FLASH DROUGHT DETECTION AND RISK EXPOSURE IN PAKISTAN: A MACHINE LEARNING APPROACH WITH MULTIVARIATE INDICES.

Mustajab Ali[1], Usman Ali[2], Syed Hasnain Gillani[3]
[1-3]Department of Civil Engineering
Mirpur University of Science and Technology

Email[1]mustajab.ce@must.edu.pk, [2]aliu70536@gmail.com, [3]syedhasnaingillani03@gmail.com
* Corresponding author: aliu70536@gmail.com

Abstract:
Global warming disrupting the rainfall patterns, intensifying droughts, particularly resulting in flash droughts. We evaluated the drought severity in Pakistan (1991-2022) using the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) both being the effective tools for Pakistan's arid and semi-arid climate. High-resolution satellite data (0.25°x0.25°) for precipitation, temperature, and evapotranspiration was utilized for monitoring. Our analysis discovered a severe drought period (1999-2002) with SPI and SPEI values of -1.6 to -2.0, indicating disruptions in rainfall patterns. Additionally revealed a 2012 drought in some regions which was linked to high temperatures. Tharparkar (Sindh), parts of Balochistan, and Punjab districts were most affected. Our study put forward an increased frequency and intensity of flash droughts during Pakistan's critical spring-summer crop season, possibly impacting the previously unaffected areas. Rising temperatures and evapotranspiration are key drivers for flash droughts occurrence. Effective drought monitoring using SPI and SPEI is crucial for water resource management and future drought prediction efforts.

Keywords- Drought indices, Flash droughts, Pakistan, SPEI, SPI.

1. Introduction:

Drought arises as a natural challenge resulting from a blend of hydrological, atmospheric, and biophysical mechanisms resulting in significant effect on water accessibility, socio-economic systems, and ecological sustainability **[1-3].**Droughts have become a prominent global issue, particularly affecting developing nations, with Pakistan being a historical victim of recurrent and elongated periods of droughts. In recent times, a novel and harmful occurrence known as flash droughts has surfaced in the area. These flash droughts distinguish themselves from conventional droughts by their sudden onset and intense nature **[4]**.These occurrences are more prone to causing significant harm to agriculture, livestock, and ecosystems, primarily leading to economic setbacks and food insecurity [**5].** These drought events are not solely triggered by reduced precipitation but rather by a mix of factors, predominantly including rising temperatures attributed to climate change and increased evapotranspiration. Consequently, this leads to a swift decline in soil moisture **[6]** and groundwater levels **[7].**

Flash droughts are classified into two types established on basis of their driving factors: heat wave flash drought **[8]** and precipitation deficit (P-deficit) flash drought **[9].** In P-deficit flash droughts, dry conditions are mainly the driving force and high air temperature (T_{air}) is the resultant **[8].** While, in case of heat wave flash droughts, T_{air} is the major forcing factor, in addition to the other contributory factors being the soil moisture and evapotranspiration response **[9].** Flash droughts are becoming increasingly prevalent due to the escalation of global temperatures, as the world anticipates experiencing warmer climates in the coming years **[10]**. A recent study focusing on the impacts on the meteorological droughts on agricultural activities **[11]** observed and revealed the existence of lateral drive of droughts from southern Punjab to some cities and districts of central

Punjab making the case for the proper mitigation strategies to be developed accordingly. Consequently, the potential occurrence of drought in regions previously considered less susceptible to such events cannot be overlooked, especially as they now grapple with the consequences of climate disturbance.

Study Area:

Pakistan lies at a latitude of 23.5°–37.5° N and longitude of 62°–75° E having a total area of 803,940 km^2 **[12] & [13].**

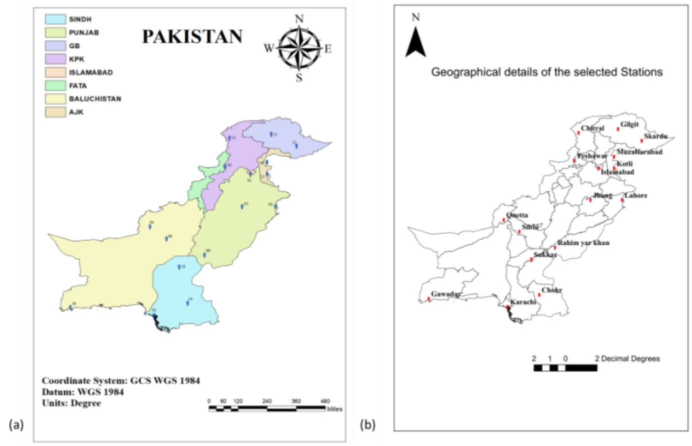

Figure 1: a) Study area map b) Geographical locations of sixteen stations considered on the basis of annual rainfall and temperature.

2. Literature review:

2.1 Impact of meteorological drought on agricultural production in different scales in Punjab

A study that quantifies the adverse effects of meteorological drought on maize yield in South Punjab, Pakistan **[11].** The research employs SPI analysis and finds that drought notably diminishes maize yields, especially during crucial growth phases **[14].** However, prior studies **[11]** are limited by geographic exclusions and reliance on coarse data. Conversely, our research encompasses all of Pakistan and employs both SPI and SPEI indices to assess drought from 1990 to 2022. The inclusion of SPEI enhances drought type classification accuracy. Furthermore, our study investigates the largely overlooked phenomenon of flash droughts in Pakistan and integrates risk exposure assessments for a comprehensive evaluation.

2.2 Comparison of various drought indices to monitor drought status in Pakistan

Numerous studies have evaluated drought indices to analyze drought conditions in Pakistan, emphasizing the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Reconnaissance Drought Index (RDI) **[13]**. These indices exhibit robust efficacy in monitoring drought intensity, particularly in arid and semi-arid areas where drought occurrences are escalating in frequency and severity **[14].** The findings indicate that temperature significantly influences drought conditions, with various indices reflecting an upward trend in drought severity. Nonetheless, prior research **[13]** exhibits deficiencies, including an uncertain criteria for the 58 meteorological stations selected, omission of the Azad Jammu and Kashmir (AJK) region, and absence of risk exposure assessments. Conversely, our investigation rectifies these deficiencies by selecting stations grounded in extensive temperature and precipitation data throughout Pakistan, incorporating the AJK region, and integrating risk exposure analyses. Additionally, our research investigates flash droughts, a phenomenon that has received minimal attention within the Pakistani framework.

2.3 Projected drought pattern under climate change scenario using multivariate analysis

Drought projections under climate change indicate increased temperatures, higher evapotranspiration, reduced precipitation, and more frequent droughts **[15]**. Studies predict a rise in temperatures and evapotranspiration by at least 5% and a precipitation decline exceeding 40%, exacerbating drought conditions .However, limitations in existing research include the exclusion of specific regions, reliance on coarse data, and a lack of focus on flash drought risks. Our study comprehensively covers Pakistan, utilizing SPI and SPEI indices to assess drought from 1990 to 2022. Employing SPEI allows for a more precise categorization of drought types during this timeframe. While prior studies emphasize rising temperatures and decreased precipitation, they neglect the increasing prevalence of precipitation-deficit flash droughts in Pakistan and Southern Asia, as recent findings suggest **[16][17].**

3. Research Methodology:

3.1 Data and methods:

Grid Based climatic data from 1991-2022 for the meteorological factors like precipitation(P), temperature maximum (T_{max}), Temperature minimum (T_{min}) and relative humidity(H) of high resolution 0.25°x0.25° was acquired from Copernicus Fifth generation of European Reanalysis Data (ERA5) except evapotranspiration which was calculated by using Food and Agriculture Organization(FAO)calculator(http://www.fao.org/land-water/databases-and-software/eto-calculator/en/). Root zone soil moisture data was taken from The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2a).

3.2 Methodology:

Standardized Precipitation Index (SPI) was established by **[18]** for the purpose of drought monitoring. It also calculates the alterations in climatic conditions at different periods **[19].**

$$SPI = \frac{X-\mu}{\sigma} \qquad (1)$$

X denotes the quantity of precipitation documented throughout the monitored duration (1990-2022).
U signifies the average precipitation during the monitored duration (1990-2022).
σ represents the standard deviation of precipitation across the identical duration

.

SPEI's working is primarily based upon the basis of SPI algorithm proposed by **[18]** the sole distinction between the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) lies in the fact that SPI relies solely on precipitation data, whereas SPEI incorporates both rainfall and reference evapotranspiration (ET_o) and calculated SPEI as follows**[20]**:

$$SPEI = W - \frac{C0+C1W+C2W^{\wedge}2}{1+d1W+d2W^2+d3W^{\wedge}3}(2)$$

When P≤0.5, W = √−2 ln(P), and when P>0.5, W = √−2 ln(1 − P), C_0=2.5155,C1=0.8028, C2=0.0203, d1 = 1.4327, d2 = 0.1892, d3 = 0.0013.

4. Results:

Time series over time using monthly datasets from 1990-2022 high lightening longest drought period in Asia during 1999-2001**[13]**, 2012 drought in Tharparkar in Sindh , parts of Baluchistan province, and some districts in Punjab high-lightened by the negative values of SPI corresponding to below-average moisture levels**[11][13][15]&[16].**

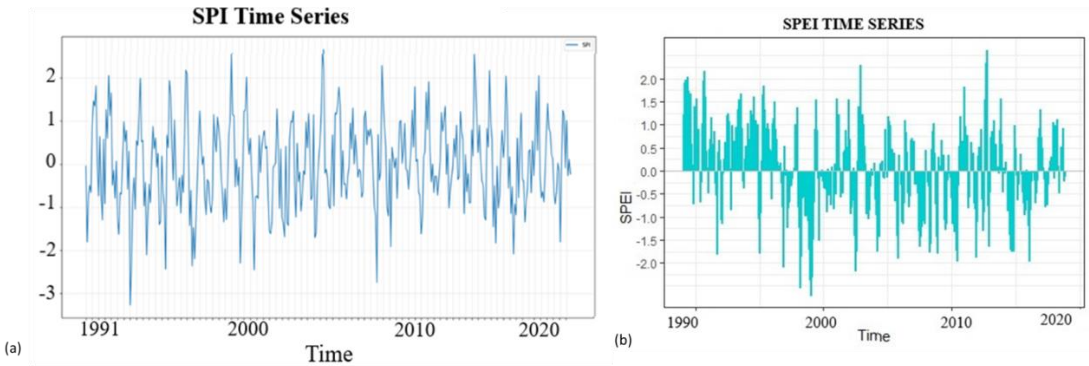

Figure 2 Time series for Flash Drought in Pakistan from 1990-2022 using (a) SPI (b) SPEI.

Table 1 SPI/SPEI Values signifying Drought severity

SPI/SPEI Value	Drought Severity Level
>2	Extremely Wet
1.5 - 2	Very Wet
1 – 1.4	Moderately Wet
-1 – 0.9	Normal
-1.5- -1.1	Moderately Dry
-2 - -1.6	Severely Dry
<-2	Extremely Dry

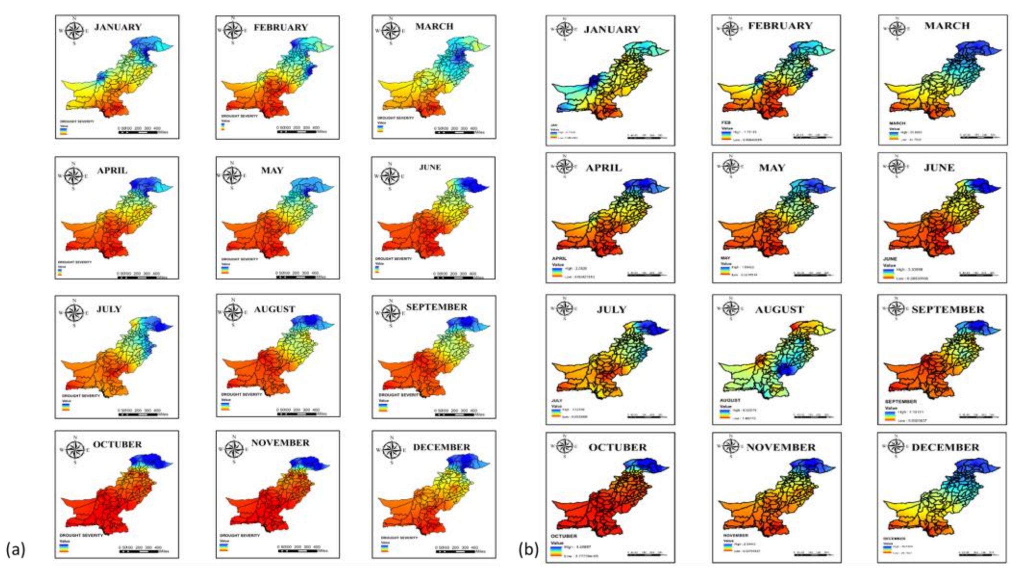

Figure 3 Drought severity categorization mapping from 1990-2022 using a) SPI and b) SPEI

The outcomes derived from the spatial representation exhibited pronounced spatial heterogeneity in the categorizations of drought as determined by these metrics. Meteorological and agricultural drought events were identified through the utilization of SPI and SPEI. Analysis of the SPI and SPEI spatial diagrams indicates that regions primarily in Sindh and Balochistan, along with a portion of southern Punjab, encountered drought conditions in the early stages of the 1999-2002 period **[13][14].** During the timeframe spanning from 2005 to 2012, a substantial northward extension is observed, wherein sections of southern Punjab and Khyber Pakhtunkhwa exhibited severe drought conditions as discerned through time series analysis. Presently, altered precipitation patterns and escalating temperatures are evidenced in the spatial representations, illustrating a shift in drought classification from normal to mild towards the moderate to severe category in the central and northern areas of Punjab **[11]**, underscoring subpar moisture levels **[21].**

5. Practical Implications:

Analysis of remote sensing data encompassing the years 1990 to 2022 has underscored the historical susceptibility of southern and western regions of Pakistan to drought occurrences, particularly within the vital Indus River Basin**[22],**crucial for both populace and agricultural activities. Significantly, these data visuals demonstrate a progression of drought towards the northern territories, as evidenced by evolving severity trends. While the southern and western zones persistently exhibit darker hues denoting heightened severity, the northward advancement of darker shades further accentuates this directional trend **[11]**which would affect the irrigated land reducing the cultivation and production of maize and rice crops **[14]** thereby affecting the economic condition of Pakistan which is heavily reliant on agriculture being an agricultural country.

6. FD Risk Exposure:

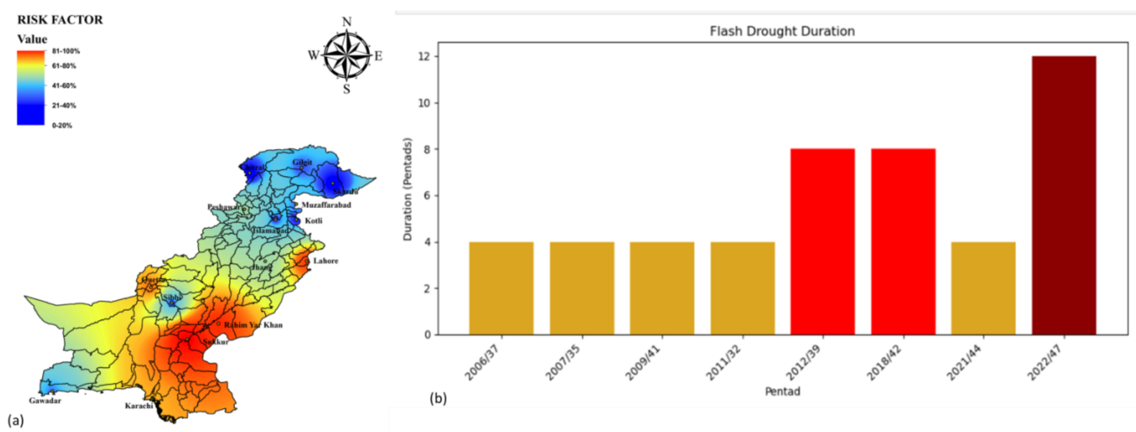

Figure 4a) Flash Drought risk exposure computed by using the at risk days of occurrence into account by multiplying these risk days into the population **[23]** b) Flash drought intensifications observed from 2006-2022.

As predicted by **[11]** and **[15]** the Flash Drought exposure risk has increased in areas of Sindh, Punjab and Balochistan with Punjab and Sindh being severely affected regions and then Balochistan. Therefore, in-depth attribution analysis is essential to quantify the speed and occurrence of Flash Droughts development, which has far-reaching implications for developing an early warning system for hotspot regions **[17].**

7. Conclusion

Our research identified the increased intensity of flash drought occurrence over the spring summer season in the upcoming years as a result of the increases temperature and evapotranspiration and rapid decline in the soil moisture percentile. Mapping and time series of data spanning from 1990-2022 exposed a troubling pattern of increased drought frequency and intensity in Pakistan. The presence of negative values of indices have indicated the severity of droughts from mild to severe especially during the frame of 1999-2001 and normal to mild from 2012-2013 drought period. The severe nature of drought was evident from the spatial plots when the values plummet below 2 and the fluctuation in values from 0.8-1.6 has affected the regions of Baluchistan and Sindh over the years depicting a mild drought over the course of time because of the below moisture conditions. However recent trends have shown that a shift of droughts is likely to happen over the least affected areas because of the anthropogenic turn of events. The implementation of proactive strategies based on our results is essential for promoting resilient water resource management and achieving the objectives set forth in the UN SDGs, particularly in relation to clean water and sustainable urban development.

8. References:

1. Wilhite, D. A. (2000). Drought as a natural hazard: Concepts and definitions in drought : A global assesment.
2. Mukherjee, S., Mishra, A., & Trenberth, K. E. (2018). Climate change and drought: A perspective on drought indices. Current Climate Change Reports, 4(2), 145–163. https://doi.org/10.1007/s40641-018-0098-x.
3. Haile, G. G., Tang, Q., Li, W., Liu, X., & Zhang, X. (2020). Drought: Progress in broadening its understanding. Wiley Interdisciplinary Reviews: Water, 7(2), e1407
4. Christian, J.I., Basara, J.B., Lowman, L.E., Xiao, X., Mesheske, D. and Zhou, Y., 2022. Flash drought identification from satellite-based land surface water index. *Remote Sensing Applications: Society and Environment*, *26*, p.100770.
5. Zhang, L., Liu, Y., Ren, L., Teuling, A. J., Zhu, Y., Wei, L.,& Yin, H. (2021). *Analysis of Flash Drought in China using Artificial Intelligence models. Hydrology and Earth System Sciences Discussions, 2021, 1-33*..
6. Pendergrass, A.G., Meehl, G.A., Pulwarty, R. et al. (n.d.). Flash droughts present a new challenge for subseasonal-to-seasonal prediction. Nat. Clim. Chang. 10, 191–199 (2020). https://doi.org/10.1038/s41558-020-0709-0.
7. Ashraf, S., Ali, M., Shrestha, S., Hafeez, M.A., Moiz, A. and Sheikh, Z.A., 2022. Impacts of climate and land-use change on groundwater recharge in the semi-arid lower Ravi River basin, Pakistan. *Groundwater for Sustainable Development*, *17*, p.100743.
8. Mo, K. C., and Lettenmaier, D. P. (2015). Heat wave flash droughts in decline.Geophys. Res. Lett., 42, 2823–2829, https://doi.org/10.1002/.
9. Mo and Lettenmaier D. P. (2016). Precipitation Deficit Flash Droughts over the United States. Journal of Hydrometeorology, 17(4), 1169-1184 https://doi.org/10.1175/JHM-D-15-0158.1..
10. Gu, L., Chen, J., Yin, J., Sullivan, S.C., Wang, H.M., Guo, S., Zhang, L. and Kim, J.S., 2020. Projected increases in magnitude and socioeconomic exposure of global droughts in 1.5 and 2∘ C warmer climates. *Hydrology and Earth System Sciences*, *24*(1), pp.451-472.
11. Waseem, M., Khurshid, T., Abbas, A., Ahmad, I., & Javed, Z. (2022). Impact of meteorological drought on agriculture production at different scales in Punjab, Pakistan. *Journal of Water and Climate Change*, *13*(1), 113-124.
12. Spatio-temporal mapping to determine LST, MSI, NDVI and Savi over Kalat, Pakistan. Javid, B. A. (n.d.)(PDF) Spatio-temporal MAPPING TO DETERMINE LST, MSI, NDVI AND SAVI OVER KALAT, PAKISTAN (researchgate.net)
13. Adnan, S., Ullah, K., Shuanglin, L., Gao, S., Khan, A.H. and Mahmood, R., 2018. Comparison of various drought indices to monitor drought status in Pakistan. Climate Dynamics, 51, pp.1885-1899.
14. Rahman, M. A., Ali, M., Mojid, M. A., Anjum, N., Haq, M. E., Kainose, A., & Dissanayaka, K. D. C. R. (2023). Crop coefficient, reference crop evapotranspiration and water demand of dry-season Boro rice as affected by climate variability: A case study from northeast Bangladesh. Irrigation and Drainage, 72(1), 148-165
15. Waseem, M., Ajmal, M., Ahmad, I., Khan, N. M., Azam, M., & Sarwar, M. K. (2021). Projected drought pattern under climate change scenario using multivariate analysis. *Arabian Journal of Geosciences*, *14*, 1-13.
16. Ali, M., Gillani, S. H., & Ali, U. (2024). Flash Drought Monitoring in Pakistan Using Machine Learning Techniques and Multivariate Drought Indices. Technical Journal, 3(ICACEE), 717-729.
17. Ullah, I., Mukherjee, S., Syed, S., Mishra, A. K., Ayugi, B. O., & Aadhar, S. (2024). Anthropogenic and atmospheric variability intensifies flash drought episodes in South Asia. *Communications Earth & Environment*, *5*(1), 267
18. McKee, T. B., Doesken, N. J., & Kleist, J. (1993, January). The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology (Vol. 17, No. 22, pp. 179-183)
19. Liu, C., Yang, C., Yang, Q., & Wang, J. (2021). Spatiotemporal drought analysis by the standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI) in Sichuan Province, China. Scientific Reports, 11(1), 1280.
20. Sergio M. Vicente-Serrano, S. M., Reig, F., & Latorre, B. (2014). Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring.
21. Rahman, K. U., Ejaz, N., Shang, S., Balkhair, K. S., Alghamdi, K. M., Zaman, K., ... & Hussain, A. (2024). A robust integrated agricultural drought index under climate and land use variations at the local scale in Pakistan. Agricultural Water Management, 2
22. Janjua, S., Hassan, I., Muhammad, S., Ahmed, S., & Ahmed, A. (2021). Water management in Pakistan's Indus Basin: challenges and opportunities. Water Policy, 23(6), 1329-1343..
23. Anthropogenic shift towards higher risk of flash drought over China.https://doi.org/10.1038/s41467-019-12692-7.