

An integrated framework for strengthening local agriculture drought management

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ABSTRACT

Drought onset is a complex phenomenon to identify, as its impact is gradual and can have a vast spatiotemporal distribution. Increased food insecurity interlinked with pre-existing poverty-driven socioeconomic vulnerabilities is a major implication of agricultural drought. To address the multidimensional nature of drought risk, solutions utilizing synergistic tools are required. Interdisciplinary measures integrating scientific outputs with local-level socioeconomic data can be an effective approach to holistically address the multifaceted challenge of drought. Assessments of socioeconomic conditions are essential to improving disaster management, as functional capacities of state agencies and citizens' resilience levels are influenced by such conditions. The study selects Pakistan's drought-prone Balochistan province to introduce an integrated framework based on vulnerability and hazard exposure assessments for managing agricultural drought. Using data from the Pakistan Social and Living Standards Measurement survey, an index is developed that quantifies the differential vulnerability in the districts of Balochistan. To identify the drought exposure on agricultural farmland, vegetation water content and root-zone soil moisture are simulated using the Coupled Land and Vegetation Data Assimilation System. The study shows that local drought management can benefit from an interdisciplinary approach that identifies linkages between socioeconomic vulnerability and scientific simulation outputs.

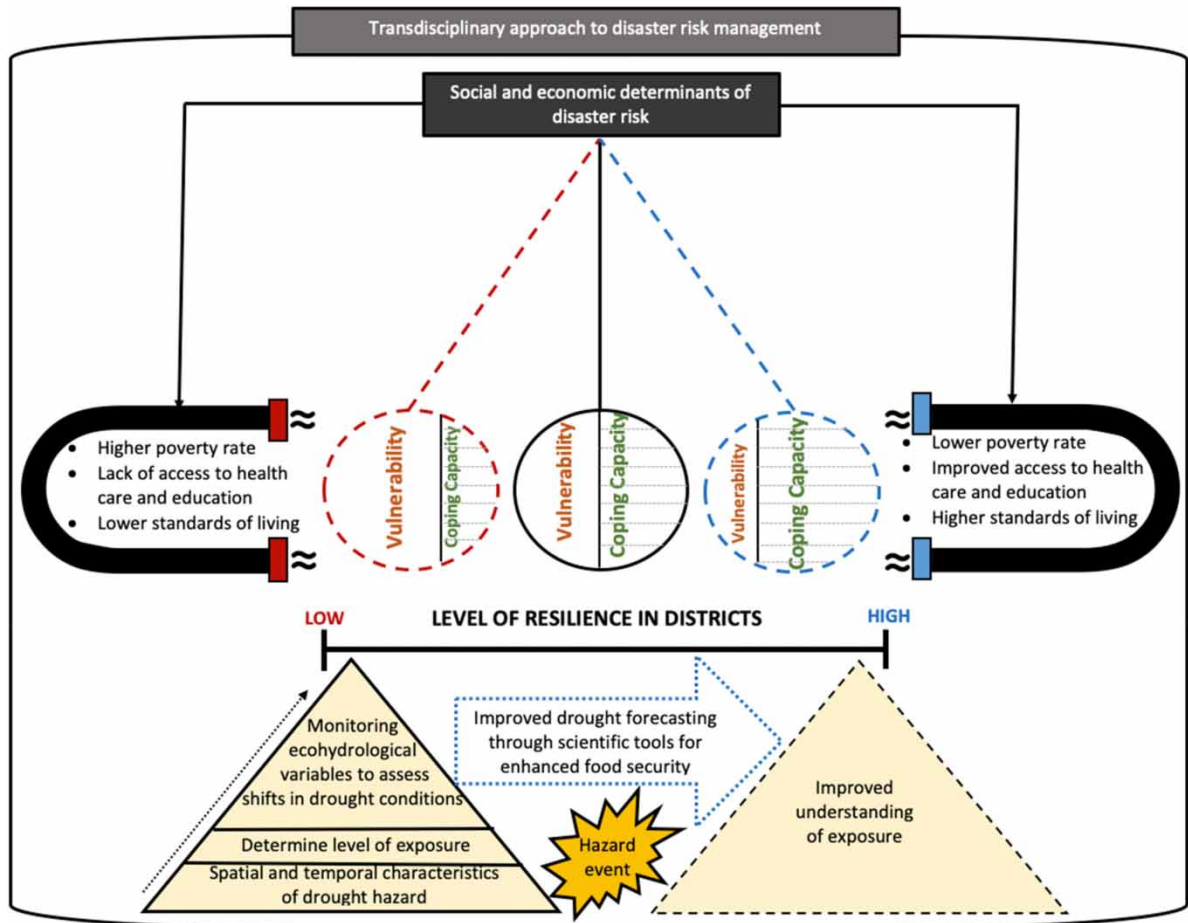
Key words: Drought monitoring, Ecohydrological variables, Hazard exposure, Interdisciplinary disaster management, Pakistan drought, Socioeconomic vulnerability index

HIGHLIGHTS

- Droughts, because of their interdisciplinary and cross-sectoral character, cannot be treated as the sole domain of disaster management.
- Identifying cause and effect interlinkages between poverty-driven socioeconomic vulnerabilities and science-based outputs assessing exposure strengthens DRR.
- Localized decision-making based on the simulation of ecohydrological variables for drought monitoring can strengthen food security.

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GRAPHICAL ABSTRACT



1. INTRODUCTION

In recent years, food insecurity has been growing due to the occurrence of droughts, especially in the rural areas of developing countries, where population growth and climate change put pressure on limited natural and economic resources. As droughts are a slow-onset hazard, their effects are not immediately visible; however, the impact is spread over vast temporal and spatial dimensions spanning across government sectors and knowledge disciplines. As such, their impact involves diverse and indirect consequences, and hence, droughts are known as creeping disasters (Van Loon 2015). Pakistan is ranked 84 in a list of 113 countries as per the Global Food Security Index (Economist Impact 2022). It is placed in the bottom 25% of countries alongside states that have been facing high levels of poverty, prolonged conflict, and famine for decades. The most severe drought in Pakistan's recent history occurred from 1998 to 2002, which showed a nationwide economic impact. The major crops registered a 10% decline in production, and the agricultural sector was contracted by 2.6%, as water supplies were reduced by 51% (Pakistan Meteorological Department (PMD) 2024). Another major drought was declared in 2019 when rural households in the provinces of Sindh and Balochistan faced increased food insecurity and high child malnutrition (United Nations Office for the Coordination of Humanitarian Affairs 2019).

In Pakistan, the province of Balochistan is prone to extended drought periods. The majority of the province is characterized by an arid climate with low rainfall and high evapotranspiration. Unlike in other provinces, the districts of southern and western Balochistan are not connected to the surface canal irrigation system of the Indus basin, and farmers primarily utilize rainwater and groundwater for agricultural production. The region is characterized by low, scanty, and uncertain amounts of rainfall. One of the major drivers of food insecurity is meteorological droughts that can lead to agricultural drought, especially in regions with low adaptive capacity in terms of alternate sources of water supply. Tackling disasters requires an understanding of a region's economic and social structures, which form the basis for development and have an indirect impact on disaster management through the functional capacities of state agencies, as well as the resilience levels of citizens in a society.

Government systems may not be particularly designed to recognize the effects of slow-onset disasters such as droughts. A depletion of water in the ecosystem can lead to agricultural drought, which causes a reduction in soil moisture required for crop and forage production, affecting both humans and livestock. Such a situation results in socioeconomic drought as populations are impacted by food insecurity and social and economic disruption. [Head \(2008\)](#) mentioned that complex public policy issues are difficult to address because the solutions may be aimed at addressing the symptoms of a problem instead of the underlying causes. This dilemma is evident in Disaster Risk Management (DRM) because institutional setups in most developing countries are inherently designed to prepare for and respond to disaster events rather than tackling the root causes of risk generation, which are not easily identifiable and spread across sectors and disciplines. Drought hazards involve complexity, which requires transdisciplinary synergistic solutions.

The study aims to introduce integrated disaster management by bridging the natural science and social policy gap. This can be practically achieved by identifying and understanding the linkages among scientific outputs and indicators of socioeconomic development. The emphasis of many drought studies has been on precipitation that utilizes the conventional standardized precipitation index or the standardized precipitation evapotranspiration index for analysis. Such investigations can limit the consideration of land surface hydrology and vegetation growth dynamics. Alternatively, the Coupled Land and Vegetation Data Assimilation System (CLVDAS) can provide important information related to hydrological and agricultural drought, as it can simulate ecohydrological variable modeling and combine it with microwave satellite earth surface observations of vegetation growth ([Sawada & Koike 2016](#)). Ecohydrological variables are important factors that provide an understanding of the relationship between the water cycle and vegetation growth. Their use can provide an effective temporal aspect of shifts among meteorological, hydrological, and agricultural droughts, thus providing authorities with timely information.

To practically implement its objectives, the study assesses and addresses underlying factors that contribute to disaster risk at the local level to improve overall drought management. As such, the province of Balochistan in Pakistan is selected to elaborate on the integrated approach. The first objective of this research is to develop a socioeconomic vulnerability index for drought-prone Balochistan province. The second objective is to improve local district-level drought management by demonstrating the use of ecohydrological variables as output parameters of CLVDAS and linking its outputs with the socioeconomic indicator of food security. To improve the understanding of the spatial and temporal characteristics of drought occurrence, the study provides an alternative to precipitation-based approaches of drought monitoring. This transdisciplinary approach can assist in simultaneously addressing the components of disaster risk by identifying: (i) the citizens' structural social and economic vulnerabilities and (ii) the intensity of hazard exposure at the local level. The findings and recommendations of the study can be utilized in the development of holistic programs for the practical implementation of maintaining food security at the local level.

2. STUDY AREA

Since the turn of the century, Balochistan has been impacted by droughts of varying intensities from 1998 to 2002, 2009, 2013 to 2015, and more recently from 2018 to 2020 (United Nations Development Programme (UNDP) 2015; Naz *et al.* 2020; Food & Agriculture Organization (FAO) 2022). Balochistan province shows the lowest performance in human development indicators in Pakistan, with high levels of inequality in education, living standards, and health (UNDP 2020). Within the province, the districts of the south and west exhibit high levels of rural poverty. Khuzdar and Awaran are two districts from this region that are included in the top five poorest districts of Pakistan (Ministry of Planning, Development & Special Initiatives (MPDSI) *et al.* 2024). Since the region has limited employment opportunities due to a lack of infrastructure and the absence of major industry, the mainstay of the majority of the rural households' livelihoods continues to be subsistence farming. Hence, a significant need exists to safeguard the rural population against the impacts of droughts, which can directly heighten food insecurity of households that are primarily dependent on agriculture for domestic food consumption and livelihoods.

Balochistan has a dry climate, which can generally be categorized into hyper-arid, arid, and semi-arid climatic zones with precipitation ranging between 100 and 400 mm. The province has 18 river basins, which mainly drain inland. These rivers generally lack permanent flows of water and become raging torrents following heavy rains, and hence, agriculture in the majority of the region is dependent on runoff farming or spate irrigation that utilizes flood water (Irrigation Department 2017). The study area in the southern and western districts of Balochistan is part of the hyper-arid and arid zones of the province, mainly drained by the Dasht River. This study simulates ecohydrological variables, in particular vegetation water content, using CLVDAS for the southwestern districts of Balochistan, namely Awaran, Khuzdar, Kech, and Panjgur. The area is affected by social and economic constraints in the form of low crop and livestock productivity, underdeveloped markets, routine prevalence of food and nutrition insecurity, with households dependent on vulnerable and fragile livelihoods (FAO 2018). The districts of Balochistan exhibit weak institutional capacity, high hazard exposure, and widespread poverty-induced vulnerabilities of food insecurity, malnutrition, and lack of basic services that weaken disaster management capacities in the region. Such circumstances, where citizens face substantial deprivations daily, increase their vulnerabilities and exposure to disaster risk.

This study utilizes the Pakistan Social and Living Standards Measurement (PSLM) survey district-level indicator data to provide policymakers with an easily comprehensible and comparative view of differential vulnerability across districts of Balochistan, some of which are the poorest in Pakistan and vulnerable to the impacts of frequent droughts. Balochistan contains districts with some of the highest poverty levels in the country. Khuzdar is the poorest district of Pakistan, ranked first in the multidimensional poverty index (MPI), and Awaran is ranked fourth out of a total of 126 districts (MPDSI *et al.* 2024). In 2018, the summer monsoon season was characterized by reduced rainfall, with Balochistan receiving 45% below-normal rain, which led the provincial government to declare 18 drought-affected districts as calamity-hit for enforcing special countermeasures such as food distributions. However, drought-like conditions had been prevailing in the province since 2013, impacting livelihoods and food security year after year (FAO 2020). The study districts in Balochistan were severely impacted by the effects of droughts due to the prevailing socioeconomic and hazard exposure conditions.

During the drought period of 2019, the affected districts, which already had low education performance indicators, recorded increased school drop-out rates as families prioritized food security over educational expenses. In some of the drought-hit districts, up to 95% of the population was living in rural areas (National Disaster Management Authority (NDMA) & United Nations (UN) 2019). This implied that a vast majority of the people were dependent on agriculture and livestock, and their main sources of subsistence and livelihoods

were the most impacted. Drought stress limits the growth of crops and vegetation and heightens the depletion of water sources. The rural population, especially the poor who already have limited opportunities and assets, face direct impacts. Availability of drinking water and food for human consumption is decreased, as well as fodder and forage availability are reduced as grazing grounds and pastures are affected.

At the peak of the drought period from May to August in 2019, about 1.79 million people were estimated to be suffering from crisis and emergency levels of acute food insecurity in the drought-affected districts of Balochistan. Additionally, more than half of the 0.4 million acutely malnourished children under 5 years of age belonged to the drought-affected districts. Children in the southwestern districts were severely impacted. Panjgur displayed extremely high global acute malnutrition rates in children (at 31.6%) and was in the most dangerous level at phase 5 of the Integrated Food Security Phase Classification (IPC) acute malnutrition analysis. Kech reported critical levels (phase 4), and Awaran faced serious conditions (phase 3) of acute malnutrition. High food insecurity in relation to the quality and quantity of food was cited as the main contributing factor behind the high levels of acute malnutrition in these districts. Other major challenges were poor water and sanitation conditions, as well as low vaccination coverage (IPC 2019). Earlier, the provincial government had declared a 'nutrition emergency' in Balochistan at the end of 2018 to combat the worsening indicators of mother and child health, as drought conditions had led to increased food insecurity (Dawn 2018). Such a situation is evidence of the disaster risk-poverty nexus, where socioeconomic vulnerabilities are exacerbated at every occurrence of a hazard event.

An integrated approach that synthesizes scientific information on drought monitoring and data on socioeconomic deficiencies can help to improve the management of local-level risk, especially food insecurity. Such an approach should be tailored to recognizing the cause-and-effect relationships between disaster risk and poverty-induced vulnerabilities and vice versa. An integrated assessment of relevant variables of drought monitoring and socioeconomic conditions can provide a deeper understanding of the intensification or reduction of drought stress, and hence enable the implementation of localized need-based measures. Drought conditions lead to a reduction in the available drinking water sources in rural areas, especially those regions that have limited sources due to their arid climate. Most households in rural Balochistan depend on natural springs, dug wells, or harvested rainwater for domestic use. A drop in the water table affects crop production and living standards as families are forced to utilize water unfit for human consumption, leading to deterioration in health conditions. Pregnant women and children under 5 are the most vulnerable to the effects of droughts in the form of worsened nutritional and health levels due to reduced and low-quality intake of food and water. This results in worsened indicators of malnutrition and maternal health, which are some of the indicators used to measure progress toward the Sustainable Development Goals (SDGs).

3. LITERATURE REVIEW

The contemporary approach to disaster risk reduction (DRR) taken by the UN and other international organizations recognizes transdisciplinary causative factors behind the existence or escalation of disaster risk in times of hazard events. In recent decades, vulnerability and climate change have been central to the global debate on the increasing impact and frequency of water-related disasters. According to the United Nations Office for Disaster Risk Reduction (UNDRR), 'vulnerability is the human dimension of disasters and is the result of the range of economic, social, cultural, institutional, political and psychological factors that shape people's lives and the environment that they live in'. Exposure is defined as 'the situation of people, infrastructure, housing, production capacities, and other tangible human assets located in hazard-prone areas' (UNDRR 2017, 2024a). The following formula summarizes the factors that determine the intensity of disaster risk (Billing & Madengruber 2005; Barrett

et al. 2021; International Federation of Red Cross & Red Crescent Societies (IFRC) 2023).

$$\text{Disaster risk} = \frac{\text{Hazard} \times \text{Exposure} \times \text{Vulnerability}}{\text{Coping Capacity}}$$

Disaster risk and impact are dependent on the interaction of different associated factors of hazard occurrence, the exposure that results from the hazard event, and the larger societal situation or circumstances. While coping capacities are the attributes of individuals and communities that can be used to mitigate the effects of hazards. Coping capacities are important to build resilience, as strengthened abilities can help to reduce prevailing vulnerabilities and hence decrease hazard impact. These abilities can be manifested through multiple forms, such as human, social, natural, physical, and financial capacities. Human capacity depends on the health, educational, and skill status of citizens, whereas social capacity represents the network of community relationships, social bonds, and common resources that society members can utilize to manage risk or disaster situations. Natural capacity depends on the availability and utilization of natural capital, such as land productivity, water, and ecosystem resources. The physical capacity of a country is shaped by the availability of equipment and infrastructure in place that enhance economic and operational functions. Whereas financial capacity represents the access to and diversity of income sources and the availability of wealth at the household and societal level that can insulate against disaster risk (Williges *et al.* 2017). To build resilience against disaster risk, it is important to understand the transdisciplinary nature of characteristics involved across all aspects of coping capacities, as such abilities can be effective for disaster impact mitigation.

Drought analysis studies on Balochistan have utilized the conventional standardized precipitation index or the standardized precipitation evapotranspiration index (Ashraf & Routray 2015; Naz *et al.* 2020; Qaisrani *et al.* 2021). The CLVDAS integrates microwave remote sensing, a land surface model driven by meteorological forcing data, a dynamic vegetation model, and a data assimilation scheme. As such, CLVDAS is able to quantify changes in ecohydrological variables such as vegetation water content, land-surface soil moisture, root-zone soil moisture, and the leaf area index through data assimilation of different model outputs. It integrates satellite-based microwave remote sensing of land surface hydrology and vegetation growth dynamics that enable monitoring of ecohydrological variables such as soil and vegetation moisture conditions (Tsutsui *et al.* 2021). This information can enable timely action to respond to changes in drought conditions in relation to agricultural, irrigation, and food security planning.

Studies utilizing indices have assessed disaster risk in Pakistan at the provincial and district levels using vulnerability and exposure analysis. Rafiq & Blaschke (2012) developed a multi-hazard risk map for districts of Pakistan based on hazard potential and vulnerability, by using hazard frequency and intensity, and vulnerability measuring indicators related to damage potential and coping capacity. Baig *et al.* (2021), while using geological and topographical indicators for hazard potential and socioeconomic, environmental, and human development indicators for vulnerability calculation, introduced vulnerability and hazard rankings for 10 northern mountainous districts of Pakistan. Whereas other studies have quantified flood risk, exposure, and vulnerability in urban and rural areas of Punjab and Khyber Pakhtunkhwa provinces of Pakistan while relying on numerous weighted indicators to establish composite indexes (Rana & Routray 2018; Khan *et al.* 2023).

4. METHODS

The study relies on survey data from two main sources to develop a composite socioeconomic vulnerability index. The PSLM survey of the Pakistan Bureau of Statistics (PBS) collects comprehensive information on households and individuals at the district level. Additionally, Pakistan's MPI report of 2024 provides information on

multidimensional poverty at the district level. The MPI measures deprivations related to the three dimensions of education, health, and living standards by including 14 indicators across these three dimensions, which are taken from the PSLM 2019–2020 survey. The MPI provides a multidimensional aspect of poverty in terms of deprivations related to basic services, which is different from traditional measurements of monetary or income-based poverty.

This study classifies districts of Balochistan into three categories of relative socioeconomic vulnerability with the use of an index. The headcount ratio or incidence of poverty indicator developed by the MPI report is utilized as the first indicator, and another seven indicators are taken from the PSLM survey. These 7 indicators are distinct from the 14 indicators used for the calculation of the MPI. Thus, the socioeconomic vulnerability index considers a comprehensive mix of indicators to inform the differential vulnerability prevailing in the districts of Balochistan. The eight indicators are grouped under four thematic components, namely poverty, education, health, and standard of living, as shown in Table 1. Each component consists of two indicators. The MPI headcount ratio indicator is given a double weightage to reflect its composite structure, as it includes 14 indicators across education, health, and standard of living. Indicators fulfilling two basic requirements are selected: (i) relevancy to measuring social and economic conditions of citizens in the districts and (ii) district-level data are available for the relevant indicator.

The index is calculated by first converting each of the eight indicators into normalized scores between 0 and 1 using the percentile ranking method. For indicators where higher values indicate greater vulnerability, such as headcount poverty ratio, the percentile rank formula is used directly, and for indicators where higher values indicate less vulnerability, such as literacy rate, the normalized score is inverted. The final score for each district is computed using a weighted average, with the poverty headcount ratio receiving a double weight. Districts are then classified into low, moderate, or high vulnerability based on 33rd and 66th percentile cutoffs in the normalized score distribution. As a general rule, the indicators are normalized on a scale of 0–1 using the logic of the formula, as shown in Figure 1. It is applied to vulnerability-enhancing indicators, namely, the MPI headcount ratio, the food insecurity experience scale (FIES), out-of-school children, and diarrhea in children under 5.

For resilience-building indicators, namely, adult literacy rate, prenatal consultations, mobile phone ownership, and household internet access, the inversed formula shown in Figure 2 is applied.

The analytical framework for assessing socioeconomic vulnerability within the context of hazard exposure and disaster risk is shown in Figure 3. The PSLM survey of 2019–2020 excluded Balochistan's districts of Chaghi, Jhal Magsi, Musakhel, Panjgur, and Zhob. Hence, the provincial average values of the PSLM survey have been substituted for the calculation of the index values of these districts.

5. DISCUSSION

To strengthen the implementation of the 2030 agenda, target 17.18 of the SDGs was framed to increase the capacity of developing countries to collect timely and reliable data, which is disaggregated across several

Table 1 | Thematic components and selected indicators.

Component	Indicator # 1/Weightage	Indicator # 2/Weightage
Poverty	MPI headcount ratio/ $\times 2$	Food insecurity experience scale (FIES)/ $\times 1$
Education	Adult literacy rate/ $\times 1$	Out-of-school children/ $\times 1$
Health	Prenatal consultations/ $\times 1$	Diarrhea in children under 5/ $\times 1$
Standard of living	Individual mobile phone ownership/ $\times 1$	Household internet access/ $\times 1$

$$P_i = \frac{R_i - 1}{N - 1} \Rightarrow \text{Highest value} = \text{Normalized score of 1}$$

$$\Rightarrow \text{Lowest value} = \text{Normalized score of 0}$$

P_i = Normalized value; R_i = Rank of the observation in ascending order (lowest = 1, highest = N); N = Total number of observations.

Fig. 1 | The percentile rank equation is used to normalize vulnerability-enhancing indicators.

$$P_r = 1 - \frac{R_r - 1}{N - 1} \Rightarrow \text{Highest value} = \text{Normalized score of 0}$$

$$\Rightarrow \text{Lowest value} = \text{Normalized score of 1}$$

P_r = Normalized value; R_r = Rank of the observation in ascending order (lowest = 1, highest = N); N = Total number of observations.

Fig. 2 | An inverse percentile rank equation is used to normalize resilience-enhancing indicators.

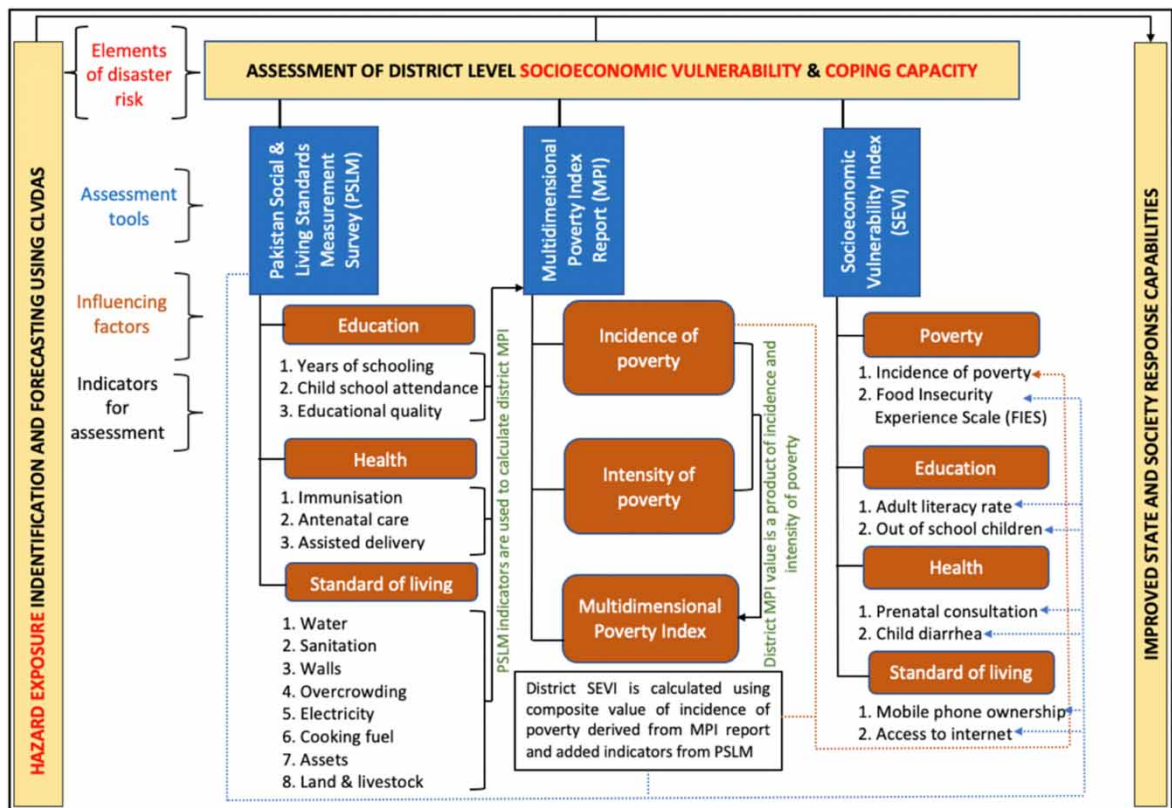


Fig. 3 | Evaluating differential socioeconomic vulnerability in districts of Pakistan.

characteristics (UN 2024). Of the 77 low- and lower-middle-income countries, Pakistan has the advantage of being part of those 36% that have in place national statistical plans which are fully funded and under implementation (UN 2023; World Bank 2023). In Pakistan, the central statistical agency is the PBS, which conducts the PSLM surveys at regular intervals. The PSLM surveys collect district-level disaggregated data across gender and urban–rural areas. Besides being used for government poverty reduction strategies, the PSLM survey data are also being utilized to monitor progress toward 31 indicators related to the SDGs (PBS 2021a). Statistical data collection is vital to achieving the Sustainable Development Agenda, as national and sub-national data are needed for formulating empirically based and interdisciplinary multipronged development policy. Availability of local-level indicator data showing performance of the social sector and status of citizens' living standards can help to address issues of poverty and socioeconomic development. As such, the study uses commonly available socioeconomic indicator data to develop the socioeconomic vulnerability index.

The interdisciplinary character of disasters in terms of resilience building, mitigation, and response underscores that relevant planning and implementation are not solely confined to a single domain. Dealing with the systemic nature of underlying factors that increase hazard impact requires that DRM cannot solely be treated as a purview of the disaster management institutions. Underlying factors such as poverty-induced vulnerabilities and weak local-level governance continue to drive disaster risk, leading to the recurrence of similar humanitarian impact and economic damage in developing countries. The 2010 and 2022 flooding in Pakistan is one such example (Hote & Koike 2025). To address complicated problems containing complex interactions, reliance on a single discipline may not be an adequate measure. A single discipline may not necessarily host sufficient knowledge required for finding solutions to the multidimensional nature of such complex issues. As such, the systemic nature of the risk creation and disaster impact can be managed using synergistic tools. These collaborative measures can be practically achieved by linking science and policy – an approach which can utilize vulnerability and hazard data and grassroots information and experience to make localized risk assessments (UNDRR 2024b).

As is typical practice in many countries, government systems or sectoral agencies perform their roles within their specified domains with insufficient coordination and synergies. Such a situation can lead to ineffective functioning and a lack of desired policy outcomes to achieve overall sustainable development. The social and economic data provide important insights into the institutional and societal capacity and prevailing circumstances of a country. As per the SDG progress report of 2024, achievement of the global targets is critically off track as only 17% of the targets have sufficient progress enabling SDG realization by 2030. Statistical data collection is imperative for a holistic approach to development that is based on integrated and multifaceted policy and investments. Availability of data on sub-national administrative tiers, which is disaggregated across parameters such as gender, urban–rural areas, and marginalized groups, can help decision-makers to formulate and implement strategies that are evidence-based to achieve improved and need-based outcomes.

Pakistan is ranked high in the major global disaster risk indexes (Marin *et al.* 2017; Bündnis Entwicklung Hilft 2024; Adil *et al.* 2025). The high rankings are evidence that the country exhibits high levels of vulnerability, exposure, and lack of coping capacity due to widespread poverty, inequality, and weak institutional arrangements. Identification of a single factor that is responsible for influencing people's vulnerability to disaster risk is a complex policy problem. Biswas & Nautiyal (2023) stated that since vulnerability is influenced by social, economic, political, and natural factors, it is difficult to select a particular aspect that affects vulnerability. However, identifying, understanding, and analyzing social and economic deficiencies prevailing in a district through an assessment of multiple numerical indicators can provide relevant insights into the socioeconomic vulnerability and coping capacity of that district's population. These indicators are able to provide a broad understanding of the prevailing social and economic conditions in a country through the use of statistics, some of which are related to the literacy rate, mother and child mortality rates, and the situation of food insecurity.

Global risk indexes provide an assessment of disaster risk at the country level; however, for effective mitigation, preparedness, and response, the need for a sub-national analysis is required, especially at the district tier in Pakistan. Different regions of the country have distinctive characteristics in terms of geographic, socioeconomic, and climatic conditions and are prone to specific disaster risks. Even within the provinces, wide-ranging disparities exist among the districts. Also, within the districts, further socioeconomic variations exist in the rural and urban areas, with rural areas faring poorly in social and economic indicators. With the use of different indicators, the socioeconomic vulnerability index can aid in identifying social and economic disparities existing at the local level, and as such can act as an effective tool to support district DRR policy.

6. RESULTS

Balochistan province has the highest poverty rate in Pakistan at 60.2% and is vulnerable to prolonged drought periods. [Table 2](#) shows the socioeconomic vulnerability index of Balochistan. Quetta, the provincial capital, due to its relatively improved facilities and higher standard of living, scores low in vulnerability, whereas rural, remote, and sparsely populated districts of Khuzdar and Awaran display higher vulnerability.

The index values are additionally used to represent the socioeconomic vulnerability using a district administrative map of Balochistan ([Figure 4](#)). It illustrates that neighboring districts generally exhibit similar levels of vulnerability, leading to geographic clustering of vulnerability patterns. This information can be useful for policy-makers to inform measures aimed at decreasing vulnerabilities and exposure and improving the coping capacities of citizens of high socioeconomic vulnerability districts.

The FIES is indicator 2.1.2 of the SDGs, which is used to measure the prevalence of moderate or severe food insecurity in a population. PBS has included this indicator in the most recent PSLM survey of 2019–2020. The FIES is an important indicator that can aid policymakers in gauging food insecurity prevalence in different districts, for making improved and evidence-based decisions. This study has also included it as an indicator to determine the socioeconomic vulnerability index for the districts of Balochistan. Balochistan, at 23.36%, has the highest percentage of population in Pakistan that is experiencing a moderate or severe degree of food insecurity. Awaran and Khuzdar, high vulnerability districts in the socioeconomic vulnerability index, show high levels of moderate and severe food insecurity above the provincial average at 35.43 and 29.26%, respectively ([PBS 2021b](#)). These figures indicate the socioeconomic conditions prevailing in these districts at the 2019 drought. The FIES, child school attendance, immunization, prenatal consultations, and access to safely managed drinking water are some of the indicators that can be monitored for countering the deterioration in health, education, and living standards caused by the onset of hazards such as droughts.

This study utilized CLVDAS and used the ecohydrological variable of vegetation water content (m^3/m^3) as an indicator for determining agricultural drought, as plants and crops require water uptake for healthy growth. Wheat is the major staple crop in Pakistan and is widely grown across all regions of the country using different sources of irrigation. However, in the districts of southwestern Balochistan, the cultivation of wheat is mainly rainfed. Therefore, the study utilizes provincial wheat yield (kg/ha) as another relevant indicator for monitoring the drought period. The wheat crop is sown in November and harvested in April; hence, the maximum growth is expected to occur in January when the wheat crop would retain sufficient amounts of water required for healthy growth. Therefore, the temporal average of vegetation water content in January for selected districts, and the annual wheat crop yield of Balochistan province, are the monitoring parameters of agricultural drought. A normalized index z -score method is used to show the variation in vegetation water content and wheat crop yield by converting the data values to standardized distribution scales for each parameter separately. Normalizing the data allows for easier comparison of data points across multiple distributions. [Figure 5](#) shows the normalized z -score

Table 2 | Socioeconomic vulnerability index for districts of Balochistan.

Sr.	District	Vulnerability score	Socioeconomic vulnerability category
1	Awaran	0.70	High
2	Barkhan	0.58	Moderate
3	Chaghi	0.47	Moderate
4	Dera Bugti	0.73	High
5	Duki	0.54	Moderate
6	Gwadar	0.29	Low
7	Harnai	0.55	Moderate
8	Jaffarabad	0.66	Moderate
9	Jhal Magsi	0.47	Moderate
10	Kachhi	0.68	High
11	Kalat	0.59	Moderate
12	Kech	0.50	Moderate
13	Kharan	0.46	Moderate
14	Khuzdar	0.83	High
15	Killa Abdullah	0.68	High
16	Killa Saifullah	0.46	Moderate
17	Kohlu	0.17	Low
18	Lasbela	0.30	Low
19	Loralai	0.25	Low
20	Mastung	0.33	Low
21	Musakhel	0.47	Moderate
22	Naseerabad	0.76	High
23	Noshki	0.24	Low
24	Panjgur	0.47	Moderate
25	Pishin	0.24	Low
26	Quetta	0.23	Low
27	Shaheed Sikandarabad	0.79	High
28	Sherani	0.67	High
29	Sibi	0.32	Low
30	Sohbatpur	0.52	Moderate
31	Washuk	0.47	Moderate
32	Zhob	0.47	Moderate
33	Ziarat	0.54	Moderate

for wheat yield in the province of Balochistan from 2006 to 2010 and from 2014 to 2023. A decline in the wheat yield can be seen after 2017 up to 2020, showing an external stress on wheat productivity. This duration matches the drought period in the province that was reported in various aid agency documents (IFRC 2019; IPC 2019; NDMA & UN 2019; FAO 2020). A closer view of the decreasing trend of wheat yield during the drought

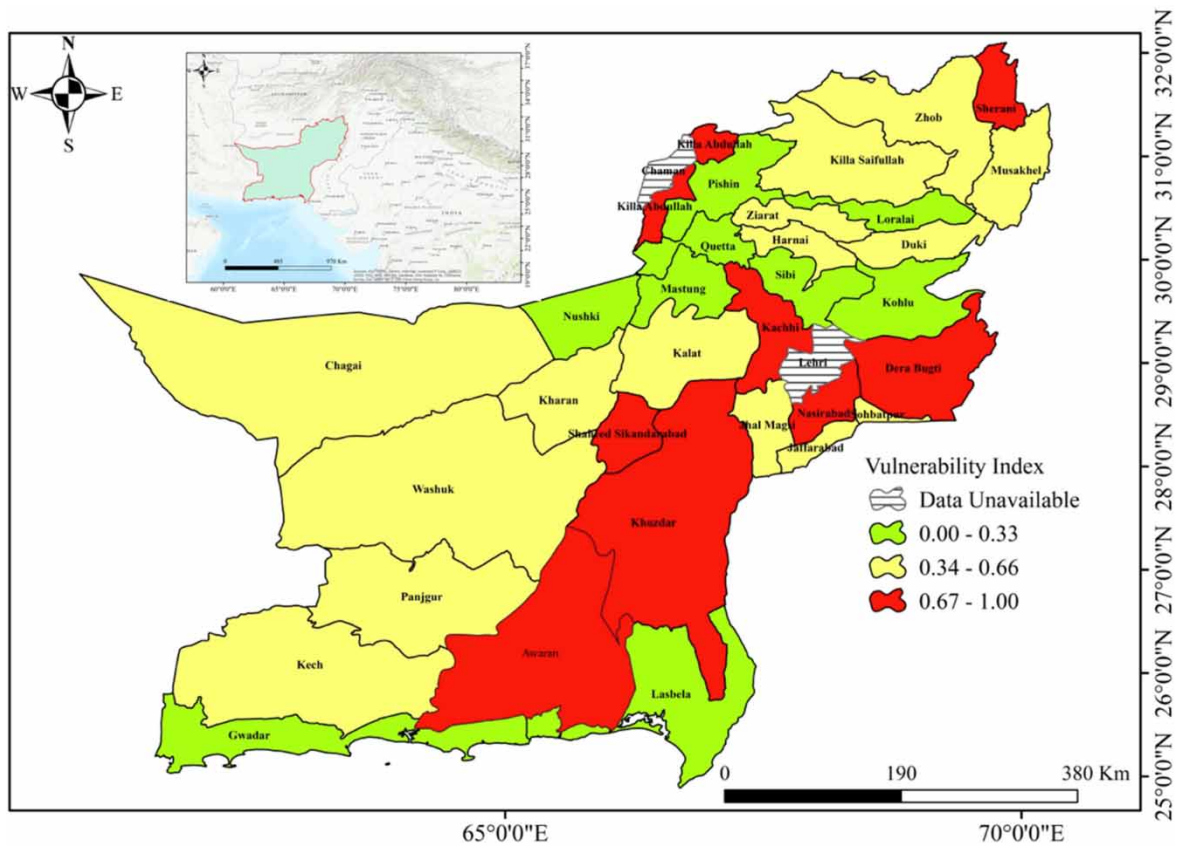


Fig. 4 | Map showing clustering tendency of socioeconomic vulnerability in Balochistan.

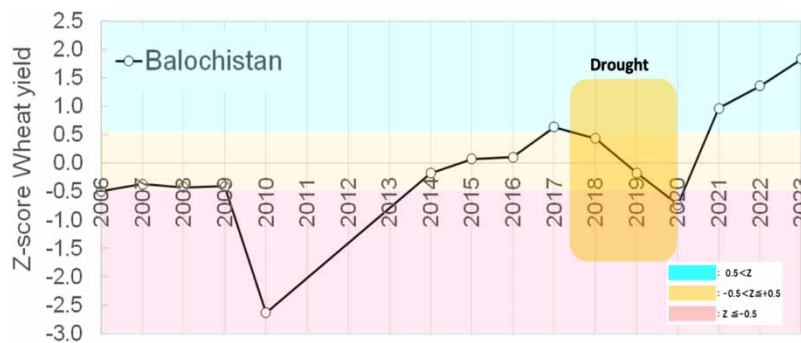


Fig. 5 | Normalized index of annual variation in wheat yield in Balochistan, showing a decrease in crop yield from 2017 to 2020, matching the drought period.

period is shown in Figure 6. The z-score trend shows that the wheat yield dropped to below-average values in 2019 and 2020.

The study generated the January monthly averages of vegetation water content for Awaran, Khuzdar, Kech, and Panjgur districts. Figure 7 shows the temporal variation in the vegetation water content in January as a

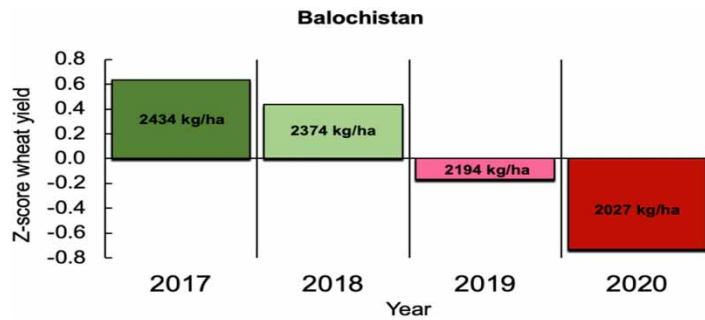


Fig. 6 | Provincial wheat yield of Balochistan decreased to below-average values in the period 2019–2020.

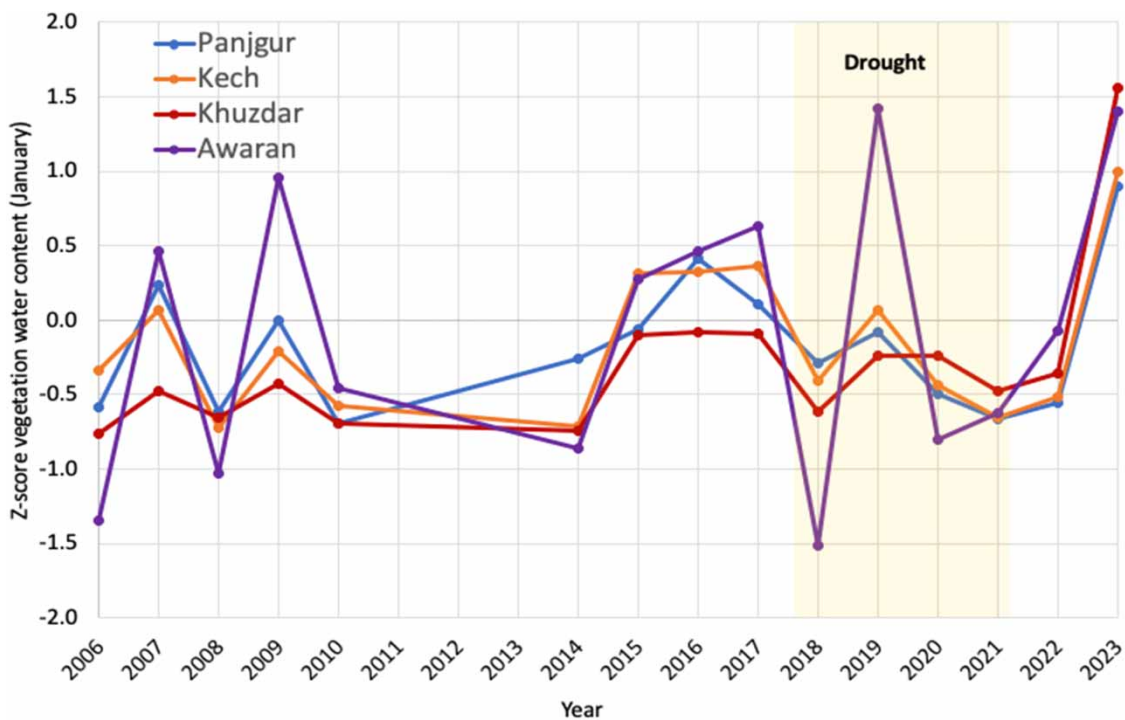


Fig. 7 | Annual variation in normalized index for vegetation water content for four districts of Balochistan (January monthly averages for the periods 2006–2010 and 2014–2023). A below-average trend in z-scores is observed between 2017 and 2022, which corresponds with the widely reported 2018–2020 drought period.

normalized index z -score for these four districts of Balochistan. Post-2017 shows a generally declining trend in the vegetation water content, which is indicative of drought conditions. This below-average trend continued up to 2022, after which the values rose considerably, indicating the easing of drought stress. While Panjgur, Kech, and Khuzdar exhibit a decreased normalized index during the drought conditions (2017–2022), Awaran shows a sharp increase in the vegetation water content in 2019, followed by a steep decline in 2020, which is in the midst of the drought period.

To analyze and ascertain the reason for the increase in vegetation water content in January 2019 for Awaran and assess its implications on signaling changes in drought stress, the study utilized two methods. First, the 12-monthly averages of the z -scores of vegetation water content for each year from 2017 to 2020 were simulated for the four districts to compare the monthly trends, as shown in Figure 8. Second, additional ecohydrological variables, namely, land-surface soil moisture, root-zone soil moisture, and leaf area index, were simulated for Awaran to analyze their values in relation to vegetation water content, as shown in Figure 9.

As shown in Figure 8, the z -scores of vegetation water content decreased across all four districts beginning in May 2018 for Panjgur, Khuzdar, and Kech and in June 2018 for Awaran, signaling the onset of agricultural drought conditions. From August 2018, an increasing trend can be observed in all four districts, which corresponds with the summer monsoon period. This increasing trend begins to decline from November and December 2018 for Kech, Khuzdar, and Panjgur, dropping to below-average values subsequently, but continues a sharp increase into January 2019 for Awaran. Although a continuous decrease in vegetation water content on an annual basis is not observed during the 2018–2020 drought period, generally below-average z -score values of vegetation water content are observed in the period. This situation is in contrast to the higher vegetation water content z -score values observed during 2015–2017, as shown in Figure 7.

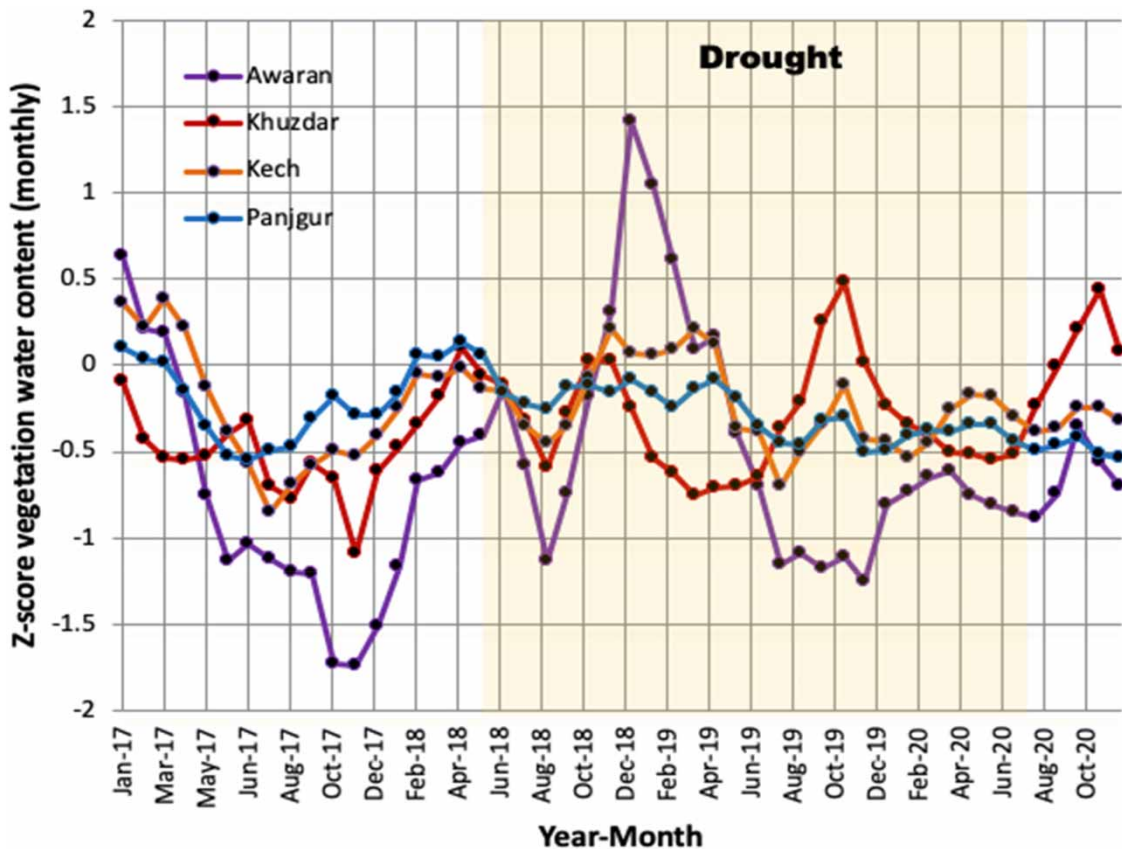


Fig. 8 | Monthly variation in normalized index for vegetation water content for four districts of Balochistan (monthly averages for the period 2017–2020). A below-average trend is observed in the z -scores after mid-2017 up to the end of 2020, corresponding to the drought period.



Fig. 9 | Graphs from top to bottom – precipitation, land-surface soil moisture, root-zone soil moisture, leaf area index, and vegetation water content for Awaran district from September 2018 to March 2019. The orange line identifies the time lag in the peaks of the ecohydrological variables following precipitation. The behavior of ecohydrological variables provides major indications for crop growth, which can inform decisions for countermeasures before and during drought periods.

Figure 9 shows the additional ecohydrological variables that were utilized to determine the cause of the increase in Awaran's vegetation water content in January 2019. The Japanese 55-year Reanalysis (JRA-55) dataset was used for obtaining precipitation occurrence in Awaran from September 2018 to March 2019. The figure shows that the district received multiple events of rainfall from the end of September to the middle of December in 2018. Resultantly, the land-surface soil moisture increased and peaked at the beginning of December 2018. Subsequently, the moisture from the land surface penetrated to the root zone, which increased the root-zone soil moisture, peaking at the end of December 2018. The higher root-zone soil moisture was absorbed by the vegetation, which increased the leaf area index and vegetation water content during January 2019. The line drawn across the graphs of the ecohydrological variables shows the time lag among the peaks of these variables.

Figure 9 also shows that the root-zone soil moisture, which presented gradually elevated levels over 3 months (November–February), started to drop in February. It roughly decreased to the same level at the end of February as it was at the end of November. This shows that the decrease in root-zone soil moisture is at a faster rate than the rate of increase. This faster rate of decrease in root-zone soil moisture indicates conditions of agricultural drought because the soil has a long retention period in terms of memory of past water storage. Soil moisture levels are influenced by previous trends of extremes in climate. As such, drier conditions may tend to induce a longer soil moisture memory whereby changes in physical soil properties can make the soil resistant to maintaining longer-term moisture, resulting in the extension of the drought period (Rahmati *et al.* 2024).

The rainfall that occurred in Awaran in October had a positive impact on the ecohydrological variables. To ascertain the precipitation situation in all study districts, the JRA-55 3-hourly precipitation data were obtained, as shown in Figure 10. It shows that relatively heavy rainfall occurred in Awaran at the end of October 2018, with low amounts in Kech, Panjgur, and Khuzdar during the same period. Hence, the higher precipitation impact can be seen on vegetation water content in Awaran, with a much lower effect in other districts. Therefore, monitoring of ecohydrological variables across spatial and temporal aspects can provide important signals of changes in prevailing drought conditions with important implications for food security and agriculture planning.

7. FINDINGS

This study introduces a design to practically show the integration of drought monitoring output parameters with socioeconomic indicators for improving district-level disaster management and decision-making. To maximize the localized benefits obtained from the integration of natural science output and social and economic policy, deepening the understanding of the linkage among hazard monitoring parameters and socioeconomic indicators is important. Table 3 provides an overview of vegetation water content simulated from CLVDAS output and the food security situation in some selected districts of Balochistan during the drought years obtained from the PSLM survey and the multi-agency IPC food security classification. The negative *z*-score values of vegetation water content at column 3 show that a generally below-average trend existed in this ecohydrological variable across nearly all districts during the 2018–2020 drought period. A positive relationship can also be generally seen between the category of socioeconomic vulnerability (column 2) and FIES (column 4) of each district, as households in districts with higher vulnerability reported experiencing higher food insecurity. The relationship between the socioeconomic vulnerability category (column 2) and the IPC food security classification (column 5) in each district is inconclusive. For example, Kech, despite being a moderate vulnerability district, shows relatively high levels of IPC-based food insecurity at 65%, but shows relatively low levels (12.42%) in the FIES.

The variances could be attributed to a number of factors. Kech district contains the largest artificial reservoir in Balochistan, the Mirani dam, which has an irrigation command area of over 33,000 acres, hence improving local food security due to irrigated agriculture, which could contribute to the low value of FIES (Water & Power Development Authority 2025). Also, Turbat city, the headquarters of the district, is the second-largest urban

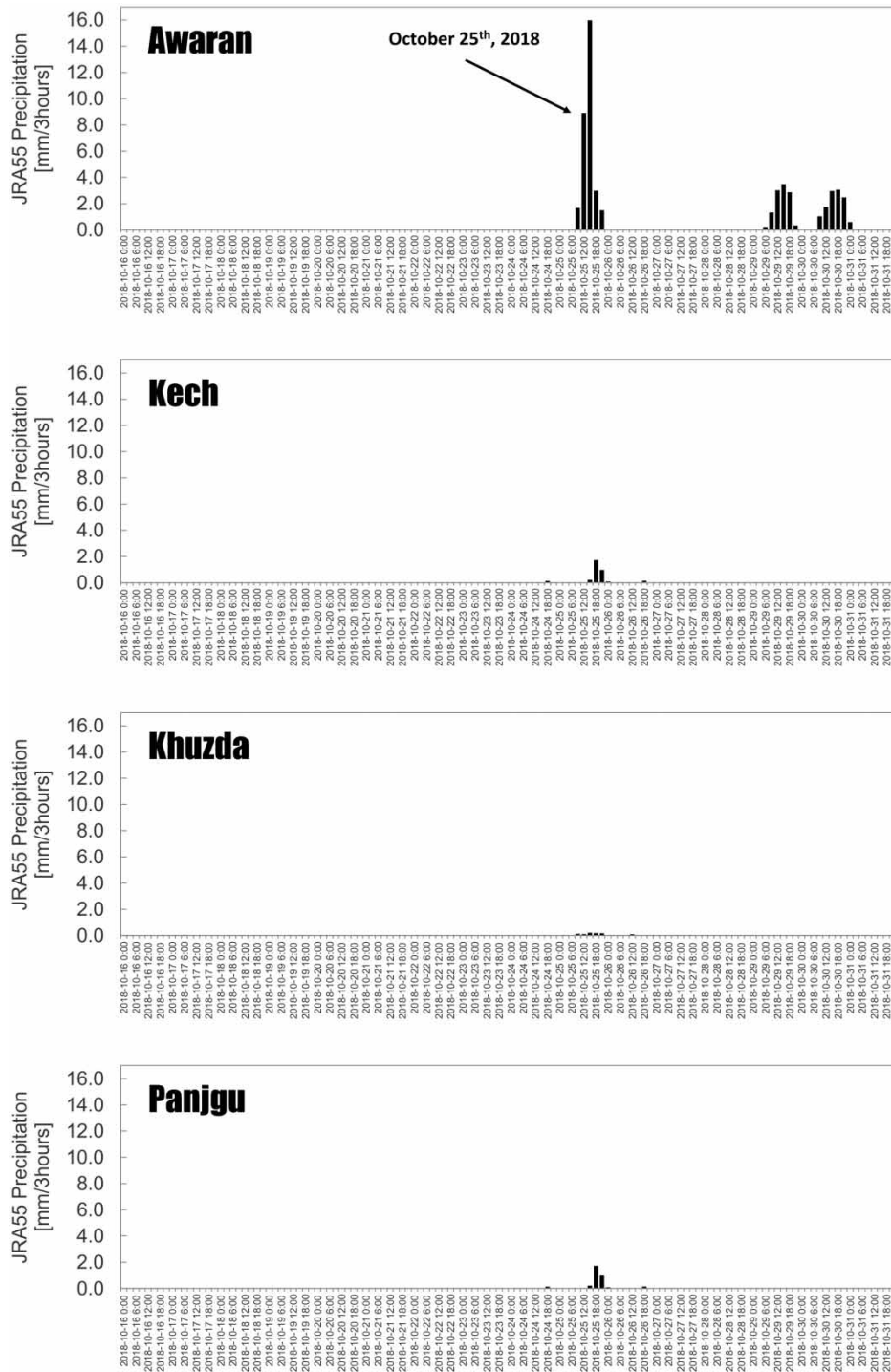


Fig. 10 | JRA-55 3-hourly precipitation data show relatively high rainfall on October 25, 2018, in Awaran and light rainfall in Kech, Khuzdar, and Panjgur, resulting in a higher value of vegetation water content for Awaran in January 2019, as shown in Figure 7.

Table 3 | Vegetation water content and food security in selected districts of Balochistan during the 2018–2020 drought period.

(1) District	(2) SEVI Category	(3) Vegetation water content z-score (January)				(4) FIES 2019–2020 (Moderate or severe) (%)	(5) IPC 2019 (Population in phase 3 and above food insecurity) (%)
		2017	2018	2019	2020		
Awaran	High	0.6322	−1.5110	1.4188	−0.8041	35.43	70
Khuzdar	High	−0.0927	−0.6135	−0.2404	−0.2383	29.26	–
Panjgur	Moderate	0.1077	−0.2897	−0.0782	−0.4983	–	55
Kech	Moderate	0.3661	−0.4028	0.0713	−0.4362	12.42	65
Gwadar	Low	1.1440	−0.1433	1.1531	−0.9815	4.59	60
Lasbela	Low	−0.5532	−0.4510	−0.7427	0.5713	16.42	–

center of Balochistan and constitutes about 25% of the population of the district. The city contains educational institutions and hospitals, and a relatively improved communications infrastructure, resulting in higher overall socioeconomic indicators for the district. A significant number of residents of the district work as migrant workers in the Middle East countries. Saleem *et al.* (2022) concluded that due to incoming foreign remittances, expenditure on healthcare by local households increased by more than 5 times, leading to improved living standards in the district. Conversely, the district is spread across 22,539 km², which accounts for disparities in access to healthcare, education, and stable food supply in the rural hinterland (PBS 2023). Hence, a complex mix of factors and processes can be responsible for impacting indicators in various ways. The key drivers behind the high food insecurity in districts were dry spells, high food prices, reduced dietary diversity, and lack of access to services in rural areas during the 2019 drought.

Similarly, Gwadar district, which is a low socioeconomic vulnerability district, shows a low percentage of the FIES but a contrasting high classification of food insecurity as per the IPC (60%). Gwadar is a coastal district, and fisheries account for a substantial part of the local economy as well as households' food intake. The reliance on locally grown crops for income generation and nutritional needs is low, as the district has the lowest production of the staple crop of wheat in all of Balochistan. The district only produced 55 tons of wheat compared with Balochistan's canal-irrigated Naseerabad district, which had a production of over 262,000 tons (Agriculture Department 2022). The high food insecurity of 60% for Gwadar, as reported in the IPC phase classification, is likely due to a host of factors such as food price inflation, unemployment, lack of dietary diversity, weak health infrastructure, malnutrition, and weak purchasing power.

The above analysis shows that, rather than reliance on a single indicator, integration of multiple indicators from multidisciplinary sources can assist in a deeper understanding of food insecurity. The low vegetation water content z-scores from 2018 to 2020 coincide with the drought period and high food insecurity levels. Such ecohydrological variables can provide an important forecast for future crop growth, enabling evidence-informed countermeasures for food security. Combining natural science outputs with multidimensional analysis outputs, such as the IPC food security classification that considers various indicators related to food consumption, nutritional status, livelihood coping strategies, and market access, enables a transdisciplinary approach for improved decision-making.

Furthermore, drought monitoring and management can benefit from analysis of land surface ecohydrology through the use of satellite remote sensing of vegetation growth dynamics, which are an important measure of drought stress. Vegetation water content is an important output parameter of CLVDAS for assessing the start of drought conditions as well as drought intensity because it can signal the loss of moisture content in plants.

This parameter can be monitored for a comprehensive assessment of district-level impacts of drought. In arid areas, a decline in socioeconomic indicators over time can be a signal of deteriorating living standards caused by drought conditions.

Effective DRM requires cross-sectoral inputs in which organizations having the relevant expertise can make use of particular disciplinary knowledge and contribute to reducing the underlying causes of risk. A policy shift in Pakistan toward the joint use of vulnerability and hazard simulation tools can be the foundational move to building district-level disaster resilience, which involves improving the precision of poverty alleviation programs and ensuring the effectiveness of early warning and climate adaptation strategies.

The socioeconomic vulnerability index developed in this study can be used by provincial-level policymakers to allocate need-based resources to different districts. The index can highlight those districts that are at higher risk of a humanitarian emergency, as such districts would have a higher proportion of the population that would not be able to meet basic needs in the case of a hazard occurrence. The index can also aid in delineating the sectoral response required toward the achievement of poverty, health, and education-related SDGs. The index is able to quantify the underlying risk factors that can help decision-makers recognize and identify the specific vulnerabilities through the use of an indicator-based approach. As and when new PSLM and MPI data are released, the index can be updated and used for the temporal analysis of socioeconomic vulnerability to gauge the impact of development measures in the districts. In Pakistan, where significant disparities are evident in development indicators across provinces and among districts within a single province, the utility of such analysis is even more pronounced.

Outputs of tools such as CLVDAS can be utilized for effective planning. The monitoring of ecohydrological variables such as root-zone soil moisture can be done regularly to identify the severity of droughts. Near-surface soil moisture may be affected by high evapotranspiration, but crops may still be able to grow if sufficient amounts of root-zone soil moisture are available. The Regional Meteorological Centres of PMD can be strengthened with improved technical, human, and financial resources for more localized and impact-based forecasting by distributing the responsibility of PMD's centralized National Drought Monitoring and Early Warning Centre. Simultaneously, precipitation information based on accurate and timely prediction can be used to inform about the effects of rainfall on soil moisture levels, which is important information for determining shifts between hydrological and agricultural droughts. Localized drought information can be relayed to farmers using mobile phone text messages, as mobile phone ownership levels are as high as 48.6% in the Pishin district of Balochistan, with average rates at 21.2% in the province (PBS 2021b). Other means, such as radios, local cable television, and services of agriculture extension workers, can also be used to relay drought-related information.

Ecohydrological variables and socioeconomic indicators can be jointly monitored to identify their linkages and pre-empt drought impacts on health, education, and living standards. Drought early warning information, when combined with food security indicators such as FIES and analysis reports such as the IPC food security phase classification, can also inform provincial and district-level decisions on maintaining food security. Cereal food stocks can be procured by the government authorities and placed in districts that may be vulnerable to incoming drought. An integrated approach enables a multidimensional view of vulnerability and enables improved early warning as well as focused measures aimed at improving health and nutrition programs in anticipation of drought stress. Recognizing these interlinkages is essential for developing district-level, evidence-based resilience operational strategies that are responsive to social and climatic factors.

Local food security is closely linked with underlying factors of the poverty-induced vulnerabilities to disaster risk and the district's institutional capacity. The situation of food security in the districts of Balochistan can be strengthened by higher-level support from the provincial and national governments. The decisions informing this support can be based on combined information related to relative vulnerabilities in the districts and science-based forecasting of changes in agricultural drought conditions.

8. CONCLUSION

Local-level DRM in developing countries can be strengthened by including localized risk information, not only during hazard events but through regular monitoring of precipitation and drought conditions, to enable timely response measures by all stakeholders. The need is to integrate the output of natural science tools with day-to-day decision-making as well as DRR policy development, by recognizing cross-sectoral and transdisciplinary connections for a whole-of-society approach. The study provides a framework for strengthening local DRM capacity by showing that drought monitoring output parameters can be used to improve social and economic functioning by minimizing hazard impacts on food security. Using the socioeconomic vulnerability index and CLVDAS, the research practically shows the benefits that can be achieved for localized decision-making by determining the impact of drought hazard exposure using specific scientific output parameters and their linkage with socioeconomic indicators, such as those concerning food security, health, and education, all of which are interlinked with poverty.

Preparedness against drought disaster risk must be based on sustained social and economic uplift of rural communities. Resilience levels and response capacity of state and society in a country can only improve with poverty reduction, as households are able to uplift their standard of living. This can be achieved by improving socioeconomic conditions that are linked with better service delivery in the health and education sectors. Strengthened social conditions lead to improved human productivity, higher incomes, and better living standards, all of which influence disaster impact mitigation. The integrated transdisciplinary design introduced in this study could help to address underlying issues that require integrated solutions of natural science and socioeconomic policy.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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