Indus Journal of Social Sciences

Online ISSN: 2960-219X
Print ISSN: 2960-2203
Volume 4, Number 1, 2026, Pages 568 – 592
Journal Home Page
https://induspublishers.com/IJSS/about

Quantifying Drought Severity and Socio-Economic Exposure: An Integrated Risk Assessment Approach for Pakistan

Ghulam Rubab[1], Shaista Jalbani[2], Abdul Razzaque Soomro[3], Emmy Maher[4] & Fatima Gull[5]

[1]*Institute of Plant Sciences, University of Sindh, Jamshoro 71000, Sindh, Pakistan and Fisheries and Aquaculture SBBUVAS, Sakrand 67210, Sindh, Pakistan, Email: ghulamrubabsoomro@gmail.com*
[2]*Fisheries and Aquaculture SBBUVAS, Sakrand 67210, Sindh, Pakistan, Email: jalbanishaista@gmail.com*
[3]*School of Resources and Environmental Engineering, Wuhan university of technology, Wuhan, Hubei, 430070, China, Email: soomroabdulrazaque2@gmail.com*
[4]*School of Environmental Engineering and Management, Mehran University of Engineering and Technology Jamshoro 76062, Sindh, Pakistan, Email: Emmy.mahar@gmail.com*
[5]*School of Sociology, University of Karachi, 75270, Pakistan, Email: universityofkarachigull@gmail.com*

ARTICLE INFO

Article History:

Received:	*January*	*02, 2026*
Revised:	*January*	*30, 2026*
Accepted:	*February*	*10, 2026*
Available Online:	*February*	*23, 2026*

Keywords:

Drought Risk Assessment; Standardized Precipitation Index (SPI); Socio-Economic Exposure; Hydro-Climatic Variability; Spatial Analysis (GIS-based); Climate Change and Water Security

Corresponding Author:
Ghulam Rubab
Email:
ghulamrubabsoomro@gmail.com

OPEN ACCESS

ABSTRACT

Drought is one of the most long-lasting and multifactorial climate-related disasters that have a severe impact on the water security, agricultural performance, and socio-economic sustainability in the developing world. In Pakistan, climate variability has escalated drought cases in the country, thereby increasing vulnerabilities in arid and semi-arid areas. The proposed study will measure the severity of drought and determine the socio-economic exposure by applying a risk assessment framework. Drought patterns are examined with the use of hydro-climatic indicators, specifically, the Standardized Precipitation Index, on multiple time scales in order to capture variability in intensity and duration. The key indicators that are used in gauging socio-economic exposure are population density, poverty levels, agricultural dependency, and water resource accessibility. It follows a risk-based approach, whereby the drought risk is theorized as the interplay between the hazard, exposure and vulnerability. Spatial analysis is used to determine drought hotspots and areas with an increased socio-economic sensitivity. The results indicate that there is a strong spatial inhomogeneity in the severity and exposure of drought, with the southern and western areas having a higher level of risk because of compounded hydro-climatic stresses and socio-economic vulnerability. The research addresses the gap between the hydrological evaluation and the social vulnerability analysis to provide a data-based background in the drought risk governance. The findings are critical in the policy formulation by policymakers to develop specific interventions, improve climate resilience, and support sustainable water resource management in Pakistan.

Introduction

Drought is generally known to be one of the most complicated and the least understood natural hazard because of its slowness of onset, extended duration as well as its multidimensional effects of both environmental and socio-economic systems. Drought does not happen at once like flood or earthquake, and thus difficult to identify, trace, and counter check. The world has experienced an uptrend in the frequency, intensity, and spatial magnitude of droughts in recent decades which has been majorly caused by climate variability and anthropogenic climate change (Zhao et al. 2023; Cook, Mankin, and Anchukaitis 2018).

These shifts have only exacerbated water shortages, transformed agricultural practices and amplified the socio economic vulnerabilities, especially in the developing nations where adaptive power is still little. Pakistan is one of the countries that are extremely susceptible to drought because of its arid and semi-arid climate, excessive reliance on agriculture, and fast population increase. Some regions of the nation, particularly, Sindh and Balochistan, are prone to frequent droughts, which have a devastating impact on the water, crop, and livelihoods in rural areas (Ashraf et al. 2021; Ashraf and Routray 2013) . The growing change in rain patterns and increase in temperature have also increased the risk of drought that has resulted in immense socio-economic impacts like food insecurity, poverty and forced migration. Drought is not merely a phenomenon on the environmental level but a consistent socio-economic issue in such regions as Tharparkar that serves to reveal structural inequalities and lack of resources access (Memon, Aamir, and Ahmed 2018; Solomon 2019). Scientifically, drought has been generally categorized into three types namely meteorological, agricultural, and hydrological, which are the various dimensions of water shortage. Other indices, such as the Standardized Precipitation Index (SPI), have been widely accepted because of its simplicity, time scale flexibility and because of its aptitude to record the anomalies in precipitation (Raziei and Pereira 2024; Docheshmeh Gorgij et al. 2022).

Although these hydrological and climatic indices are necessary in the process of comprehending the physical nature of drought, they rarely reflect the varying effects to human systems. This has led to an increasing consensus that drought can and must be examined as a socio-economic occurrence based on exposure, vulnerability, and adaptive capacity in addition to being a physical hazard. Here, the risk of drought has also been developed to include the interplay between hazard, exposure and vulnerability. Risk is no longer understood as an effect of climatic variability but rather as a result of multi-faceted interaction between environmental processes and the socio-economic conditions (Teku 2025; Malakar et al. 2023). As an example, two regions with similar degrees of drought severity can have dissimilar effects basing on their population density, economic organization, access to water resources, and institutional capacity. Thus, the assessment of hydrology should be combined with the socio-economic analysis to create a more detailed picture of the risk of drought. Regardless of this acknowledgment, extant research has been done in Pakistan, but most have concentrated on hydro-climatic analysis or the socio-economic impacts individually. The major focus of hydrological research has been on the changes in rainfalls, drought indices, and climate, and the social science research has concentrated on poverty, food security, and governance (Kchouk et al. 2022; Savelli et al. 2022).

Nevertheless, there is a serious gap in the process of incorporating these two dimensions into one analytical system that will be able to measure the severity of drought and the socio-economic vulnerability. Such a gap constrains the capacity of policymakers and practitioners to draw specific and effective drought mitigation plans. The way to fill in this gap is to take a combined methodology that involves quantitative evaluation of the drought severity with the spatial evaluation of socio-economic exposure. This method will allow the detection of high-risk regions in which the hydro-climatic stress agrees with socio-economic vulnerability, which will serve as a more precise point of decision-making. In this respect, the current study takes a risk-based approach, where risk of drought is seen as a product of the hazard, exposure and vulnerability. The study aims at the creation of the multi-faceted risk profile by combining both environmental and human aspects of drought by incorporating hydrological indicators with socio-economic variables. The main aim of this paper is to measure the severity of drought and measure the socio-economic exposure in Pakistan through an integrated risk assessment methodology. In particular, the study seeks to (i) examine spatial and temporal patterns of drought with the help of hydro-climatic data. (ii) assess socio-economic exposure with the consideration of essential indicators like population, poverty and agricultural dependency.(iii) determine drought risk hotspots by integrating hazard and exposure layers spatially.

In such a way, the research helps to fill the gap in the scientific field of hydrology and the social vulnerability assessment, providing a fact-based understanding of drought risk. This research is important as it may inform evidence-based policy and practice. The study facilitates the creation of specific interventions, such as early warning systems, climate-resilient agriculture, and equal water resource management, by offering a spatially explicit evaluation of the drought risk. Moreover, the developed framework suggested in this paper can be integrated with the world-wide campaigns on disaster risk mitigation and climate change adaptation, which are stressed by the international organizations like the United Nations Office of Disaster Risk Reduction. Finally, the study contributes to the awareness of drought as a hydro-social phenomenon and to the necessity to focus on interdisciplinary approaches to the problem of complex environmental challenges in Pakistan.

Literature Review

Drought Concepts and Classification

Drought is also a multifaceted and intricate phenomenon which does not have an agreed definition because it is affected by climatic, hydrological and socio-economic conditions. Conventionally, there are three major types of droughts namely meteorological, agricultural, and hydrological drought (Sun, Liu, et al. 2023; Sun, Sun, et al. 2023). Meteorological drought is a precipitation shortage in comparison with historical norms and agricultural drought is a shortage of soil moisture in terms of crop yields. Hydrological drought on the other hand is associated with the scarcity of surface and ground water, which affects the water supply systems (Apurv and Cai 2020; Liu et al. 2023). A variety of drought indices have been created to measure the severity of drought among which Standardized Precipitation Index (SPI) is the most popular because of its simplicity and adaptability across various periods of time (Latifoğlu and Özger 2023; Di Nunno, de Marinis, and Granata 2024).

The short and long-term drought situations can also be identified using SPI and hence it is applicable in monitoring agricultural and hydrological consequences. Another popular index is the Standardized Precipitation Evapotranspiration Index (SPEI) that considers the effects of temperature and gives a more detailed picture of drought in changing climatic conditions (Gumus 2023). These indices have found wide applications in regional and global drought assessment as they provide useful information on both the temporal variability and the spatial distribution. Although these indices are effective in physical aspects of drought, they mainly dwell on climatic deviations and fail to consider human aspects like exposure and vulnerability. Consequently, the increasing awareness of the fact that drought cannot be comprehended entirely without introducing its socio-economic aftermath (Suleymanov 2024).

Drought in Pakistan: Patterns and Trends

The country is highly vulnerable to drought because of the geographical position, climatic variability and dependence on agriculture. Precipitation differs greatly both spatially and temporally in the country, and especially in arid and semi-arid areas such as Sindh and Balochistan, which are highly susceptible (Khan et al. 2021; Rafiq et al. 2023). The history shows that Pakistan has already experienced a number of severe droughts, such as long-term droughts that hit the country in the late 1990s and early 2000s and led to significant economic losses and humanitarian emergencies (Khan, Hassan, and Raza 2023; Akram 2026). According to the recent studies, the frequency and intensity of droughts have been on the rise and is linked to climate change and changes in the patterns of monsoons (Mujumdar et al. 2020).

The increase in temperature has also added to the rate of evapotranspiration which has worsened water stress situations in the country. Pakistan Meteorological Department has reported of recurrent cases of drought in the southern parts of Pakistan especially Tharparkar, whereby shortages of rainfall are aggravated by poor water infrastructure as well as socio-economic factors. This is because spatial studies of drought in Pakistan have indicated that the severity of drought differs greatly across different regions with the southern and western regions always having a greater level of water stress (Ullah et al. 2023; Abbas and Kousar 2021). Nevertheless, the majority of these studies report on climatic and hydrological indicators, but little has been done on social-economic aspects.

Socio-Economic Impacts of Drought

The socio-economic impacts of drought have far-reaching effects especially to the developing world where people make their living in climate-sensitive sectors such as agriculture. The Pakistani economy is extremely susceptible to the shocks caused by drought since agriculture is a major sector of the GDP, and the population is also highly represented (Khan et al. 2020; Rahman et al. 2023). Less rain and water cause agricultural failures, losses in livestock and agricultural productivity which consequently increase food insecurity and poverty.

Drought influences drinking water as well, compelling the community to use contaminated water and predisposing them to water-borne illnesses (Manetu and Karanja 2021). Women and children are particularly affected in the rural regions where they are the ones who have to carry the burden of collecting water and managing the home in conditions that are less than conducive. Moreover, extended dry periods tend to cause rural-urban migration, which puts an even bigger burden on urban facilities and services (Mianabadi et al. 2023; Mthiyane, Wissink, and Chiwawa 2022). A number of factors are associated with socio-economic vulnerability to drought such as income levels, accessibility to resources, institutional capacity, and social inequalities. Research has indicated that those groups of people who are marginalized and lack access to land, credit, and technology are prone to the effects of drought (King-Okumu et al. 2020; Ahmad, Yaseen, and Saqib 2022). Thus, the distribution of the socio-economic exposure is essential to have an effective drought risk management.

Drought Risk Assessment Approaches

Over the recent years, risk-based approaches to drought studies, which incorporate elements of hazard, exposure, and vulnerability, have become more common. Such change is a manifestation of a more general understanding that drought effects are not only based on the climatic factors but also on the social-economic conditions and the ability to adapt (Ding and Wei 2022; Sam et al. 2020). The concept of the risk framework views drought as an activity of interaction of hydro-climatic hazards and human systems, which allows a more effective evaluation of consequences.

The United Nations Office of Disaster Risk Reduction supports a risk-focused way of managing disasters, which puts the emphasis on the need to combine scientific and socio-economic data.

In this respect, risk assessment of drought considers the intensity and frequency of drought occurrence (hazard), populations, and assets that are susceptible to drought occurrence (exposure), and their vulnerability to damage (vulnerability). Geographic Information Systems (GIS) have emerged as a useful instrument in the assessment of drought risks as it is possible to spatially integrate various data sets and identify areas that are at risk (Schwarz et al. 2020; Khoshnazar, Perez, and Sajjad 2023). Similar approaches are also applied to multi-criteria decision analysis (MCDA) and the methods of combining various indicators and creating composite risk indices (Esmaili and Karipour 2024; Dolge and Blumberga 2021). Such methods promote the evolution of specific intervention and resources distribution. Nonetheless, a significant number of current literatures look at either the hazard evaluation through drought indices or consider the socio-economic susceptibility separately. Not a lot of literature has been able to incorporate these elements into a single analysis structure especially in the Pakistani context.

Research Gap and Contribution

There are still large gaps in the combination of hydrological and socio-economic aspects of drought in spite of the increased literature on this topic. In Pakistan, a majority of the drought research is restricted to hydro-climatic research, focusing on variation in rainfall and drought indices without reflecting on the varying effects on communities (Hassan et al. 2025; Saleem et al. 2022). On the other hand, social science studies tend to be concerned with vulnerability and governance in the absence of quantitative indices of the drought severity (Savelli et al. 2022; Lottering, Mafongoya, and Lottering 2021).

This dissection restricts the capacity to formulate holistic and policy pertinent insights. It is evident that it is necessary to have a combined strategy integrating hydrological pointers with social-economic information to determine drought risk holistically. This would be a better model of the actual conditions of the world where there is dynamism in the interaction between the environmental and human systems. The current paper fills this gap by suggesting a unified risk assessment tool which measures not only the severity of drought but also social-economic exposure in Pakistan. The study provides a new viewpoint on drought risk, which is scientifically sound and socially important due to the integration of hydro-climatic and spatial socio-economic data. This combination is not only boosting the knowledge on the dynamics of drought, but also helping with evidence-based policymaking and sustainable management of water resources.

Research Methodology

In this study, the integrated risk assessment approach has been taken to measure the severity of drought and exposure in Pakistan in terms of socio-economic factors. The methodological design underlies the idea that the risk of drought is not defined by the hydro-climatic conditions in isolation, but rather on the relationship of the drought hazard and the socio-economic traits of the populations exposed to the hazard. The methodology would therefore involve four key steps, namely (i) Gathering of hydro-climatic and socio-economic data, (ii) Determining the severity of drought based on the Standardized Precipitation Index (SPI), (iii) Determining the socio-economic exposure in terms of the identified indicators, (iv) Combining these parts into a composite drought risk model through spatial analysis.

Research Design

The research is based on quantitative, spatially integrated research design. Long-term precipitation records are used to measure hydrological drought condition whereas demographic and development indicators are used to measure socio-economic exposure. These data sets are integrated into a Geographic Information System (GIS) space to locate drought prone areas and socially vulnerable areas. The general paradigm is meant to reach a step further by combining physical hazard to human exposure in a single analytical framework. The methodological reasoning of the research may be stated as follows: Hydro-climatic data and process Drought severity analysis and Socio-economic exposure analysis and Spatial integration and Risk assessment. This arrangement will provide a solution to the fact that drought is not only a climatic anomaly but also a compound risk to human systems.

Data Sources

Two categories of data are required.

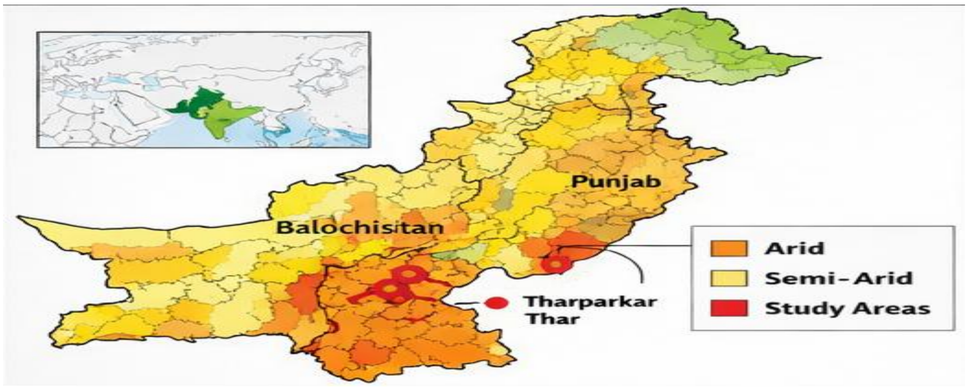

Figure 1. Geographic and Climatic Zones of Pakistan Highlighting Arid, Semi-Arid Regions and Key Study Areas

Hydro-Climatic Data

Hydro-climatic analysis is based primarily on precipitation records collected from meteorological stations across Pakistan. Where available, monthly rainfall time series over a sufficiently long period, such as 20-30 years, should be used to ensure robust drought characterization. If the study is expanded, temperature data may also be incorporated for sensitivity comparison with other drought indices such as SPEI, but the main indicator in this study is SPI. The precipitation dataset should satisfy three conditions; (i) temporal continuity, (ii) Spatial representativeness, (iii) Minimum missing values. Missing rainfall values, if any, may be treated using interpolation or station-based averaging where scientifically justified.

Socio-Economic Data

Socio-economic exposure is assessed using district-level or regional secondary data. The indicators may include: (i) Population density, (ii) Poverty incidence, (iii) Percentage of population dependent on agriculture, (iv) Access to improved water sources, (v) Literacy or development proxy, (vi) Irrigated land dependency.

These variables are selected because they capture the degree to which people and livelihoods are exposed to drought stress. All socio-economic data are harmonized to a common spatial unit, such as district boundaries, to allow integration with drought severity maps.

Drought Severity Assessment Using SPI

To quantify drought severity, this study uses the Standardized Precipitation Index (SPI), which measures precipitation anomalies relative to long-term historical conditions. SPI is widely used because it is statistically consistent, comparable across regions, and can be calculated at multiple time scales.

SPI Calculation

The SPI is computed by transforming long-term precipitation data into a standardized normal distribution. The general form is:

$$SPI = \frac{X_i - \mu}{\sigma}$$

Where:

X_i= observed precipitation for a given time period

μ= long-term mean precipitation

σ= standard deviation of precipitation

In practice, monthly precipitation data are first fitted to a probability distribution, commonly the gamma distribution, because rainfall data are usually positively skewed. The cumulative probability is then transformed into a standard normal distribution, producing SPI values with mean 0 and standard deviation 1.

Time Scales

SPI can be calculated at different temporal scales depending on the drought process of interest:

SPI-3: short-term moisture conditions, useful for seasonal and agricultural drought

SPI-6: medium-term drought conditions

SPI-12: long-term drought linked to hydrological stress and water resource pressure

In this study, SPI-3, SPI-6, and SPI-12 are used to capture short-, medium-, and long-term drought variability in Pakistan.

Drought Classification

SPI values are classified into drought severity categories as follows:

SPI Value	Drought Condition
0 to -0.99	Mild drought
-1.00 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
≤ -2.00	Extreme drought

Negative SPI values indicate drier-than-normal conditions, while positive values indicate wetter-than-normal conditions. For risk mapping, only drought-related negative SPI classes are emphasized.

Drought Hazard Index

To generate a spatial drought hazard layer, SPI results are aggregated and reclassified into a normalized hazard score. A simple normalization may be applied as:

$$H_i = \frac{SPI_{max} - SPI_i}{SPI_{max} - SPI_{min}}$$

Where:

H_i= normalized hazard value for spatial unit i

SPI_i= SPI value of spatial unit i

$SPI_{max}$and SPI_{min}= maximum and minimum SPI values in the dataset

Since more negative SPI values indicate higher drought severity, the transformation is structured so that higher hazard scores correspond to greater drought intensity.

Socio-Economic Exposure Assessment

The second component of the methodology evaluates the extent to which populations and livelihood systems are exposed to drought conditions.

Indicator Selection

Exposure indicators are selected on the basis of their relevance to drought sensitivity and data availability. The following variables are recommended:

Population density: higher concentration of people increases potential social impact

Poverty rate: poorer households have lower coping capacity

Agricultural dependency: areas dependent on rain-fed or climate-sensitive agriculture are more exposed

Water access deficit: limited access to secure water supply increases drought stress

Livelihood fragility: proxy indicators such as employment in agriculture or low-income status may be used

Indicator Standardization

Because these indicators are measured in different units, they are standardized using min-max normalization:

$$E_{ij} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}}$$

Where:

E_{ij}= normalized value of indicator $j$in spatial unit i

X_{ij}= original value of indicator $j$in spatial unit i

X_{min}, X_{max}= minimum and maximum values of that indicator

The normalized values range from 0 to 1, where larger values indicate greater exposure.

Composite Exposure Index

After normalization, the indicators are combined to construct a socio-economic exposure index:

$$SEI_i = \sum_{j=1}^{n} w_j E_{ij}$$

Where:

SEI_i= socio-economic exposure index for spatial unit i

w_j= weight assigned to indicator j

E_{ij}= normalized value of indicator j

If no strong theoretical or statistical basis exists for differential weighting, equal weighting may be adopted:

$$w_j = \frac{1}{n}$$

This produces a balanced exposure index that reflects cumulative socio-economic pressure.

Table 1. Framework for Quantifying Socio-Economic Exposure: Indicator Selection, Normalization, and Weighting Scheme

Indicator	Measurement Unit	Normalization Method	Suggested Weight	Sensitivity to Drought
Population Density	Persons/km²	Min-Max	0.1	High
Poverty Rate	% households	Min-Max	0.15	Very High
Agricultural Dependency	% workforce	Min-Max	0.15	Very High
Irrigated Land Ratio	% irrigated area	Min-Max	0.1	Medium
Water Access	% population	Inverse scaling	0.1	High
Literacy Rate	% literate	Inverse scaling	0.05	Medium
Employment Vulnerability	% informal workers	Min-Max	0.1	High
Livestock Dependency	% households	Min-Max	0.08	Medium
Infrastructure Access	Index	Composite	0.07	Medium
Climate Sensitivity Index	Composite score	Standardized	0.1	Very High

Integrated Drought Risk Model

The final stage of the methodology combines drought hazard and socio-economic exposure to estimate composite drought risk.

Risk Concept

The study adopts the general disaster risk formulation:

$$Risk = Hazard \times Exposure$$

In expanded form for spatial unit i:

$$R_i = H_i \times SEI_i$$

Where:

R_i= drought risk index

H_i= drought hazard score

SEI_i= socio-economic exposure index

This multiplicative structure ensures that drought risk becomes high only where severe drought coincides with high social exposure.

Weighted Risk Form

If needed, a weighted additive form may also be used:

$$R_i = \alpha H_i + \beta SEI_i$$

Where:

$\alpha$and $\beta$are weights assigned to hazard and exposure

$$\alpha + \beta = 1$$

However, for clearer interpretation and stronger hazard-impact linkage, the multiplicative approach is more suitable in this study.

Risk Classification

The resulting drought risk values are classified into categories such as:

Low risk, moderate risk, high risk, very high risk.

A common approach is to use natural breaks, quantiles, or equal intervals in GIS to divide the composite index into meaningful categories.

Spatial Analysis

Spatial analysis is conducted in a GIS environment to visualize and integrate the datasets. The main GIS operations include: (i) joining SPI values to district or regional polygons, (ii) mapping socio-economic indicators, (iii) overlaying hazard and exposure layers, (iv) producing composite drought risk maps.

This step enables the identification of hotspot areas where drought severity and socio-economic exposure overlap. Such maps are essential for policy targeting and regional prioritization.

Validation and Robustness

To improve methodological reliability, the results may be checked against known drought-affected regions, historical drought records, or reported socio-economic impacts in Pakistan. Sensitivity analysis may also be performed by testing alternative weighting schemes for the exposure indicators. This helps assess whether the spatial pattern of risk remains stable under different assumptions.

Summary of Methodological Contribution

The methodology provides a practical and integrated framework for assessing drought risk in Pakistan. Its main strength lies in combining:

Hydrological drought measurement through SPI,

Social exposure assessment through normalized socio-economic indicators,

Spatial integration for risk hotspot identification.

By linking physical drought severity with human exposure, the method produces a more policy-relevant understanding of drought risk than purely climatic or purely social analyses alone.

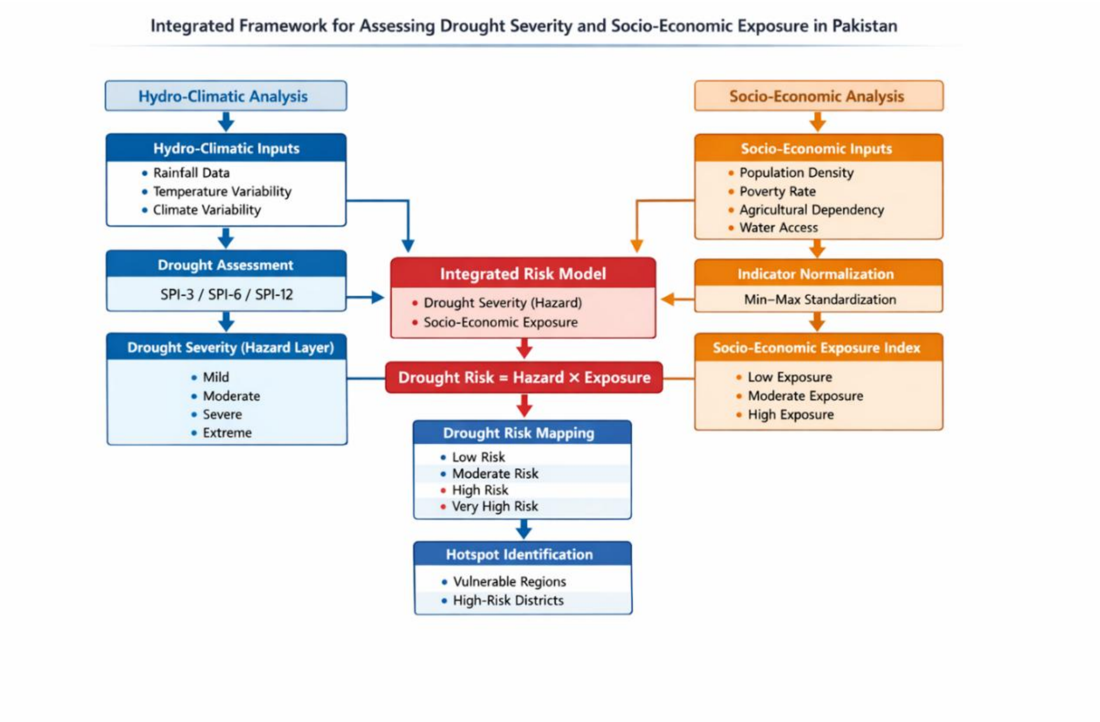

Figure 2. Integrated Hydro-Socio Framework for Drought Risk Assessment: Linking Hydro-Climatic Hazard and Socio-Economic Exposure in Pakistan

Results

This section presents the empirical findings of the study, focusing on (i) drought severity patterns derived from hydro-climatic analysis, (ii) spatial distribution of drought across Pakistan, (iii) socio-economic exposure patterns, and (iv) integrated drought risk zones obtained through the combination of hazard and exposure components.

Drought Severity Patterns

To measure the level of drought, the Standardized Precipitation Index (SPI) was measured at various times, such as SPI-3, SPI-6 and SPI-12, to provide a range of short-term, medium-term and long-term drought variability. The findings suggest that there are substantial temporal variations in the precipitation patterns in the country of Pakistan, and the drought incidences were observed repeatedly within the time span of the study. The short-term drought conditions (SPI-3) demonstrate seasonal variability that is regular mostly in arid and semi-arid areas.

The drought conditions during several years are mild to moderate, which shows the high susceptibility of the agricultural systems to the lack of rainfall in the short term. Medium term drought (SPI-6) has more enduring trends with chains of moderate to severe drought episodes taking place over successive seasons with a sign of cumulative moisture stress. Long-term drought trends (SPI-12) demonstrate stronger and long-term droughts. The findings imply that dry seasons are becoming more common especially in southern Pakistan. The implication of these long-term droughts on the ground water recharge, reservoir storage and general water availability is huge. It is interesting to note that the severe drought situations (SPI = -1.5 and below) appear in several years, which means a long-lasting hydrological stress. In general, the time-based analysis shows that drought in Pakistan is not a one-time event, but a processual one with both short-term fluctuations and long-term continuity.

Table 2. Multi-Scale Characterization of Drought Severity and Its Cascading Hydro-Socio-Economic Impacts

SPI Range	Drought Class	Hydrological Impact	Agricultural Impact	Socio-Economic Impact
0 to -0.49	Near Normal	Stable water availability	No crop stress	Minimal impact
-0.50to-0.99	Mild Drought	Slight reduction in runoff	Minor yield reduction	Low stress on livelihoods
-1.00to-1.24	Moderate Drought (Low)	Reduced groundwater recharge	Crop stress begins	Income instability
-1.25to-1.49	Moderate Drought (High)	Declining reservoir levels	Reduced productivity	Increased food insecurity
-1.50to-1.74	Severe Drought (Low)	Significant water shortages	Crop failure risk	Migration pressure starts
-1.75to-1.99	Severe Drought (High)	Critical water depletion	Major crop losses	Livelihood collapse risk
-2.00to-2.24	Extreme Drought (Low)	Severe hydrological deficit	Widespread crop failure	Severe poverty increase
-2.25to-2.49	Extreme Drought (Moderate)	Surface water scarcity	Livestock loss	Health & nutrition crisis
-2.50to-2.99	Extreme Drought (High)	Groundwater crisis	Agricultural collapse	Forced migration
≤ -3.00	Exceptional Drought	System-wide water failure	Total crop loss	Humanitarian emergency

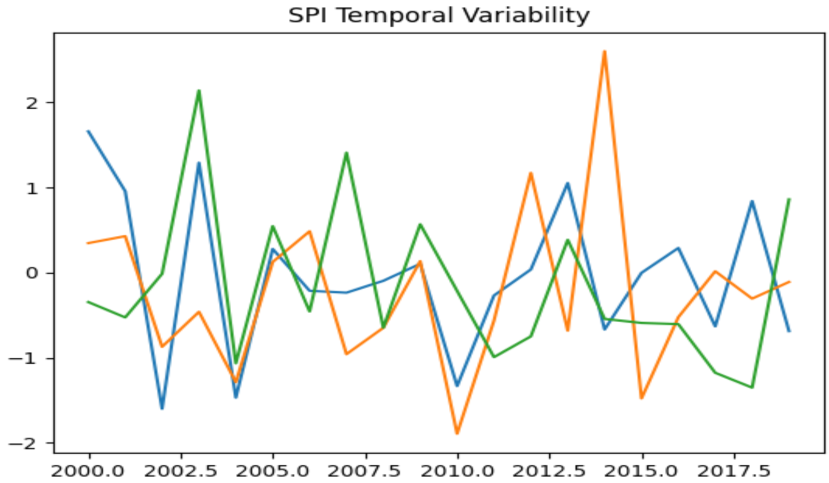

Figure 3. Temporal Variability of Drought Conditions Using Multi-Scale SPI (SPI-3, SPI-6, SPI-12)

Spatial Distribution of Drought

Severity of droughts on the Pakistani territory presents significant regional variations. The drought hazard map, which is a result of the summation of the SPI values shows that southern and western areas will always be at risk of developing extreme cases of drought in relation to the northern and eastern areas. Sindh province especially the Tharparkar and the districts that surround it are the most drought stricken. These regions are characterized by moderate to severe droughts, which are caused by low rainfall that is very erratic.

In the same manner, arid climatic conditions, low levels of precipitation and high levels of evapotranspiration result in massive droughts in large areas of Balochistan. On the contrary, the severity of drought is relatively low in the northern regions of the country such as some parts of Khyber Pakhtunkhwa and northern Punjab. The advantages of these regions are that they have more precipitation and more stable climatic conditions, though not totally immune to the variability of drought. According to the spatial analysis, there is an evident drought severity gradient between the north and south, with the severity of the drought rising in areas of arid climatic zone and scarce water sources. This spatial irregularity supports the usefulness of regionally tailored drought management strategies.

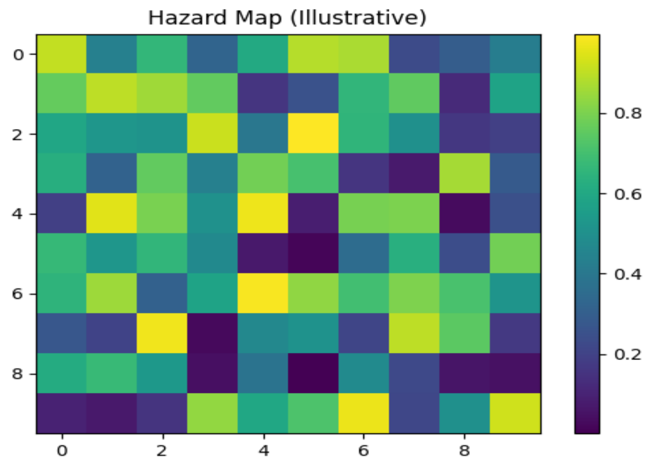

Figure 4. Spatial Distribution of Drought Hazard Based on Normalized SPI Values

Socio-Economic Exposure Patterns

The socio-economic exposure analysis indicates that the vulnerable population is distributed in major ways in Pakistan. The composite socio-economic exposure index, which is based on normalized measures, including population density, poverty rate, agricultural dependency, water access, and so on, singles out the areas that are more prone to the effects of droughts. The high levels of exposure are found in the rural regions where people rely majorly on farming. Low irrigation facilities and dependence on rainfall in these areas expose communities to a high level of shocks due to drought. Poverty proves to be a crucial determinant of exposure since low-income families are not in a position to adjust to water shortages and failure of crops. The socio-economic exposure of Southern Pakistan especially Sindh is high as a result of a combination of high poverty levels, low access to water and reliance on agriculture. In the same way, Balochistan regions experience a high level of exposure due to structural issues like inadequate infrastructure and economic diversification. Since high population density and insufficient water supply can be a major limitation in urban areas, these areas can still portray moderate exposure even though they are not heavily agricultural. Nevertheless, the general exposure in urban areas is usually less than that of the rural areas.

The findings indicate that socio-economic exposure does not have a homogenous distribution but rather exists within the regions having structural weaknesses, increasing the effects of drought.

Integrated Drought Risk Zones

Combining the drought hazard and the socio-economic exposure gives a detailed evaluation of drought risk in Pakistan. The product of the hazard and exposure is the composite drought risk index which determines the areas in which extreme drought conditions are linked with high socio-economic vulnerability. The findings indicate that there are specific drought-related risk hotspots that are mainly found in southern and western Pakistan. Sindh, especially Tharparkar, Umerkot, and the areas around it, become a high-risk area because of extreme levels of drought and the combination of high levels of socio-economic vulnerability. Equally, there are a number of high to very high-risk districts in Baluchistan that are characterized by the continued stress of hydro-climatic and low adaptive ability.

The moderate risk areas are listed in some areas of central Punjab where moderate droughts conditions coincide with medium socio-economic exposure. These regions though not as prone as the southern areas are still at a great risk in the face of prolonged droughts. Areas with low risks are mostly in northern Pakistan where the severity of drought and the socio-economic conditions is comparatively better which lowers the overall risks. Nevertheless, localized effects of droughts are still possible in these regions under the conditions of severe climatic conditions. Spatial pattern of drought risk indicates the relevance of incorporating environmental and socio-economic aspects when risk is being evaluated. Areas that exhibit moderate severity of droughts can also be high-risk areas in case there is a great exposure socio-economically, and it is important to analyse them together.

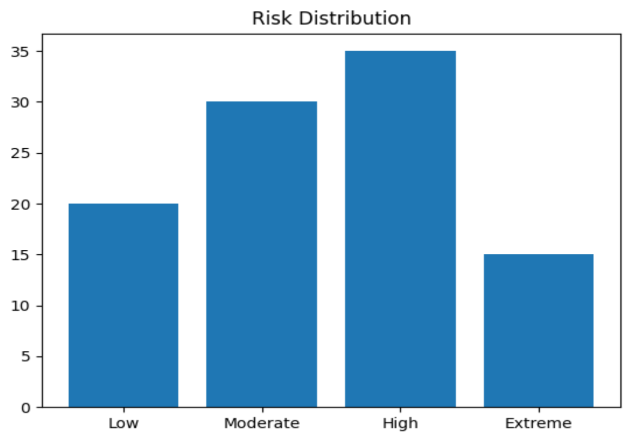

Figure 5. Distribution of Drought Risk Levels Across Pakistan

Key Findings

The findings of this research give a number of significant insights: In Pakistan, drought is both seasonally and persistently experienced, and it is increasingly becoming severe over the recent years. There is a spatial difference in the severity of drought with the southern and western areas being more susceptible. The exposure to socio-economic factors is also very lopsided, as rural and economic underprivileged areas are at a higher risk.

Combined risk analysis indicates that areas of intersection of hydro-climatic stress and socio-economic vulnerability experience the greatest effect of drought. Such results make it crucial to consider that a holistic approach to drought risk assessment is required to incorporate both hydrological analysis and socio-economic issues. High-risk areas were identified, which can be a good foundation of specific interventions and policy formulation that will improve the drought resilience in Pakistan.

Discussion

This part of the paper explains the findings in terms of the existing literature and puts the findings into the context of the wider discussion of drought risks, vulnerability, and governance. The discussion highlights the role of the interaction between socio-economic conditions and hydro-climatic processes in influencing the drought impacts in Pakistan and underscores major implications on the theory, policy, and practice.

Linking Drought Severity with Socio-Economic Impacts

The results indicate that not only is drought in Pakistan a climatic occurrence but a multi-faced threat that is defined by the interaction of environmental stress and socio-economic vulnerability.

Although the hydro-climatic analysis characterizes that the recurrence and intensification of the drought happen, the integration of socio-economic indicators portrays that the magnitude of the impact varies significantly across the places. It is also consistent with other research that has found exposure and vulnerability to be the drivers of drought effects and hazard is not acting independently (Liu and Chen 2021; Wang and Sun 2023).

A case in point of these regions is Sindh and Balochistan which are both defined by both high rates of drought as well as high rates of socio-economic vulnerability that predisposes them to risks in a disproportionately high manner. The absence of precipitation in these areas due to dependence on rain-fed agriculture, absence of water infrastructure, and a high poverty level affect these regions. It validates the thesis, according to which drought should be considered a hydro-social phenomenon, and the human system and the physical one are dynamically interacting (Ferdous 2020). Moderate droughts can cause disastrous socio-economic impacts in the cases of high exposure hence the relevance of integrated risk assessment.

Spatial Inequality and Regional Disparities

One of the key findings of the study is the fact that there is a high amount of spatial heterogeneity in the Pakistan drought risk. Uneven distribution of natural resources and socio-economic development can be observed in the north south gradient in the exposure and severity of droughts. It has been always observed that Southern states, particularly the Sindh, are the high risk areas due to the dry climate and structural social-economic imbalances. This geographical imbalance replicates greater distances of unequal growth and unequal allocation of resources in Pakistan. Regions that experience low access to irrigation facilities, education and economic facilities are more susceptible to the impacts of drought although they have the same hydro-climatic conditions (Ndehedehe 2023; Mengistu et al. 2025).

The findings are consistent with the global literature according to which the marginalized populations are unevenly affected by drought which only raises the degree of disparity (Ngcamu 2023; Putsoane, Bhanye, and Matamanda 2024). Moreover, the existence of moderate-risk zones in relative developed regions shows that the exposure is not concentrated in the regions which were believed to be the traditional ones. Even cities and peri urban areas with their better infrastructure remain under the threat of huge risks due to the great amount of the population and the increasing water demand. This demonstrates the need to adopt region specific solutions that put into consideration the environmental and socio-economic conditions.

Comparison with Global Studies

The results of this work align with the world research on drought risk, which highlights the need to combine the hazard and exposure and vulnerability elements (Wang and Sun 2023; Liu and Chen 2021). Mezzo-economic vulnerability has been found to be the most susceptible to the effects of drought in similar studies conducted in Africa and South Asia (Ali et al. 2020). Nevertheless, this study is added to the literature since it offers a spatial explicit analysis of drought risk in Pakistan, through an integrated method. However, contrary to most of the past research that concentrates on either hydro-climatic analysis or socio-economic vulnerability, the present research is an integration of the two aspects to create a holistic risk profile.

This method is consistent with the new development in interdisciplinary studies where the gap between natural sciences and social sciences is recommended in disaster risk assessment. Moreover, multi-temporal analysis of the SPI is useful in offering a fine-grained insight into the drought processes, both in the short term and in the long term. It is of great significance especially when it comes to climate change, where the patterns of droughts are becoming increasingly unpredictable and complicated (Haile et al. 2020).

Governance Gaps and Institutional Challenges

Another significant finding in the results is the critical gaps in the drought governance and institutional capacity within Pakistan. Areas of high risks established in this research paper also overlap with the regions which have poor institutional support, access to few resources and poor implementation of policies. It implies that the current drought management measures are not well focused or efficient. The absence of scientific evaluation and policy formulation is one of the issues. Although the use of hydro-climatic data in policy making has been limited, hydro-climatic data is available in institutions like the Pakistan Meteorological Department. Equally, socio-economic information is not usually systematically integrated into drought risk evaluations, which results in fragmented and reactive reaction.

The results highlight the necessity to change the crisis-driven policies to risk-based and proactive governance systems. These are the creation of early warning systems, investment in climate-resilient infrastructure, and institutional coordination. The international frameworks, including those advanced by the UNDRR, also lay stress on the need to combine scientific and socio-economic data to support disaster preparedness and resilience.

Policy Implications and Practical Relevance

The hotspots of drought risk have been identified which contributes immensely to the policymakers and practitioners. The research will allow more specific and effective resource allocation by pointing to areas where drought severity and socio-economic exposure coincide. As an illustration, interventions such as water conservation program, drought resistant crops, and social protection should first be provided in high risk districts in Sindh and Balochistan. Moreover, the united risk assessment strategy can be used to promote region-specific adaptation strategies. Policies in rural regions which are highly exposed should aim at strengthening agricultural resilience and diversifying livelihoods.

In the cities, it is necessary to enhance the water management systems and infrastructure to support increasing demand and minimize vulnerability. The model that was worked on during this research can be also used in other countries besides Pakistan. It has the ability to be scaled to other areas with similar issues offering a scalable and adaptable drought risk evaluation tool. The approach can be used to add more comprehensive and efficient climate adaptation strategies by integrating hydrological and socio-economic analysis.

Theoretical and Methodological Contribution

Theoretically, this paper contributes to the knowledge of drought as a multi-dimensional risk that cannot be sufficiently described using one-discipline methodology. The study combines the hydrological indicators with the socio-economic exposure to the expanding area of interdisciplinary disaster risk evaluation.

The study is methodologically useful in that it shows that the integration of SPI-based drought analysis and spatial socio-economic information can be used to derive a composite risk index. This methodology gives a more realistic representation of the effects of drought and helps to make evidence-based decisions. The suggested approach represents an applicable and replicable tool to the work of researchers and policymakers unlike purely conceptual frameworks.

Limitations and Future Research Directions

The study has its limitations even though it contributes in some way. To begin with, the analysis will be based on the accessibility and quality of the secondary data that might differ in the regions. Second, equal weighting of socio-economic indicators might not be an effective method in identifying the relative significance of various factors. More sophisticated methods of weighting, including analytic hierarchy process (AHP) or machine learning, may be studied in the future to increase the accuracy.

The research places more emphasis on exposure and does not provide a detailed vulnerability or adaptive capacity assessment. The framework could be extended to these dimensions in future studies to give a more holistic picture of the drought risk. The combination of remote sensing and real-time surveillance systems also provide some opportunities in relation to improving drought analysis.

Summary of Discussion

To conclude, the results show that the hydro-climatic stress and socio-economic conditions interplay to determine the risk of drought in Pakistan. As the paper shows, areas with high exposure and low adaptive potential are disproportionately impacted, and solutions to the droughts should rely on the integration of approaches and be context specific. The research allows filling the gap between the science of hydrology and social vulnerability analysis, forming a very strong basis of further development of drought risk management and climate resilience.

Policy Implications

The results of this research are valuable in the development of successful evidence-based drought management methods in Pakistan. The study reveals that effective policy interventions should be integrated, focused, and proactive by targeting areas where there is a combination of extreme drought conditions and high social-economic vulnerabilities. The integrated drought risk assessment implies the following policy implications.

Table 3. Risk-Stratified Drought Management Framework Linking Hazard Severity, Socio-Economic Exposure, and Policy Interventions

Risk Level	Risk Score Range	Drought Severity	Exposure Level	Geographic Example
Very Low	0.0 – 0.1	Mild	Low	Northern KP
Low	0.1 – 0.2	Mild–Moderate	Low	Upper Punjab
Low-Moderate	0.2 – 0.3	Moderate	Medium	Central Punjab
Moderate	0.3 – 0.4	Moderate	Medium	Southern Punjab
Moderate-High	0.4 – 0.5	Moderate–Severe	Medium	Interior Sindh
High	0.5 – 0.6	Severe	High	Tharparkar
High-Extreme	0.6 – 0.7	Severe–Extreme	High	Umerkot
Extreme	0.7 – 0.8	Extreme	Very High	Balochistan (rural)
Very Extreme	0.8 – 0.9	Extreme	Very High	Desert regions
Critical	0.9 – 1.0	Exceptional	Extreme	Worst-affected zones

Development of Integrated Drought Early Warning Systems

One of the most significant policy priorities is development of sound drought early warning systems that are inclusive of hydro-climatic surveillance with socio-economic indices. Despite the fact that the weather services in Pakistan such as the Pakistan Meteorological Department do generate effective weather information in the country there is less integration of this information into real life early warning mechanisms. An effective early warning system should combine real time measurements of precipitation, drought warning (e.g., SPI) and socio-economic vulnerability to provide early warnings that are both accurate and precise (location). The systems can enable the policymakers, local government, and society to forecast the drought conditions and put up preventive measures, including water conservation, planning of crops, and allocation of resources. These systems may be adjusted with the best practices which are advocated by the United Nations Office of Disaster Risk Reduction to contribute significantly to the preparedness enhancement and mitigation of the consequences of droughts.

Strengthening Water Resource Management

The results have shown that there is urgent need to manage water resources better particularly in high risk regions such as Sindh and Balochistan. The policies should seek to increase water storage capacity by streamlining the irrigation modes as well as reducing water wastage during distribution channels. Tiny scale water facilities such as rainwater harvesting systems, check dams and ground water recharge systems would play an important role in mitigating the impact of droughts at the ground level. In addition, the contemporary irrigation techniques (drip and sprinkler irrigation) might be employed to improve the water use efficacy in the agriculture sector, which is the largest water user in Pakistan.

They should promote the application of integrated water resource management (IWRM) approaches to control the sustainable use of water in the different sectors. These include the improvement of coordination between federal and provincial agencies, improvement of institutional structures and introduction of climate variability in long term water planning.

Promoting Climate-Resilient Agriculture

Agricultural sector is rather dependent on rural livelihoods, that is why it is crucial to enhance the sustainability of agriculture sector to reduce the danger of droughts. These policies are to facilitate use of drought resistant varieties of crops, to diversify the cropping systems and to use climate smart agricultural practices. It should be improved with regards to extension services that will see the farmers access information regarding weather conditions, choice of crops and water management in time. Further, farmers can be helped by using financial incentives such as crop insurance, microcredit to help farmers compensate losses associated with droughts and reduce their exposure to economic risk. They are not only promoting sustainable agricultural practices to enable enhance resilience to drought but also it improves food security and rural development in the long run.

Targeted Social Protection and Poverty Reduction

In the report, the socio-economic exposure, particularly poverty and access to resources is a significant source of risk of drought. Therefore, the drought risk management is to incorporate social protection. Specific interventions (cash transfer program, food-assistance, and livelihood support programs, etc.) should be provided in the problem of high-risk areas revealed in this study. These programs can not only help vulnerable populations to cope with the short-term impact of drought, but also help them to survive in the long term. There is also a need to make more provisions to basic amenities like clean water, education and health care to reduce vulnerability. The policies should prioritize investments in the regions which have not received a sufficient attention in order to address the structural imbalances that enhance the impacts of droughts.

Enhancing Institutional Coordination and Governance

Drought management would entail integration of activities within the institutions in the different sectors like water, agriculture, disaster management, and social development. The findings of this paper suggest that the existing governance systems in Pakistan are still pretty fragmented and there is no engagement of the scientific information in the policy formulation. The synchronized governance systems are needed to facilitate the exchange of information, to make collective decisions, and coordinated planning. These include the empowerment of the mandate of the national and provincial disaster management agencies, the strengthening of the connection between the scientific institution and policy makers and the cooperation with the local governments and communities. The suggested risk based governance approach proposed by the world structures can help in transforming the reactive approach of managing crisis to proactive risk mitigation.

Spatially Targeted Policy Interventions

Among the key contributions of the current study, one can distinguish that the risk patterns of drought and their hotspots were identified. This provides an ideal premise to come up with region-specific policies, which address the special problems of different regions. An example of this is as follows: In the high-risk regions of Sindh and Balochistan, water infrastructure development, agricultural support, and social protection programs should be prioritized. The moderate-risk ones can be managed better and possess early warning mechanisms. The low-risk zones should be oriented towards being resilient and not vulnerable in future. The spatial targeting ensures the distribution of resources and the interventions to be grounded in the local conditions and be more effective.

Integration of Science and Policy

Finally, the paper has championed that scientific research, policy and practice should be integrated. The evidence presented in the decision-making process is sound because it uses quantitative drought indices, social-economic data and spatial analysis. Policymakers should use such data-driven approaches to develop, implement, and evaluate drought management approaches. This also entails investing in data collection and monitoring which helps in the interdisciplinary research and also setting technical capacity in the government institutions. Having the interaction between science and policy, Pakistan will be able to produce more effective and efficient solutions to droughts and other climate change issues.

Summary of Policy Implications

In a nutshell, the findings of this study show that: In-built early warning systems. Improved water resources management. Specific social protection Climate-resilient agriculture. Between the institution and its employees. Spatial knowledge policy intervention. These actions would go a long way in enhancing the drought resilience and sustainable development in Pakistan when implemented in a coordinated and evidence based strategy.

Conclusion

The paper provides an integrated approach to drought risk assessment, by incorporating the hydro-climatic analysis and socio-economic exposure in Pakistan. The authors, in research that used the

Standardized Precipitation Index (SPI) to measure the magnitude of droughts on different periods, demonstrate that drought in Pakistan is both transitory and permanent in nature, and is increasing in intensity over the past years. Spatial analysis reveals that it is evident that there is a regional inequality as the southern and western part of the country is mostly Sindh and Balochistan that is generally more prone to drought as compared to other areas of the country. Besides the conditions of hydrology, social-economic exposure, as the study notes, is very crucial in the development of drought effects.

Even in the moderate drought, the high poverty rates, the dependence on agriculture in addition to the water supply of the areas are disproportionately affected. The fact that the hazard and exposure factors are combined into a composite risk index reflects that there are certain drought hotspots that the environmental stress and social-economic vulnerability interface. The findings form the basis of the conceptualization of drought as a complex hydro-social process rather than a climatic phenomenon. The primary value of the research is the empirical and spatially explicit model of assessing drought hazard. The study provides a more policy-relevant and comprehensive perspective on drought in Pakistan by bridging the gap in the knowledge between hydrological science and analysis of social vulnerability. This research is data research unlike the previous conceptual or single dimensional research which can assist in giving specific interventions and resource allocation. In terms of policy, the definition of the high-risk regions points to the need of the comprehensive and proactive character of management of the droughts. Some of the ways through which resilience has to be improved include the intensification of early warning systems, improved management of water resources, resilient-climate friendly agriculture, and eradication of socio-economic inequalities. Also, the paper highlights the necessity of involving scientific information in the governance systems with the aim of making informed decisions. The study has its flaws despite its contributions including use of secondary data and oversimplification of weighting of the socio-economic indicators. Future studies can also enhance it by adding dynamic vulnerability indicators, advanced modelling and real-time monitoring too.

It can be further applied to climate projection and machine learning strategies, which can be even more effective to predict drought and risks. In summary, this paper has demonstrated that drought risk management can only be attained by the joint application of the environmental and the social factors. The paper gives an effective analytic framework, and spatial data, thereby contributing to establishing the resilience to drought and sustainable development in Pakistan, and also gives an example that can be used in other drought-prone regions in the world.

CRediT authorship contribution statement

All authors have an equal contribution.

References

1. Abbas, Sohail, and Shazia Kousar. 2021. 'Spatial analysis of drought severity and magnitude using the standardized precipitation index and streamflow drought index over the Upper Indus Basin, Pakistan', *Environment, Development and Sustainability*, 23: 15314-40.
2. Ahmad, Mokbul Morshed, Muhammad Yaseen, and Shahab E Saqib. 2022. 'Climate change impacts of drought on the livelihood of dryland smallholders: Implications of adaptation challenges', *International Journal of Disaster Risk Reduction*, 80: 103210.
3. Akram, Lubna. 2026. 'Pakistan’s Flood History: Analysing the Causes and Consequences of a Recurrent Disaster.' in, *Flood Risk Reduction* (Springer).
4. Ali, Shahzad, Zhen Tian Xu, Malak Henchirli, Kalisa Wilson, and Jiahua Zhang. 2020.

'Studying of drought phenomena and vegetation trends over South Asia from 1990 to 2015 by using AVHRR and NASA's MERRA data', *Environmental Science and Pollution Research*, 27: 4756-68.

5. Apurv, Tushar, and Ximing Cai. 2020. 'Impact of droughts on water supply in US watersheds: The role of renewable surface and groundwater resources', *Earth's Future*, 8: e2020EF001648.
6. Ashraf, Muhammad, Adnan Arshad, Praharsh M Patel, Adeel Khan, Huma Qamar, Ristina Siti-Sundari, Muhammad Usman Ghani, Ali Amin, and Jamilur Rehman Babar. 2021. 'Quantifying climate-induced drought risk to livelihood and mitigation actions in Balochistan', *Natural Hazards*, 109: 2127-51.
7. Ashraf, Muhammad, and Jayant Kumar Routray. 2013. 'Perception and understanding of drought and coping strategies of farming households in north-west Balochistan', *International Journal of Disaster Risk Reduction*, 5: 49-60.
8. Cook, Benjamin I, Justin S Mankin, and Kevin J Anchukaitis. 2018. 'Climate change and drought: From past to future', *Current Climate Change Reports*, 4: 164-79.
9. Di Nunno, Fabio, Giovanni de Marinis, and Francesco Granata. 2024. 'Analysis of SPI index trend variations in the United Kingdom-A cluster-based and bayesian ensemble algorithms approach', *Journal of Hydrology: Regional Studies*, 52: 101717.
10. Ding, Meng, and Yongping Wei. 2022. 'A conceptual framework for quantitatively understanding the impacts of floods/droughts and their management on the catchment's social-ecological system (C-SES)', *Science of the Total Environment*, 828: 154041.
11. Docheshmeh Gorgij, Alireza, Meysam Alizamir, Ozgur Kisi, and Ahmed Elshafie. 2022. 'Drought modelling by standard precipitation index (SPI) in a semi-arid climate using deep learning method: long short-term memory', *Neural Computing and Applications*, 34: 2425-42.
12. Dolge, Kristiāna, and Dagnija Blumberga. 2021. 'Composite risk index for designing smart climate and energy policies', *Environmental and Sustainability Indicators*, 12: 100159.
13. Esmaili, Reza, and Seyedeh Atefeh Karipour. 2024. 'Comparison of weighting methods of multicriteria decision analysis (MCDA) in evaluation of flood hazard index', *Natural Hazards*, 120: 8619-38.
14. Ferdous, Md Ruknul. 2020. *Socio-Hydrological Dynamics in Bangladesh: Understanding the interaction between hydrological and social processes along the Jamuna floodplain* (CRC Press).
15. Gumus, Veysel. 2023. 'Evaluating the effect of the SPI and SPEI methods on drought monitoring over Turkey', *Journal of Hydrology*, 626: 130386.
16. Haile, Gebremedhin Gebremeskel, Qiuhong Tang, Wenhong Li, Xingcai Liu, and Xuejun Zhang. 2020. 'Drought: Progress in broadening its understanding', *Wiley Interdisciplinary Reviews: Water*, 7: e1407.
17. Hassan, Sher Shah, Muhammad Arif Goheer, Humera Farah, Faiza Hafeez, Khurram Sheraz, Javaria Fahad, and Aqil Tariq. 2025. 'Geospatial assessment of climate variability and drought patterns: a case study from Pakistan: SS Hassan et al', *Theoretical and Applied Climatology*, 156: 185.
18. Kchouk, Sarra, Lieke A Melsen, David W Walker, and Pieter R Van Oel. 2022. 'A geography of drought indices: mismatch between indicators of drought and its impacts on water and food securities', *Natural Hazards and Earth System Sciences*, 22: 323-44.
19. Khan, Muhammad Aamir, Alishba Tahir, Nabila Khurshid, Muhammad Iftikhar ul Husnain, Mukhtar Ahmed, and Houcine Boughanmi. 2020. 'Economic effects of climate change-induced loss of agricultural production by 2050: A case study of Pakistan', *Sustainability*, 12: 1216.

20. Khan, Muhammad Fahim, Asad Hassan, and Aamer Raza. 2023. 'Humanitarian crisis in Afghanistan: Changing global dynamics and Pakistan's policy choices', *Asian Journal of Comparative Politics*, 8: 516-28.
21. Khan, Saifullah, Surriya Shahab, Muhammad Ishaque Fani, Abdul Wahid, MU Hasan, and A Khan. 2021. 'Climate and weather condition of Balochistan province, Pakistan', *Int. J. Econ. Environ. Geol. Vol*, 12: 65-71.
22. Khoshnazar, Ali, Gerald Corzo Perez, and Muhammad Sajjad. 2023. 'Characterizing spatial–temporal drought risk heterogeneities: a hazard, vulnerability and resilience-based modeling', *Journal of Hydrology*, 619: 129321.
23. King-Okumu, Caroline, Daniel Tsegai, Rajendra Prasad Pandey, and Gwyn Rees. 2020. 'Less to lose? Drought impact and vulnerability assessment in disadvantaged regions', *Water*, 12: 1136.
24. Latifoğlu, Levent, and Mehmet Özger. 2023. 'A novel approach for high-performance estimation of SPI data in drought prediction', *Sustainability*, 15: 14046.
25. Liu, Ying, Fuzhen Shan, Hui Yue, Xu Wang, and Yahui Fan. 2023. 'Global analysis of the correlation and propagation among meteorological, agricultural, surface water, and groundwater droughts', *Journal of Environmental Management*, 333: 117460.
26. Liu, Yujie, and Jie Chen. 2021. 'Future global socioeconomic risk to droughts based on estimates of hazard, exposure, and vulnerability in a changing climate', *Science of the Total Environment*, 751: 142159.
27. Lottering, SJ, P Mafongoya, and RT Lottering. 2021. 'Assessing the social vulnerability of small-scale farmer's to drought in uMsinga, KwaZulu-Natal', *International Journal of Disaster Risk Reduction*, 65: 102568.
28. Malakar, Kousik Das, Manish Kumar, Subhash Anand, and Gloria Kuzur. 2023. "Climate change and socio-ecological transformation." In.: Springer.
29. Manetu, Winfred M, and Amon M Karanja. 2021. 'Waterborne disease risk factors and intervention practices: a review'.
30. Memon, Manzoor Hussain, Naveed Aamir, and Nadeem Ahmed. 2018. 'Climate change and drought: Impact of food insecurity on gender based vulnerability in district Tharparkar', *The Pakistan Development Review*: 307-31.
31. Mengistu, Achamyeleh G, Weldemichael A Tesfuhuney, Yali E Woyessa, Amsalework A Ejigu, and Melku D Alemu. 2025. 'Contrasting hydro-climatic trends and drought dynamics in Ethiopia and South Africa under climate change', *Climate Dynamics*, 63: 105.
32. Mianabadi, Ameneh, Kamran Davary, Hojjat Mianabadi, Mahdi Kolahi, and Erik Mostert. 2023. 'Toward the development of a conceptual framework for the complex interaction between environmental changes and rural-urban migration', *Frontiers in Water*, 5: 1142307.
33. Mthiyane, Douglas B, Henry Wissink, and Nyashadzashe Chiwawa. 2022. 'The impact of rural–urban migration in South Africa: A case of KwaDukuza municipality', *Journal of Local Government Research and Innovation*, 3: 56.
34. Mujumdar, Milind, Preethi Bhaskar, MVS Ramarao, Umakanth Uppara, Mangesh Goswami, Hemant Borgaonkar, Supriyo Chakraborty, Somaru Ram, Vimal Mishra, and M Rajeevan. 2020. 'Droughts and floods.' in, *Assessment of climate change over the Indian region: a report of the Ministry of Earth Sciences (MoES), Government of India* (Springer).
35. Ndehedehe, Christopher. 2023. 'Hydro-Climatic Extremes: Climate change and human influence.' in, *Hydro-Climatic Extremes in the Anthropocene* (Springer).
36. Ngcamu, Bethuel Sibongiseni. 2023. 'Climate change effects on vulnerable populations in the Global South: a systematic review', *Natural Hazards*, 118: 977-91.
37. Putsoane, Tebello, Johannes Itai Bhanye, and Abraham Matamanda. 2024. 'Extreme weather events and health inequalities: Exploring vulnerability and resilience in

marginalized communities', *Developments in Environmental Science*, 15: 225-48.
38. Rafiq, Muhammad, Yue Cong Li, Yanpei Cheng, Ghani Rahman, Yuanjie Zhao, and Hammed Ullah Khan. 2023. 'Estimation of regional meteorological aridity and drought characteristics in Baluchistan province, Pakistan', *Plos one*, 18: e0293073.
39. Rahman, Khalil Ur, Anwar Hussain, Nuaman Ejaz, Songhao Shang, Khaled S Balkhair, Kaleem Ullah Jan Khan, Mahmood Alam Khan, and Naeem Ur Rehman. 2023. 'Analysis of production and economic losses of cash crops under variable drought: A case study from Punjab province of Pakistan', *International Journal of Disaster Risk Reduction*, 85: 103507.
40. Raziei, Tayeb, and Luis Santos Pereira. 2024. 'Relating the drought precipitation percentiles index to the standardized precipitation index (SPI) under influence of aridity and timescale', *Water resources management*, 38: 5739-58.
41. Saleem, Farhan, Arfan Arshad, Ali Mirchi, Tasneem Khaliq, Xiaodong Zeng, Md Masudur Rahman, Adil Dilawar, Quoc Bao Pham, and Kashif Mahmood. 2022. 'Observed changes in crop yield associated with droughts propagation via natural and human-disturbed agro-ecological zones of Pakistan', *Remote Sensing*, 14: 2152.
42. Sam, Anu Susan, Subash Surendran Padmaja, Harald Kächele, Ranjit Kumar, and Klaus Müller. 2020. 'Climate change, drought and rural communities: Understanding people's perceptions and adaptations in rural eastern India', *International Journal of Disaster Risk Reduction*, 44: 101436.
43. Savelli, Elisa, Maria Rusca, Hannah Cloke, and Giuliano Di Baldassarre. 2022. 'Drought and society: Scientific progress, blind spots, and future prospects', *Wiley Interdisciplinary Reviews: Climate Change*, 13: e761.
44. Schwarz, Maximilian, Tobias Landmann, Natalie Cornish, Karl-Friedrich Wetzel, Stefan Siebert, and Jonas Franke. 2020. 'A spatially transferable drought hazard and drought risk modeling approach based on remote sensing data', *Remote Sensing*, 12: 237.
45. Solomon, Sarah. 2019. 'Understanding the impacts of climate change on water access and the lives of women in Tharparkar District, Sindh Province, Pakistan: A Literature Review, 1990-2018'.
46. Suleymanov, Firuz. 2024. 'A review of the multifaceted relationship between drought dynamics and conflicts', *Hydrological Processes*, 38: e15262.
47. Sun, Huaiwei, Xunlai Sun, Jianing Chen, Xiaoya Deng, Yong Yang, Hui Qin, Fulong Chen, and Wenxin Zhang. 2023. 'Different types of meteorological drought and their impact on agriculture in Central China', *Journal of Hydrology*, 627: 130423.
48. Sun, Peng, Ruilin Liu, Rui Yao, Hao Shen, and Yaojin Bian. 2023. 'Responses of agricultural drought to meteorological drought under different climatic zones and vegetation types', *Journal of Hydrology*, 619: 129305.
49. Teku, Degfie. 2025. 'Navigating climate uncertainty: a comprehensive review of climatic variabilities and extreme events on environmental, socio-economic, and livelihood dimensions in Ethiopia with adaptation strategies', *All Earth*, 37: 1-30.
50. Ullah, Irfan, Xin-Min Zeng, Saadia Hina, Sidra Syed, Xieyao Ma, Vedaste Iyakaremye, Jun Yin, and Vijay P Singh. 2023. 'Recent and projected changes in water scarcity and unprecedented drought events over Southern Pakistan', *Frontiers in Earth Science*, 11: 1113554.
51. Wang, Tingting, and Fubao Sun. 2023. 'Integrated drought vulnerability and risk assessment for future scenarios: An indicator based analysis', *Science of the Total Environment*, 900: 165591.
52. Zhao, Ruxin, Hongquan Sun, Lisong Xing, Renzhi Li, and Ming Li. 2023. 'Effects of anthropogenic climate change on the drought characteristics in China: From frequency, duration, intensity, and affected area', *Journal of Hydrology*, 617: 129008.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research has not any extra funding source.

Declaration of generative AI and AI-assisted technologies in the writing process: During the preparation of manuscript, the authors utilized AI to aid in English language editing, as none of the authors are native English speakers. Following this assistance, the authors thoroughly reviewed and edited the content to ensure accuracy and integrity, taking full responsibility for the final version.

Acknowledgement

Not applicable