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Flash Drought Monitoring in Pakistan Using Machine Learning Techniques and Multivariate Drought Indices

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ABSTRACT

The rising global temperature owing to global warming has led to a disruption in the annual rainfall pattern and an increase in drought severity. Various drought indices have been developed over the period out of which the Standardized Precipitation Index (SPI) and Standardized Precipitation and Evaporation Index (SPEI) were found to be the best performing under the Pakistan climate that comprises mostly arid and semi-arid regions. Precipitation, Temperature, and evapotranspiration are among the most notable hydrological parameters to identify drought which were used for the calculation of these indices. The grid-based satellite data (1991-2022) of resolution 0.25°x0.25° has been used for Precipitation and Temperature and Evapotranspiration has been calculated by the Hargraves method. SPI was calculated by comparing precipitation for a given period to historical data at the same location and timescale. While, SPEI was calculated by considering climatic water balance, incorporating precipitation and evapotranspiration datasets. During the drought monitoring assessments, a severe drought period from 1999-2002 was witnessed in Pakistan with a negative value of SPI and SPEI ranging between 1.6-2.0 signifying severe drought conditions over that period. The main reason for such drought events was disruption in the rainfall patterns. In addition, it was observed that drought in some regions in 2012 was mainly caused by an increased maximum temperature. The most severely affected areas were Tharparkar in Sindh, parts of Baluchistan province, and some districts in Punjab. Such mapping and monitoring of flash droughts are important to plan our water resources well.

KEYWORDS: Climate change, flash drought, multivariate drought indices, machine learning, SPI, SPEI, Pakistan.

1 INTRODUCTION

Drought is a natural disaster caused by a combination of hydrological, atmospheric, and biophysical processes [1,2].While Pakistan has long been affected by traditional and prolonged droughts, a new and insidious threat known as flash droughts has emerged.These flash drought events have the potential to cause significant damage to crops, livestock, and natural systems, leading to economic losses and food insecurity[3]

Flash droughts differ from traditional droughts in terms of their speed and intensity. These droughts are not solely caused by a lack of rainfall, but rather by a combination of factors. Factors causing flash droughts include increased temperatures, which are driven by climate change and accelerate evapotranspiration, resulting in a rapid depletion of soil moisture[4].Additionally, the erratic patterns of rainfall contribute to flash droughts.

Although the annual precipitation may remain constant, its distribution becomes uneven, with intense bursts of rainfall followed by prolonged dry periods [5].Another contributing factor is the presence of sandy soils, which have poor water-holding capacity and exacerbate the effects of rapid drying [6].
Pakistan is particularly vulnerable to flash droughts for several reasons. First, the arid and semi-arid climate of the country means that large areas already receive limited rainfall [7,8], making them more susceptible to rapid moisture depletion [9]. Then, the melting of glaciers, which provide water to rivers, is also exposed to large barren landscapes that are prone to rapid drying [10]. Flash droughts are also common because of the rising of the global temperature. A recent study [1] has confirmed the movement of droughts from southern Punjab to some cities and districts of central Punjab.
Thus, we can't rule out the possibility of drought occurring over regions that didn't seem very prone to droughts initially. There seem to be not enough studies currently addressing the flash droughts issue. Hence, the purpose of our study is to map the occurrence and severity of flash drought in recent years, a period of 30 years from 1991 to 2022.The analysis is based upon satellite data as the original field data is not frequently available in Pakistan for most of the stations, we have included this data to calculate SPI and SPEI, the best-performing indices for the region such as Pakistan [11].

2 STUDY DATA

2.1 Study Area

Pakistan is located in the domain of 23°39N–37°01N and 60°49E–77°40E.The overall climate is arid and semi-arid because of the presence of monsoon and other seasonal activities making the temperature cold and rainy during December, extremely dry and hot in April, hot and very humid in September, and cool to dry in November[10]. We selected sixteen stations across Pakistan as shown in Figure 1. Factors that played a vital role in the selection of these stations (Table 1) are the long-term temperature and precipitation variation among stations as they lie at different altitudes with varied hydro-meteorological features, which are important in the flash drought assessments.

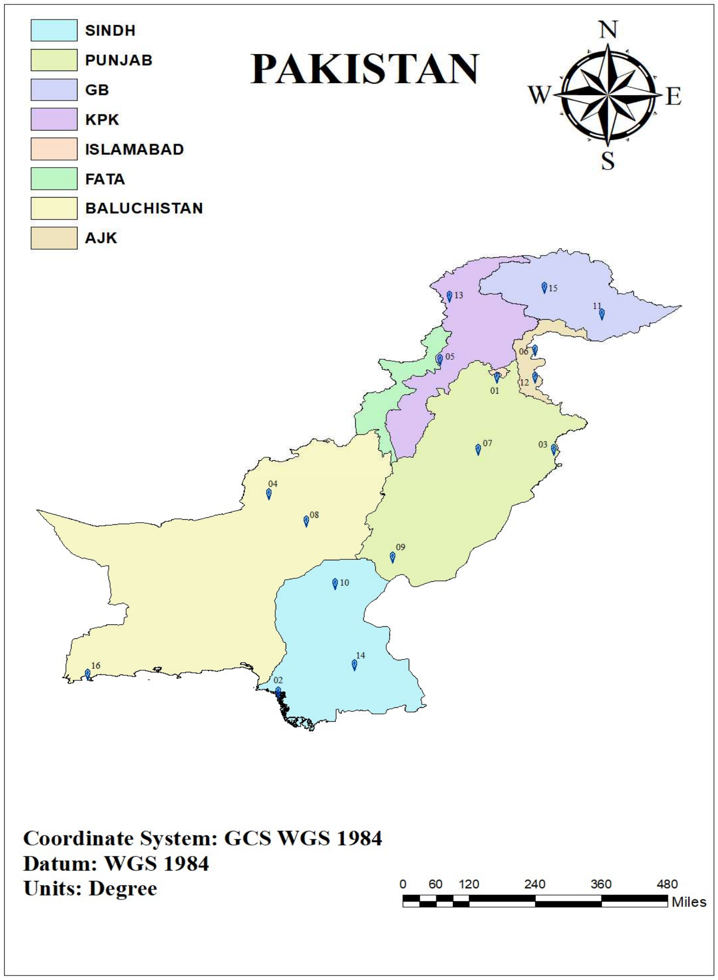

Figure 1: Study area map showing the location of selected sixteen stations.

2.2 Geographical Details of Selected Stations

The selection of stations was important as the different factors have different behaviours based upon location as per Table I. So, the areas having similar parameters have shown the same behaviour which might mix up the results. So, it was important to select stations which would be impactful for our research. Temperature and precipitation played important role in station selection.

Table 1: Details of Selected Station

Sr.No	Name of Station	Subdivision	Latitude	Longitude
01	Islamabad	Capital	33.5	73
02	Karachi	Sindh	24.75	67.25
03	Lahore	Punjab	31.5	74.5
04	Quetta	Baluchistan	30.25	60

05	Peshawar	KPK	34	71.5
06	Muzaffarabad	Azad Kashmir	34.25	74
07	Jhang	Punjab	31.5	72.5
08	Sibbi	Baluchistan	29.5	68
09	Rahimyarkhan	Punjab	28.5	70.25
10	Sukkar	Sindh	27.75	68.75
11	Skardu	GB	35.25	75.75
12	Kotli	Azad Kashmir	33.5	74
13	Chitral	KPK	35.75	71.75
14	Chohr	Sindh	25.5	69.25
15	Gilgit	GB	36	74.25
16	Gwadar	Baluchistan	25.25	62.25

2.3 Data

The long-term climatic data of precipitation, temperature, and evapotranspiration from Copernicus ERA5 (11) (calculated using the Hargreaves PET method) from 1991-2022 has been used in this research to calculate drought indices like SPI, and SPEI. Satellite remote sensing data was further compared with a few of the available actual data (station) from the Climate Data Processing Centre, PMD, Pakistan to check the accuracy. Statistical parameters such as coefficient of determination (R-square), and Mean Square Error (MSE) are utilized here

3 METHODOLOGY

Our analysis focused on three key factors influencing flash droughts in Pakistan: precipitation, evapotranspiration, and temperature using SPI and SPEI. The SPI is calculated using the cumulative distribution function of the gamma distribution. The formula for SPI is given by:

$$SPI=(X-\mu)/\sigma \qquad (1)$$

Where:

- X is the observed precipitation over a specified time.
- μ is the mean precipitation over the same time.
- σ is the standard deviation of precipitation over the same period.

The formula for SPEI is given by:

$$SPEI=(P-PET)/\sigma \qquad (2)$$

Where:

- P is the observed precipitation over a specified period.
- PET is the potential evapotranspiration over the same period.

σ is the standard deviation of the climatic water balance (difference between precipitation and PET) over the same period.

3.1 Drought Index Selection

Suitable drought indices for arid and semi-arid regions like Pakistan were evaluated. Standardized Precipitation Index (SPI) and Standardized Precipitation-Evapotranspiration Index (SPEI) emerged as the most appropriate, considering their effectiveness in capturing both precipitation and evapotranspiration deficits.

3.2 Drought Categories using SSI & SPEI

The drought severity is categorized in terms of the value of SPI and SPEI as shown in Table 2 below:

Table 2: Drought Severity Indices and their Pros and Cons

Drought Index	Drought variable	Advantages	Limitations	Drought Severity From [9]&[12]
SPI	Precipitation	Flexible time scale. Relates to the probability of occurrence. Symmetric for both dry and wet spells.	Requires long-term data. Does not consider evaporation, temperature, soil water holding capacity, etc. Assumes other variables as stationary. May give misleading results in regions with small seasonal	• Generally, less than 0.5 = Normal • 0.5 to 0.8 = Mild • 0.8 to 1.2 = Moderate • 1.2 to 1.6 = severe • 1.6 to 2.0 = Extreme • below 2 = Exceptional
SPEI	Climatic water balance anomalies: defined as differences in precipitation and potential evapotranspiration	Flexibility of timescale. Simple calculation (same as SPI). It uses both precipitation & Evapotranspiration	Requires long-term data Sensitive to the method of evapotranspiration calculation. It may be sensitive to the probability distribution fitted.	

4 RESULTS AND DISCUSSIONS

The results of the data are plotted in the form of scattered charts and Spatial plots which are shown in the below figures.

4.1 Time Series Plots

The below scatter plot shown in Figure 2 represents the SPI and SPEI values showing the different severities of droughts during different time scales (1991-2022). This shows a higher intensity of flash droughts (5.2) for 2019. In addition, the year 2007 has also shown the severity of flash droughts, however, its intensity (4.0) is quite low compared to the flash drought observed in 2019.

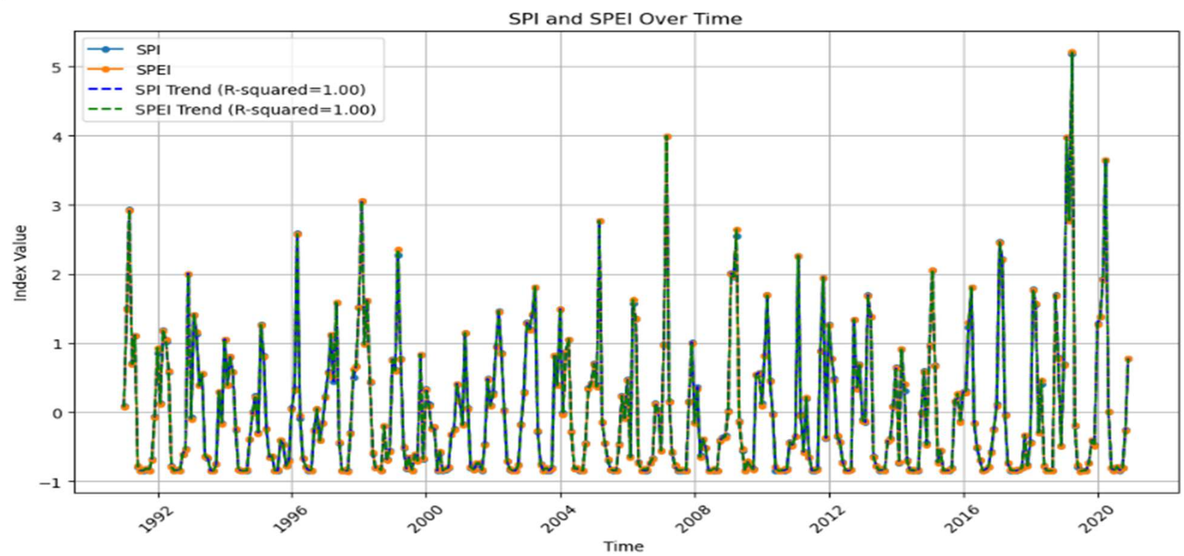

Figure 2: SPI and SPEI averaged over 1991-2022 using monthly datasets

Figure 3 below illustrates that for the majority of the previous three decades, the Standardized Precipitation Index (SPI) has remained below zero, indicating a prevalent presence of drought conditions in the area. Specifically, in the years 1999-2002, the SPI reached a value of -2.0, signifying a severe drought event. Positive SPI values are indicative of above-average moisture levels. On the contrary, negative SPI values correspond to below-average moisture levels. The magnitude of the SPI determines the severity of either wet or dries conditions, with larger absolute values representing more extreme circumstances. To classify varying degrees of drought, thresholds are commonly employed, such as mild, moderate, severe, and extreme drought categories.

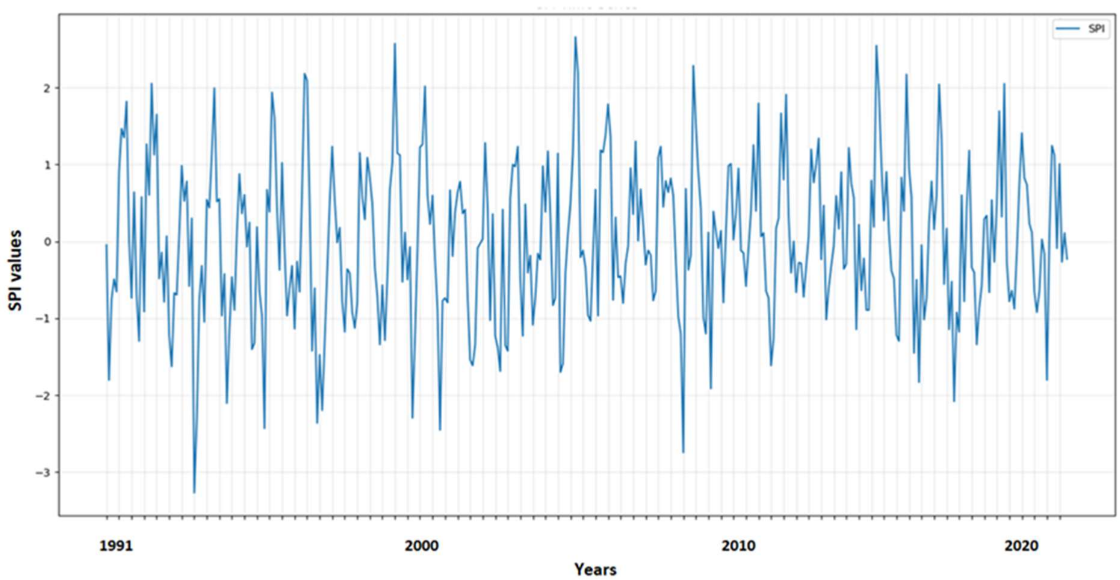

Figure 3: SPI time series for 1991-2022 using monthly datasets

Figure 4 suggests that the region has encountered both moist and arid periods throughout the span of 30 years. The existence of unfavourable SPEI values signifies intervals of drought. The SPEI values dropping to -2.0 or below implies that the region may have faced severe droughts during the specific period of 1999-2002. Favourable SPEI values signify conditions that are wetter than the average. While unfavourable SPEI values signify conditions that are drier than the average. The threshold for severe drought is often regarded as an SPEI value of -2.0 or lower.

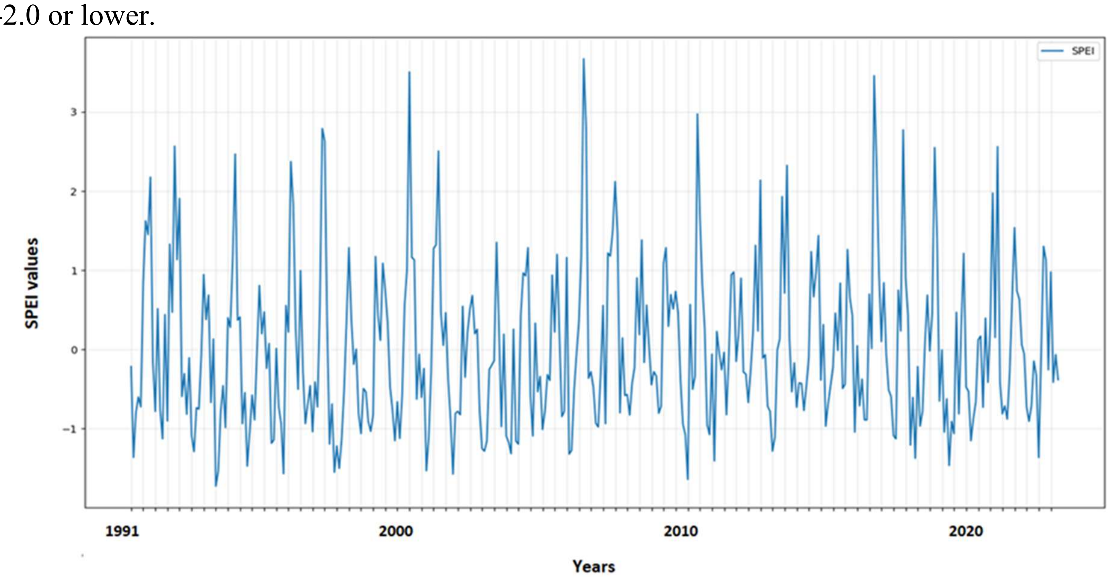

Figure 4: SPEI time series over time (1991-2022) using monthly datasets

4.2 Spatial Plots

Spatial data provide a visual overview of the indices calculated SPI&SPEI. From the SPI and SPEI spatial plots, it is evident that mostly the parts of Sindh and Baluchistan and a fraction of southern Punjab were affected by the droughts early on as the severity being highlighted by the red colour however now due to the disrupted rainfall patterns and an increasing temperature it can be seen in the October November and December spatial plots the drought category which was normal to mild is becoming mild to severe moving upwards the central and northern parts of Punjab with the red colour becoming more and more prominent high lightening below average moisture conditions however it has not taken full effect yet but the shortages of wheat, rice and maize recently emphasizes the trend of flash drought as shown in Figure 5 and 6. During the1999-2001 drought episode, severe drought conditions (dark red) were similarly concentrated in Sindh and Baluchistan. By the 2005-12 times period significant northward expansion is observed, with parts of southern Punjab and Khyber Pakhtunkhwa experiencing severe drought being identified by the help of time series (Figure 5).

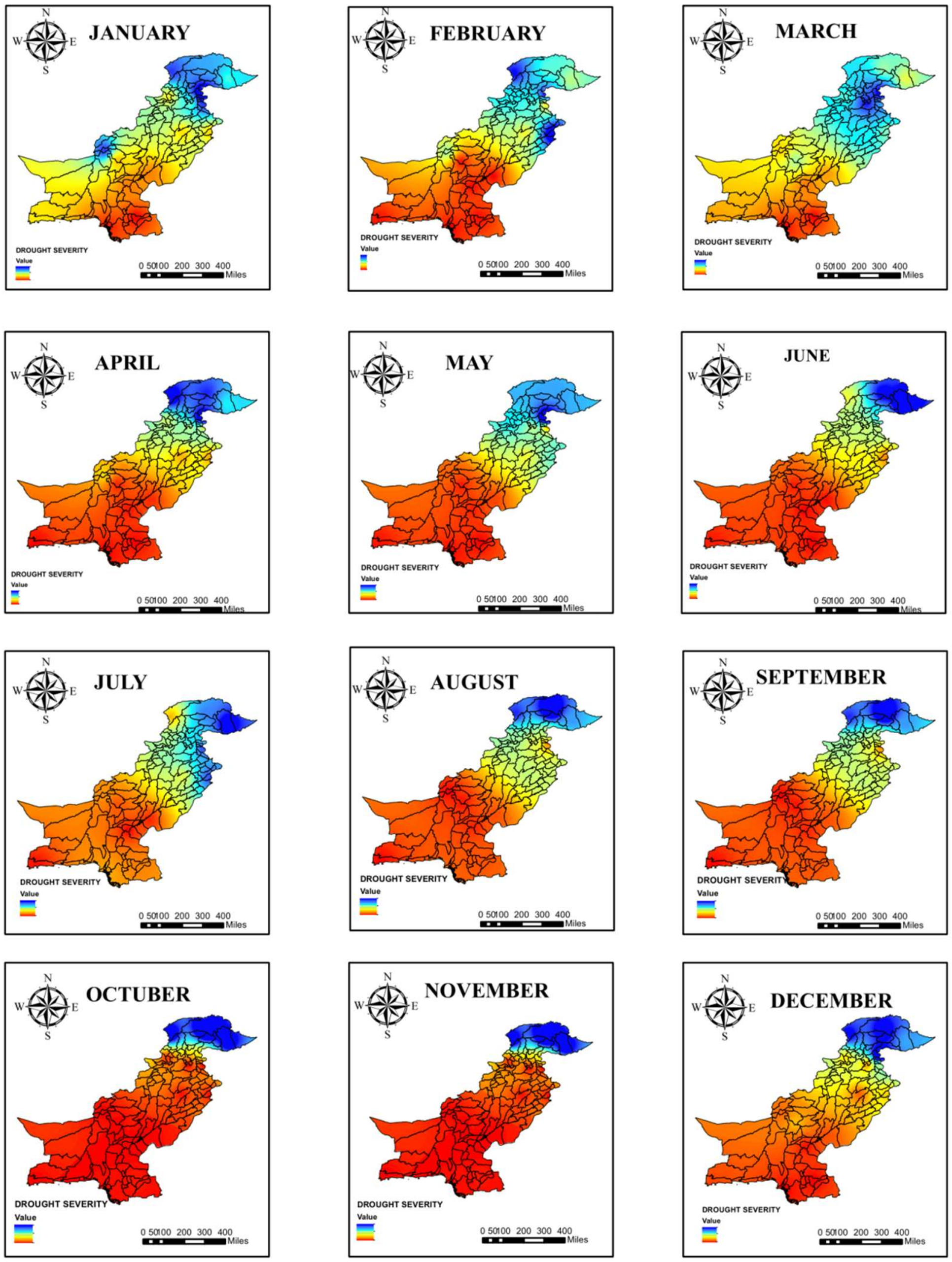

Figure 6: Drought severity spatial mapping using SPI

The recent trends highlight the below-average moisture conditions in historically less drought-prone areas. Previous researches affirm the effectiveness of the Standardized Precipitation Index (SPI) and Standardized Precipitation-Evapotranspiration Index (SPEI) for estimating drought severity in regions like Pakistan [11, 15]. Pakistan has indeed witnessed an alarming rise in drought frequency and intensity over recent decades [14]. Droughts like the 1999-2002 and 2012 episodes, highlighted by negative SPI and SPEI values, are becoming more common place [17]. Recent analysis (Figure 5) suggests a worrying northward movement of flash drought occurrences, potentially impacting rain-fed agriculture and water supplies due to temperature anomalies [18, 19].

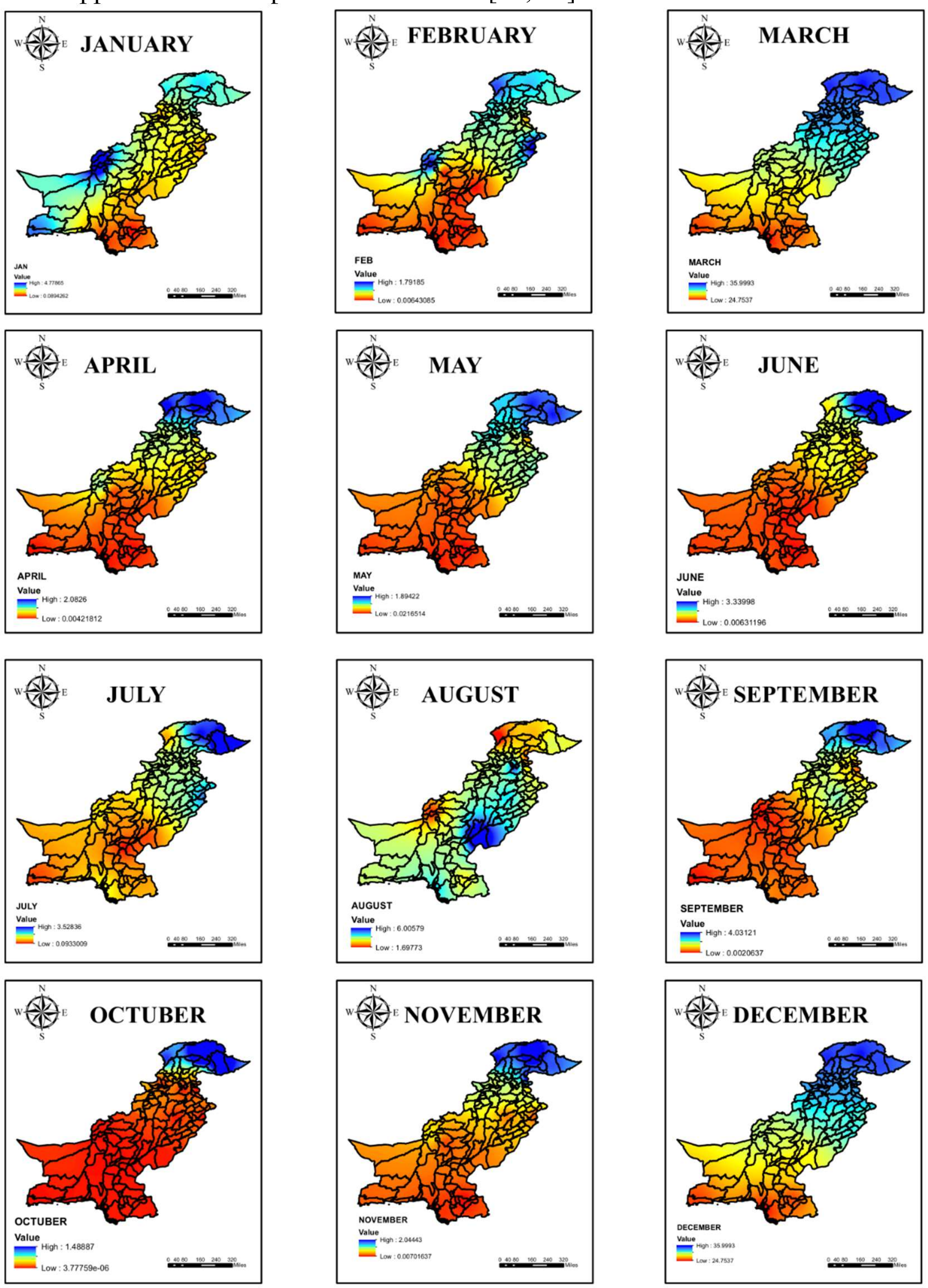

Figure 6: Drought severity spatial mapping using SPEI

Drought severity calculated by SPI and SPEI for the period 1991-2022 are presented in two forms: Time series graphs which capture temporal trends and variations in drought severity over time well and spatial images offer spatial visualization of drought patterns concerning geographical distributions. Remote sensing data spanning 1991-2022 have highlighted the historical drought vulnerability of southern and western Pakistan, including the Indus River Basin, a crucial region for population and agriculture**.** Notably, these visuals reveal a lateral movement of drought towards northern regions, evident in the changing severity patterns. While southern and western areas remain markedly darker (Figure 5 and 6) (indicating high severity), a northward progression of darker shades further emphasises this trend [14], [18].

5 CONCLUSIONS

The analysis of remote sensing imagery and SPI/SPEI time series from the data from 1991 to 2022 reveals a concerning trend of increasing drought frequency and severity in Pakistan. This is evidenced by the negative values of the SPI and SPEI explaining the threshold of the drought severity with mild to severe during the 1999-2001 time period. The drought period was established to be quite catastrophic with the SPI and SPEI values ranging below -2 and between 0.8-1.6 as we move further down the conditions in Baluchistan and Sindh (most affected ones) remained below average with the values between 0.8-1.2 moderate and in some instances 1.2-1.6 depending upon the season but from 2005 to 2012 the drought severity was although mild the drought moved laterally towards the Khyber Pakhtunkhwa and southern Punjab and the recent trends of the precipitation and temperature data make it evident that the droughts are moving towards the northern parts which were the least drought-affected areas.

These findings have significant implications for Pakistan's future. Decreased soil moisture and heat stress threaten crop yields, while depleted water resources raise concerns about impending water scarcity. Furthermore, the observed northward shift of flash droughts suggests a potential disruption in Pakistan's rainfall patterns, possibly attributable to global temperature changes. The effectiveness of SPI and SPEI in accurately monitoring drought events, including the severe 1999-2002 and 2012 droughts, validates their utility for future drought prediction efforts. Incorporating data from these indices, alongside RCP and SSP scenarios, can enhance predictive models and inform proactive drought mitigation strategies.

Overall, this research underscores the urgency of addressing Pakistan's growing drought crisis. Utilizing advanced monitoring tools like SPI and SPEI, coupled with robust predictive models, will be crucial for implementing effective drought management strategies and safeguarding the nation's water resources and agricultural productivity.The major limitation is that drought monitoring uses current and historical rainfall temperature and evapotranspiration but has limited ability to predict future events for which GCMS and CIMP6 data can be utilized for drought risk assessment and better management.

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