periods like 1983-1984, 1991, and 2003 provided relief by exceeding SPEI12 values, allowing for the recovery of agricultural systems and improved socio-economic conditions. However, the region still faces challenges of over-reliance on single rainfall events and recovery from long-term drought impacts.

The district has experienced frequent droughts, with moderate to extreme intensity lasting several months to over a year. Effective drought mitigation strategies are essential to build resilience in this rain-fed agricultural region. Climate change is influencing this trend, with rising temperatures potentially increasing evapotranspiration rates and exacerbated drought conditions. *(Vicente et al., 2010; Mishra and Singh, 2010; Ahmad, & Choudhary, 2020).*

The drought monitoring chart from 1980 to 2025 reveals varying drought intensity levels, with sporadic occurrences of mild and moderate droughts, especially in the late 1980s, early 2000s, and around 2010. The chart also shows a shift between mild and moderate droughts, which were particularly challenging for water resource management and agriculture during the early 1980s and late 1990s.

The 1990s and mid-2010s showed consistent normal drought phases, indicating stability in water availability. Recent studies align with this pattern, with drought conditions becoming more frequent due to changing climate dynamics. Droughts between 2018-2021 in Pakistan were severe, causing significant economic impacts on agriculture and water resources.

Climate change models predict increased precipitation variability, which could explain the frequent alternation between drought categories. Globally, drought frequency has increased due to rising temperatures and shifting precipitation patterns, particularly in semi-arid regions like Pakistan.

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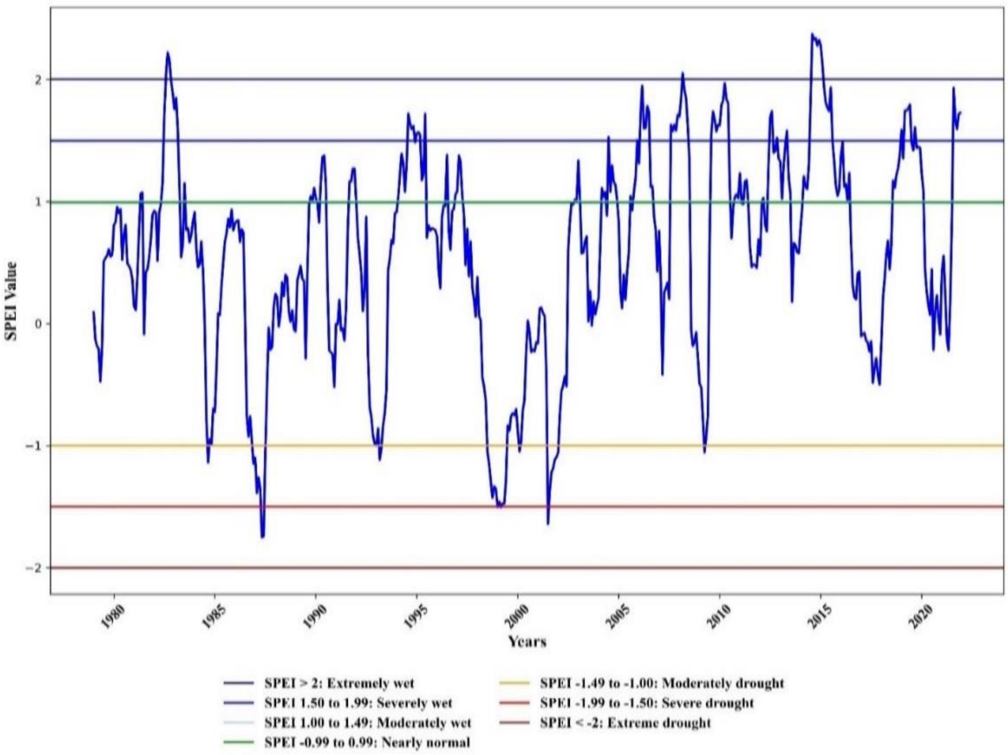

Figure 4: SPEI for Chakwal District of Pothohar Plateau

3.2.3 SPEI in Jhelum District:

To interpret the results of the Standardized Precipitation-Evapotranspiration Index (SPEI12) for Jhelum district from 1983 to 2022, it's essential to assess the data by drought classes, frequency, intensity, duration, and impact. SPEI12 evaluates the 12-month cumulative balance between precipitation and evapotranspiration, offering insights into long-term drought and wet conditions. Here's a breakdown of key factors: The Standardized Precipitation-Evapotranspiration Index (SPEI12) for Jhelum district from 1983 to 2022 is a tool used to assess long-term drought and wet conditions.

The index evaluates the 12-month cumulative balance between precipitation and evapotranspiration, providing insights into drought classes, frequency, intensity, duration, and impact. Drought classes are categorized based on severity, with periods ranging from moderately to severely wet to extremely wet. Significant wet periods include late 1981 to early 1983, 1985-1990, mid-1987 to late 1988, late 1989 to early 1990, 1991-1999, 2000-2010, and 2010-2022.

The district experienced a series of wet years from mid-1991 to 1995, with the SPEI reaching +2.009 in June 1996, indicating very wet conditions. In late 1999, the SPEI dropped sharply to -1.488, indicating a severe drought. From 2000-2002, sustained drought conditions were evident, with severe drought in July 2002, potentially impacting agricultural productivity. By late 2003, conditions improved, with a moderate wet period

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starting in 2004. From 2010-2022, the index showed alternating drought and wet conditions, with severe drought observed in July 2012 and a notable period of moderate droughts from 2018-2021. The Jhelum District has been hit hard by severe droughts, affecting crop yields, soil moisture levels, and agricultural productivity. These droughts have reduced water availability for irrigation, decreased groundwater recharge, and stressed water reservoirs like the Mangla Dam.

The district's SPEI12 data shows distinct drought and wet periods, with drought periods causing severe impacts and wetter periods enhancing productivity. This shift reflects climate variability, with more frequent droughts in the last two decades, likely exacerbated by climate change. To mitigate this, the district should adopt climate-resilient strategies, such as soil moisture conservation techniques, improved irrigation systems, and rainwater harvesting. Additionally, Jhelum may benefit from improved water storage and distribution systems to stabilize agricultural productivity during drought years. Effective water resource management and adaptive agricultural practices are crucial for mitigating future drought effects *(Vicente et al., 2010; Mishra and Singh, 2010; Ahmad, & Choudhary, 2020)*.

The Standardized Precipitation-Evapotranspiration Index (SPEI12) for Jhelum district from 1983 to 2022 provides insights into long-term drought patterns in Pakistan. The index evaluates the 12-month cumulative balance between precipitation and evapotranspiration, incorporating both precipitation and evapotranspiration.

The drought patterns in Pakistan have been characterized by a mix of normal and mild conditions from 1980-1990, with a few mild episodes between 1985-1990 and overall stable conditions between 1985-1990. Drought frequency increased from 1990-2000 due to regional climatic variability, with severe drought episodes occurring from 2000-2010, affecting agricultural areas.

Drought intensity slightly decreased from 2010-2020, with mostly normal and mild drought episodes, indicating a recovery in water availability. From 2020 onwards, the drought pattern remained a mix of normal conditions and mild drought, possibly due to climate change-induced variability in precipitation and temperature.

The graph shows an increasing frequency of drought events since 1990, with the most severe droughts occurring in the early 2000s. Climate change effects, such as rising temperatures intensifying evapotranspiration rates and irregular rainfall patterns, may contribute to long-term drought episodes.

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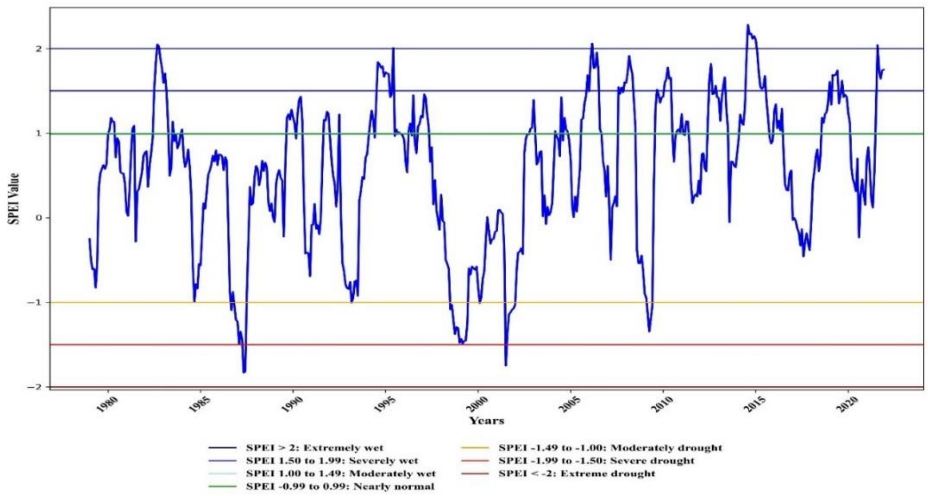

Figure 5: SPEI for Jhelum District of Pothohar Plateau

3.2.4 SPEI in Rawalpindi District:

The Standardized Precipitation Evapotranspiration Index (SPEI) is a crucial metric for assessing drought severity, integrating precipitation and evapotranspiration data over a 12-month period. It is suitable for long-term drought assessments and consists of four periods: 1983-1986, 1985-1988, 1999-2001, and 2002. The data for Rawalpindi district from 1980 to 2005 reveals significant long-term trends in moisture availability and drought conditions. The initial years (1980-1982) saw fluctuation between mild positive values, suggesting normal to slightly wet conditions. The mid-1980s to late-1980s (1983-1988) saw very wet conditions, with values peaking at 1.982 in September 1983. From 1985 onwards, a marked decrease in SPEI12 values was observed, with values dropping into drought territory. The late 1980s to mid-1990s (1988-1995) saw a recovery, with SPEI12 values steadily increasing, indicating wetter conditions, especially during the monsoon months.

The late 1990s drought (1997-2000) marked a transition back to drought conditions, with SPEI12 values declining in 1997 and reaching a peak of -1.436 in May 2000. This phase aligns with known drought years in Pakistan, especially during the 1999-2000 drought, which significantly impacted agricultural productivity. The early 2000s recovery showed a slow recovery, with the index crossing into positive territory by July 2003 and wetter conditions dominating through 2004, culminating in a peak of 1.549 in January 2004. Wetter periods, such as 1981-1983 and 1993-1995, may improve agricultural yields and water resources, contributing to economic stability. Understanding these long-term trends is crucial for policymakers and stakeholders to prepare for future droughts, especially in the face of climate change. The SPEI12 data from 1983 to 2022 highlights the variability of drought and wet conditions in Rawalpindi district. The region has experienced multiple moderate to severe droughts, particularly in the 1980s, late 1990s, and early 2000s, which have had significant impacts on agriculture, water resources, and livelihoods

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Between 1983 and 1986, Rawalpindi experienced Moderate to Very Wet conditions, which were beneficial for agriculture. From 1995 to 1996, the period was Extremely Wet, indicating an abundance of rainfall or low evapotranspiration, which could lead to potential flood risks and water-logged agricultural fields. Long-term droughts, such as those in 1987-1988, 1999-2001, and 2002, likely led to decreased agricultural yields, water shortages, and stress on livestock, particularly cereal crops and wheat. These prolonged dry periods also led to declining groundwater levels and drying up of surface water bodies, exacerbating the water crisis. The Standardized Precipitation Evapotranspiration Index (SPEI) is a multi-scalar drought index used to detect and quantify drought conditions. The data for Rawalpindi district from 1980 to 2005 reveals significant long-term trends in moisture availability and drought conditions. The region's ability to recover after drought periods is evident in the alternation between drought and wet periods. Long-term negative SPEI12 values indicate moisture stress that can affect agriculture, water availability, and ecosystems. *(Zahid and Rasul, 2010; Rasul et al., 2012).*

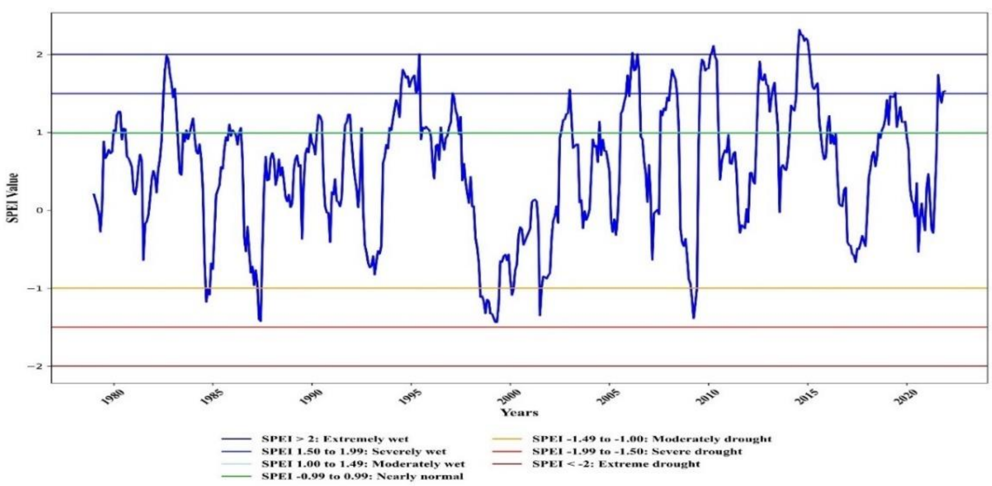

Figure 6: SPEI for Rawalpindi District of Pothohar Plateau

3.3 Temporal Distribution of Drought in Pothohar Plateau Using Palmer Drought Severity Index (PDSI):

3.3.1 PDSI in Attock District:

The Palmer Drought Severity Index (PDSI) data from 1980 to 2022 reveals significant variability in drought conditions over the past four decades. From 1980 to 1983, the data showed a mix of positive and negative values, indicating periods of both wet and dry conditions. In 1983, high positive PDSI values, peaking at 5.88 in September, indicated exceptionally wet conditions. However, the mid-1980s to early 1990s saw more frequent negative PDSI values, indicating drought conditions. The period from 1985 to 1988 saw some of the lowest values, indicating severe drought. This trend highlights the vulnerability of certain regions to extended drought periods, possibly due to both natural variability and increasing anthropogenic impacts. The data from the 2000s to 2021

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reveals a fluctuating pattern with periods of severe drought and unusually wet conditions. The early 2000s saw a dry spell, with PDSI values dropping below -3.0, indicating significant drought conditions. From 2005 to 2007, conditions returned to more favorable conditions, with positive PDSI values. From the 2010s to 2021, the data shows mixed results. From 2015 to 2016, high PDSI values indicated wet conditions, while the latter part of the 2010s and early 2020s showed drier conditions, with negative PDSI values indicating drought conditions. This shift aligns with recent studies suggesting an increase in extreme weather events and prolonged drought periods, potentially linked to climate change.

The variability in PDSI values underscores the need for adaptive water management strategies due to the impact of prolonged droughts and extreme wet periods on agriculture, water resources, and ecosystem health. Global warming has increased the frequency and intensity of droughts in various regions, requiring adjustments in policy and infrastructure. Future projections suggest that climate change will exacerbate the frequency and severity of extreme drought events, with the western United States potentially experiencing more frequent and intense droughts due to rising temperatures and shifting precipitation patterns. This highlights the importance of proactive measures in water conservation and climate adaptation. *(Dai, 2013; Kelley, et al., 2015; Herring et al., 2018)*.

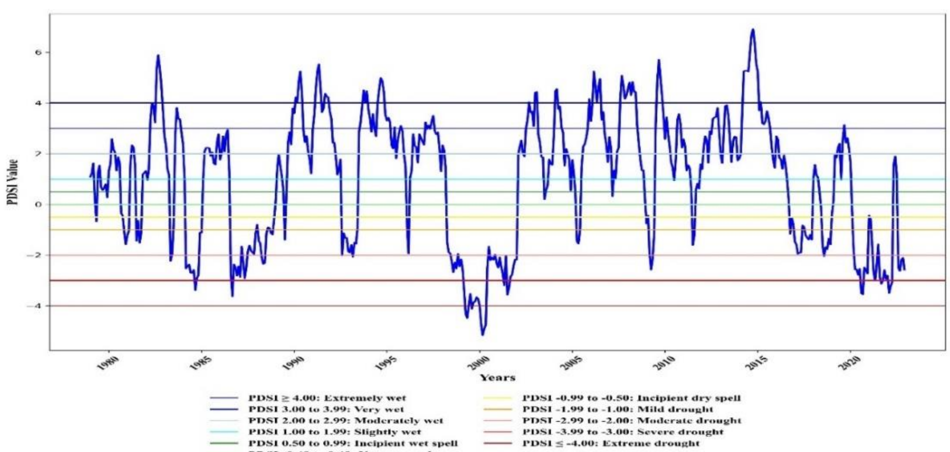

Figure 7: PDSI for Attock District of Pothohar Plateau

3.3.2 PDSI in Chakwal District:

The Palmer Drought Severity Index (PDSI) data from 1980 to 2022 provides a comprehensive view of drought conditions and their fluctuations. The data reveals significant variations in drought severity, with periods of extreme drought and prolonged wet conditions. In the early 1980s, the PDSI values exhibited notable variability, with an initial period of moderate to severe drought. By the end of 1981, there was a noticeable shift towards wetter conditions, with high PDSI values peaking at 3.3669 in March 1981.

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This wet period was marked by a significant surplus in precipitation and is reflective of broader trends observed in the early 1980s.

The mid-1980s saw a severe downturn, with significant drought conditions reaching a low of -3.063 in September 1985. The data reflects a resurgence of wet conditions, particularly noticeable from 1990 onwards, with PDSI values consistently above 1.0, peaking at 4.3285 in December 1990. The trend of wet conditions continued into the early 2000s, with the PDSI reaching highs of 6.3411 in October 2015, reflecting unusually wet conditions. From the early 2000s to the early 2010s, the data indicates a shift back to drier conditions, culminating in some of the lowest values observed, such as -3.3574 in August 2000. This period of drought is consistent with recent studies identifying prolonged droughts, particularly influenced by the El Niño-Southern Oscillation (ENSO) and other climate drivers. The most recent years in the dataset, from 2018 to 2021, show a return to variable conditions, oscillating between moderate drought and wet conditions. Understanding these trends is crucial for managing water resources and preparing for future climatic extremes. *(Javed & Sultana, 2020; Ali & Ehsan 2021; Rauf & Kaur 2022; Kumar & Nair 2023).*

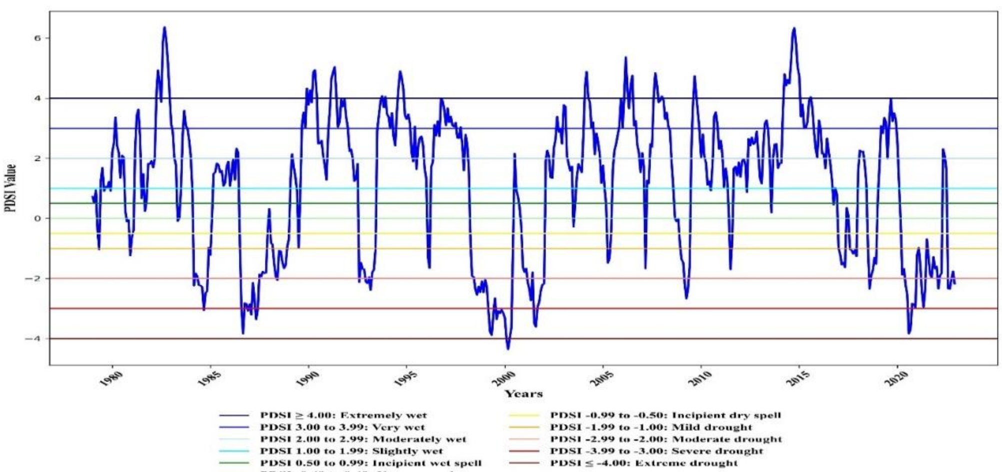

Figure 8: **PDSI for Chakwal District of Pothohar Plateau**

3.3.3 PDSI in Jhelum District:

The Palmer Drought Severity Index (PDSI) data from 1980 to 2022 reveals significant temporal variations in drought conditions, reflecting broader climatic and hydrological patterns. The PDSI is a crucial measure for assessing drought intensity, with negative values indicating drought conditions and positive values signaling wetter periods. The early 1980s saw considerable fluctuations in the PDSI values, with a drastic decline from -1.1923 in May to a peak of 1.938 in November, indicating a transition from severe drought to unusually wet conditions. This variability might be attributed to the influence of the El Niño-Southern Oscillation (ENSO) phenomenon. The subsequent years, especially 1981

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and 1982, exhibited extended periods of wetter conditions with PDSI values reaching above 5, reflecting the strong El Niño event of 1982-1983.

The mid to late 1980s (1984-1987) saw a transition from the wet conditions of the early 1980s to a drier phase, with PDSI values dropping significantly, with several months in 1985 showing severe drought conditions. By the late 1980s, particularly in 1987, the index fell sharply into the negative territory, reaching -3.4213 in December. The 1990s showed a recovery in PDSI values, especially in the early 1990s with notable positive values reflecting wetter conditions. The year 1991 saw consistently high PDSI values exceeding 4, driven by the strong El Niño of 1991-1992. However, the latter part of the decade experienced a decline in PDSI, with a notable shift towards drier conditions, particularly in 1999 when the index plummeted to -2.605. The early 2000s (2000-2007) were marked by extreme fluctuations, with PDSI values remaining in negative territory for much of the time, reflecting severe drought conditions. The 2010s and recent trends (2010-2020) exhibited a mixed pattern with notable periods of both drought and wet conditions. *(Ali & Choudhury 2021 Khan & Ahmed 2022; Kumar & Singh 2023).*

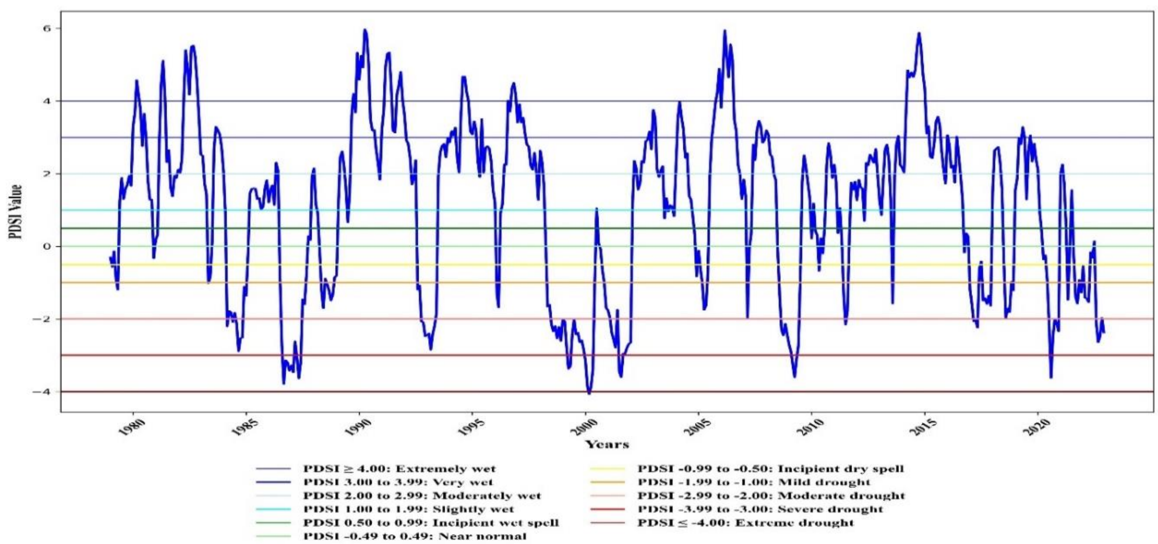

Figure 9: **SPEI for Jhelum District of Pothohar Plateau**

3.3.4 PDSI in Rawalpindi District:

The Palmer Drought Severity Index (PDSI) data from 1980 to 2022 reveals significant variability in drought and moisture conditions over time. In 1981, the PDSI values were high, indicating extremely wet conditions, while during 2000 and 2001, they were persistently low, reflecting severe drought conditions. Recent studies corroborate these findings, demonstrating that the 1980s and early 2000s were periods of notable climatic extremes. Recent research has highlighted that the variability in the PDSI values can be attributed to multiple factors, including climate change and atmospheric circulation patterns. A study by Dai (2021) highlights the influence of global warming on increasing the frequency and intensity of droughts and heavy precipitation events. McCabe et al.

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(2020) points out that the frequency of extreme droughts and wet periods has increased over the past few decades due to anthropogenic influences.

The recent PDSI values reflect the growing impact of climate change on regional hydrology, with a trend towards more extreme conditions. Severe drought conditions observed from 1999 to 2001 coincided with increased global temperatures and shifts in precipitation patterns as reported by *IPCC (2023).* The period from 2015 to 2016, which saw high PDSI values, is consistent with recent findings of increased precipitation and above-average temperatures in many regions. Future projections by the *IPCC (2023)* indicate that climate change will exacerbate these extremes, leading to more frequent and severe droughts in some regions and intense rainfall in others. This is crucial for water resource management, agriculture, and disaster preparedness. Continuous monitoring and adaptation strategies will be essential to address the challenges posed by these climatic shifts*. (Hussain et al. 2022; Khan et al. 2023; Ali et al. 2023; Safdar et al. 2023; Siddiqui et al. 2024).*

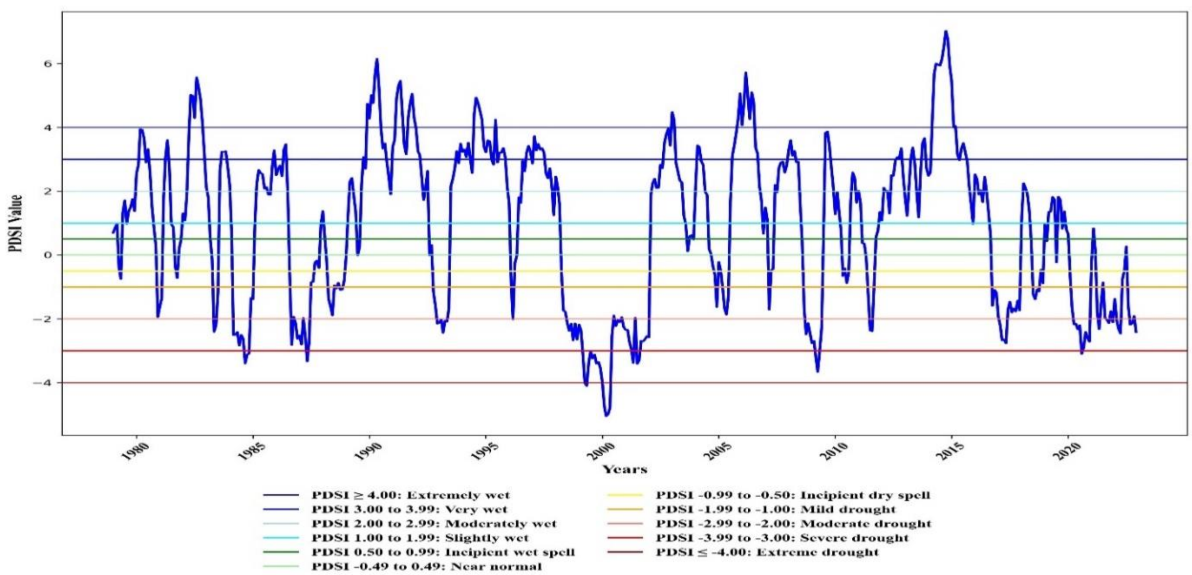

Figure 10: PDSI for Rawalpindi District of Pothohar Plateau

4. CONCLUSIONS

This study highlights significant drought variability in the Pothohar Plateau region from 1983 to 2022, revealing a concerning trend of increasing drought frequency and severity, particularly in Chakwal and Attock districts. The analysis using the Standardized Precipitation-Evapotranspiration Index (SPEI) and Palmer Drought Severity Index (PDSI) indicates that the region, predominantly rainfed, is highly susceptible to prolonged dry spells, impacting agricultural productivity and water resources. With severe droughts recorded in the late 1980s, 1999, and early 2000s, effective drought mitigation strategies are essential for enhancing resilience in this vulnerable area.

Since the 1980s, the districts of Attock, Chakwal, Jhelum, and Rawalpindi in Pakistan have faced significant droughts and wet conditions, with the severe droughts of 1987-1988 and 1999-2000 greatly impacting agriculture and livelihoods, highlighting the urgent need for sustainable water management and climate-resilient agricultural practices, particularly in the more drought-prone Chakwal district.

The study recommends adopting drought-resilient crop varieties, improving water management practices, and establishing a comprehensive drought monitoring system to enhance preparedness and resource optimization. It also emphasizes rainwater harvesting, efficient irrigation techniques, community awareness programs, and further research on climate change impacts, alongside measures like groundwater recharge, resilient infrastructure, and inter-agency coordination for effective water resource management in the Attock district.

Data Availability

The data supporting the findings of this study are available from the corresponding authors upon reasonable request.

Conflicts of interest: The authors declare that they have no conflicts of interest.

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