A COMPREHENSIVE REVIEW OF DROUGHT IN PAKISTAN

S. Munir* and S. A. Shirazi

Department of Geography , Forman Christian College, (A Chartered University) Lahore-54600, Pakistan
Institute of Geography, University of the Punjab, Lahore- 54590, Pakistan
* Corresponding Author Email: sulmanmunir@fccollege.edu.pk

ABSTRACT: Droughts are a recurring natural hazard with significant socioeconomic and environmental implications, particularly in water-scarce regions like Pakistan. Accurate identification and timely assessment of droughts are essential for implementing effective mitigation and adaptation strategies. This review study aims to provide a comprehensive analysis of various studies about drought indices and use of remote sensing techniques used for drought identification and mitigation in Pakistan. Through an extensive literature review, we examine the key findings of different studies, identify research gaps, and suggest potential improvements for better drought monitoring and management in Pakistan.

Keywords: Drought, Drought indices, Natural hazard, Remote sensing, Pakistan.

(Received 13.07.2023 Accepted 16.09.2023)

INTRODUCTION

Drought is a complex and multifaceted phenomenon that affects many regions around the world. It is a natural disaster that arises from a prolonged period of below-average precipitation and high temperatures (Hao *et al.*, 2017). Drought is a slow-onset disaster that can have significant environmental, social, and economic consequences, including crop failures, water shortages, and increased risk of wildfires (Wilhite and Pulwarty, 2017). In recent years, there has been an increasing concern about the frequency and intensity of drought events, and their impact on human societies and natural ecosystems (Allen *et al.*, 1998).

The frequency, duration, and intensity of drought events are expected to increase due to climate change, which poses a significant threat to human societies, ecosystems, and economies. In recent years, droughts have become more frequent and severe, affecting millions of people and ecosystems worldwide (Dai, 2011). In the early 2000s, several regions of the world experienced prolonged and severe droughts that caused significant social and economic impacts. This essay aims to provide an overview of the drought phenomenon, its causes, impacts, and possible solutions, with a focus on the drought events that occurred in the early 2000 (Sheffield and Wood, 2007).

Droughts are complex natural hazards that can be caused by a variety of factors, including meteorological, hydrological, and socio-economic factors. Meteorological droughts are caused by a lack of precipitation, while hydrological droughts occur when surface and groundwater resources are depleted. Socio-economic droughts are caused by the inability of human societies to cope with water scarcity due to social, economic, or political factors.

Climate change is considered one of the main causes of droughts. The increase in global temperatures leads to changes in precipitation patterns, with some regions experiencing more frequent and severe droughts. The Intergovernmental Panel on Climate Change (IPCC) predicts that the frequency and severity of droughts will increase in many regions of the world due to climate change, especially in arid and semi-arid regions (Lewis *et al.*, 2018; IPCC, 2022). The El Niño-Southern Oscillation (ENSO) phenomenon is another factor that can cause droughts. El Niño is a warming of the sea surface in the central and eastern Pacific, while La Niña is a cooling of the same area. Both events can cause changes in global weather patterns, leading to droughts in some regions and floods in others (Lyon, 2004).

Droughts can have significant impacts on the environment, social, and economic systems, leading to food and water insecurity, poverty, and even famine. The impacts of droughts are often long-lasting and can affect entire communities and ecosystems. In addition to its impact on economic sectors, drought can also have significant social and environmental consequences. Water scarcity and reduced access to safe drinking water can lead to health issues, such as the spread of waterborne diseases. Drought can also contribute to social conflict, as competition for limited water resources increases. Furthermore, drought can have long-term environmental impacts, such as reduced biodiversity and soil erosion.

While drought has always been a natural phenomenon, there is increasing evidence to suggest that climate change is exacerbating its frequency and severity. Climate models predict that many regions around the world will experience more frequent and intense droughts in the coming decades. This has significant implications for global food security and water resource management.

Efforts to address drought and its impacts have focused on a range of strategies, including water conservation, drought-resistant crops, and improved irrigation practices. In addition, there is growing interest in the use of early warning systems and drought forecasting tools to help communities prepare for drought events.

Drought in Pakistan: Pakistan is an important country of South Asia with significant temporal and spatial climatic diversity while most of its part has arid and semiarid characteristics (Mazhar *et al*., 2021; Mazhar *et al.*, 2022). Summer monsoon winds are the main source of rainfall in the country which contribute about 59% of total annual rainfall. As an arid to semi-arid country, Pakistan is vulnerable to drought events, which are driven by climatic variations, irregular monsoons, and extreme weather conditions. Droughts have profound impacts on the nation's agricultural productivity, water availability, and food security, affecting the livelihoods of millions of people who depend on agriculture as their primary source of income. Moreover, droughts can lead to environmental degradation, increased water scarcity, and heightened risk of food crises in the country.

As per climate risk index (CRI), Pakistan stood at 5^{th} among top 10 highly affected countries by drought. (Eckstein, Künzel and Schäfer, 2021). Overall, increase of average 0.1^{0} C temperature per decade is reported in Pakistan by different scholars since 1960 (del Rio *et al.*, 2013). The period of 1998-2002 observed extreme drought in Southwest Asia in result of El Nino Southern Oscillation (ENSO) of 1997-1998. As per the results of different global climatic models, future climate of Pakistan is expected to be as much severer which will influence water balance, food supply, ecosystem sustainability, health and eventually after sector of life. Southern and central parts of the country e.g. most of Balochistan province, interior and eastern Sindh, southern parts of Khyber Pakhtunkhwa and the Punjab etc. which are already facing water stress are expected to be adversely affected as more water stress will worsen the demand and supply of water in those particular areas (Hina *et al.*, 2021). Increase in population, deforestation, urbanization, climate change and other factors will intensify the hazard.

Drought Indices: Drought identification and drought indices play a crucial role in understanding and monitoring one of the most devastating natural hazards affecting various regions worldwide. Droughts are prolonged periods of abnormally low precipitation that result in water scarcity, leading to severe ecological, agricultural, and socio-economic impacts. Drought monitoring is a vital component of drought management and preparedness, providing essential information for assessing and mitigating the impacts of drought on various sectors. Droughts, characterized by extended periods of reduced precipitation and water scarcity, have far-reaching consequences for agriculture, water resources, ecosystems, and socio-economic systems. Monitoring drought conditions involves the systematic collection, analysis, and interpretation of meteorological, hydrological, and socio-economic data to evaluate the severity, duration, and spatial extent of drought events. To effectively assess and manage drought conditions, scientists and policymakers rely on drought identification techniques and the use of drought indices. These indices serve as quantitative measures that integrate multiple meteorological, hydrological, and agricultural variables to characterize and quantify drought severity, duration, and spatial extent.

Standardized Precipitation Index (SPI): The Standardized Precipitation Index is a meteorological drought index that focuses solely on precipitation data. It standardizes the accumulated precipitation data over a certain time scale (e.g., 1 month, 3 months, 12 months) and expresses it in terms of standard deviations from the long-term mean. SPI is valuable for understanding short-term droughts associated with precipitation deficits (McKee, Nolan and Kleist, 1993).

Palmer Drought Severity Index (PDSI): The Palmer Drought Severity Index, developed by Wayne Palmer in the 1960s, is one of the most widely used drought indices. It takes into account precipitation, temperature, and soil moisture to measure drought severity over a longer period. The PDSI provides information about both short-term and long-term drought conditions (Palmer, 1965).

Standardized Precipitation Evapotranspiration Index (SPEI): Similar to SPI, the Standardized Precipitation Evapotranspiration Index incorporates both precipitation and potential evapotranspiration data. This index provides a more comprehensive assessment of drought by accounting for the effect of temperature on water demand from the atmosphere (Vicente-Serrano, Beguería and López-Moreno, 2010).

Crop Moisture Index (CMI): The Crop Moisture Index is a drought index primarily used for agricultural purposes. It integrates soil moisture, precipitation, and evapotranspiration to assess the moisture conditions that affect crop growth and development (Heim, 2002).

Drought Identification and Monitoring in Pakistan: Drought identification and monitoring in Pakistan play a critical role in managing the nation's water resources and mitigating the devastating impacts of water scarcity on agriculture, economy, and livelihoods. With Pakistan's predominantly arid to semi-arid climate and growing population, droughts have become recurrent and more severe in recent years. Addressing this challenge necessitates accurate and timely detection of drought events, as well as a robust monitoring system to assess drought severity and extent. Utilizing advanced scientific methods, such as remote sensing, climate indices, and hydrological modeling, researchers and policymakers can better understand the dynamics of drought in Pakistan and develop effective strategies to safeguard against its far-reaching consequences.

Adnan & Ullah (2022) analyzed climatic trends in Pakistan, including evapotranspiration, temperature, and precipitation. Data from 60 weather stations spanning from 1951 to 2019 were used to identify seasonal trends. Penman-Monteith method was employed to calculate evapotranspiration. The study concluded a minor increase in maximum temperature in Azad Kashmir, Gilgit Baltistan, and Balochistan, and a notable increase in minimum temperature in Punjab, Sindh, and Balochistan. The remaining regions showed decreasing trends. Evapotranspiration increased in Azad Kashmir and Balochistan but decreased in Punjab. Precipitation exhibited a minor increase in Punjab and K.P.K. Drought monitoring was done using SPI, SPEI, and decile index, indicating a negative trend in AJK and a positive trend in Punjab and K.P.K at a 95% confidence level.

Moazzam *et al*. (2022) conducted a research in the Gilgit Baltistan region, which lacks real-time meteorological data, to analyze rainfall variability and monitor short-term and long-term droughts. They used CHIRPS monthly precipitation data from 1981 to 2020 and applied SPI to calculate district-wise precipitation patterns and 1- and 12-month droughts. Statistical tests (Mann-Kendall and Spearman’s rho) were used to determine drought trends.

The study identified severe drought years in 1982-83 and 2000-2001 in key districts like Gilgit, Astor, Diamer, Ghizer, and Ghanche. Increasing rainfall trends were observed, suggesting that snowfall was converting into rainfall due to global warming and rising temperatures. Future precipitation projections using CMIP5-GCMs indicated a 4% growth in the 21st century. The projections showed that the first half of the century would be wet with a 13% increase in precipitation, potentially leading to severe floods. In contrast, the latter half of the century was expected to experience drought, with a 9% decrease in precipitation.

Ullah *et al*. (2022) studied climate change and drought in Pakistan. They found an increase in drought magnitude in semiarid to arid areas for both seasons. Temperature played a key role in defining droughts, while precipitation was influential in western areas. Large-scale climate drivers like temperature, geopotential height anomalies, wind speed, and humidity influenced droughts. Nino-Southern Oscillation (ENSO4.0), Nino4, and sea surface temperature were significant factors for seasonal droughts across the country. The study highlights the impact of climate change on drought patterns in Pakistan.

Niaz *et al*. (2022) proposed an approach called 'Regional Intensive Continuous Drought Probability Monitoring System (RICDPMS)' based on copulas functions, steady-state probabilities, and Monte Carlo Feature Selection (MCFS) to overcome the challenge of providing quick and comprehensive information about drought in a homogenous environment using the Standardized Precipitation Index (SPI). They applied this approach to precipitation data from six weather stations in northern Pakistan and found that RICDPMS effectively assessed regional drought and provided a quantitative measure of deficits with varying drought intensities. The study suggests that RICDPMS could be used for drought monitoring and developing mitigation policies.

Adnan & Ullah (2020) developed the Drought Hazard Index (DHI) for Pakistan using precipitation and soil moisture data. They identified 19 districts as extremely vulnerable to drought, with central and southern regions facing severe drought and northern districts experiencing milder drought events. The index focused solely on meteorological drought and did not consider other important factors like stream flow, temperature, and vegetation.

Khan *et al*. (2020) used machine learning algorithms for the first time to predict drought in Pakistan. They employed Princeton Global Forcing (PGF Version-3) gridded data to measure temperature and precipitation due to limited meteorological stations. Three machine learning techniques (ANN, SVM, and KNN) were applied, and SVM-based models proved most effective in capturing drought attributes. Results showed a positive correlation between SPEI and relative humidity during the Rabi season, highlighting wind speed, relative humidity, and temperature as crucial elements for developing a drought prediction model in Pakistan.

Khan *et al*. (2020) analyzed the occurrence of meteorological droughts and associated problems in the Cholistan region of Southern Punjab. They collected precipitation data from 10 weather stations for 33 years (1981-2013) to calculate the Standardized Precipitation Index (SPI) and assess rainfall patterns, drought intensity, and duration. Field surveys were conducted for result validation. The study found that the Cholistan region was predominantly arid, and meteorological droughts were a common phenomenon. The frequent occurrence of droughts disrupted the entire ecosystem and made life extremely challenging for the people in the area. As a result, permanent settlement was not feasible, and the population had to lead nomadic lives to cope with the repeated threat of different types of droughts.

Ahmed *et al*. (2019)used the Standardized Precipitation Index (SPI) and a statistical approach to calculate climate change uncertainties in seasonal drought severity area frequency curves in the arid region of Balochistan, covering 44% of Pakistan's total area. Gridded precipitation data from GPCC was used for historical drought events, and Support Vector Machine (SVM) and quantile mapping were applied to downscale future precipitation. Model performances were validated using statistical tests. SPI was used with historical and future rainfall data to depict seasonal droughts during crop growing periods. Drought severity area frequency curves were developed for the historical period (1961-2010) and projected period (2010-2099). The results showed that droughts with higher return periods affected larger areas, while lower severity and return period droughts affected larger areas in future projections. High severity and return period droughts impacted lesser areas in the future projections of droughts.

Adnan *et al*. (2018) compared 15 drought indices using ground data of precipitation and temperature from 58 meteorological stations. They employed various statistical tests, including confidence level, STDEV, RMSE, and CRM, to validate the results. SPI was considered the prime index due to its simplicity and versatility, with values of R2 ranging from 0.12 to 0.77. SPI, SPEI, and RDI demonstrated good capability in monitoring drought scenarios in Pakistan. Timeseries analysis showed that Sc-PDSI and SSMAI slightly decreased, while others exhibited increasing trends. Pearson correlation coefficient ranged from 0.34 (for SSMAI) to 0.88 (for SPEI) in assessing the indices' performance.

Adnan *et al*. (2015) conducted research on drought monitoring in Sindh using the Standardized Precipitation Index (SPI). They downloaded 60 years of gridded precipitation and soil moisture data from the Global Precipitation Climatological Center and Climate Prediction Center, respectively, with a spatial resolution of (0.50 x 0.50) for the period of 1951-2010. The Regional Drought Identification Model (ReDIM) was utilized to compute SPI for various time scales (3, 6, 9, 12, and 24 months). The researchers performed different statistical tests, including Kendall τ-test, student t-test, and Sen’s slope method, to determine confidence levels and assess randomness, trend, and magnitude. The study identified monsoon months as highly vulnerable to drought, with the most severe drought episodes observed during 1972-1974 and 2000-2002. Drought hazard maps were generated, revealing that 10 districts in Sindh were extremely vulnerable to drought. The research provided valuable information on meteorological drought magnitude, frequency, and intensity for disaster management agencies.

Mazhar & Nawaz (2014)conducted a study comparing three interpolation techniques to develop drought intensity surfaces using precipitation data from 34 randomly distributed districts in Pakistan over a 30-year period (1980-2010). The study found that spline interpolation with a tension variogram was the most suitable method to depict drought intensity patterns, and it showed a high correlation with drought data provided by the government for the years 2000-2001, which were severe drought years. The results indicated that northern districts experienced low to mild drought, while southern districts were facing mild to severe drought conditions.

Drought Mitigation in Pakistan: Drought mitigation is a critical component of disaster risk reduction and climate change adaptation strategies aimed at minimizing the adverse impacts of drought events on ecosystems, water resources, agriculture, and communities. Droughts are recurrent natural disasters with far-reaching consequences, including water scarcity, reduced crop yields, food insecurity, and economic losses. Mitigating the impacts of droughts requires a comprehensive and integrated approach that encompasses various measures such as water conservation, sustainable land management, improved irrigation techniques, early warning systems, and climate-resilient agricultural practices.

Drought mitigation in Pakistan is a complex and multifaceted issue that requires coordinated efforts from various stakeholders. Over the years, several studies have been conducted to understand the impact of drought and to propose measures to mitigate its adverse effects. These studies provide valuable insights into the vulnerability of different regions to drought, the impact of climate change, and strategies to build resilience in agriculture and water resource management. It is crucial for policymakers and practitioners to consider these research findings and implement comprehensive and proactive drought mitigation measures to safeguard the country's water and food security.

In their book, Ahmad *et al*., (2004) present a comprehensive study which is part of the Regional Project on "Drought Assessment and Potential for Mitigation in Southwest Asia," conducted by IWMI in collaboration with regional partners, with a focus on drought-related issues and measures in Pakistan's Baluchistan and Sindh provinces. Pakistan frequently experiences droughts, affecting agriculture and non-agriculture sectors. Coping strategies like water conservation and groundwater exploitation have been adopted by farmers. However, there is a lack of institutional mechanisms for long-term drought preparedness and mitigation. The study recommends strengthening monitoring and information sharing, promoting efficient water management technologies, encouraging indigenous water-harvesting systems, adopting conjunctive use of water resources, and training farmers in efficient water-use practices. Additionally, establishing comprehensive drought-mitigation infrastructure at federal, provincial, and district levels and formulating a national drought policy are proposed to enhance resilience and coordination in tackling drought impacts.

Pomee, Khan and Ali (2005) emphasized that to tackle potential drought implications on various disciplines, a National Drought Policy is urgently required. The policy should prioritize preparedness, insurance, relief, and incentives while coordinating federal services with local entities. Implementing an autonomous National Drought Commission is recommended due to weak coordination among agencies. Additionally, an integrated water management approach, including demand management, water conservation, and modern technologies for crop production, is crucial for sustainable food supplies. Evaluating Participatory Irrigation Management and constructing multipurpose reservoirs are also essential steps.

Ahmed *et al*., (2016) analyzed that droughts are particularly destructive when they coincide with crop growing seasons. To better inform drought mitigation efforts, a study in Balochistan, Pakistan, used precipitation data to reconstruct historical droughts during different climatic seasons. Seasonal drought events were identified using the standardized precipitation index, and return periods were calculated to determine their frequency. The study revealed varying patterns of drought occurrence across the province, with different regions experiencing different types of droughts at different intervals.

The arid climate, rough topography, and high rainfall variability in Balochistan contribute to its vulnerability to droughts. The study's findings can be used to adapt and implement proper mitigation measures, benefiting disaster management, agriculture, and development authorities. However, the complexity of drought calls for more comprehensive studies, including examining the socioeconomic impact, groundwater propagation, and geographical distribution of drought risk. Future studies could also investigate projected precipitation data to understand the pattern of future droughts in the context of climate change and variability.

Ali, Li and Ali (2021) used a remote sensing approach for drought monitoring and vegetation dynamics assessment by analyzing multi-satellite data. They utilized TRMM data for the period of 2001-2017 and prepared a land use and land cover map of Pakistan using the MODIS (MCD12Q1) product. Various indices like DSI, NAP, VCI, NVSWI, NDVI, and ET were incorporated to calculate drought frequency. The study found that TVDI, DSI, and NDVI were useful for assessing drought frequency, and all indices showed significant positive correlations. The results highlighted severe droughts in Pakistan in 2001, 2002, and 2006. DSI and NVSWI were identified as the best indices for drought monitoring, leading to recommendations for experts, planners, and researchers to use these indices for disaster risk reduction and improving drought mitigation strategies.

Application of Remote Sensing in Drought Studies: The application of remote sensing in drought studies has revolutionized our ability to monitor, assess, and manage drought conditions over large spatial scales (Abro *et al.*, 2022). Remote sensing, using satellite and airborne sensors, provides a valuable tool for capturing comprehensive and timely information on various drought-related parameters, including precipitation, soil moisture, vegetation health, and water availability. By analyzing the spectral signatures and radiometric properties of Earth's surface, remote sensing enables the estimation of key drought indicators and the mapping of drought severity, extent, and impacts.

The application of remote sensing in drought studies has proven to be invaluable in the context of Pakistan, where drought events pose significant challenges to agricultural productivity, water resources, and socio-economic well-being (Ali *et al.*, 2023). Remote sensing techniques provide a powerful tool for monitoring and assessing drought conditions in this region, enabling timely and accurate information on key drought indicators. By leveraging satellite imagery and other remote sensing data sources, researchers and policymakers in Pakistan can gain insights into various aspects of drought, such as vegetation health, soil moisture, and precipitation patterns. This section aims to highlight the specific application of remote sensing in drought studies within Pakistan, emphasizing the importance of these techniques in enhancing understanding, preparedness, and mitigation strategies for drought events in the country. The discussion will be supported by references to relevant studies and resources that demonstrate the use of remote sensing in drought monitoring and assessment specifically in Pakistan.

Ali *et al*., (2023) emphasizes the significance of drought monitoring in Pakistan using multi-satellite data and various indices like NVSWI, DSI, VCI, and NAP. It identifies severe drought years in 2001, 2002, and 2006 and notes a downward trend in overall drought frequency from 2001 to 2017. The positive correlations between VHI, VCI, NDVI, and NVSWI values are also highlighted. Effective drought mitigation strategies and risk reduction can be achieved with the help of DSI and NVSWI indices at regional and national levels.

In their study, Khan *et al*. (2020) calculated six drought indices - TCI, VCI, SPI, PCI, SMCI, and SPEI - over a 15-year period (2000-2015) for the Potowar Region in Punjab, Pakistan. Remote sensing data, including MODIS NDVI and land surface temperature, were used to assess drought for the region, covering the districts of Chakwal, Jhelum, Rawalpindi, and Attock. Data related to soil moisture, precipitation, and temperature were obtained from TerraClimate, and SPI and SPEI were computed at different intervals. The study found that drought severity was influenced by multiple factors, including temperature, soil moisture, and precipitation. Precipitation strongly affected soil moisture, while temperature had a significant impact on vegetation cover. Chakwal and Attock experienced the highest surface temperatures, while Rawalpindi was the coldest during the study period. Attock and Rawalpindi also had the highest soil moisture levels during drought periods. The years 2000, 2001, 2002, 2004, 2009, 2010, and 2012 were identified as severe drought years by all indices studied. The research highlighted that drought mitigation and severity were not dependent on a single factor but were influenced by a combination of factors.

Baig *et al*. (2020)assessed drought in the Chitral Kabul Basin Region using remote sensing data from CHIRPS and MOD13Q1 products, as well as in-situ station data. The study covered the period from 2000 to 2018. They obtained rainfall data with a spatial resolution of 0.050 and LST data at 250m resolution. Soil moisture data was acquired from NASA's FLDAS_NOAH01_C_GL_M at a resolution of 0.10 x 0.10. Real-time data from nearby PMD stations during monsoon seasons from 2000 to 2016 was also used. The researchers utilized various tools in ArcMap, such as mask, cell statistics, and bilinear interpolation, to process the data. They employed the Non-Microwave Integrated Drought Index (NMIDI) to derive meteorological drought and the Scale Drought Condition Index (SDCI) to evaluate agricultural drought.

Amin *et al*. (2020) conducted a research on agricultural drought and its impact on wheat crop in the arid Thal region of northwest Punjab, comprising the districts of Bhakkar, Khushab, Jhang, Layyah, and Muzaffargarh. Geospatial techniques were used, and CHIRPS and MOD13Q1 data were acquired for the period of 2000-2015 to assess drought patterns and magnitude. CHIRPS data had 4.8 km spatial and one-month temporal resolution. NDVI, SPI (6 months), VCI, STVI, and wheat crop yield anomalies were measured to evaluate the severity of drought. The results revealed that 2000-2002 were extreme drought years with poor crop yield, while 2011-2014 were normal years in comparison to others. Weighted overlay analysis generated a combined risk map, showing 59.12% of the total area as having no drought, 12.76% with moderate drought, and 28.15% with slight drought. This study highlights the significance of drought monitoring in the region to mitigate economic troubles related to wheat production.

Usman & Nichol (2020) conducted a study in the arid Tharparkar desert of Sindh Province, known for its food insecurity due to low and variable rainfall. They provided timely estimates of seasonal growth indicators in cultivable areas and used satellite-based rainfall and biomass data. Satellite rainfall data from TRMM and CHIRPS showed good correlation (ranging between R = 0.75-0.97) with ground station data. CHIRPS data was used for further modeling to predict drought, compare rainfall criteria with NDVI-based biomass productivity, and derive spatial estimates of phenological variables. Rainfall mapping revealed significant differences between precipitation and NDVI values in both dry and wet seasons. Intense rainfall caused crop destruction during ripening, but overall, sustained water supply was more critical than total annual rainfall. Difficulty in predicting droughts in the early growing season was observed due to extreme climatic diversity. The study's results can be used to recommend permanent settlements in areas with more consistent rainfall patterns. This research contributes valuable insights for improving agricultural practices and water management in the region.

Mazhar *et al*. (2018) conducted a study to measure desertification patterns in three arid areas of Punjab, Pakistan: Bahawalpur, Rahimyar Khan, and Rajanpur. They used MODIS products to calculate various indices like NDVI, PET, SAVI, and MSI to assess desertification trends. The Desert Difference Index (DDI) showed a negative correlation with NDVI and was computed to measure desertification trends based on albedo values. The study found that 11.09% of the area was highly vulnerable to desertification, with a 28.47% increase in medium vulnerability and a 39.88% decrease in low vulnerability.

Shaheen & Baig (2011) measured drought severity in the Thal Doab Region using Landsat, SPOT images, and meteorological data. Positive correlations were observed between SPI, NDVI anomalies, crop yield, and rainfall, while crop yield showed a negative correlation with evapotranspiration. Drought severity maps were developed, helping planners understand the situation in the study area, with 2001 identified as the worst drought year.

These studies collectively emphasize the importance of remote sensing in providing timely and spatially explicit information for drought preparedness and mitigation strategies in Pakistan. Continued research and advancements in remote sensing applications are essential for strengthening drought resilience and sustainable water resource management in the country.

Summary: This review article comprehensively examines the recent research and advancements in drought monitoring and mitigation in Pakistan. Droughts have become increasingly recurrent and severe in the region, posing significant challenges to agriculture, water resources, and socio-economic stability. To address this critical issue, a plethora of studies have been conducted over the years, focusing on drought indices, identification, monitoring techniques, and the utilization of remote sensing technologies.

The first section of the review delves into various drought indices used in Pakistan to assess the severity and duration of drought events. These indices, including the Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), and the Crop Moisture Index (CMI), are evaluated for their effectiveness in capturing different aspects of drought patterns in the country. The discussion emphasizes the importance of selecting appropriate indices tailored to the unique climatic and hydrological conditions of Pakistan.

Next, the review discusses the various drought mitigation strategies employed in the country. These include water management practices, such as rainwater harvesting and water storage techniques, as well as crop selection and agronomic practices that promote drought resistance. Additionally, the study explores the role of community-based approaches and policy interventions in mitigating the socio-economic impacts of droughts.

The integration of remote sensing technologies in drought monitoring is a key focus of the third section. Remote sensing offers a valuable tool to assess and map drought conditions over large areas in near real-time, enabling timely and informed decision-making for policymakers and stakeholders. Studies utilizing satellite-based platforms such as MODIS, Landsat, and Sentinel data have played a crucial role in enhancing drought monitoring capabilities in Pakistan.

In conclusion, this review article provides a comprehensive overview of the current state of knowledge on drought indices, identification, monitoring, and mitigation strategies in Pakistan. The synthesis of various studies underscores the importance of a multidisciplinary and integrated approach to tackle the challenges posed by droughts in the region. The insights gained from these studies can serve as a foundation for policymakers and researchers to develop effective drought management strategies, thereby building resilience and adaptive capacity in the face of future drought events in Pakistan.

Conflicts of Interest: All authors declare that there is not any personal or financial conflicts of interest.

REFERENCES

Abro, M. I. *et al.* (2022) 'Estimation of a trend of meteorological and hydrological drought over Qinhuai River Basin', *Theoretical and Applied Climatology*. Springer Vienna, 147(3–4), pp. 1065–1078. doi: 10.1007/s00704-021-03870-z.

Adnan, S. *et al.* (2018) 'Comparison of various drought indices to monitor drought status in Pakistan', *Climate Dynamics*. Springer Berlin Heidelberg, 51(5–6), pp. 1885–1899. doi: 10.1007/s00382-017-3987-0.

Adnan, S. and Ullah, K. (2020) 'Development of drought hazard index for vulnerability assessment in Pakistan', *Natural Hazards*. Springer Netherlands, 103(3), pp. 2989–3010. doi: 10.1007/s11069-020-04116-3.

Adnan, S. and Ullah, K. (2022) 'Long-term trends in climate parameters and multiple indices for drought monitoring over Pakistan', *Meteorology and Atmospheric Physics*. Springer Vienna, 134(4), pp. 1–22. doi: 10.1007/s00703-022-00908-3.

Ahmad, S. *et al.* (2004) *Drought Mitigation in Pakistan : Current Status and Options for Future Strategies*. IWMI.

Ahmed, K. *et al.* (2016) 'Characterization of seasonal droughts in Balochistan Province, Pakistan', *Stochastic Environmental Research and Risk Assessment*. Springer Berlin Heidelberg, 30(2), pp. 747–762. doi: 10.1007/s00477-015-1117-2.

Ahmed, K. *et al.* (2019) 'Climate change uncertainties in seasonal drought severity-area-frequency curves: Case of arid region of Pakistan', *Journal of Hydrology*. Elsevier, 570(February 2017), pp. 473–485. doi: 10.1016/j.jhydrol.2019.01.019.

Ali, F., Li, B. Z. and Ali, Z. (2021) 'Strengthening Drought Monitoring Module by Ensembling Auxiliary Information Based Varying Estimators', *Water Resources Management*. Springer Netherlands, 35(10), pp. 3235–3252. doi: 10.1007/s11269-021-02888-2.

Ali, S. *et al.* (2023) 'Impact assessment of drought monitoring events and vegetation dynamics based on multi-satellite remote sensing data over Pakistan', *Environmental Science and Pollution Research*. Springer Berlin Heidelberg, 30(5), pp. 12223–12234. doi: 10.1007/s11356-022-22995-w.

Allen, R. G. *et al.* (1998) *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56*, *Irrigation and Drainage*. doi: 10.1016/j.eja.2010.12.001.

Amin, M. *et al.* (2020) 'Monitoring agricultural drought using geospatial techniques: A case study of thal region of Punjab, Pakistan', *Journal of Water and Climate Change*, 11(1S), pp. 203–216. doi: 10.2166/wcc.2020.232.

Baig, M. H. A. *et al.* (2020) 'Assessing meteorological and agricultural drought in Chitral Kabul river basin using multiple drought indices', *Remote Sensing*, 12(9). doi: 10.3390/RS12091417.

Dai, A. (2011) 'Drought under global warming: A review', *Wiley Interdisciplinary Reviews: Climate Change*. doi: 10.1002/wcc.81.

Eckstein, D., Künzel, V. and Schäfer, L. (2021) *GLOBAL CLIMATE RISK INDEX 2021*.

Hao, Z. *et al.* (2017) 'An overview of drought monitoring and prediction systems at regional and global scales', *Bulletin of the American Meteorological Society*, 98(9). doi: 10.1175/BAMS-D-15-00149.1.

Heim, R. R. (2002) 'A review of twentieth-century drought indices used in the United States', *Bulletin of the American Meteorological Society*. doi: 10.1175/1520-0477(2002)083<1149:AROTDI>2.3.CO;2.

Hina, S. *et al.* (2021) 'Droughts over Pakistan: possible cycles, precursors and associated mechanisms', *Geomatics, Natural Hazards and Risk*, 12, pp. 1638–1668. doi: 10.1080/19475705.2021.1938703.

IPCC (2022) 'Summary for Policymakers, Global Warming of 1.5 ◦C—IPCC Special Report on the Impacts of Global Warming of 1.5 ◦C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways', *IPCC: Geneva, Switzerland*, 2(October), p. 32. Available at: www.environmentalgraphiti.org.

Khan, A. A., Safdar[2], Q. and Khan[3], K. (2020) 'Occurrence pattern of meteorological droughts and associated problems in Cholistan region of Pakistan: A spatio-temporal view', *Basic Research Journal of agricultural Science and Review*, 8(3), pp. 38–051.

Khan, N. *et al.* (2020) 'Prediction of droughts over Pakistan using machine learning algorithms', *Advances in Water Resources*. Elsevier Ltd, 139(January). doi: 10.1016/j.advwatres.2020.103562.

Khan, R. *et al.* (2020) 'Satellite-based (2000–2015) drought hazard assessment with indices, mapping, and monitoring of Potohar plateau, Punjab, Pakistan', *Environmental Earth Sciences*. Springer Berlin Heidelberg, 79(1), pp. 1–18. doi: 10.1007/s12665-019-8751-9.

Lewis, E. *et al.* (2018) 'Intergovernmental Panel on Climate Change', in *Sustainaspeak*, pp. 153–154. doi: 10.4324/9781315270326-109.

Lyon, B. (2004) 'The strength of El Niño and the spatial extent of tropical drought', *Geophysical Research Letters*, 31(21). doi: 10.1029/2004GL020901.

Mazhar, N., Ali Shirazi, S. and Javid, K. (2018) 'Desertification vulnerability and risk analysis of Southern Punjab Region, Pakistan using geospatial techniques', *J Biodivers Environ Sci*, 12(6), pp. 273–282. Available at: http://www.innspub.net.

Mazhar, N. and Nawaz, M. (2014) 'PRECIPITATION DATA INTERPOLATION FOR METEOROLOGICAL DROUGHT MAPPING IN PAKISTAN.', *Pakistan Journal of Science*, 66(4).

Mazhar, U. *et al.* (2022) 'Long-time Variation and Mechanism of Surface Energy Budget over Diverse Geographical Regions in Pakistan', *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*. IEEE, 15(1), pp. 1–13. doi: 10.1109/jstars.2022.3185177.

Mazhar, U., Jin, S. and Bilal, M. (2021) 'Land surface temperature variability over various land covers in Punjab (Pakistan) from MODIS data', in *2021 28th International Conference on Geoinformatics*, pp. 1–5. doi: 10.1109/IEEECONF54055.2021.9687662.

McKee, T. B., Nolan, J. and Kleist, J. (1993) 'The relationship of drought frequency and duration to time scales', *Preprints, Eighth Conf. on Applied Climatology, Amer. Meteor, Soc.*, (January).

Moazzam, M. F. U. *et al.* (2022) 'Trends of Rainfall Variability and Drought Monitoring Using Standardized Precipitation Index in a Scarcely Gauged Basin of Northern Pakistan', *Water (Switzerland)*, 14(7). doi: 10.3390/w14071132.

Niaz, R. *et al.* (2022) 'A new comprehensive approach for regional drought monitoring', *PeerJ*, 10, pp. 1–19. doi: 10.7717/peerj.13377.

Palmer, W. C. (1965) 'Meteorological drought, Research Paper No. 45: US Weather Bureau', *Office of Climatology, US Weather Bureau, Washington DC*.

Pomee, M. S., Khan, M. A. and Ali, I. (2005) 'Guidelines for field calibration of irrigation outlets commonly used in Indus Basin irrigation system Drought Mitigation Measures : An Overview Under Pakistan ' s Perspective', *Pakistan Journal of Water Resources*, (January).

del Rio, S. *et al.* (2013) 'Recent mean temperature trends in Pakistan and links with teleconnection patterns', *International Journal of Climatology*, 33, pp. 277–290. doi: 10.1002/joc.3423.

Shaheen, A. and Anwar Baig, M. (2011) 'Drought Severity Assessment in Arid Area of Thal Doab using Remote Sensing and GIS', *International Journal of Water Resources and Arid Environments*, 1(2), pp. 92–101.

Sheffield, J. and Wood, E. F. (2007) 'Characteristics of global and regional drought, 1950-2000: Analysis of soil moisture data from off-line simulation of the terrestrial hydrologic cycle', *Journal of Geophysical Research Atmospheres*, 112(17). doi: 10.1029/2006JD008288.

Ullah, I. *et al.* (2022) 'Observed changes in seasonal drought characteristics and their possible potential drivers over Pakistan', *International Journal of Climatology*, 42(3), pp. 1576–1596. doi: 10.1002/joc.7321.

Usman, M. and Nichol, J. E. (2020) 'A spatio-temporal analysis of rainfall and drought monitoring in the Tharparkar region of Pakistan', *Remote Sensing*, 12(3). doi: 10.3390/rs12030580.

Vicente-Serrano, S. M., Beguería, S. and López-Moreno, J. I. (2010) 'A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index', *Journal of climate*. American Meteorological Society, 23(7), pp. 1696–1718.

Wilhite, D. A. and Pulwarty, R. S. (2017) 'Drought and water crises: Lessons drawn, some lessons learned, and the road ahead', in *Drought and Water Crises: Integrating Science, Management, and Policy, Second Edition*. doi: 10.1201/b22009.