Assessing Drought Conditions using SPEI in Bahawalpur Division, Punjab, Pakistan

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This research study analyzes drought conditions using the Standardized Precipitation Evapotranspiration Index (SPEI) in Bahawalpur Division, South Punjab, Pakistan. Drought is one of the most complex natural disasters and is difficult to predict due to several involved factors. Among all natural hazards, drought causes significant damage to human lives and other living communities. Nearly 85% of all disasters are related to weather events, and drought is one of the most damaging among them. In Pakistan, drought causes damage in many areas, and Bahawalpur Division is one of those facing severe drought conditions. Temporal data on temperature and rainfall were collected from the Pakistan Meteorological Department for the period 1992 to 2020. The data were analyzed spatially using GIS technology. Precipitation and temperature data were analyzed using SPEI to monitor drought in three selected districts in Bahawalpur Division: Bahawalnagar, Bahawalpur, and Rahim Yar Khan. The study revealed that less rainfall was recorded in all three districts, leading to drought conditions. Moreover, this reduced rainfall severely affected the concerned districts.

Keywords: Climate Change, Drought, Rainfall, Variability, SPEI

Introduction:

Drought is a significant natural hazard that has far-reaching impacts on various sectors, such as agriculture, the economy, the environment, and human health [1]. It is characterized by a prolonged period of below-normal precipitation, leading to water scarcity and a lack of moisture for crops and other living organisms [2]. Drought can be categorized into different types, including meteorological drought, hydrological drought, and agricultural drought, each with distinct characteristics and impacts [3][4]. The causes of drought are complex and include global warming, climate change, changes in weather patterns, natural factors, and deforestation [5]. Global warming, primarily intensified by human activities and the emission of greenhouse gases, leads to higher temperatures and evaporation, along with reduced water availability, ultimately contributing to the occurrence of drought [6][7]. Climate change, which refers to long-term shifts in weather patterns, may alter the frequency and intensity of droughts that affect different regions [8]. Deforestation plays a key role in drought occurrence because trees release moisture into the air, contributing to cloud formation and rainfall. When forests are cleared, there are fewer chances of water availability for the water cycle, making the region more susceptible to drought hazards [9].

According to the scientific literature on climate science, drought has various impacts on different sectors, such as environmental impacts, food shortages [10], and reduced drinking water availability for plants and animals, further leading to reductions in their food sources and habitat. Similarly, the migration of wildlife has been observed as they search for water and food [11]. In addition, social impacts include health problems related to poor water quality that arise from drought, as water sources become contaminated or scarce. Drought can cause the loss of human life due to dehydration, heat waves, and related health complications. Moreover, health issues are caused by dust and air pollution, which can increase during drought periods.

In South Asia, particularly in Pakistan, climate change has had a significant impact on precipitation patterns, resulting in a higher frequency of droughts in the southern part of the country [12]. An increase in temperature leads to more arid regions, as warm air absorbs more water than cold air [13]. The gradual rise in temperature changes in precipitation patterns [14] might lead to extreme weather conditions, such as droughts, floods, and desertification. Climate change also affects large-scale atmospheric circulation patterns, causing shifts in storm tracks and contributing to weather extremes [15]. Droughts affect various regions in Pakistan, particularly in the areas of Sindh, Balochistan, and Punjab. The southern regions of Sindh face moderate to severe drought conditions, while Balochistan experiences drought in multiple districts. Droughts in Punjab, including Cholistan, have severe consequences, along with historical drought events that occurred in 1920, 1935, and 1999-2002. Water scarcity is a severe threat in Pakistan, with projections indicating that the country may face extreme water shortages by the years 2025 and 2026. Factors contributing to water scarcity include population growth, deforestation, mismanagement, and urbanization. At the global level, climate change is specifically considered a major challenge to the environment [16]. In terms of climate science, temperature and precipitation are the two most significant hydro-climatic variables [17][18] and these specific changes in climate are mainly linked to human interference with the environment [19][20]. At both global and regional levels, changes in climate patterns have been assessed and analyzed using average temperature and rainfall as important parameters [21][22][23]. Climate change has caused drastic changes in precipitation patterns, duration, intensity, and trends [16][24].

Material and Methods:

Study Area:

Bahawalpur is a small but historically significant city located in the South Punjab region of Pakistan. It consists of three districts: Bahawalpur, Bahawalnagar, and Rahim Yar Khan (Figure 1). The city has a hot and dry climate in summer and a dry and cold climate in winter,

with temperatures ranging from 7 ºC to 48 ºC. The region is known for its defense and security importance due to its border with India and its rich biodiversity. The districts are divided into the riverine region, the flooded region, and the desert region. Cholistan, a desert region, is famous for its sand ridges. Bahawalpur is also recognized for its carpet embroidery and poetry. The district has an average annual growth rate of 5% but remains relatively underdeveloped compared to other areas in Punjab.

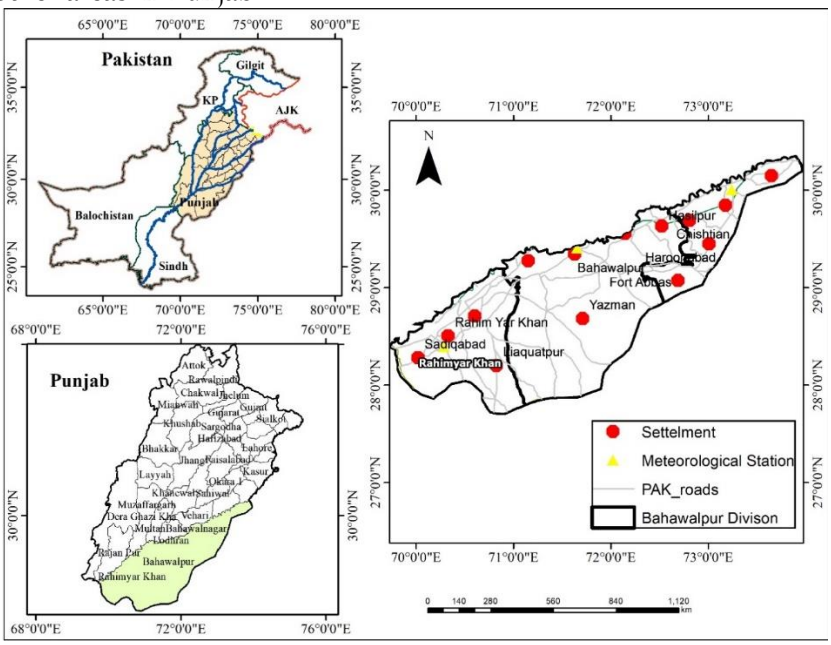


Figure 1. Study area showing major settlements and meteorological stations

Research Objectives:

To assess drought conditions spatio-temporally in Bahawalpur Division

To evaluate appropriate strategies to mitigate drought hazards in the study area

To identify the key causes of drought hazards in the study region

Standardized Precipitation Evapotranspiration Index (SPEI):

In this study, SPEI is used to identify drought conditions. SPEI extends the Standardized Precipitation Index (SPI) to address criticisms of SPI's calculations in the case of precipitation data (Figure 2). SPEI has the advantage of being computed at various time scales and takes potential evapotranspiration into account. It is easily comparable across time and space and has been utilized extensively in recent research to monitor drought conditions. The SPEI can evaluate drought severity based on its intensity and duration, as well as the start and end of drought episodes, similar to the PDSI and the SPI. SPEI can be calculated across a variety of climates, allowing comparison of drought severity over time and place.

Table 1. SPEI Classes

Range	Condition
SPEI≤ -2	Extreme Drought
-2<SPEI≤ -1.5	Severe Drought
-1.5<SPEI≤ -1	Moderately Drought
-1<SPEI≤ 1	Near Normal
1<SPEI≤ 1.5	Moderately wet
1.5<SPEI≤ 2	Severely wet
SPEI≥ 2	Extremely wet

Source: Modified after McKee et al. (1993)

The categories of droughts were calculated from rainfall departures on 3-, 6-, 9-, and 12-month timescales by analyzing the data over 1992–2021. An SPEI value of 2 or above indicates

an extremely wet area. If the value ranges from 1.50 to 1.99, it is considered a severely wet area. Similarly, if the value falls between 1.00 and 1.49, it is a moderately wet area. If the SPEI value falls within the range of -0.99 to 0.99, it is a near-normal area. If the value falls between -1.00 and -1.49, it is considered a moderately dry area. Furthermore, if the value is between -1.50 and -1.99, it is a severely dry area. Conversely, if the value is below -2.00, the area is considered extremely dry. In this study, the Inverse Distance Weighted (IDW) method is used to monitor drought conditions. Using the IDW technique, cell values are estimated by averaging the values of sample data points near each processing cell. The closer a point is to the approximated cell's center, the greater its effect or weight on the averaging process.

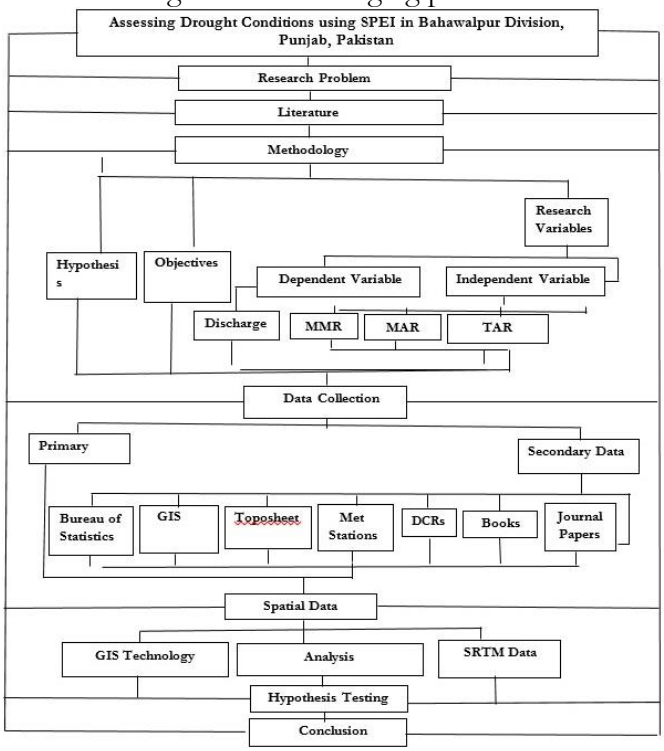
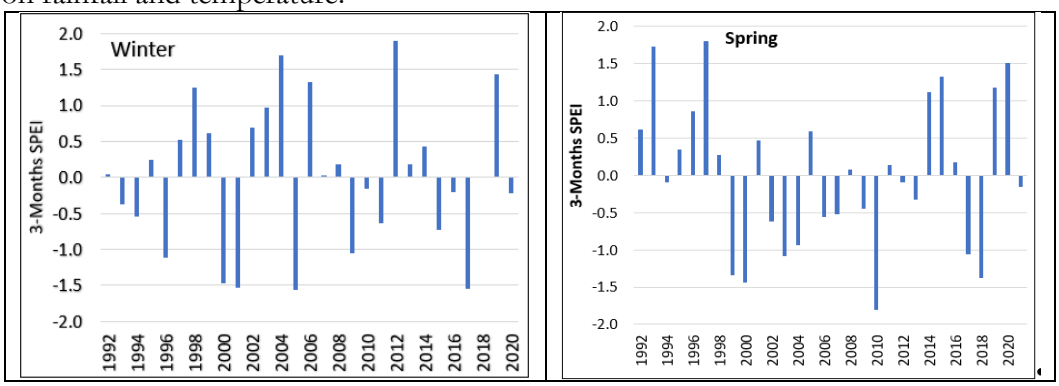


Figure 2. Research Framework Model

Results and Discussion:

Bahawalnagar:

Drought, a very complex natural phenomenon, causes numerous problems for economies and ecosystems. In the analysis section, a comprehensive assessment of drought is carried out in Bahawalpur Division. Examining several aspects of drought conditions, such as hydrological and meteorological, this study aims to provide a better understanding of drought dynamics in the study area. In the current study, drought data from three meteorological stations were analyzed to assess drought in Bahawalpur Division. These meteorological stations provided data on rainfall and temperature.



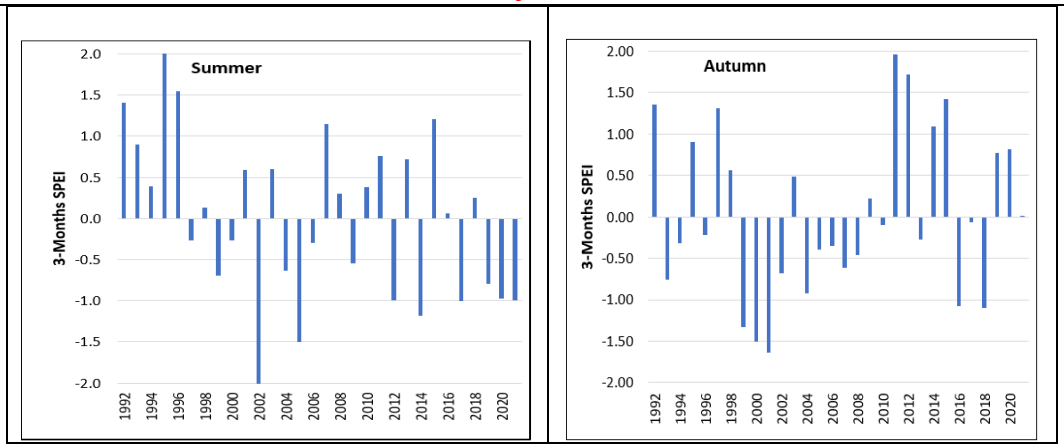


Figure 3. SPEI-based assessment of seasonal drought variations in Bahawalnagar

According to Figure 3, in the winter season (Rabi), the study region faced severe drought conditions in the years 2003, 2005, and 2017. Similarly, in the summer months, extremely dry conditions occurred in the year 2000. Likewise, in the spring season, the year 2010 faced severely dry conditions, while in the autumn season, the year 2003 faced severely dry conditions. The remaining years show slight variations in terms of drought conditions.

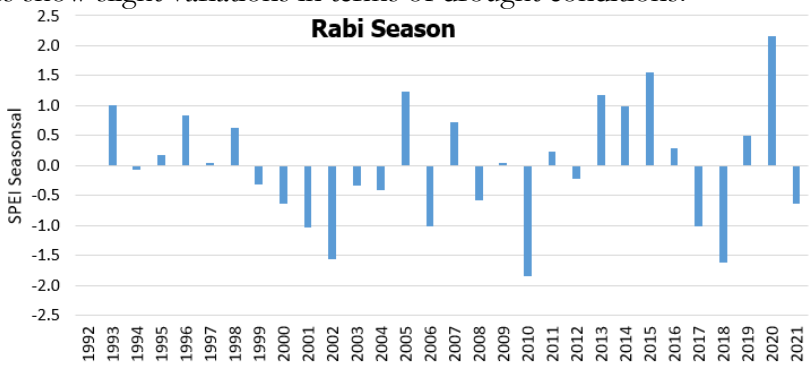


Figure 4. Bahawalnagar temporal rainfall pattern of 6-Months SPEI for Rabi season

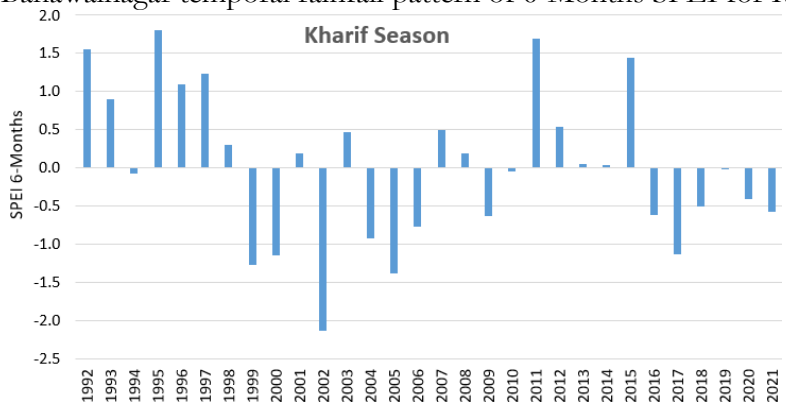


Figure 5. Bahawalnagar temporal rainfall pattern of 6-Months SPEI for Kharif season

The Rabi season, also known as the "winter season," starts in November and ends in April. In contrast, the Kharif season (summer season) starts in June and ends in October. Both seasons are crucial for food production in Asia, particularly in Pakistan. In these two distinct seasons, farmers plan their cultivation according to the climatic conditions of the region. Figure 4 shows that severe drought conditions occurred in 2010, whereas in the Kharif season, extreme drought occurred in the year 2002 (Figure 5). The remaining years exhibit variability in terms of drought conditions. Moreover, Figure 6 shows extreme drought conditions in the year 2002. In the same figure, the study area recorded the least rainfall. Likewise, the other years documented significant rainfall variability.

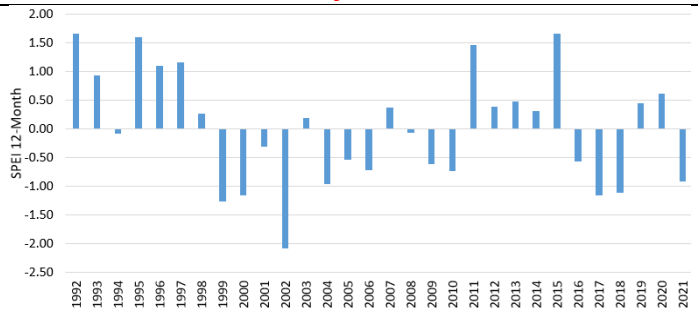


Figure 6. Bahawalnagar temporal pattern of 12-Months SPEI

Bahawalpur:

The city of Bahawalpur is located in the southern part of Punjab Province. According to the census of 2017, it is the 11th largest city in Pakistan in terms of population, known for its pottery, embroidery, and carpets. According to Figure 7, in the winter season, the region faced severe drought conditions like in 2002. Similarly, in spring, severe dry conditions occurred in the year-2002 and 2004, respectively. In the summer season, the years 1996, 1998, and 2002 faced severely dry conditions to extremely dry conditions because the SPEI graph line exceeded -1.50 to -2.00 dry conditions, and in autumn the year 1999 faced severely dry conditions.

In the same way, according to Figure 6, in the Rabi and Kharif seasons, extreme drought occurred in 2002. Because they exceeded the limit of the SPEI value of extremely drought conditions. The remaining years express no prominnent rainfall flux.

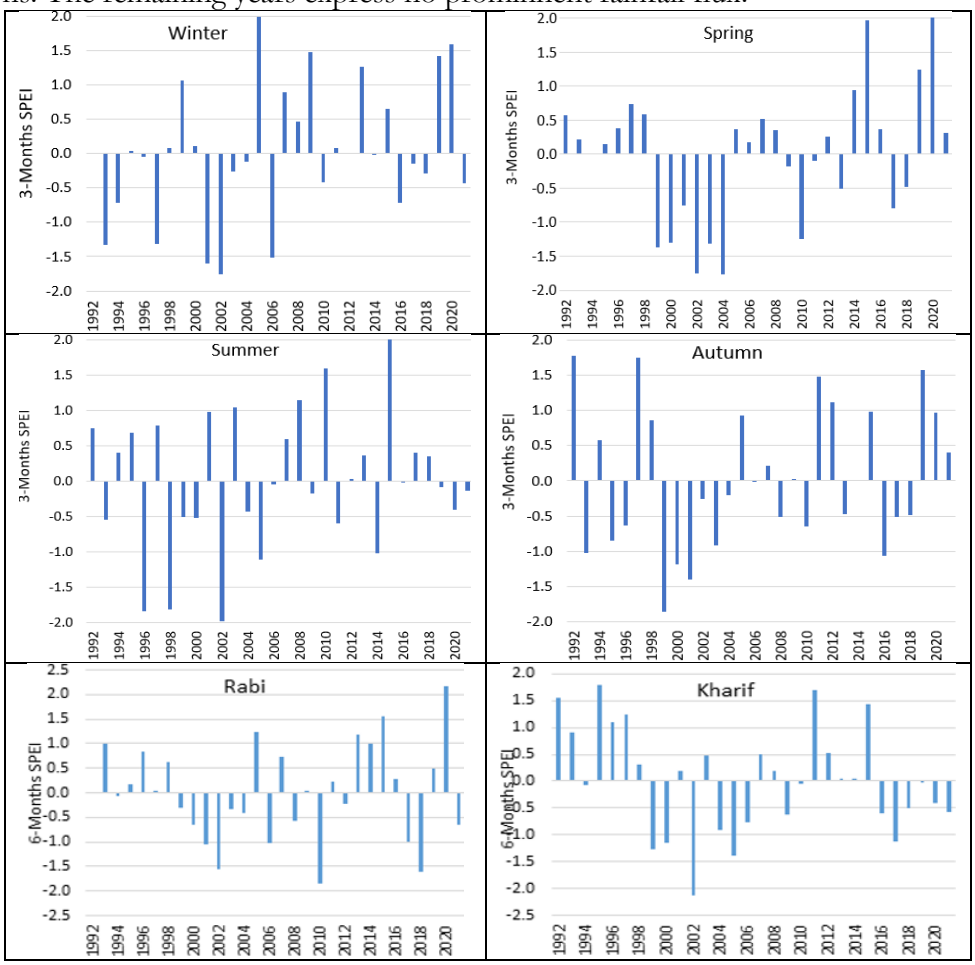


Figure 7. Bahawalpur temporal rainfall pattern of 6-Months SPEI

According to Figure 7, extreme drought conditions occurred in 2002, where the least rainfall was recorded.

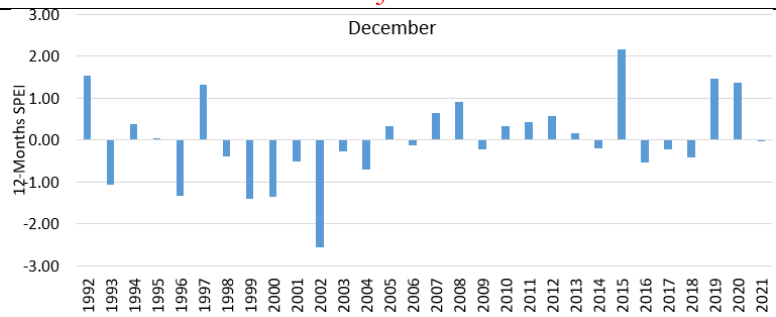


Figure 8. Bahawalpur temporal rainfall pattern of 12-Months SPEI

Rahim Yar Khan:

According to Figure 9, in the winter season, the region faced moderate drought conditions in the years 2006 and 2021. In spring, moderate dry conditions occurred in the years 2002 and 2018. In the summer season, the year 2002 experienced extremely dry conditions because the SPEI graph line exceeded -1.50, and in autumn, the years 2002 and 2018 faced severely dry conditions.

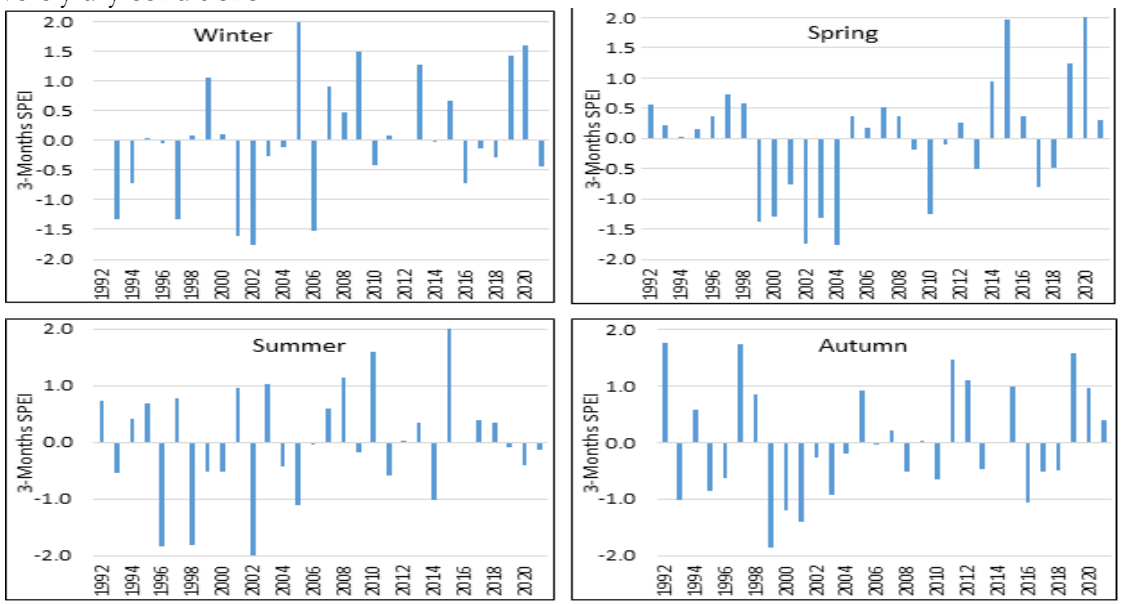


Figure 9. Rahim Yar Khan temporal rainfall pattern of 3-Months SPEI

According to Figure 10, in the Rabi season, severe drought occurred in 2004, and in the Kharif season, severe drought occurred in 2018.

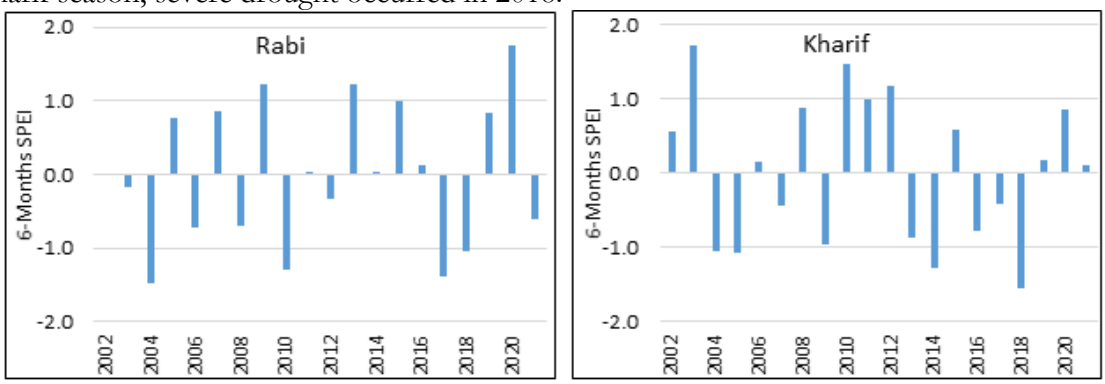


Figure 10. Rahim Yar Khan temporal rainfall pattern of 6-Months SPEI

According to Figure 10, a severe drought event occurred in 2008, where the SPEI value is more than -1.50, and thus the least rainfall was recorded.

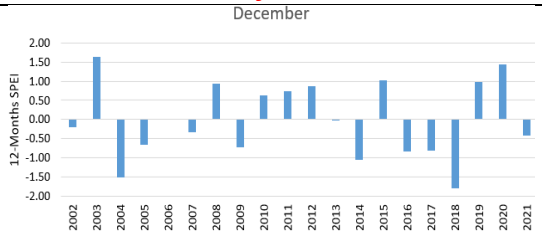


Figure 11. Rahim Yar Khan temporal rainfall pattern of 12-Months SPEI

The mean data for every 10 years of SPEI-3 in Bahawalpur Division show that from 1992–2001 (Figure 12), Bahawalnagar faced drought conditions, followed by Rahim Yar Khan, and lastly Bahawalpur. Similarly, the mean data for 2002–2011 show that Rahim Yar Khan faced severe drought conditions, Bahawalpur also faced minor drought conditions, but in these years, Bahawalnagar received more rainfall than these two districts. The mean data for 2012–2021 show that Bahawalpur District experienced drought and received the least rainfall in these years.

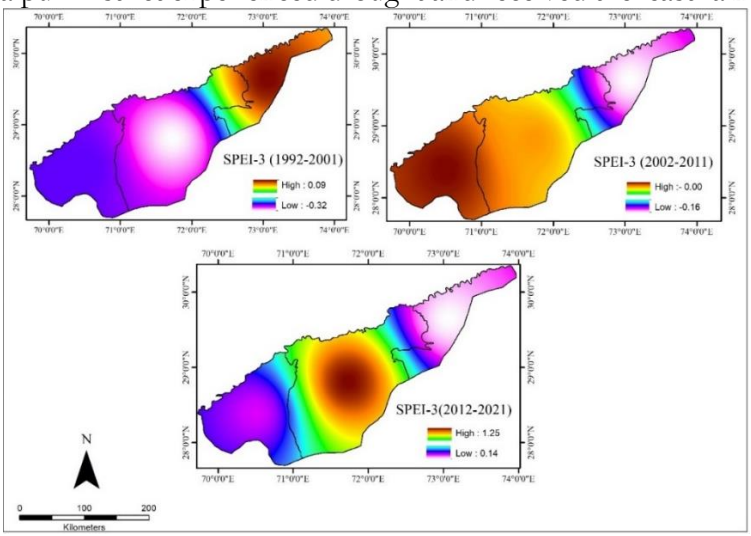


Figure 12. Spatial rainfall pattern of 3-month SPEI

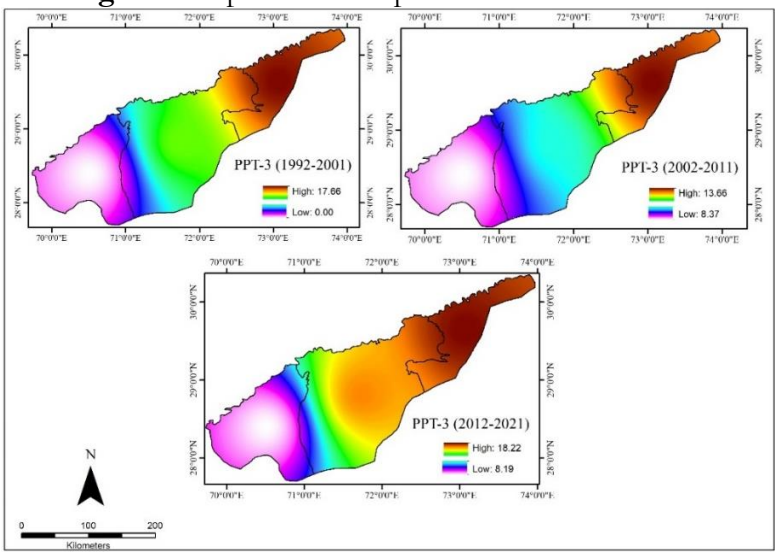


Figure 13. Mean annual rainfall of the 3-month SPEI

The mean data for every 10 years of PPT-3 in Bahawalpur Division show that from 1992–2001 (Figure 13), Bahawalnagar received the highest rainfall, followed by Bahawalpur, and lastly Rahim Yar Khan. Similarly, the mean data for 2002–2011 show that Bahawalnagar again received the highest rainfall. The mean data for 2012–2021 show that Bahawalnagar and Bahawalpur Districts received the highest rainfall.

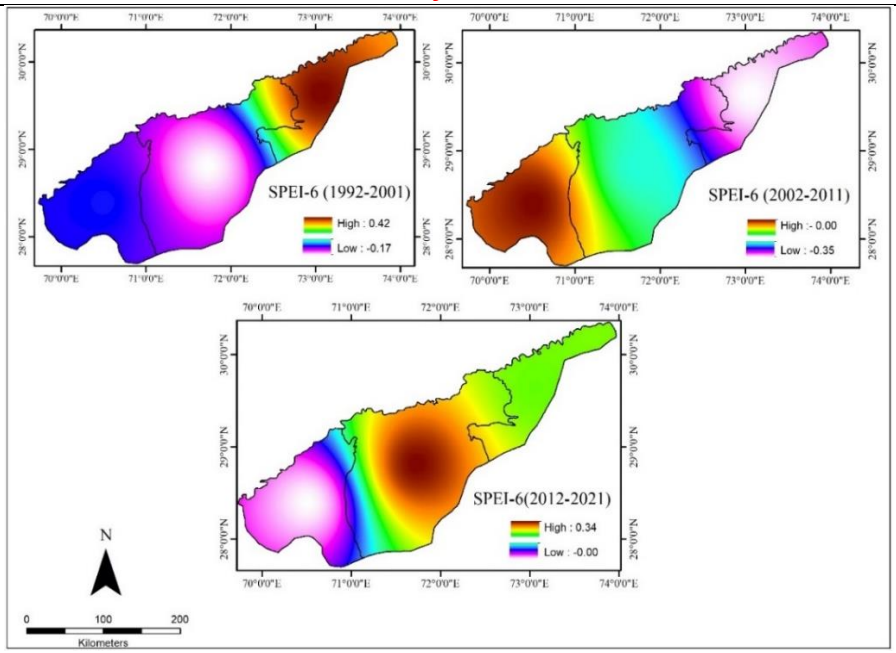


Figure 14. Spatial rainfall pattern of 6-month SPEI

The mean data for every 10 years of SPEI-6 in Bahawalpur Division show that from 1992–2001 (Figure 14), Bahawalnagar faced drought conditions, followed by Rahim Yar Khan, and lastly Bahawalpur. Similarly, the mean data for 2002–2011 show that Rahim Yar Khan faced severe drought conditions, followed by Bahawalpur, while Bahawalnagar received more rainfall than these two districts. The mean data for 2012–2021 show that Bahawalpur District experienced drought, and Bahawalnagar was also in a high-alert zone and received the least rainfall in these years.

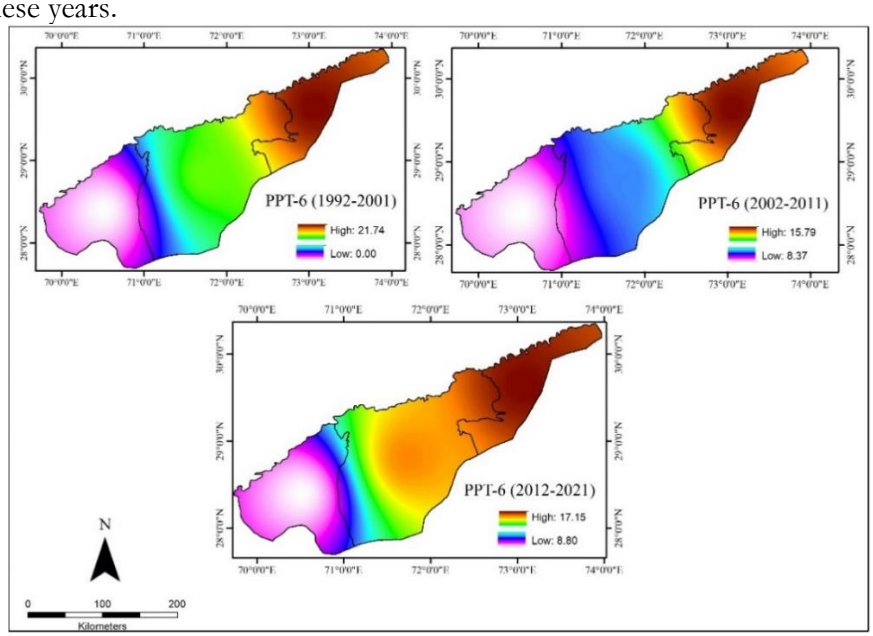


Figure 15. Mean annual rainfall of the 6-month SPEI

The mean data for every 10 years of PPT-6 in Bahawalpur Division show that from 1992–2001 (Figure 15), Bahawalnagar received the highest rainfall, followed by Bahawalpur. Rahim Yar Khan received the least rainfall. Similarly, the mean data for 2002–2011 show that Bahawalnagar again received the highest rainfall, but Bahawalpur received lower rainfall. The mean data for 2012–2021 show that Bahawalnagar and Bahawalpur Districts received the highest rainfall.

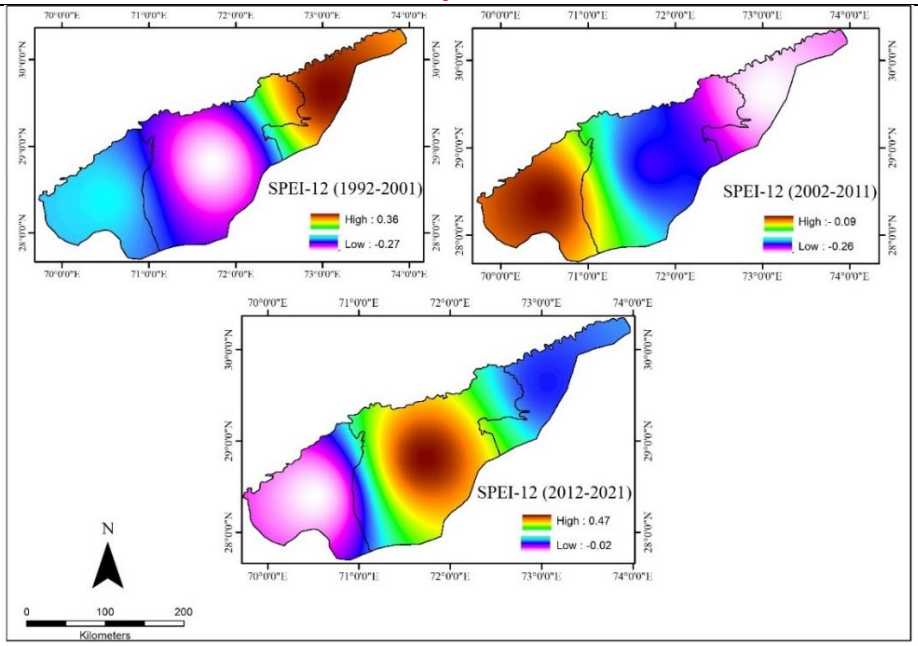


Figure 16. Spatial rainfall pattern of 12-month SPEI

The mean data for every 10 years of SPEI-12 in Bahawalpur Division show that from 1992–2001 (Figure 16), Bahawalnagar faced drought conditions, followed by Rahim Yar Khan, and lastly Bahawalpur. Similarly, the mean data for 2002–2011 show that Rahim Yar Khan faced severe drought conditions, followed by Bahawalpur District, and Bahawalnagar received more rainfall than these two districts. The mean data for 2012–2021 show that Bahawalpur District experienced drought and received the least rainfall in these years.

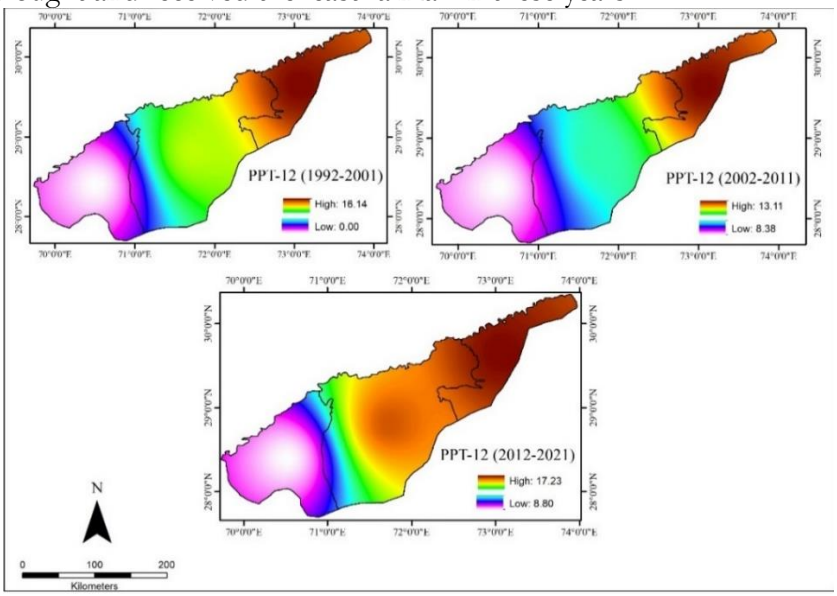


Figure 17. Mean annual rainfall of the 12-month SPEI

The mean data of every 10 years of PPT-12 of Bahawalpur Division shows us that from 1992-2001 (Figure 17), Bahawalnagar received the highest rainfall, then Bahawalpur, and last Rahim Yar Khan. Similarly mean data of (2002-2011) shows us that Bahawalnagar received again highest rainfall and Bahawalpur received gradually low rainfall. And the mean data of (2012-2021) shows us that the Bahawalnagar and Bahawalpur districts received the highest rainfall.

Discussion:

Time-series data on rain and temperature were acquired from the Pakistan Meteorological Department (1992–2020). The available data were assessed and analyzed spatially

using GIS technology. The current study shows that relatively less rainfall has been documented in all three districts, leading to drought conditions in the study region. Furthermore, this reduced rainfall severely affected the affected districts. In this study, the results highlight the spatial and temporal variations in drought hazards in Bahawalpur Division, Pakistan, using SPI and SPEI approaches. These findings indicate that this region is relatively vulnerable to recurring drought conditions, reflecting that it receives limited rainfall. Moreover, SPEI provides a relatively comprehensive understanding of drought conditions compared to the SPI [25][20].

Furthermore, the resulting analysis reveals that Bahawalpur experiences recurrent meteorological droughts with high severity during the summer season, when evapotranspiration demand is at its peak. These results are consistent with past research studies conducted in other regions in Pakistan that have confirmed similar seasonal patterns [26][27][28]. These observations align with findings where prolonged drought periods have been noted due to small amounts of rain and long dry episodes [29][30]. Similarly, the spatial patterns of drought conditions assessed from SPEI show that the other districts in Bahawalpur Division, such as Rahim Yar Khan and Bahawalnagar, exhibit high vulnerability to drought compared to Bahawalpur District. The increasing intensity of drought, verified using SPEI, is an indication of climate change [31][32][33]. This has a significant impact on agricultural activities in Bahawalpur Division, Pakistan, which relies mostly on canal irrigation. Consequently, as SPEI offers a robust understanding of drought conditions, its precision largely depends on the quality of temporal climatic data. In conclusion, the present study determines that Bahawalpur Division, comprising three key districts—Bahawalpur, Bahawalnagar, and Rahim Yar Khan—is highly prone to frequent droughts, ultimately increasing the risk of climate change.

Conclusion:

In this study, drought has been assessed using the SPEI technique. Monthly data from the years 1992 to 2021, using rainfall and temperature time-series data from three meteorological stations in Bahawalpur Division, were calculated and analyzed. Based on SPEI-3 for the years 1992–2001, Bahawalnagar received less rainfall and fell into the category of drought, while according to SPEI-6 and 12, Bahawalpur and Rahim Yar Khan received less rainfall. Based on SPEI-6 and 12, in the period 2002–2011, Rahim Yar Khan faced drought conditions, which extended to Bahawalpur as well. The drought in Rahim Yar Khan was reduced because Bahawalpur also received low rainfall. Similarly, in the period 2012–2021, Bahawalpur received the least rainfall and consequently experienced drought, but according to SPEI-3, it had a significant impact on Bahawalnagar. Areas that received the highest rainfall are still vulnerable to drought. The present study assists researchers in monitoring drought areas for future predictions to mitigate drought conditions.

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