Centre of Excellence – Climate Change & Disaster Management (CoE-C2DM)

INDIVIDUAL RESEARCH PAPERS

RESEARCH COMPENDIUM

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Partial Fulfillment of

Certificate Course in Disaster Management

C2DM P-09/26

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National Disaster Management Authority

Prime Minister's Office

Government of Pakistan

About CoE-C2DM

C2DM course equips participants with the knowledge and practical abilities to understand the science of climate change, its relationship with disasters and strategies for resilience building. It integrates Climate Change Adaptation (CCA) and Disaster Risk Reduction (DRR) into a unified framework consistent with all international frameworks, treaties, conventions and agreements on Disaster Risk Reduction, Climate Change. Through interactive lectures, individual research case, simulations and lab exercises, participants learn to assess climate risks, design adaptive strategies and implement resilience measures with advanced technologies as Artificial Intelligence (AI), Machine Learning (ML), Remote Sensing and GIS/GoeAI. The C2DM Courses offered by NDMA Center of Excellence facilitates national and international Government officials in disaster/crisis/emergency management, environment/climate, planning and related departments/offices, Provincial/state PDMA/GBDMA/SDMA staff and technical officers from national and equivalent international offices, Multilateral Institutions/organizations as World-bank, ADB, UN etc. and INGO personnel engaged in humanitarian response and resilience development projects as well as Private sector senior managers in industry and energy sectors, Researchers in relevant/linked disciplines/technologies of disaster management, environment, climate change or academics and development sectors. This Research Compendium is from participants of C2DM Course P-09/26 (5th October – 23th October 2026) participants.

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PARTICIPANT RESEARCH PAPER

A Comparative Analysis of the 2010 and 2022 Flood Events in Pakistan

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Abdul Rehman

Certificate Course in Disaster Management

C2DM P-09/26

Center of Excellence - Climate Change & Disaster Management

National Disaster Management Authority

Government of Pakistan

Abstract

This paper compares the 2010 and 2022 floods in Pakistan to identify differences in hazard mechanisms, human impacts, economic consequences and disaster risk reduction priorities. It uses a desk-based comparative method drawing on official damage assessments, NDMA publications, climate-attribution research and international policy frameworks. The 2010 disaster was predominantly riverine, although northern flash floods were also destructive. In 2022, exceptional rainfall produced combined riverine, flash and urban flooding with prolonged inundation in southern provinces. Approximately 20 million people were affected in 2010 and 33 million in 2022, while retrospective reported mortality was higher in 2010. Economic comparisons require caution because monetary values, reporting dates and assessment categories differ. The analysis identifies priorities in inclusive evacuation, local drainage, livelihood recovery, community participation and institutional accountability. It recommends integrating scientific forecasts with local knowledge and accessible last-mile communication. The study concludes that resilient recovery requires coordinated governance and attention to exposure and vulnerability, rather than reliance on engineering protection or national loss totals alone.

Keywords: Pakistan; floods; vulnerability; early warning; resilience.

1. Introduction

Pakistan's 2010 and 2022 floods provide important cases for examining how extreme weather interacts with settlement patterns, infrastructure and social inequality. Comparing them is relevant to climate adaptation, disaster management and disaster risk reduction (DRR), because national totals alone cannot explain why communities experience different losses or recover at different speeds.

The research problem is how differences in flood mechanisms and vulnerability shaped impacts and what the comparison supports about future preparedness. The objectives are to compare hazard geography, examine human and economic consequences, identify scientific and institutional gaps, and propose practical resilience measures. The scope is national, with provincial distinctions where the reviewed evidence permits.

The methodology is a qualitative comparative case study using published institutional assessments and descriptive statistics. Sources include the 2010 damage assessment, the 2022 Post-Disaster Needs Assessment (PDNA), and NDMA/NIDM's retrospective review. No interviews, original satellite mapping or causal evaluation were undertaken. Differing reporting dates, definitions and monetary bases limit direct comparison; recommendations are analytical proposals rather than measured achievements.

2. Regional Context and Hazard Profile

Pakistan's Indus Basin connects mountainous catchments, densely settled plains and downstream agricultural areas. In 2010, intense rainfall in northern catchments produced flash floods and large river flows moving downstream. Early destruction in Khyber Pakhtunkhwa did not mean it had the greatest national monetary share: the published assessment summary assigned approximately 43.6% of assessed impacts to Sindh and 25.7% to Punjab (Ali, 2013).

The 2022 PDNA describes riverine, urban and flash flooding, while exceptional rainfall in Sindh and Balochistan generated extensive inundation beyond the main river corridor (Government of Pakistan, 2022). The literature therefore supports preparedness for multiple flood mechanisms. Two selected events, however, cannot establish a long-term statistical trend in national flood frequency.

In this analysis, hazard means a potentially damaging flood process; exposure concerns people and assets situated where flooding can occur; vulnerability describes conditions

increasing susceptibility to harm; and disaster risk concerns potential losses arising from their interaction with capacity (United Nations Office for Disaster Risk Reduction [UNDRR], 2017). Flooding becomes a disaster through this interaction, rather than rainfall magnitude alone.

World Weather Attribution (2022) concluded that warming likely intensified the heavy rainfall, while model limitations and strong regional variability prevented precise quantification of the overall human influence. Rainfall-attribution findings should not be interpreted as an equivalent percentage increase in deaths or economic losses.

3. Risk and Vulnerability Assessment

Approximately 20 million people were affected in 2010 and 33 million in 2022. NDMA/NIDM reports retrospective death totals of 1,985 and 1,739 respectively (National Disaster Management Authority & National Institute of Disaster Management [NDMA & NIDM], n.d.). Using these rounded population estimates, the affected total increased by about 65%, while reported deaths fell by approximately 12.4%. This does not establish improved response effectiveness: hazard geography, exposure and reporting conditions also differed.

The published 2010 assessment summary reports approximately US$10.056 billion in damage and losses (Ali, 2013). For 2022, the PDNA estimates US$14.9 billion in damage, US$15.2 billion in economic losses and US$16.3 billion in recovery needs (Government of Pakistan, 2022). Needs are a separate financing requirement and must not be added to damage and losses as another measure of destruction. Inflation, exchange rates and assessment coverage prevent treating the nominal ratio as a physical severity ratio.

The 2010 assessment documents extensive housing damage and the vulnerability of weaker housing stock (Government of Pakistan et al., 2010). In 2022, housing, agriculture and livestock, and transport and communications suffered major damage (Government of Pakistan, 2022). Livelihood disruption extends beyond destroyed assets: inaccessible markets, lost livestock and waterlogged fields can reduce income and delay agricultural restart. Food security depends on restoring production and household purchasing power alongside emergency food assistance.

Vulnerability assessment should examine poverty, insecure tenure, fragile construction, disability, age and caregiving responsibilities. Gender analysis should consider access to

warnings, safe transport, privacy, sanitation and maternal healthcare. These are assessment priorities rather than newly measured differences between the events. Sex-, age- and disability-disaggregated data are needed to identify exclusion and target assistance fairly.

4. Community Resilience Factors

Community resilience depends partly on social capital: relationships through which people share information, organize assistance and support recovery. The 4RF promotes community-driven recovery and participation by affected groups (Government of Pakistan, 2023). This provides a policy basis for involving neighbourhood networks, women's groups, volunteers and local organizations in planning, rather than treating households only as aid recipients.

Practical options include community evacuation maps, agreed assistance for residents with limited mobility, locally managed contact lists and collective protection of essential documents or livestock. These are proposed coping measures; this study does not claim that they operated uniformly in either disaster. Participation must include tenants, displaced households and people outside influential local networks.

Local and indigenous knowledge can help identify remembered flood routes, drainage obstructions and accessible safe locations. It should be documented through participatory mapping and checked against scientific information, because changing rainfall and development can make past experience unreliable. Follow-up fieldwork should examine which networks reached vulnerable households and whether community participation influenced recovery decisions.

5. Scientific and Institutional Gaps

The comparison reveals an analytical gap in data harmonization. Published sources use different cut-off dates and definitions of affected people, housing damage, economic losses and inundated area. This paper therefore does not present a comparable national flood-footprint calculation. A common database should preserve original definitions, reporting dates and uncertainty rather than merging incompatible indicators.

Technology proposals require similar caution. Artificial intelligence and machine learning (AI/ML) could be tested for flood detection, exposure screening and forecast interpretation, but this study does not measure their operational adoption. Any pilot

should evaluate local accuracy, missing data, false alarms, explainability and maintenance costs before routine use. Satellite information requires validation and cannot independently establish household needs.

Institutional evaluation should distinguish announced plans from outcomes. The reviewed documents demonstrate major response and recovery efforts, but do not provide a controlled comparison of warning receipt, evacuation coverage or assistance speed. District-level research should examine staffing, equipment, coordination and capacity constraints through dated records and interviews. Climate-model limitations also require uncertainty to be communicated rather than hidden behind precise-looking forecasts.

6. Mitigation Strategies and Best Practices

Structural measures should combine maintained embankments, drainage capacity, safer bridges and resilient public facilities. Their design should consider catchment processes, changing rainfall and downstream effects. Protection in one locality can redistribute water elsewhere; engineering appraisal should therefore examine system-wide consequences rather than isolated structures.

Non-structural measures include risk-sensitive land-use planning, protection of drainage corridors, construction enforcement, preparedness education and household evacuation planning. Capacity building should connect practical training with seasonal drills involving health services, schools and local responders. Agricultural recovery should address seed access, livestock services and timely restoration of market connections.

The Sendai Framework provides an international benchmark through understanding risk, strengthening governance, investing in resilience and improving preparedness and recovery (UNDRR, 2015). Nationally, the 4RF offers a framework for integrated reconstruction (Government of Pakistan, 2023). These are relevant policy practices; their existence alone is not evidence that implementation achieved the intended results.

7. Risk Communication and Early Warning

The contrasting flood mechanisms imply different warning requirements. River forecasts can support downstream evacuation, while intense local rainfall and drainage-related flooding require locally relevant alerts. Messages should state the expected location, timing, likely impacts, required action and source of further information. A technically accurate forecast has limited protective value if residents cannot act on it.

Proposed last-mile arrangements should combine mobile messages, radio, public announcements and trusted community contacts, with alternatives for power or network failure. Local-language messages and accessible audio or visual formats should be tested with intended users. Community engagement should include feedback on whether warnings are understandable and whether evacuation routes are realistic.

Gender-sensitive systems should involve women in designing messages, identifying safe shelters and evaluating transport barriers, consistent with UNDRR's emphasis on women's participation in DRR (UNDRR, n.d.). Performance indicators should include warning receipt and comprehension by group, usable lead time, drill participation and the proportion of residents able to reach safe shelter. These are proposed measures, not findings from a completed warning-system audit.

8. Policy Recommendations

Federal and provincial authorities should establish shared reporting definitions and interoperable records, while district authorities maintain locally usable risk and evacuation plans. NDMA, PDMAs and DDMAs should coordinate with meteorological, irrigation, health and local-government bodies. Responsibilities, reporting schedules and escalation procedures should be explicit.

Planning and finance authorities should connect climate adaptation funding to drainage maintenance, resilient infrastructure and livelihood restoration. Proposed monitoring measures include completed maintenance, restored services, time to resume cultivation and reconstruction compliance. Allocation criteria should consider vulnerability and access to assistance alongside asset values.

District authorities should institutionalize community participation through representative planning meetings, practical drills and accessible grievance mechanisms. Women, people with disabilities and marginalized households should help assess shelter suitability and communication barriers. Community participation should inform decisions, rather than merely validate completed plans.

Technology investments should begin with validated pilots, trained staff and sustainable maintenance budgets. Independent evaluations should compare warning coverage, assistance exclusion, service restoration and household recovery across consistently

selected districts. Transparent reporting can help distinguish policy commitments from measurable improvements.

9. Conclusion

The 2010 and 2022 floods demonstrate that disaster severity cannot be reduced to one national indicator. The latter affected more people and produced a greater nominal economic burden, while retrospective reported mortality was higher in 2010. Different flood mechanisms require preparedness for both river flows and widespread rainfall-driven inundation.

Science-based planning should therefore combine reliable forecasts and exposure information with community networks, critically assessed local knowledge, inclusive communication and accountable institutions. Technology can support these functions when validated and maintained. Integrated governance and recovery that restores livelihoods and services are essential to reducing future vulnerability. These conclusions remain bounded by secondary-source data and require district-level evaluation.

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PARTICIPANT RESEARCH PAPER

Urban and Riverine Flood Risk in Larkana District: Drainage Constraints, Exposure, and Early Warning Systems

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Certificate Course in Disaster Management

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Abstract

Larkana District in Sindh Province, Pakistan, represents a critical convergence of urban and riverine flood risks, exacerbated by climate change and inadequate disaster risk reduction infrastructure. This paper examines the multifaceted flood vulnerability of Larkana through an analysis of drainage constraints, population exposure, and early warning system effectiveness. Drawing on recent government assessments, satellite-based studies, and institutional reports, the analysis reveals that the district faces a compound risk profile: the Indus River has migrated significantly closer to urban centres, while the urban drainage system remains fundamentally compromised by non-functional treatment infrastructure and canal-dependent disposal mechanisms. The 2022 floods demonstrated the catastrophic consequences of these deficiencies, with Larkana among the worst-affected districts in Sindh. Current interventions, including a major Japanese-funded dike improvement project, signal recognition of the riverine threat, yet urban drainage and early warning gaps persist. The paper concludes that integrated flood risk management must address the intersection of urban infrastructure failure and riverine hazard, with enhanced early warning systems tailored to the district's specific institutional and geographic context.

Keywords: Riverine Flood, Drainage, Urban, Larkana District, Early Warning Systems

1. Introduction

Pakistan is among the world's most climate-vulnerable nations, with flood hazards posing recurrent and escalating threats to lives, livelihoods, and infrastructure. The catastrophic 2022 monsoon floods, which submerged approximately one-third of the country's land area and affected over 33 million people, underscored the systemic inadequacies in flood risk management across the Indus River basin. Within Sindh Province, Larkana District emerged as one of the most severely impacted areas, with the northwestern districts of Jacobabad, Larkana, Shikarpur, and Kashmore experiencing the highest flood inundation levels.

Larkana's flood vulnerability is compounded by its dual exposure to riverine and urban flooding. The Indus River flows along the district's eastern boundary, while the western portion faces flash flood risks from the Khirthar mountain range. The district's disaster management plan explicitly acknowledges that "weak and damaged parts of the canals and protection Bund on the river Indus can, unexpectedly, create a disaster like situation in the district." This assessment reflects a broader recognition that Larkana's flood risk is not solely a function of hydrological extremes but is substantially mediated by infrastructure deficiencies and institutional constraints.

This paper addresses three interconnected dimensions of flood risk in Larkana District. First, it examines drainage constraints, analysing how urban wastewater management failures and canal-dependent disposal systems exacerbate flood exposure. Second, it assesses population and infrastructure exposure, drawing on recent vulnerability assessments and historical flood data. Third, it evaluates the effectiveness of early warning systems within the district's institutional framework. The analysis is situated within the broader context of climate change adaptation and disaster risk reduction (DRR), arguing that Larkana's experience illustrates the critical need for integrated approaches that address both structural and non-structural flood risk drivers.

2. Study Area: Larkana District

Larkana District is located in the northwestern region of Sindh Province, approximately 40 kilometres west of the Indus River (Figure 1). The district comprises four talukas Larkana, Dokri, Bakrani, and Rato Dero and is predominantly agricultural,

with the majority of households engaged in farming and livestock rearing. The district's topography is characterised by alluvial plains on the eastern side and the foothills of the Khirthar range to the west, creating distinct hydrological and hazard profiles across the territory.

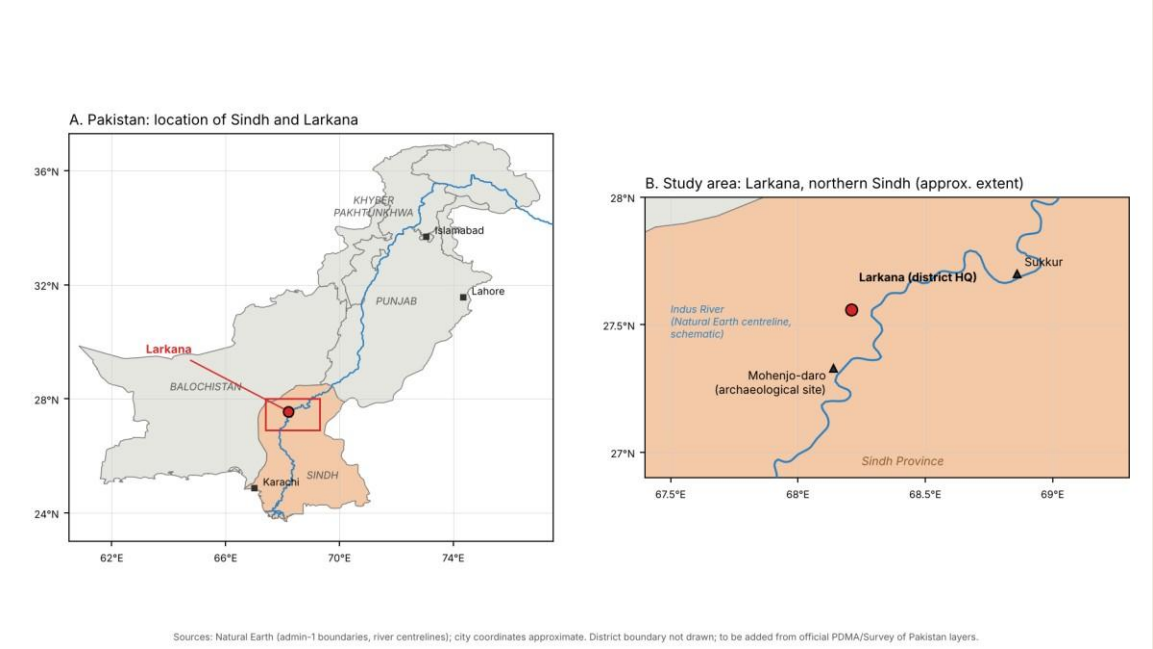


Figure 1. Location map of Larkana District within Sindh Province, Pakistan, showing tehsil boundaries, major canals, and the Indus River.

The district's flood risk profile is defined by its dual exposure. The eastern portion, adjacent to the Indus River, is susceptible to riverine flooding during monsoon season, while the western talukas face flash flood risks from hill torrents originating in Balochistan. The Larkana Division contingency plan identifies Larkana, along with Kashmore and Shikarpur, as riverine flood-prone, while Jacobabad and Kambar are primarily flash flood-prone. This geographic differentiation has important implications for early warning system design and evacuation planning.

Historically, Larkana has experienced repeated flood events. The 2010 floods affected 115 to 204 villages across seven union councils, impacting approximately 92,000 people. During that event, floodwater at 1,100,000 cusecs passed through the Aqil-Aghani and Nusrat Loop Banks, submerging 1,650 villages in the katcha area of Larkana, Shikarpur, and Khairpur districts. The 2022 floods proved even more devastating, with satellite-based assessments estimating that floodwaters directly

inundated approximately 2.5 million hectares across Sindh, with Larkana among the districts experiencing the highest agricultural losses.

3. Drainage Constraints and Urban Flood Risk

Larkana's urban drainage infrastructure presents a critical vulnerability that compounds riverine flood exposure. The district's wastewater management system is fundamentally compromised: municipal waste flows untreated into the Rice Canal and Dadu Canal, which also serve as sources of drinking water for downstream communities (Figure 2). Four oxidation ponds constructed in 1998 to treat municipal waste have reportedly been nonfunctional since 2007, with encroachments preventing rehabilitation. The drainage system relies predominantly on irrigation infrastructure, a design choice that creates silting problems and reduces system capacity during high-flow periods.

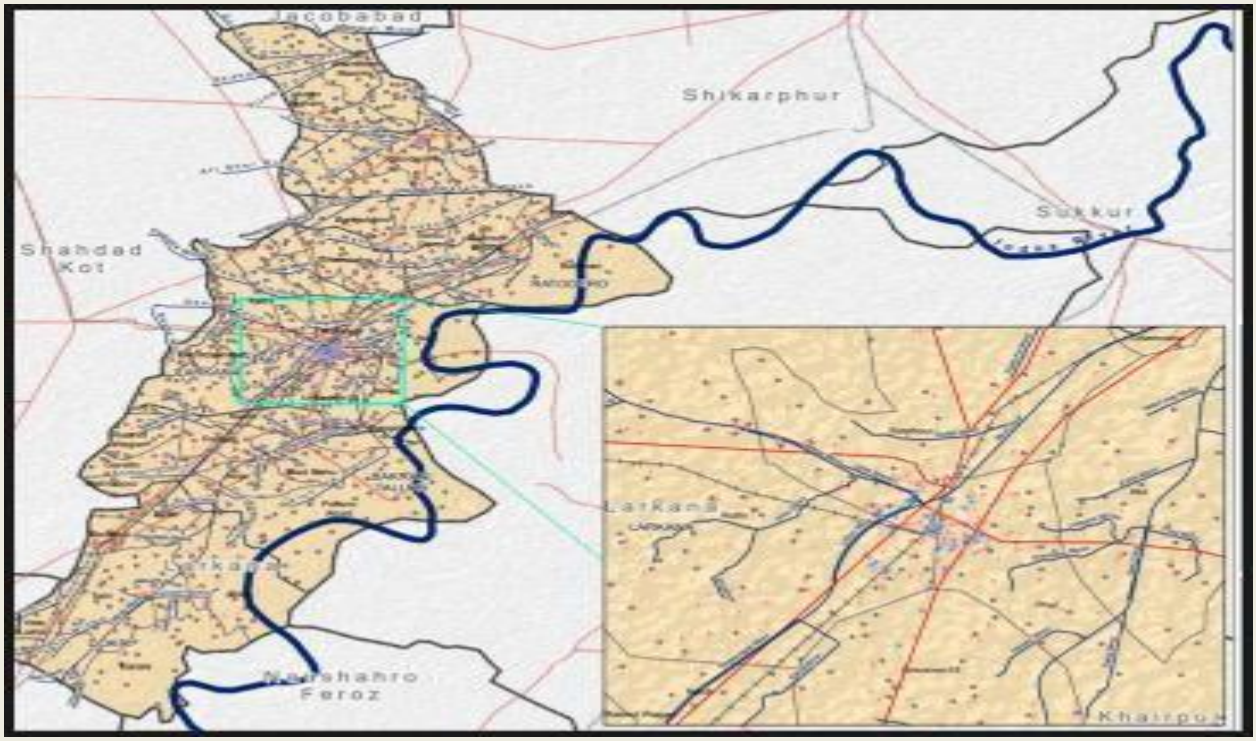


Figure 2. Drainage and canal network of Larkana District showing the Indus River, Rice Canal, Dadu Canal, and urban wastewater disposal points.

The institutional assessment of Larkana's disaster management plan acknowledges these deficiencies, noting that the drainage system should "make use of natural falls and minimize pumping needs," yet the current configuration largely operates against

these principles. This disconnect between design intent and operational reality reflects broader governance challenges in urban infrastructure management, where coordination between irrigation departments, municipal authorities, and disaster management agencies remains fragmented.

The implications for flood risk are significant. When urban drainage systems rely on irrigation canals that are simultaneously used for wastewater disposal and drinking water supply, the system's capacity to manage stormwater during extreme rainfall events is severely constrained. The 2022 monsoon season demonstrated this vulnerability, with urban flooding in Larkana attributed in part to "poor drainage systems and unplanned urban growth." The projected 2025 monsoon season similarly identified urban flooding as particularly likely in Larkana due to these same factors.

The drainage constraint problem is further complicated by the district's reliance on embankment protection for riverine flood defence. The Old Abad Bund, located within 10 kilometres of Larkana's urban area, has experienced extensive erosion damage, with significant seepage and water leakage and no implemented countermeasures. The 2010 Tori Bund breach, which devastated large parts of Sindh, was attributed in part to encroachments including settlements and fish ponds established inside the loop bund. These examples illustrate how infrastructure maintenance failures and land-use encroachments interact to amplify flood risk.

4. Exposure Assessment: Population and Critical Infrastructure

Quantifying flood exposure in Larkana District requires attention to both the scale of potentially affected populations and the vulnerability of critical infrastructure. A recent AHPGIS based flood susceptibility analysis classified 63.89% of the district as high risk and 7.65% as very high risk, with only 0.12% classified as low risk (Figure 3). The northern portion of the district emerged as particularly vulnerable, with rainfall, river proximity, slope, and elevation collectively accounting for over 80% of flood risk.

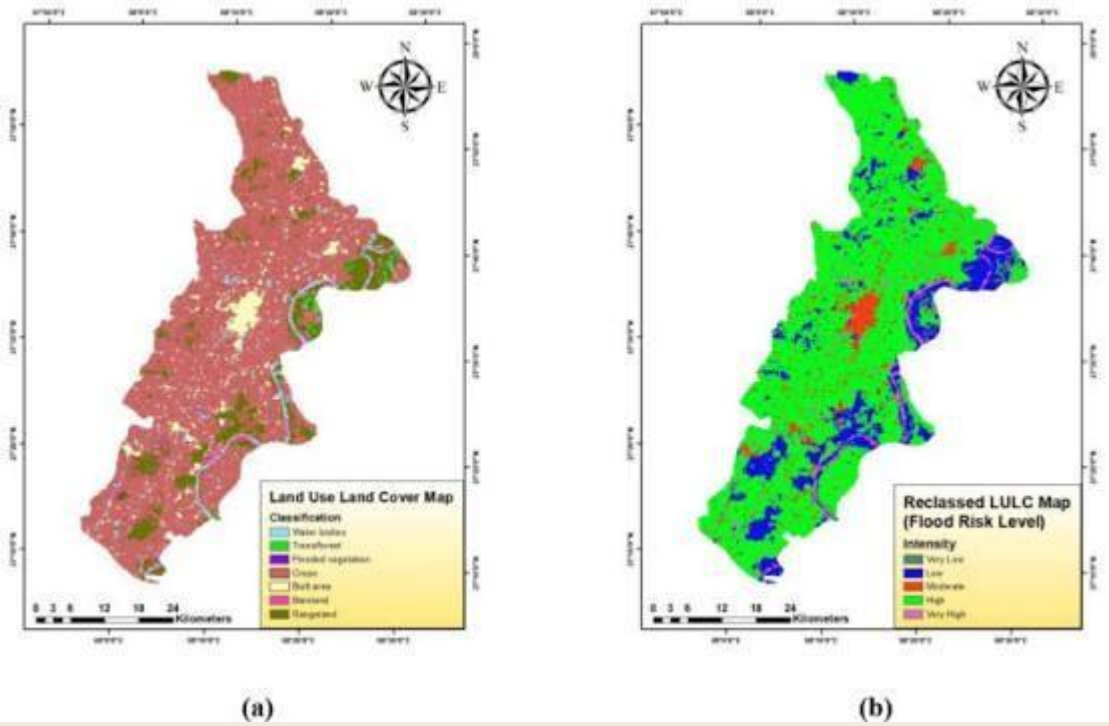


Figure 3. Flood susceptibility map of Larkana District based on AHP-GIS weighted overlay analysis showing very high, high, moderate, and low risk zones.

The provincial contingency plan for Larkana Division estimates an anticipated vulnerable population of 10,850 persons (approximately 1,800 families) in Larkana District under a likely riverine and flash flood scenario. This calculation is based on 5.5% of the Katcha area population and 0.5% of flash flood-prone areas, reflecting the historical pattern of flood impact concentrated in specific geographic zones.

However, the 2022 flood experience suggests that these planning figures may substantially underestimate actual exposure under extreme events. The catastrophic nature of the 2022 floods, which affected over 33 million people nationally and displaced approximately 8 million, indicates that conventional probabilistic planning assumptions may not adequately capture the tail risks associated with climate-amplified monsoon systems. Satellite-derived flood extent mapping for the 2022 event documented extensive inundation across the Larkana plain, including the formation of a 100 square kilometre flash flood lake between Dera Ghazi Khan and Larkana (Figure 4).

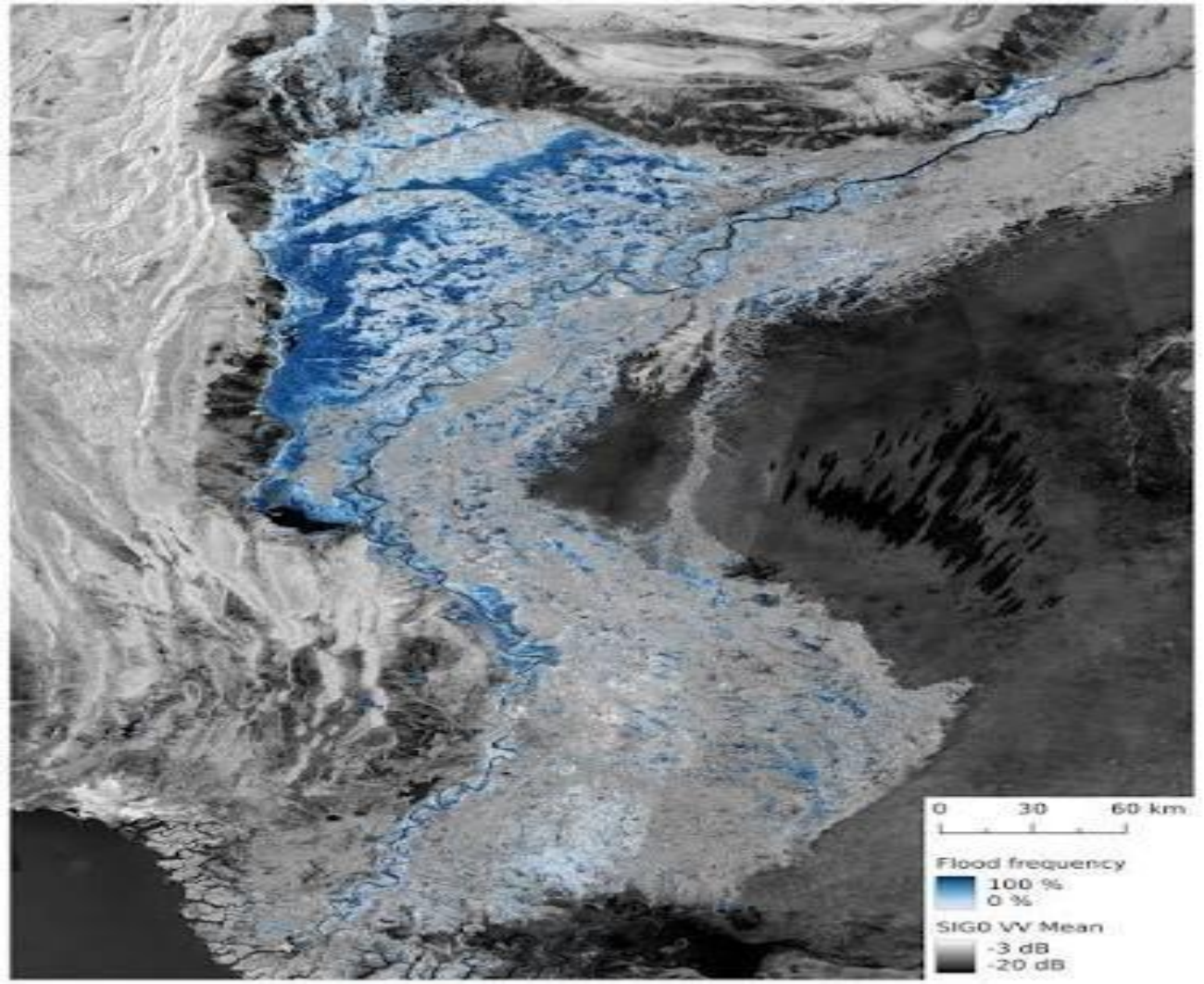


Figure 4. Extent of 2022 flood inundation in Larkana District and surrounding areas derived from Sentinel-1 SAR imagery.

Critical infrastructure vulnerability represents a parallel dimension of exposure. Educational infrastructure in Larkana sustained significant damage during the 2010 floods, with approximately 541 schools reported as fully affected, more than 90% damaged due to use as shelter by internally displaced persons. Health infrastructure was also impacted, with Taluka Hospital Rato Dero and Taluka Hospital Dokri partially damaged. Water supply infrastructure is particularly concerning: piped water is available to only 1% of housing units in the district, while 73% of households rely on hand pumps, which are highly susceptible to contamination during flood events (Figure 5).

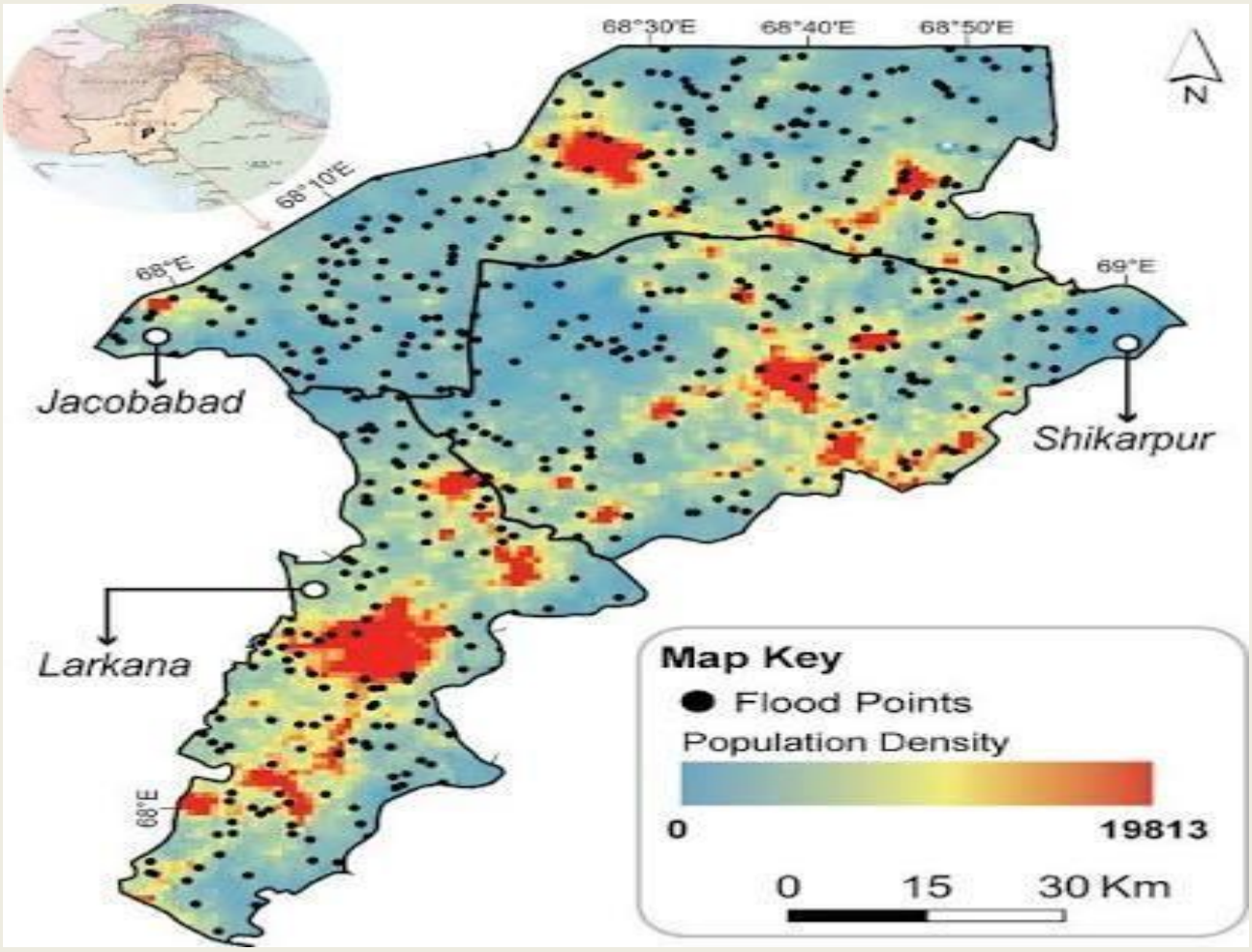


Figure 5. Population density and critical infrastructure exposure to flood hazards in Larkana District.

Agricultural exposure is a defining feature of Larkana's flood risk profile. The district is agrobased, with majority households engaged in farming and livestock rearing. The 2022 floods caused unprecedented damage to agriculture across Sindh, with estimated losses including 1.9 million tons of rice (80% of expected production), 10.5 million tons of sugarcane (61% loss), and 3.1 million bales of cotton (88% loss). Direct economic losses to these three crops alone were estimated at USD 1.30 billion, with additional losses to vegetable crops, livestock, and agricultural infrastructure. Larkana, as one of the worst-affected districts, bore a significant share of these losses.

5. Early Warning Systems: Institutional Framework and Gaps

Early warning systems in Larkana operate within a multi-tiered institutional framework spanning national, provincial, and district levels. The Pakistan Meteorological Department (PMD) provides weather forecasting and flood warnings, while the National Disaster Management Authority (NDMA) coordinates national-level disaster management, with Provincial Disaster Management Authority (PDMA) Sindh and District Disaster Management Authority (DDMA) Larkana responsible for provincial and district-level implementation. The provincial contingency plan specifies that early warning systems have been designated and safe evacuation sites identified for vulnerable districts including Larkana (**Figure 6**).

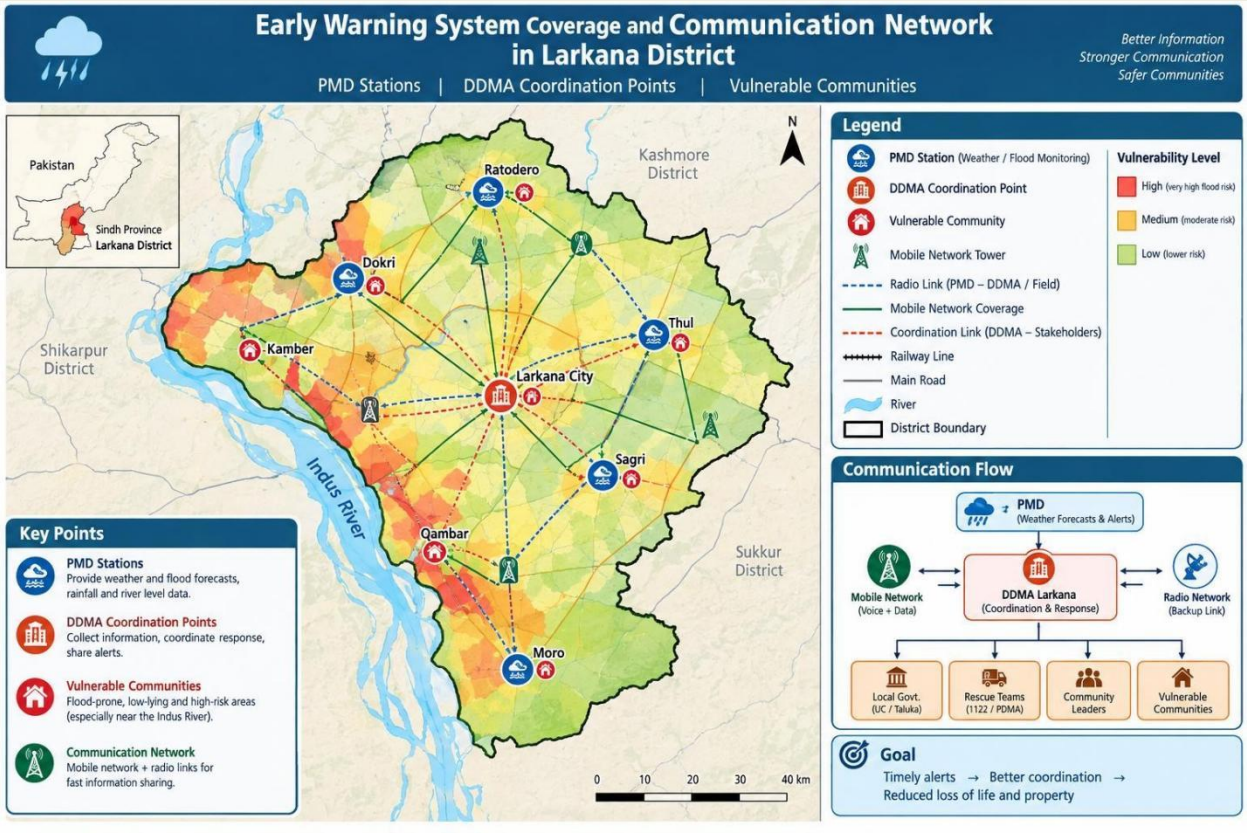


Figure 6. Early warning system coverage and communication network in Larkana District showing PMD stations, DDMA coordination points, and vulnerable communities.

However, the effectiveness of these systems faces significant constraints. The provincial contingency plan acknowledges "limited capacity in weather and flood forecasting, particularly for flash floods." The district disaster management plan for

Larkana further identifies that early warning dissemination relies on informal and locally influential sources of information, including religious leaders, teachers, NGO workers, and local government officials. While these actors may command community trust, they require training to effectively communicate warning information.

A critical gap exists in the translation of flood forecasts into actionable warnings at the community level. The NDMA's institutional framework includes provisions for communication systems between NDMA, PMD, provincial PDMAs, and district DDMAs, yet the practical challenges of timely information dissemination to at-risk populations remain substantial. The 2010 flood experience, during which thousands of people were trapped in kutcha areas despite the existence of warning systems, suggests that dissemination and response mechanisms were inadequate.

The institutional response to these challenges has included international partnerships and infrastructure investment. The Japan International Cooperation Agency (JICA) signed a grant agreement in September 2026 for the "Project for Flood Protection and Dike Improvement on Indus River in Sindh Province," targeting Larkana District with a maximum grant of 2,585 million Japanese Yen. The project aims to reduce dike breach risk through river erosion protection structures and consulting services, with an anticipated benefit to approximately 790,000 residents in the target area. While this investment addresses the structural dimension of riverine flood risk, it does not directly address urban drainage deficiencies or early warning system gaps.

The district disaster management plan identifies several measures to strengthen early warning effectiveness. These include organizing awareness programmed through the DDMA on land use planning and building codes, training community volunteers for warning dissemination, identifying safe land for low-income residents near flood-prone areas, and utilizing radio for early warning transmission with safeguards against false reports. These recommendations reflect recognition that early warning systems must integrate technical forecasting capacity with community-level communication and response mechanisms.

6. Discussion: Integrating Drainage, Exposure, and Early Warning

The three dimensions of flood risk examined in this paper drainage constraints, exposure, and early warning systems are not independent but interact in ways that

amplify overall vulnerability. Urban drainage failures increase the probability that moderate rainfall events will cause localized flooding, while riverine flood protection deficiencies create catastrophic risk under high-flow conditions. The same institutional and governance weaknesses that undermine drainage maintenance also constrain early warning dissemination and response.

Climate change represents an exacerbating factor across all three dimensions. The 2022 floods were unprecedented in scale, with the NDMA documenting over 1,700 deaths, more than 2.3 million homes damaged or destroyed, and over 1.7 million hectares of crops wiped out nationally. The economic damage and loss were estimated at USD 14.9 billion, with total rehabilitation needs of USD 16.3 billion. These figures illustrate that conventional planning assumptions based on historical flood records may be inadequate for a changing climate characterised by increased monsoon variability and extreme precipitation events.

The JICA dike improvement project represents a recognition that structural protection remains a necessary component of flood risk management in the Indus basin. However, the project's focus on riverbank erosion protection and dike reinforcement, while critical, addresses only the riverine component of Larkana's compound flood risk. Urban drainage deficiencies, which contributed to flooding during the 2022 monsoon and remain unaddressed, require parallel investment and institutional reform.

Early warning system enhancement must similarly adopt an integrated approach. The distinction between riverine and flash flood warning needs, acknowledged in the provincial contingency plan, has implications for system design and community preparedness. Riverine flood warnings can provide lead times of days, enabling evacuation and asset protection, while flash flood warnings may provide only hours or minutes. Larkana's exposure to both hazard types requires warning systems capable of addressing both temporal scales.

The District Disaster Management Plan's emphasis on community-based warning dissemination through trusted local actors represents a pragmatic response to institutional limitations. However, this approach requires sustained investment in training and communication infrastructure to be effective. The NDMA's stated

intention to introduce an e-library and online volunteer registration portal suggests institutional recognition of the need for enhanced information sharing and community engagement.

7. Conclusion and Recommendations

Larkana District exemplifies the compound flood risk challenges facing urban and periurban areas in Pakistan's Indus basin. The district's exposure to both riverine flooding from the Indus and urban flooding from inadequate drainage infrastructure creates a risk profile that cannot be addressed through single-sector interventions. The 2022 floods demonstrated the catastrophic consequences of these intersecting vulnerabilities, with Larkana among the most severely affected districts in Sindh.

Three priority areas emerge for enhanced flood risk management in Larkana. First, urban drainage infrastructure requires urgent rehabilitation, including restoration of wastewater treatment capacity and redesign of stormwater management systems that currently rely on irrigation canals. Second, early warning systems must be strengthened through investment in forecasting capacity, communication infrastructure, and community-based dissemination networks, with specific attention to the distinct requirements of riverine and flash flood hazards. Third, the interaction between structural protection measures including the JICA-funded dike improvements and land-use planning must be addressed to prevent encroachment on flood protection infrastructure and ensure that development does not increase exposure in high-risk areas.

The integration of climate change adaptation into disaster risk reduction planning is not optional but essential. The NDMA's Multi-Hazard Vulnerability and Risk Assessment framework provides a foundation for evidence-based planning, but its effectiveness depends on sustained implementation, periodic review, and adequate resource allocation. For Larkana, the path toward flood resilience requires recognition that the district's vulnerability is not solely a function of hydrological extremes but is substantially mediated by infrastructure deficiencies, institutional fragmentation, and planning failures. Addressing these underlying drivers is the necessary condition for meaningful risk reduction.

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PARTICIPANT RESEARCH PAPER

Climate Change as a Key Driver of Increasing Disaster Risk

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Abstract

Climate change is increasing disaster risk in Pakistan, but it does not act alone. This paper reviews how a warming climate changes hazards such as heatwaves, heavy rain, floods, drought and glacial lake outburst floods (GLOFs), and how exposure and vulnerability turn these hazards into disasters. It draws on international assessments, official damage data and recent studies, with a focus on the 2022 and 2025 monsoon floods. The review finds that climate change has made some hazards stronger, with the clearest evidence for heat and heavy rain, while evidence for other hazards is more mixed. Losses were larger because of building in flood zones, weak infrastructure, poverty and gaps in warning. In 2025, a household survey in three districts of Khyber Pakhtunkhwa found that 85% of families received no warning before flash floods. The paper also identifies gaps in science, institutions, financing and gender inclusion. It recommends stronger early warning, local risk assessments, risk-informed land use, inclusive community participation and funded implementation of adaptation plans. Reducing exposure and vulnerability can limit damage even as hazards intensify.

Keywords: climate change, disaster risk reduction, early warning, floods, Pakistan

1. Introduction

Disaster risk is rising in many regions, and Pakistan shows the pattern clearly. In 2022, monsoon floods affected about 33 million people (World Weather Attribution [WWA], 2022). In 2025, another monsoon season affected about 6.9 million people and caused more than 1,000 deaths ("Pakistan's 2025 Monsoon Floods," 2026). These events raise a simple question: how far is climate change responsible for growing disaster risk?

Some key terms help to answer it. Climate change is a long-term change in temperature and weather patterns, now mainly driven by human activity, which has warmed the world by about 1.1°C (Intergovernmental Panel on Climate Change [IPCC], 2023). A hazard is an event that can cause harm, such as a flood or heatwave. A disaster occurs when a hazard seriously harms people, property and services because they are exposed and vulnerable (United Nations Office for Disaster Risk Reduction [UNDRR], 2017).

Climate change is often blamed for every disaster, but this is too simple. The purpose of this paper is to show how climate change changes hazards, and how exposure and vulnerability decide the damage that follows. The objectives are to explain the climate–hazard link, profile hazards and risk in Pakistan, review resilience, gaps and good practice, and propose policy actions. The scope is a review of secondary sources, mainly international assessments, official data and recent studies, with a focus on floods. No primary data were collected.

2. Regional Context and Hazard Profile

Pakistan has glaciers and mountain valleys in the north, flood-prone plains along the Indus River, and a low-lying coast in the south, so several climate-sensitive hazards can occur at once. Table 1 shows how each hazard relates to climate change and why it matters for Pakistan.

Table 1. Climate-Sensitive Hazards and Their Relevance for Pakistan

Hazard	Link with climate change	Relevance for Pakistan

Hazard	Link with climate change	Relevance for Pakistan
Heatwaves	Hot extremes have become more frequent and intense over most land regions since the 1950s (IPCC, 2023).	The 2022 heatwave was described as climate change-induced (World Bank, 2022b).
Heavy rain and floods	Warmer air holds more moisture, and human influence has likely raised heavy rainfall (IPCC, 2023).	Record monsoon rain in 2022 and heavy rain with flash floods in 2025 (WWA, 2022, 2025).
Drought and water shortage	Human influence has likely increased drought in some regions; effects differ by place (IPCC, 2023).	Heat and floods reduce crop and livestock yields (World Bank, 2022b).
Glacier melt and GLOFs	Melting glaciers form lakes that can burst and flood downstream areas.	There are 3,044 glacial lakes in the north; 33 are hazardous and 7.1 million people are vulnerable (United Nations Development Programme [UNDP], 2022).
Sea-level rise	Higher seas increase coastal flooding and storm surge risk (IPCC, 2023).	The low-lying coast is exposed (IPCC, 2023).
Cyclones	Evidence is mixed and varies by region (IPCC, 2023).	Claims must be made carefully.

Note. Based on IPCC (2023), UNDP (2022), WWA (2022, 2025) and World Bank (2022b). The strength of evidence differs by hazard. The link to warming is clearest for heat and heavy rain. For the 2022 floods, scientists estimated that the highest five-day rainfall in

Sindh and Balochistan was about 75% more intense, based on observed trends, while some climate models suggested an increase of up to 50% (WWA, 2022). For the 2025 floods, the best estimate was about 15%, with large uncertainty (WWA, 2025). Climate change should therefore be described as a factor that can make hazards stronger or more frequent, not as the only cause of every disaster (IPCC, 2023).

3. Risk and Vulnerability Assessment

Risk depends on more than the hazard. It can be understood as hazard combined with exposure and vulnerability, reduced by the capacity to prepare, respond and recover (UNDRR, 2017). This is a way of thinking, not an exact calculation.

The 2022 floods show the combination. More than 1,700 people died (World Bank, 2022b), and about 70% of damage and losses were in Sindh (World Bank, 2022a). The official assessment recorded damages of USD 14.9 billion, economic losses of USD 15.2 billion and reconstruction needs of USD 16.3 billion (Government of Pakistan et al., 2022). Scientists noted that building on floodplains and weak infrastructure made the floods worse (WWA, 2022). In 2025, weak enforcement of building codes and building in flood zones raised the damage, and house collapses caused 164 of the 300 deaths recorded by 3 August (WWA, 2025).

Vulnerability is not equal across society. Impacts fall hardest on poor and marginalized people (IPCC, 2023), and in 2025 women, children and other vulnerable groups were disproportionately affected (“Pakistan’s 2025 Monsoon Floods,” 2026). Gender gaps in communication matter: nationally, 93% of men own mobile phones compared with 68% of women (World Bank, 2026), which limits women’s access to warnings.

Future risk may be higher. Climate and environmental risks could cut Pakistan’s GDP by at least 18–20% by 2050 if unaddressed (World Bank, 2022b). This is a projection, not an observed figure, and it depends on policy choices.

4. Community Resilience Factors

Communities are not only the victims, they are also first responders. In 2025, the flash floods in KP, mostly warned households received warning through mosque sounding, from relatives and alert signals from neighbors, while only a few through the official warning systems (World Bank, 2026). One village, an imam responded to a phone call

from one of the local officials and used his loudspeaker, saving lives (World Bank, 2026). Such social capital is successful because it is local and immediate and trusted.

Local and Indigenous knowledge is also important since it can contribute to effective adaptation (IPCC, 2023). In the northern part of Pakistan early warning coupled with community preparedness is already being used implemented in GLOF projects (UNDP, 2022).

But the force is a limited one. Men were more likely to receive information from informal networks (Elephants and Governance, Men have access to information first) and women were more likely to get information second-hand from a male family member (World Bank, 2026). Goodwill is not enough, formal support, inclusion and resources are necessary to make resilience a reality.

5. Scientific and Institutional Gaps

Several scientific gaps limit risk management. Attribution is uncertain: climate models struggle to reproduce monsoon rainfall in this region, so estimates of how much climate change intensified a flood carry wide uncertainty (WWA, 2022, 2025), and evidence for cyclones is mixed (IPCC, 2023). Risk data are also thin. In Khyber Pakhtunkhwa, multi-hazard vulnerability and risk assessments exist for only three of 36 districts, and planning focused on river floods, so fast flash floods in mountain terrain fell into a blind spot (World Bank, 2026).

Institutional gaps are also clear. Pakistan approved a National Adaptation Plan in 2023 (Ministry of Climate Change and Environmental Coordination [MoCCEC], 2023), but experts criticized its top-down preparation, limited consultation, unclear financing and the omission of drainage, and noted that large parts repeat earlier policies (Ebrahim, 2023). Key sectors such as irrigation and agriculture are provincial matters, and provinces may not have budgeted for the tasks given to them (Ebrahim, 2023). Adaptation needs are estimated at USD 152 billion for 2023–2030, and most of this remains unfinanced (WWA, 2025). Plans therefore risk being written but not implemented.

6. Mitigation Strategies and Best Practices

Risk can be reduced by acting on hazard, exposure, vulnerability and capacity. Structural measures include climate-resilient infrastructure, well-maintained drainage and flood protection. Non-structural measures include land-use planning, flood-risk maps,

evacuation plans, training and awareness. Nature-based solutions such as reforestation and wetland restoration, together with strict land-use rules, can reduce the number of people exposed to floods (WWA, 2025).

Some good practices already exist. Pakistan's GLOF projects pair early warning with community preparedness (UNDP, 2022). Globally, disaster mortality is about six times higher in countries with limited multi-hazard early warning systems (World Meteorological Organization [WMO], 2025), which shows the life-saving value of warning. After a disaster, recovery should "build back better" so that reconstruction lowers future risk (World Bank, 2022a). These actions match the Sendai Framework priorities of understanding risk, strengthening governance, investing in resilience and improving preparedness (UNDRR, 2015).

7. Risk Communication and Early Warning

Early warning saves lives only if it reaches people, is understood and leads to action. The 2025 flash floods show how far Pakistan is from this goal. On 15 August 2025, 150 millimeters of rain fell in one hour in Buner district. A survey of 1,207 households in three severely affected districts found that 85% of families received no warning, and for those who did, half had less than thirty minutes to act. The same survey showed a risk-perception gap: 85% of respondents did not believe their village was at risk, yet 56% said it had flooded before (World Bank, 2026).

Earlier studies show that these problems are not new. After the 2010 floods, the early warning system for the Islamabad–Rawalpindi basin was criticized for its technical approach, jargon-heavy messages, little public involvement and token attention to gender (Mustafa et al., 2015). A survey in Khyber Pakhtunkhwa found that people failed to heed or misread alerts, and recommended local-language messages and two-way communication (Shah et al., 2023). People-centred, gender-sensitive warnings delivered through trusted channels, such as mosques, are therefore essential (World Bank, 2026).

8. Policy Recommendations

The evidence supports six priority actions for NDMA and its partners:

I. **Strengthen the whole early warning chain.** Link monitoring and forecasting with community response, and formally include mosque networks and trusted local leaders (WMO, 2025; World Bank, 2026).

II. **Complete local risk assessments.** Finish multi-hazard assessments for all districts and publish accessible flood-risk maps, including for mountain flash floods (World Bank, 2026).

III. **Enforce risk-informed land use.** Stop building on floodplains and enforce building codes, especially in informal settlements (WWA, 2022, 2025).

IV. **Invest in resilient infrastructure.** Build climate-resilient infrastructure and maintained drainage, and build back better after disasters (Ebrahim, 2023; World Bank, 2022a).

V. **Make response inclusive.** Recruit women responders, use women health workers and teachers as warning channels, and keep records of vulnerable households (World Bank, 2026).

VI. **Fund and coordinate implementation.** Turn the National Adaptation Plan into funded provincial plans with clear roles for NDMA, PDMAs and DDMAs, and consult communities (Ebrahim, 2023; MoCCEC, 2023).

9. Conclusion

Climate change is increasing disaster risk in Pakistan, but it is one part of a larger system. It can make hazards such as heat and heavy rain stronger, with clearer evidence for some hazards than for others. Whether a hazard becomes a disaster depends on exposure, vulnerability and capacity. The 2022 and 2025 floods show that building in flood zones, weak infrastructure, inequality and missing warnings turned extreme rain into large human and economic losses. Because these factors can be changed, risk is not fixed. Science-based planning, early warning that reaches everyone, the use of local knowledge and social capital, and funded, coordinated implementation of policy can save lives and reduce losses. Future research should test these findings with primary data from affected communities.

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PARTICIPANT RESEARCH PAPER

Assessment of Flood and Drought Risks in Rahim Yar Khan District: Implications for Agriculture, Water Security, and Rural Livelihoods

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Abstract

Rahim Yar Khan district exhibits a unique climate risk profile, characterized by concurrent exposure to riverine floods along the Indus River and acute arid droughts in the Cholistan desert. This research paper evaluates the multi-hazard dynamics of Rahim Yar Khan, synthesizing empirical data from the 2023 Population Census, Pakistan Meteorological Department (PMD), and Provincial Disaster Management Authority (PDMA) Punjab. The study investigates the cascading impacts of climate extremes on agricultural productivity, rural livelihoods, and water security across its three distinct physical landscapes: the Katcha riverside, canal-irrigated plains, and the Cholistan desert. Key findings indicate that recurrent hydrological shocks—such as the 2010, 2015, and 2025 Indus floods, alongside severe heatwave-induced droughts in 2022 and 2026—severely threaten regional cotton-wheat systems and pastoral security. The paper identifies critical institutional and scientific gaps, including the absence of integrated multi-hazard district plans, limited groundwater monitoring, and deficient gender-disaggregated impact data. Finally, actionable policy recommendations are proposed, emphasizing community-based early warning systems, rehabilitation of indigenous water reservoirs (*tobas*), and integrated climate-smart governance.

Keywords: Rahim Yar Khan; Flood Risk; Drought; Disaster Risk Reduction; Cholistan; Agriculture Security.

1. Introduction

Rahim Yar Khan, situated in the southern part of Punjab, Pakistan, represents a microcosm of Pakistan's broader vulnerability to climate change. Spanning an area of 11,880\text{ km}^2 with a population exceeding 5.56 million, the district faces severe geographic and environmental dichotomies. The northern boundary is shaped by the Indus River, exposing riverside settlements to devastating riverine floods, while its southern expanse bleeds into the arid Cholistan Desert, making it equally susceptible to meteorological and agricultural droughts.

The rationale of this research lies in the urgent need to shift from reactive disaster response to proactive, integrated Disaster Risk Reduction (DRR). While individual hazards—such as floods or droughts—are frequently studied in isolation, Rahim Yar Khan experiences compounding shocks that erode community resilience, disrupt rural livelihoods, and jeopardize national food security. The purpose of this study is to examine the localized multi-hazard exposure of Rahim Yar Khan, evaluate existing institutional frameworks, and propose evidence-based mitigation strategies. The scope encompasses all four administrative tehsils—Rahim Yar Khan, Sadiqabad, Khanpur, and Liaquatpur—analyzing physical, socio-economic, and institutional dimensions to safeguard sustainable regional development.

2. Regional Context & Hazard Profile

Regional Context and Literature Review

The district is geographically segregated into three distinct physical zones: the Riverside (*Katcha*) area along the Indus River, the canal-irrigated agricultural core, and the desert landscape of Cholistan. Literature on southern Punjab's climate trends indicates an escalation in extreme weather variability, characterized by compressed, high-intensity monsoon rainfall patterns and prolonged summer heatwaves.

Vulnerability Profile and Historical Events

Historical records demonstrate recurrent exposure to severe hydrological events:

- **2010 Super Flood:** The Indus River peaked at 794,000 cusecs at Taunsa and 1,148,000 cusecs at Guddu, inundating parts of Rahim Yar Khan and Sadiqabad while forcing mass evacuations near Munchan Bund.

- **2015 Indus Flood:** Affected 56,000 people across all four tehsils (with Liaquatpur bearing the brunt), displacing 34,715 individuals and damaging 41,391 acres of standing crops, including sugarcane, moong, and cotton.
- **2022 Heatwave and Drought:** A prolonged 41-day heatwave (March 19 – April 19, 2022) recorded extreme temperatures reaching 50.8\text{ }^\circ\text{C} at Khanpur, severely depleting soil moisture and water storage in Cholistan.
- **2025 Floods:** Flood surges exceeding 660,000 cusecs passed Chachran Sharif alongside Panjnad outflows surpassing 668,000 cusecs, prompting the evacuation of roughly 12,000 residents across Khanpur and Liaquatpur riverbeds.
- **2026 Drought Indicators:** Assessments of Cholistan's traditional water ponds (*tobas*) reveal that out of approximately 1,150 total reservoirs, only about 180 held water by April 2026, threatening pastoral communities.

Core Definitions

- **Hazard:** A dangerous phenomenon, human activity, or condition that may cause loss of life, injury, property damage, social disruption, or environmental degradation (e.g., Indus riverine floods, Cholistan droughts).
- **Exposure:** The presence of people, livelihoods, species or ecosystems, environmental functions, services, and infrastructure in places that could be adversely affected.
- **Vulnerability:** The characteristics and circumstances of a community, system, or asset that make it susceptible to the damaging effects of a hazard.
- **Risk:** The combination of the probability of an event and its negative consequences, driven by the interaction of hazard, exposure, and vulnerability.

3. Risk & Vulnerability Assessment

Socio-Economic Impacts and Livelihood Disruption

Disaster risks in Rahim Yar Khan are deeply intertwined with rural socio-economic structures. The district's economy relies heavily on agrarian output and livestock grazing. Recurrent floods result in immediate losses of harvested and standing crops, structural damage to mud-brick homes (*jhuggis*), and livestock mortality. Conversely, meteorological droughts in Cholistan undermine pastoral livelihoods, which support an estimated 1.318 million livestock units in the desert belt.

Vulnerable Groups and Gender Dimensions

Vulnerability within the district is unevenly distributed. Marginalized populations—particularly landless tenant farmers in the *Katcha* belt and semi-nomadic pastoralists in Cholistan—possess the lowest adaptive capacities. Gender dimensions remain acute; women and children bear disproportionate burdens during displacements and water scarcity crises, responsible for fetching water over long distances in Cholistan while managing household safety during flood evacuations. Comprehensive gender-disaggregated impact data, however, remains critically scarce in official district assessments.

4. Community Resilience Factors

Communities in Rahim Yar Khan exhibit localized resilience mechanisms rooted in social capital and indigenous knowledge:

- **Social Networks and Mutual Aid:** Informal community networks facilitate early warning communication across riverbanks and mobilize traditional boat fleets for emergency rescue before official administrative intervention arrives.
- **Indigenous Knowledge Systems:** In Cholistan, pastoralists rely on generational tracking of weather patterns, herd mobility, and the strategic utilization of ancestral rainwater harvesting structures known as *tobas* and underground masonry tanks (*kunds*).
- **Local Coping Strategies:** During dry spells, pastoralists practice seasonal migration (*hath*) toward canal-irrigated zones, temporarily shifting herds to secure fodder and water resources.

5. Scientific & Institutional Gaps

Despite established disaster management tiers, several structural bottlenecks hinder effective DRR in Rahim Yar Khan:

- **Research and Data Deficits:** There is a distinct absence of localized vulnerability indices, comprehensive post-disaster loss accounting for agriculture and livestock (such as undocumented animal losses during the 2022 heatwave), and baseline groundwater quality metrics.

- **Technology Limitations:** Limited adoption of advanced Artificial Intelligence (AI) and Machine Learning (ML) models for predictive hydrological modeling and localized micro-drought forecasting.
- **Institutional Weaknesses:** Fragmented coordination between irrigation authorities, agricultural departments, and disaster management bodies. Early warning advisories—such as PMD's 2022 heatwave alerts—frequently fail to trigger immediate, localized municipal water supply interventions.

6. Mitigation Strategies & Best Practices

To counter recurring climate extremes, a hybrid of structural and non-structural measures is required:

- **Structural Interventions:** Strengthening and regularizing protective embankments (*bunds*) along vulnerable river sections in Khanpur and Liaquatpur; scaling up the construction of concrete *kunds* and desilting existing *tobas* in Cholistan.
- **Non-Structural Measures:** Establishing community-based disaster management committees in every Union Council (UC); conducting mandatory annual evacuation drills in high-risk riverside settlements.
- **Best Practices:** Integrating past institutional successes—such as the vaccination campaigns that treated over 53,800 cattle against waterborne diseases during the 2015 floods—into standard operating procedures.

7. Risk Communication & Early Warning

Effective disaster mitigation relies heavily on last-mile risk communication. While provincial bodies issue macro-level alerts, last-mile dissemination in Rahim Yar Khan faces community resistance and communication gaps (evidenced in 2012 when riverside residents ignored early flood warnings).

A paradigm shift toward people-centred and gender-sensitive early warning systems (EWS) is essential. This entails utilizing localized mosque loudspeakers, mobile SMS alerts in regional dialects (Saraiki/Punjabi), and visual warning flags along the Indus River banks to ensure that vulnerable households in remote *Katcha* and desert zones comprehend impending threats and act promptly.

8. Policy Recommendations

To foster long-term resilience, the following phased policy framework is recommended:

Timeline	Strategic Action	Lead Agency	Verification Metric
0–1 Year	Deploy targeted household warnings and execute annual evacuation drills in high-risk UCs of Khanpur and Liaquatpur.	PDMA Punjab / District Administration	Percentage of riverside UCs conducting verified community drills.
0–1 Year	Desilt, clean, and rehabilitate Cholistan *tobas*; pre-position emergency water bowsers/tankers.	Cholistan Development Authority (CDA) / PDMA	Proportion of functional *tobas* holding water reserves (expanding from baseline 180/1,150).
1–3 Years	Institutionalize comprehensive post-disaster loss tracking for crops and livestock disaggregated by tehsil.	Provincial Agriculture & Livestock Departments	Availability of standardized damage tracking reports post-calamity.
1–3 Years	Formulate a unified, multi-hazard district contingency plan integrating flood and drought protocols.	PDMA / NDMA	Formal notification and UC-level committee establishment.
3–5 Years	Scale up climate-smart agricultural practices and expand strategic water infrastructure near Cholistan borders.	Agriculture & Irrigation Departments	Adoption rates of resilient crop varieties and improved irrigation efficiency.

9. Conclusion

Rahim Yar Khan district exemplifies the complex challenges posed by concurrent hydrological and thermal extremes under a shifting global climate. The coexistence of riverine flood exposure in the north and arid drought vulnerability in the south demands a

departure from single-hazard planning. By integrating science-based forecasting, honoring indigenous knowledge systems, upgrading decentralized water infrastructure, and strengthening community-based social capital, Rahim Yar Khan can transition toward a resilient future characterized by minimized asset loss, secured rural livelihoods, and accelerated post-disaster recovery.

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PARTICIPANT RESEARCH PAPER

Climate Change Impacts on Food Security and Agricultural Systems

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Abstract

Climate change is reshaping agricultural systems through rising temperatures, erratic rainfall, floods and droughts, with direct consequences for food availability, access, utilisation and stability. This paper examines how climate change affects food security and agricultural systems, with a regional focus on Pakistan, one of the world's most climate-exposed agrarian economies. Drawing on peer-reviewed literature and institutional reports, it analyses hazard trends, socio-economic vulnerability, gender dimensions, community resilience, scientific and institutional gaps, mitigation practices and early warning systems. The findings show that warming has already depressed yields, that disasters impose heavy losses on smallholder-dependent systems, and that women and poor rural households carry disproportionate risk. The 2022 floods in Pakistan illustrate how a single hazard can cascade through livelihoods, markets and nutrition. The paper recommends integrated governance, climate-smart agriculture, people-centred early warning, investment in data and digital tools, and meaningful inclusion of community and indigenous knowledge in disaster risk reduction.

Keywords: climate change, food security, agricultural systems, disaster risk reduction, Pakistan

1. Introduction

Agriculture is among the most climate-sensitive sectors of the global economy, and the food systems built upon it determine whether people can eat well. Food security exists when people have reliable physical and economic access to sufficient, safe and nutritious food, and it is conventionally understood through four dimensions: availability, access, utilisation and stability (Intergovernmental Panel on Climate Change [IPCC], 2022). Climate change pressures all four. The latest global assessment estimates that 645 million people (7.8%) faced hunger in 2025 and about

2.1 billion experienced moderate or severe food insecurity, with weather extremes among the forces that could undermine further progress (Food and Agriculture Organization of the United Nations [FAO] et al., 2026).

The problem is that agricultural systems, especially rainfed and smallholder systems, are being exposed to hazards faster than institutions and farmers can adapt. This matters for disaster risk reduction (DRR) because food insecurity is both a consequence of disasters and a driver of vulnerability to the next one. The purpose of this paper is to analyse how climate change affects food security and agricultural systems and to identify practical DRR responses. Its objectives are to (a) review hazard trends and regional context, (b) assess risk and vulnerability, (c) examine community resilience, knowledge gaps, mitigation and early warning, and (d) propose policy recommendations. The scope combines global evidence with a regional focus on Pakistan, whose economy and rural livelihoods depend heavily on climate-sensitive agriculture.

2. Regional Context and Hazard Profile

Key terms: A hazard is a process or event that may cause harm, such as a flood or heatwave; exposure refers to the people, crops, livestock and assets located in hazard-prone areas; vulnerability is the set of conditions that make them susceptible to damage; and risk is the likelihood of losses arising from the interaction of these elements (United Nations Office for Disaster Risk Reduction [UNDRR], n.d.).

Global trends: Warming has already affected production. Lobell et al. (2011) estimated that climate trends since 1980 reduced global maize and wheat yields by 3.8% and 5.5% respectively, relative to a world without those trends. Zhao et al. (2017) found that each additional degree Celsius lowers global yields of wheat, rice and maize by roughly 6.0%,

3.2% and 7.4%. Ortiz-Bobea et al. (2021) concluded that climate change has reduced global agricultural productivity growth by about 21% since 1961, with the steepest declines in warmer regions. Disasters add a second layer of loss: FAO (2023a) estimates that crop and livestock production worth about USD 3.8 trillion was lost to disasters over thirty years, roughly USD 123 billion annually or 5% of global agricultural GDP, with losses reaching up to 15% of agricultural GDP in low- and lowermiddle-income countries.

Regional context: Pakistan illustrates these dynamics. Agriculture contributes roughly one-fifth of GDP and employs around 40% of the labour force (Ministry of Climate Change and Environmental Coordination [MoCC], 2023). Production depends on the Indus irrigation system, which is fed by monsoon rainfall and glacier and snow melt, making it sensitive to both flood and drought (IPCC, 2022). The 2022 monsoon floods were a defining event. They affected about 33 million people and caused damages of USD 14.9 billion and economic losses of USD 15.2 billion, with agriculture and livestock among the three worst-hit sectors, suffering USD 3.7 billion in damage (Ministry of Planning, Development and Special Initiatives [MoPDSI], 2022).

3. Risk and Vulnerability Assessment

Socio-economic impacts and livelihood disruption: Climate hazards reduce farm output and also destroy productive assets such as seed stocks, livestock, irrigation channels and storage. After the 2022 floods, agriculture was projected to contract more than any other sector, with damage spilling over into industry, trade and services (MoPDSI, 2022). Household-level effects include lost income, debt, distress sales of livestock and reduced spending on food, health and education.

Food security dimensions: Availability falls when yields and cropped area decline; access deteriorates when production shocks raise prices and erode incomes; utilisation suffers when floods contaminate water and spread disease, reducing nutrient absorption; and stability is undermined by recurrent shocks that prevent recovery between events (IPCC, 2022).

Vulnerable groups and gender dimensions: Exposure and susceptibility are unevenly distributed. Smallholder farmers practising rainfed agriculture are among those most affected by disasters (FAO, 2023a), because they often lack irrigation, savings, insurance and diversified incomes. Landless tenants, pastoralists and rural labourers are similarly

susceptible. Women are central to crop, livestock and postharvest work yet face unequal access to land, credit, inputs, extension services and information (FAO, 2023b). The post-disaster needs assessment recorded notable losses of women's livelihoods in agriculture and livestock after the 2022 floods (MoPDSI, 2022). Vulnerability is therefore shaped not by hazard alone but by poverty, insecure land tenure, weak infrastructure, gender inequality and limited access to services, so the same flood or drought produces very different outcomes across households.

4. Community Resilience Factors

Resilience depends on what communities can do before, during and after shocks. Social capital, meaning trust, reciprocity and networks, allows households to share labour, seed, information and credit, and it shapes how effectively collective adaptation takes place (Adger, 2003). Kinship ties, farmer groups, village organisations and remittance networks frequently provide the first line of support when formal assistance is delayed.

Indigenous and local knowledge is a further asset. Communities hold detailed understanding of seasonal signs, flood-prone land, drought-tolerant landraces, watersharing rules and livestock management. Mercer et al. (2010) argue that DRR is most effective when indigenous and scientific knowledge are integrated rather than treated as competing, which is relevant to Pakistan's diverse agro-ecological zones. Local coping mechanisms include crop and income diversification, seed saving, staggered planting, livestock mobility, grain storage and rotational irrigation arrangements such as *warabandi*. Community participation in planning builds ownership and ensures that measures reflect local priorities, while women's groups and youth networks widen the pool of capacities. However, coping strategies can be exhausted by repeated shocks, so they must be supported rather than assumed.

5. Scientific and Institutional Gaps

Several gaps constrain effective action. Scientifically, downscaled climate projections and crop models are often unavailable at district or farm level, and evidence on compound events, such as heat stress followed by floods, is limited. FAO (2023a) notes that data on disaster impacts in agriculture are partial and inconsistent, particularly for fisheries, aquaculture and forestry, which hampers loss accounting and planning.

Technology adoption is another gap. Artificial intelligence and machine learning, combined with remote sensing and digital agriculture, can improve yield forecasting, pest detection and targeted advisories (Basso & Antle, 2020), yet uptake in smallholder systems is limited by connectivity, cost, digital literacy and a shortage of locally validated models. Institutionally, responsibilities for agriculture, water, climate and disaster management are spread across federal and provincial bodies, which can lead to duplication, weak coordination and slow response. Capacity gaps in extension services, meteorological coverage and local disaster management units, together with limited adaptation finance, further weaken implementation.

6. Mitigation Strategies and Best Practices

Structural measures include modernising irrigation, lining canals, building water storage, improving drainage, protecting embankments, and developing climateresilient storage and cold chains to reduce post-harvest losses. **Non-structural measures** are equally important. Climate-smart agriculture (CSA) seeks to raise productivity, strengthen adaptation and reduce emissions where possible (Lipper et al., 2014). Practical examples include heat- and drought-tolerant and short-duration varieties, adjusted sowing dates, water-saving irrigation, conservation agriculture, crop diversification and integrated crop and livestock systems. Crop and livestock insurance and social protection can cushion income shocks.

Anticipatory action is a leading international best practice: FAO (2023a) reports that each USD 1 invested in anticipatory action can yield up to USD 7 in benefits and avoided losses for rural families. Capacity building, farmer and extension-worker training, awareness campaigns and preparedness planning, including seed and fodder reserves, turn these measures into practice. At policy level, the Sendai Framework calls for stronger disaster risk governance and investment in resilience (UNDRR, 2015), while Pakistan's National Adaptation Plan prioritises climate-smart agriculture, modernised irrigation and incentives for farmers (MoCC, 2023).

7. Risk Communication and Early Warning

Early warning systems convert forecasts into protective action only when warnings are understood, trusted and acted upon. The Sendai Framework sets a global target to substantially increase the availability of, and access to, multi-hazard early warning

systems by 2030 (UNDRR, 2015), and the Early Warnings for All initiative aims to protect everyone through such systems (World Meteorological Organization [WMO], 2022). For agriculture, warnings must go beyond hazard alerts to include seasonal outlooks, heat and frost advisories, flood forecasts and agro-advisories that tell farmers what to do, such as harvesting early, moving livestock or delaying sowing.

People-centred and gender-sensitive design means consulting users, using local languages and visual formats, and ensuring that women, who may have limited mobility or phone access, receive information through trusted channels such as women extension workers and community groups. Last-mile dissemination should combine SMS and mobile applications with radio, mosque and village announcements, community volunteers and local leaders. Continuous community engagement, drills and feedback loops build trust and keep systems relevant.

8. Policy Recommendations

a) **Integrated governance.** Establish coordination mechanisms linking agriculture, water, climate and disaster agencies across federal and provincial levels, and embed DRR in agricultural planning (UNDRR, 2015).

b) **Climate adaptation.** Implement the National Adaptation Plan with dedicated finance for climate-smart agriculture, irrigation modernisation and flood- and drought-tolerant seed systems (MoCC, 2023).

c) **Community participation.** Involve farmer organisations, women and holders of local and indigenous knowledge in planning and monitoring (Adger, 2003; Mercer et al., 2010).

d) **Technology integration.** Invest in agro-meteorological networks, remote sensing and AI-enabled advisories, ensuring access for smallholders (Basso & Antle, 2020).

e) **Institutional strengthening.** Build extension and local disaster management capacity and strengthen loss and damage data systems for agriculture (FAO, 2023a).

f) **Evidence-based finance.** Scale anticipatory action, crop insurance and social protection, prioritising the poorest households and women farmers (FAO, 2023a, 2023b).

9. Conclusion

Climate change is already reducing yields, destabilising agricultural systems and deepening food insecurity, with the poorest and most exposed communities bearing the heaviest burden. Pakistan's 2022 floods show how one hazard can cascade from crop and livestock losses to livelihoods, markets and nutrition. The analysis shows that vulnerability is socially produced and that resilience depends on both formal systems and community strengths. Science-based planning, social capital, indigenous knowledge, appropriate technology and integrated governance reinforce one another, and no single measure is sufficient alone. Acting early, through anticipatory action, people-centred early warning and sustained investment in adaptation, is more effective than responding after disasters. Aligning agricultural policy with DRR and climate adaptation is therefore essential to protect food security in a warming world.

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Annex A: Hazard–Impact Matrix for Agricultural Systems

Hazard	**Agricultural impact**	**Food security dimension most affected**
Heatwaves and warming	Heat stress on crops and livestock; lower yields; shorter grain-filling periods	Availability; utilisation
Drought and water scarcity	Reduced irrigation supply; crop failure; fodder shortages	Availability; access
Floods	Loss of standing crops, seed, livestock and infrastructure; soil damage	Access; stability
Glacier and snowmelt variability	Shifts in river flow timing affecting canal irrigation	Stability; availability

Note. Adapted from IPCC (2022), Zhao et al. (2017) and MoPDSI (2022).

PARTICIPANT RESEARCH PAPER

Climate-Induced Migration and Displacement: Policy Challenges and Humanitarian Response

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Abstract

The migration and refugee policy and humanitarian system to assist migrants and refugees is disorganized, and the impact of climate change is growing even more significant as a migration driver. The paper therefore discusses the connections between climate hazards and migration and displacement, the existing policy and programming gaps, and how to improve humanitarian action. Drawing on recent trends in displacement, World Bank projections, legal research, and lessons learned from Bangladesh and Pakistan, it suggests that displacement does not address vulnerability, it simply moves it: those who are displaced from climate-stressed rural areas often end up in the city in informal settlements without legal access, services, or welfare entitlements. There are three gaps that are highlighted: lack of an effective international protection framework for climate-induced migrants; fragmented institutional protection between adaptation, disaster management, and urban planning, and poor, non-inclusive early warning and data systems. The paper highlights, among others, the importance of integrated governance, mobile social protection, financed national displacement policies, people-centred early warning and community involvement as called for by the Sendai Framework.
Keywords: climate justice, disaster risk reduction, displacement, early warning, internal migration

1. Introduction

Climate change is reshaping where people can live and work. In 2025 alone, disasters triggered 29.9 million internal displacements worldwide, and 13.6 million people were still displaced by disasters at the end of the year (Internal Displacement Monitoring Centre [IDMC], 2026). The World Bank projects that slow-onset impacts such as water scarcity, crop failure, and sea-level rise could move as many as 216 million people within their own countries across six world regions by 2050, with migration hotspots emerging as early as 2030 (Clement et al., 2021). These figures matter for South Asia, where floods, cyclones, and salinity already uproot millions.

Despite this scale, no binding international regime protects people displaced by climate change, and national systems often treat displacement as a short-term relief problem rather than a development and governance challenge. This paper asks: how do current policy frameworks and humanitarian responses address climate-induced migration and displacement, and where do they fall short? Its objectives are to (1) explain how climate hazards drive displacement, (2) identify policy and institutional gaps, and (3) recommend practical reforms. The scope is South Asia, with Bangladesh and Pakistan as case studies, and the focus is internal displacement, which is what the available global data and projections mainly measure.

2. Regional Context & Hazard Profile

A hazard is a potentially damaging event, such as a flood or cyclone; exposure is the presence of people and assets in hazard-prone areas; vulnerability is the susceptibility to harm shaped by poverty, location, and access to services; and risk is the potential for loss that results from their interaction.

South Asia recorded 4.64 million disaster displacements in 2025, about 8.3% of the global total, including 3.05 million in Pakistan and 105,000 in Bangladesh (IDMC, 2026). Global totals fell sharply from 2024, yet storms alone caused 17.9 million movements, so year-to-year variation should not be read as a downward trend (IDMC, 2026). The most severe recent regional event was Pakistan's 2022 floods, which affected about 33 million people, displaced 7.9 million, and damaged or destroyed more than 2.3 million homes (Office for the Coordination of Humanitarian Affairs [OCHA], 2023). In coastal Bangladesh, repeated cyclones and riverbank erosion push rural households toward

Dhaka (International Organization for Migration [IOM], 2019; World Bank, 2023), and saline intrusion in districts such as Bagerhat and Satkhira adds to the pressure.

The literature falls into three strands. First, the environment–migration literature shows that slow-onset change, not only sudden disasters, will drive large-scale movement, most of it within countries (Clement et al., 2021). Second, the legal literature finds that the 1951 Refugee Convention protects people with a well-founded fear of persecution and generally does not cover people fleeing disasters (Gagnon & Lagacé-Roy, 2024). In Teitiota v. New Zealand, the UN Human Rights Committee rejected the claim but held that returning people to places where climate impacts threaten the right to life could trigger non-refoulement obligations (United Nations Human Rights Committee, 2020). Third, the institutional literature highlights the isolation of adaptation planning from urban planning and the resulting execution deficit (Islam, 2018).

3. Risk & Vulnerability Assessment

Climate displacement begins with livelihood loss. In a survey in Rahim Yar Khan, southern Punjab, 98% of respondents said floods were the main reason they left home; flooding destroyed 70–80% of cotton crops in the area, and most affected people depended on agricultural labour (Sadri, 2025). Migrant households reported high food and water insecurity and difficulty obtaining clean drinking water (Sadri, 2025). In Bangladesh, saline intrusion has reduced rice cultivation and rural wage labour in the south-west coast, leaving few options other than leaving.

Arrival in the city does not end vulnerability. In Dhaka, groundwater has fallen by more than three meters a year (World Bank, 2023), about 40% of municipal refuse goes uncollected, and informal syndicates charge three to four times public prices for electricity and water in settlements such as Korail and Kamrangirchar (Nurullah & Islam, 2022). Social welfare tied to a rural address means that moving to the city can strip migrants of state protection and push them into insecure informal work (World Bank, 2023). This is the central finding: displacement shifts the risk from the rural edge to the urban core.

Vulnerability is unevenly distributed. Landless and tenant households, daily-wage workers, and informal settlers have the least capacity to absorb shocks. Gender matters: women and girls in Pakistan had limited access to early flood warnings (Sadri, 2025), and Bangladesh's national strategy calls for disaggregated data so the needs of women,

children, older people, and persons with disabilities can be seen and addressed (Siddiqui et al., n.d.).

4. Community Resilience Factors

Communities are the first responders to displacement. Kinship and neighbourhood networks typically shape where households go, how quickly they find shelter and work, and whether they can borrow money or share food. Local coping strategies include temporary or seasonal migration, livelihood diversification, and mutual support during floods. Community-based flood mitigation and preparedness programmes are among the measures recommended for Pakistan (Sadri, 2025). Local knowledge of rivers, embankments, and seasonal patterns can strengthen scientific forecasts when communities are consulted rather than only informed. However, resilience has limits: informal settlers who lack tenure, legal recognition, and services cannot build resilience on social capital alone, so community strengths should complement, not replace, state responsibility.

5. Scientific & Institutional Gaps

Data is the first gap. Global estimates are useful but must be downscaled to district and settlement level, and displacement data are rarely disaggregated by sex, age, and disability (Siddiqui et al., n.d.). Pakistan still lacks a reliable early warning system and needs better data collection to support response and recovery decisions (Sadri, 2025). Emerging tools such as machine learning could improve flood forecasting and anticipatory targeting, but they depend on good local data and institutions able to act on the outputs.

The institutional gaps are larger. Pakistan has 27 stakeholders and 39 ministries involved in disaster management, creating coordination problems (Sadri, 2025). Bangladesh has progressive policy: its 2021 National Strategy on Internal Displacement Management covers prevention, protection, and durable solutions (Government of Bangladesh, 2021), with 112 targets and a 2022–2042 action plan (Siddiqui et al., n.d.). Yet implementation lags: the National Task Force on Displacement and the Technical Advisory Committee are not yet established, local coordination committees do not routinely address displacement, no Displacement Trust Fund exists, and development partners still tend to treat displacement as a humanitarian rather than a development issue (Siddiqui et al.,

n.d.). Internationally, the only binding instrument that obliges states to protect people displaced in natural disasters is the African Union's Kampala Convention, and the Global Compact for Migration is non-binding (Gagnon & Lagacé-Roy, 2024).

6. Mitigation Strategies & Best Practices

Effective mitigation combines structural and non-structural measures. Embankments and polders protect coastal land but, as Bangladesh's experience shows, engineering alone does not address where people go when protection fails (World Bank, 2023). Non-structural measures include risk-informed land use, livelihood diversification, preparedness training, and public awareness. Prevention is cost-effective: anticipatory measures can reduce costs by 75% compared with recovery investment (Siddiqui et al., n.d.).

Several practices are worth adapting. Bangladesh's strategy organizes action around prevention, protection during displacement, and durable solutions (return, local integration, or resettlement) (Government of Bangladesh, 2021). The Kampala Convention shows how a binding regional treaty can make protection a state duty (Gagnon & Lagacé-Roy, 2024). The Global Compact for Safe, Orderly and Regular Migration encourages humanitarian visas, and temporary work permits after sudden-onset disasters and planned relocation for slow-onset change (Gagnon & Lagacé-Roy, 2024). All of this aligns with the Sendai Framework's emphasis on understanding risk and strengthening governance (United Nations Office for Disaster Risk Reduction [UNDRR], 2015).

7. Risk Communication & Early Warning

Warnings save lives only when they reach people and are acted on. In Pakistan's 2022 floods, 58% of survey respondents did not receive early warning information, and women and girls had limited access to it (Sadri, 2025). People-centered systems need last-mile channels that people actually use, such as community volunteers, local leaders, mobile messaging, and loudspeaker announcements, delivered in local languages. They should be gender-sensitive, with women involved in design and dissemination, and two-way, so communities can report conditions and feedback on what failed. Warnings should also tell people where shelters are and how to reach them. For people already displaced, risk

communication should continue in destination cities, giving migrants clear information on services, entitlements, and hazards in informal settlements.

8. Policy Recommendations

Drawing on the evidence above, six measures are recommended:

I. **Integrate governance.** Create a single coordination mechanism linking climate adaptation, disaster management, and urban planning, and give it clear lead agency authority to reduce the fragmentation seen in Pakistan and Bangladesh.

II. **Fund and implement national displacement strategies.** Establish the missing institutions, such as task forces and a dedicated trust fund, and add displacement to local development committee agendas (Siddiqui et al., n.d.).

III. **Make social protection portable.** De-link welfare from permanent rural addresses, which currently cost migrants their entitlements (World Bank, 2023), so that benefits follow migrants, with temporary urban ration cards and skills training.

IV. **Include displaced people in cities.** Shift from forced eviction to slum upgrading, extend utilities to informal settlements, and invest in secondary cities to ease pressure on megacities.

V. **Strengthen data and early warning.** Collect disaggregated displacement data and build people-centred, gender-sensitive warning systems, with community participation in design.

VI. **Advance international protection and finance.** Support clearer legal protection for people displaced by climate impacts and direct climate finance, including loss and damage, toward displacement prevention and response.

9. Conclusion

Climate-induced displacement is a present reality and a growing one. The evidence from Bangladesh and Pakistan shows that displacement relocates vulnerability from rural ecology to urban informality, and that policy and humanitarian systems still respond to it in pieces. Closing the gap requires science-based planning that anticipates movement, integrated governance that connects adaptation, disaster management, and urban planning, social protection that follows people, and warning systems that reach everyone, including women and the poorest households. Building on community networks and local knowledge, rather than ignoring them, will make these measures more legitimate and

more durable. Treating displacement as a development and rights issue, not only an emergency, is the central step toward resilience.

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PARTICIPANT RESEARCH PAPER

Climate Change as a Key Driver of Disaster Risk

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Abstract

Climate change is increasingly shaping disaster risk by altering the likelihood, intensity, duration, and timing of certain climate-related hazards. However, a hazard does not automatically become a disaster: the scale of loss also depends on who and what is exposed, the vulnerability of communities and infrastructure, and the capacity of institutions to prepare, respond, and recover. This paper examines the relationship between climate change and disaster risk, using Pakistan and Balochistan as a regional focus. It reviews major hazards—including floods, flash floods, drought, extreme heat, coastal hazards, and water stress—and considers their social, economic, and institutional consequences. The paper uses a qualitative, desk-based approach, drawing on authoritative climate assessments, Pakistan's policy documents, and post-disaster assessments. It identifies persistent challenges in risk information, local early-warning communication, land-use planning, resilient infrastructure, inter-agency coordination, and inclusive preparedness. The paper argues that disaster risk reduction must be integrated into climate adaptation, development planning, and local governance. Priority actions include district-level multi-hazard risk mapping, accessible early-warning systems, community-led preparedness, protection of vulnerable groups, climate-resilient infrastructure, and transparent monitoring of policy implementation. The analysis concludes that climate change is a major risk multiplier, while effective governance and reduced vulnerability can prevent hazards from escalating into disasters.

Keywords: adaptation, Balochistan, climate change, disaster risk, early warning, resilience

1. Introduction

Climate change has become a central challenge for environmental management and sustainable development. Rising temperatures influence the water cycle, increase the likelihood of extreme heat, and can intensify some heavy-precipitation events. Depending on the region, climate change can also worsen drought conditions, increase wildfire-conducive weather, and contribute to sea-level rise. These pressures interact with rapid urbanisation, environmental degradation, poverty, and weak infrastructure to create complex disaster risks. The Intergovernmental Panel on Climate Change (IPCC) emphasises that climate impacts are shaped not only by the physical hazard but also by exposure and vulnerability (IPCC, 2022).

Pakistan illustrates this interaction. The 2022 floods affected approximately 33 million people and caused extensive damage to housing, agriculture, transport, and livelihoods. The post-disaster assessment estimated more than US$30 billion in damages and economic losses, alongside substantial reconstruction needs (Government of Pakistan et al., 2022; World Bank, 2022). Such events highlight the need to move beyond emergency response towards prevention, preparedness, and climate-resilient recovery.

Balochistan faces a particularly varied hazard profile because of its large area, arid and semi-arid conditions, mountainous terrain, long coastline, dispersed settlements, and uneven access to services. Communities may experience drought and water scarcity as well as sudden flash floods, extreme heat, coastal hazards, and damage to roads, homes, crops, and livestock. This paper aims to explain how climate change influences disaster risk, assess the regional context and vulnerability factors, examine resilience and institutional gaps, and recommend practical policy measures for Pakistan, particularly Balochistan.

Objectives: (1) explain the relationship between climate change and disaster risk; (2) identify key climate-related hazards and exposed groups in Pakistan and Balochistan; (3) assess social, economic, community, scientific, and institutional vulnerability; and (4) propose evidence-based mitigation, adaptation, preparedness, and policy measures. The scope is a qualitative review of secondary sources rather than original field research.

2. Regional Context and Hazard Profile

Disaster risk is commonly understood through the interaction of hazard, exposure, vulnerability, and capacity. Climate change affects the hazard component, while settlement patterns, livelihoods, public services, and governance influence exposure and vulnerability. Consequently, the same rainfall event may cause limited damage in a well-prepared area but severe losses where homes are poorly constructed, drainage is inadequate, warnings are inaccessible, or evacuation routes are missing (IPCC, 2012; IPCC, 2022).

Floods and flash floods: Heavier rainfall over short periods can overwhelm drainage and river systems. In Balochistan, intense rainfall in mountainous catchments may produce rapid runoff and flash flooding, damaging roads, bridges, homes, agricultural land, and water infrastructure. Flood impacts are amplified when construction occurs in natural drainage channels or flood-prone areas.

Drought and water stress: High temperatures increase evaporation and water demand. Irregular precipitation and prolonged dry periods can place pressure on groundwater, rangelands, livestock, and rain-fed agriculture. Where livelihoods depend on livestock or seasonal farming, repeated drought can reduce household income, food security, and the ability to recover before the next shock.

Extreme heat: Rising average temperatures increase the risk of dangerous heat exposure. Outdoor workers, older people, children, people with disabilities, and households with limited access to cooling or reliable electricity may be particularly affected. Heat also places pressure on health services, water supplies, labour productivity, and electricity systems.

Coastal and other hazards: Coastal communities may face storm impacts, erosion, saltwater intrusion, and longer-term sea-level rise. Mountainous areas can face landslides and other hazards when heavy rainfall interacts with steep slopes and unstable terrain. These hazards should be assessed locally; climate change does not affect every hazard in the same way or with equal certainty.

The 2022 Pakistan floods demonstrated the scale of cascading impacts. Flooding disrupted transport, schooling, health services, agriculture, and household livelihoods, and recovery needs extended well beyond immediate relief. The event should not be attributed to climate change through a single-cause explanation: disaster outcomes

reflected extreme rainfall together with exposure, vulnerability, infrastructure, and preparedness.

3. Risk and Vulnerability Assessment

Social impacts: Disasters can cause death, injury, displacement, interrupted education, health risks, and psychological distress. Damage to clinics, roads, water systems, and schools can prolong the effects long after floodwaters recede or a heatwave ends. People living in informal or remote settlements may face greater barriers to receiving warnings and accessing assistance.

Economic and livelihood impacts: Floods can destroy crops, livestock, stored food, irrigation systems, shops, and transport links. Drought can reduce pasture and agricultural productivity, while heat can lower outdoor labour capacity and raise water and energy costs. Low-income households often have fewer savings, insurance options, or alternative income sources, making recovery slower and increasing the risk of debt.

Food and water security: Climate hazards can disrupt food production and markets while damaging drinking-water infrastructure. Floodwater may contaminate wells and sanitation systems; drought may reduce water availability and increase competition between household, agricultural, and livestock needs. Emergency planning should therefore include safe water, sanitation, food distribution, and continuity of essential services.

Gender and vulnerable groups: Women and girls may face additional barriers where evacuation, transport, sanitation, privacy, or access to information is inadequate. Children, older adults, people with disabilities, and people with chronic health needs may require tailored support. Risk assessments should disaggregate information by sex, age, disability, income, and location, while ensuring meaningful participation in planning.

Exposure and susceptibility: Settlements near rivers, seasonal streams, coastlines, unstable slopes, or poorly drained urban areas may face elevated exposure. Susceptibility increases when buildings are weak, drainage is blocked, vegetation and soils are degraded, services are distant, or households lack resources to prepare. These conditions are not inevitable: land-use enforcement, safer infrastructure, social protection, and accessible warnings can reduce risk.

A practical risk assessment should combine hazard maps, historical disaster records, population and infrastructure data, livelihood information, local knowledge, and an

assessment of response capacity. Data should be updated regularly and used to prioritise investment rather than treated as a one-time technical exercise.

4. Community Resilience Factors

Community resilience is the capacity to anticipate, withstand, adapt to, and recover from shocks. Social networks can help households share warnings, transport, food, shelter, and information. Local knowledge can identify seasonal streams, past flood paths, water sources, drought indicators, and safe evacuation routes. Such knowledge is valuable when combined with meteorological and scientific information, rather than used as a substitute for it.

Resilience is strengthened by trusted local leadership, active community organisations, schools, health workers, trained volunteers, and links with district disaster-management authorities. Women, youth, older residents, people with disabilities, and livelihood groups should participate in preparedness planning. Community plans should identify safe shelters, accessible routes, emergency contacts, livestock arrangements, and support for people who cannot evacuate independently.

Resilience also requires resources. Communities cannot compensate indefinitely for unsafe infrastructure, limited public services, or absent government support. Preparedness grants, livelihood diversification, climate-smart agriculture, water conservation, ecosystem restoration, and social-protection programmes can help households recover without selling productive assets or taking on unsustainable debt.

5. Scientific and Institutional Gaps

First, local climate and disaster data may be fragmented across departments, vary in quality, or be difficult for district officials and communities to access. Incomplete records make it harder to compare risk between districts, track changing patterns, and evaluate whether adaptation investments work. A shared, regularly updated multi-hazard information system would improve planning.

Second, warnings do not always translate into protective action. Forecasts must be understandable, timely, locally relevant, accessible in appropriate languages and formats, and delivered through channels that work when electricity or mobile networks fail. Last-mile communication and clear instructions are as important as technical forecasting.

Third, institutional responsibilities may overlap or remain unclear across climate, disaster management, irrigation, health, agriculture, local government, and infrastructure departments. Weak coordination can delay decisions and make accountability difficult. Risk reduction also competes with immediate development needs and limited budgets.

Fourth, there is a gap between policy commitments and implementation. Pakistan has national climate policy and adaptation planning instruments, but effectiveness depends on funding, provincial and district capacity, measurable targets, public reporting, and coordination across levels of government (Government of Pakistan, 2021, 2023).

Finally, advanced tools such as geographic information systems, remote sensing, and artificial intelligence or machine learning may support forecasting, damage assessment, and risk mapping. However, they require reliable data, trained staff, maintenance, transparent methods, and safeguards against excluding communities with limited digital access. Technology should support—not replace—local knowledge, public institutions, and human judgement.

6. Mitigation Strategies and Best Practices

Structural measures include climate-resilient roads, bridges, culverts, drainage, water-supply systems, health facilities, and schools. Infrastructure should be designed using updated hazard information and maintained before emergencies. Construction should avoid blocking natural waterways, and critical facilities should have continuity plans for power, water, communications, and access.

Non-structural measures include land-use planning, building standards, drought-management plans, heat-health action plans, insurance or risk-financing mechanisms where feasible, and protection of floodplains and watersheds. Nature-based measures—such as restoring vegetation, protecting wetlands where present, improving watershed management, and conserving soils—can complement engineered infrastructure when designed for local ecological conditions.

Preparedness should include regular community drills, school safety plans, emergency stockpiles, evacuation routes, trained local responders, and pre-agreed arrangements for transport and shelters. Livelihood measures may include water-efficient farming, improved rangeland management, diversified income, and climate-informed agricultural

advice. Recovery should follow the principle of “Build Back Better,” rebuilding homes and services to reduce future risk rather than reproducing previous vulnerabilities.

Best practice is context-specific. Measures should be selected through local risk assessments, cost-benefit analysis, consultation with affected groups, and monitoring. No single intervention—whether a wall, a forecast model, tree planting, or an awareness session—can independently eliminate disaster risk.

7. Risk Communication and Early Warning

An effective early-warning system connects four elements: knowledge of risk; monitoring and forecasting; communication of understandable warnings; and the capacity to respond. A warning is useful only when people receive it in time, trust it, understand what action is required, and have realistic means to act.

Pakistan and Balochistan should strengthen coordination among meteorological services, disaster-management authorities, district administrations, local governments, health services, and community organisations. Warnings should specify the hazard, expected timing and location, likely impacts, recommended actions, and where to obtain help. Messages should be available in relevant local languages and through multiple channels, including SMS, radio, mosque announcements where appropriate, community volunteers, and door-to-door communication for isolated households.

Communication must be people-centred and gender-sensitive. Plans should consider people without smartphones, people with hearing or visual impairments, people who cannot read, and households without private transport. Evacuation routes and shelters must be safe and accessible. After an event, authorities should communicate clearly about water safety, health risks, relief registration, and recovery support.

Early-warning systems should be tested through drills and reviewed after every major event. Useful indicators include the proportion of at-risk households receiving warnings, the time between warning and impact, public understanding of messages, evacuation performance, and whether vulnerable groups can access assistance.

8. Policy Recommendations

A. **Develop district-level multi-hazard risk profiles.** Map flood, flash-flood, drought, heat, coastal, and landslide risks where relevant; identify exposed settlements, critical infrastructure, and vulnerable groups. Update profiles at regular intervals.

B. **Fund local implementation, not only policy development.** Allocate predictable budgets to provincial and district authorities, with clear responsibilities, implementation timelines, and public reporting.

C. **Integrate climate risk into land-use and infrastructure decisions.** Require climate and disaster-risk screening for major public projects, enforce safer construction, protect natural drainage routes, and maintain existing infrastructure.

D. **Strengthen last-mile early warning.** Connect forecasts to clear protective actions, multilingual communication, community volunteers, accessible shelters, and evacuation support.

E. **Make preparedness inclusive.** Include women, children, older people, people with disabilities, remote communities, and livelihood groups in risk assessments and response planning.

F. **Protect livelihoods and essential services.** Expand drought preparedness, water conservation, climate-resilient agriculture, safe drinking-water planning, heat-health measures, and continuity arrangements for schools and clinics.

G. **Improve data sharing and applied research.** Create interoperable datasets and partnerships among universities, government departments, and local organisations. Publish non-sensitive risk information in usable formats.

H. **Use technology responsibly.** Pilot GIS, remote sensing, and AI/ML tools only where data quality, technical capacity, transparency, maintenance, and community access can be assured.

I. **Monitor results and learn after disasters.** Track warning reach, infrastructure resilience, recovery time, budget delivery, and impacts on vulnerable groups. Conduct independent reviews and incorporate lessons into revised plans.

J. **Coordinate national, provincial, and local policy.** Align disaster-risk reduction with Pakistan's National Climate Change Policy, National Adaptation Plan, and relevant disaster-management frameworks, while adapting actions to local conditions.

9. Conclusion

Climate change is a key driver of disaster risk because it changes important climate hazards and places additional pressure on ecosystems, infrastructure, health, and

livelihoods. Yet climate change alone does not explain why a hazard becomes a disaster. Exposure, poverty, land-use decisions, building quality, public services, governance, and preparedness strongly shape the final outcome. Pakistan's experience, including the devastating 2022 floods, demonstrates the human and economic consequences of climate-related shocks. Balochistan's combination of water stress, drought, extreme heat, flash-flood risk, remote settlements, and coastal exposure makes locally tailored planning especially important.

The central policy lesson is to shift from reactive relief towards prevention, preparedness, and resilient recovery. Science-based risk mapping must be combined with community knowledge, inclusive early-warning systems, reliable public infrastructure, livelihood protection, and accountable institutions. National policies provide an important foundation, but success depends on implementation at provincial and district levels, adequate funding, and measurable results. A coordinated approach can reduce avoidable losses and strengthen the ability of communities to adapt to a changing climate.

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PARTICIPANT RESEARCH PAPER

Multi-Hazard Exposure, Infrastructure Damage, and Repair Burden in Baltistan's Hydropower Sector, Pakistan

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Abstract

Hydropower infrastructure in glacier-fed mountain regions is exposed to interacting hydrometeorological, geomorphic, cryospheric, and seismic hazards, yet plant-level evidence linking these hazards to documented infrastructure disruption remains limited. We compiled a field-verified, asset-level dataset for 46 hydropower stations in Baltistan, northern Pakistan, combining administrative repair or disruption records, inflation-adjusted repair expenditure, and GIS-derived relative hazard-conditioning indicators for 2010–2019 and 2024–2025. The archive contained 150 repair or disruption records, and 25 of the 46 stations experienced at least one recorded disruption event during 2010–2019. Flash floods were the most frequently assigned hazard category, followed by landslides, heavy snowfall, rockfall, earthquakes, and glacial lake outburst floods. Documented damage and repair expenditure were concentrated in power-generation units, headworks, transformers, and penstocks. Installed capacity increased from 17.18 MW in 2009 to 65.319 MW in 2025. Skardu contained more than half of the regional installed capacity despite having a lower relative hazard-conditioning score than Shigar, which recorded the largest raw disruption burden and the highest relative hazard-conditioning score. This mismatch shows that recent capacity expansion has increased the amount of infrastructure potentially exposed to mountain hazards, highlighting the need to integrate hazard screening into future investment and upgrading decisions.

Keywords: hydropower; multi-hazard exposure; infrastructure damage; repair burden; glacier-fed catchments; Karakoram; Baltistan

Introduction

Hydropower is an important source of low-carbon electricity because of its technological maturity, high water-to-wire conversion efficiency, long operational life, and comparatively low operating costs [1,2]. Its performance and reliability, however, are particularly sensitive in glacier-fed mountain regions, where water availability is strongly influenced by seasonal snowmelt and glacier melt and where infrastructure is located within steep, geomorphically active terrain. Across High Mountain Asia, warming, changing precipitation regimes, glacier mass loss, snow-cover variability, and hydroclimatic extremes are altering runoff timing, sediment transport, and slope stability. These changes interact with existing topographic and geological conditions and may contribute to compound and cascading processes involving flash floods, debris flows, landslides, and glacial lake outburst floods (GLOFs)[3-8].

Within Pakistan, Baltistan Division lies in the glacierized headwaters of the Upper Indus Basin and has substantial potential for hydropower development. This potential coexists with steep relief, confined valleys, unstable slopes, sediment-rich channels, and cryosphere-influenced hydrology. Events such as the 2010 Attabad landslide and the 2022 Shisper–Hassanabad GLOF demonstrate that high-mountain hazards can affect hydropower-relevant infrastructure both directly and indirectly through damage to roads, bridges, transmission systems, and other services required for continued operation[9,10].

Existing research relevant to high-mountain hydropower vulnerability can be grouped into four broad strands. First, cryospheric and hydrological studies have quantified glacier change, snowmelt and glacier-melt contributions, and runoff seasonality across High Mountain Asia and the Upper Indus Basin[3,11]. These studies establish the regional importance of cryospheric water storage and seasonal runoff but do not directly quantify infrastructure disruption or repair burden. Second, hazard-focused research has examined GLOFs, landslides, debris flows, flash floods, and compound or cascading processes in high-mountain environments[4-6,8,12], primarily at event, catchment, or regional scales rather than through systematic records for individual hydropower assets. Third, regional GIS and remote-sensing studies have assessed flood susceptibility and the spatial interaction of hazard, exposure, and vulnerability in Pakistan and neighbouring regions[13-15]. These assessments identify areas of relative susceptibility or risk but do not

show which hydropower components were damaged or the repair expenditure associated with documented disruption. Fourth, energy-system studies have examined decentralized and hybrid electricity options in Gilgit-Baltistan, including the potential role of hydropower in improving electricity access in remote communities[16] , but have generally not incorporated hazard histories or component-level damage records. Together, these research strands reveal an important evidence gap. Regional susceptibility maps and basin-scale hydrological assessments indicate where potentially hazardous conditions may occur, but they do not identify how frequently individual hydropower stations are disrupted, which civil and electro-mechanical components are affected, or what repair burden results. This gap is particularly important in Baltistan, where intakes, headworks, channels, penstocks, powerhouses, access roads, bridges, transformers, and transmission lines are concentrated within narrow glacier-fed valleys. A single event may therefore affect several interconnected components and interrupt both plant operation and access for inspection and repair.

This study addresses this gap by linking 150 administrative repair or disruption records with 46 individual hydropower stations and their local environmental and infrastructure characteristics. Structured field verification was used to cross-check administrative records against site conditions and professional accounts and to resolve discrepancies where the available documentation was incomplete or ambiguous. Field information was used for verification and quality control rather than to generate an independent set of disruption records. The study therefore provides a rare field-verified, asset-level evidence base for Baltistan linking documented mountain hazards with affected hydropower components, inflation-adjusted repair expenditure, installed capacity, and relative hazard-conditioning indicators.

The study addresses three questions: (1) How do documented disruption frequency and repair burden differ among hazard categories? (2) Which civil and electro-mechanical components account for the largest shares of documented damage and repair expenditure? and (3) How are disruption burden, infrastructure concentration, and relative hazard conditioning distributed among districts and individual stations? Throughout the analysis, three conceptually distinct elements are considered: physical hazard conditioning, referring to the environmental setting; infrastructure exposure,

represented by the location and installed capacity of hydropower assets; and observed consequences, represented by documented repair or disruption records and repair expenditure. The GIS-derived scores are interpreted as relative hazard-conditioning indicators rather than as absolute probabilities of failure or estimates of expected annual loss.

Study Area

The study area comprises the districts of Skardu, Shigar, Ghanche, and Kharmang in Baltistan Division, Gilgit-Baltistan, northern Pakistan (Fig. 1). Baltistan lies within the glacier-fed headwaters of the Upper Indus Basin in the central Karakoram, part of the wider Hindu Kush–Karakoram–Himalaya mountain system. The region is characterised by steep topography, deeply incised glacial valleys, and pronounced elevation gradients that influence hydrological processes, accessibility, and infrastructure siting. Hydropower facilities are concentrated along narrow river corridors and tributary valleys, where active channels, unstable slopes, and limited valley-floor space increase the potential for infrastructure disruption[17,18]. These conditions underscore the need for systematic assessment of the environmental and hazard-conditioning factors surrounding hydropower assets. Baltistan has a cold-arid to semi-arid high-mountain climate with marked spatial variability caused by elevation and orographic effects. Precipitation is comparatively low in the main valleys but increases substantially at higher elevations. Winter and spring precipitation associated with western disturbances contributes much of the high-altitude snow accumulation, while warm-season precipitation provides additional moisture. Regional runoff is strongly seasonal and reflects the combined influence of snow accumulation, seasonal snowmelt, glacier melt, and episodic rainfall[17,18]. This seasonality affects hydropower operation throughout the year, as reflected in the observed contrast between winter and summer operating output.

The broader regional hazard environment includes flash floods, debris flows, landslides, rockfall, heavy snowfall, avalanches, earthquakes, and glacial lake outburst floods (GLOFs). These processes arise through different hydrometeorological, cryospheric, geomorphic, and geophysical pathways and should not be attributed uniformly to a single driver such as climate change. Instead, they are treated as interacting hazards within a climate-sensitive high-mountain environment. Although debris flows and avalanches

occur in Baltistan, they were not coded as independent hazard categories in the administrative repair or disruption database used in this study. The database contained six categories: flash flood, landslide, heavy snowfall, rockfall, earthquake, and GLOF. Debris-flow impacts were generally represented within flash-flood or landslide records according to the dominant process documented in the source records. Avalanche-related impacts could not be identified independently from the available records and were therefore not analysed as a separate category. This hazard-prone setting supports a substantial and expanding hydropower network. The analysed inventory comprises 46 operational hydropower plants with a combined installed capacity of 65.319 MW: 16 plants in Skardu, 12 in Ghanche, 11 in Kharmang, and 7 in Shigar. Skardu contains the largest share of installed capacity, followed by Ghanche, Kharmang, and Shigar. As shown later, this distribution does not correspond directly to the districts' relative hazard-conditioning scores. Plant locations extend approximately from 34.21 to 35.87° N and from 75.00 to 76.60° E. Plant names, district affiliations, and installed capacities are provided in Supplementary Table S1.

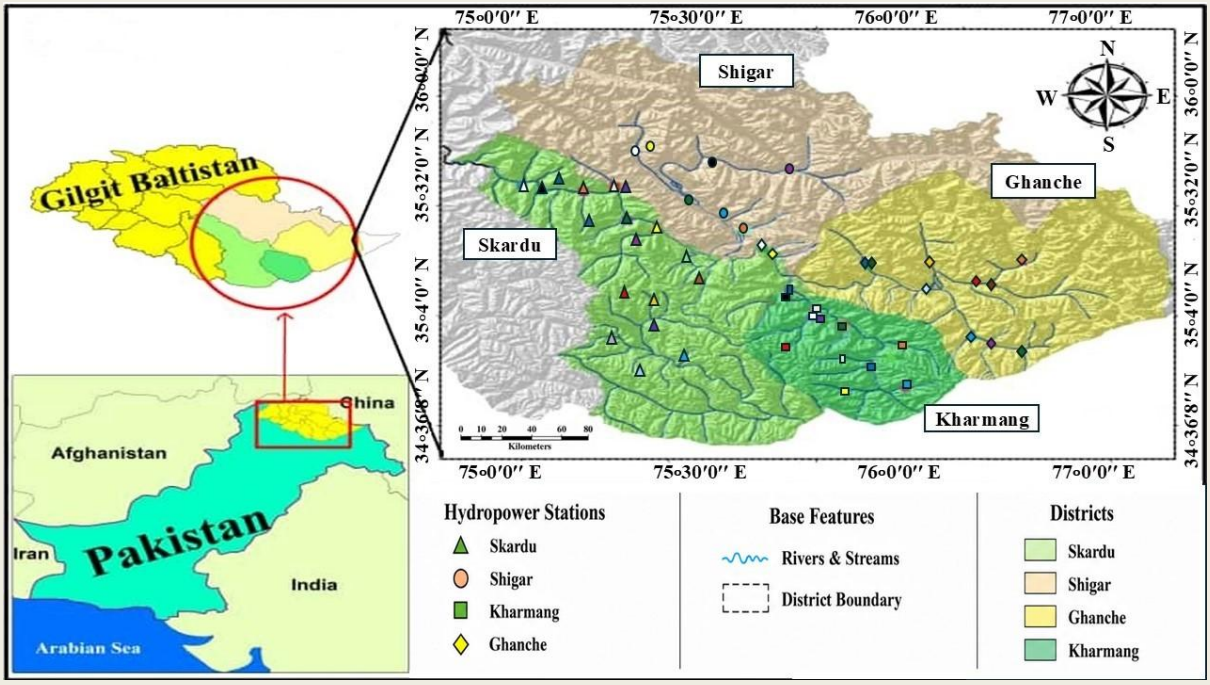


Fig 1. Location of the study area and distribution of the analysed hydropower stations in Baltistan, northern Pakistan.

Data and methods

Study design and analytical framework

This study integrates four evidence streams: plant-level administrative records, field verification, geospatial hazard-conditioning datasets, and cryosphere/generation data into a single asset-level assessment. The analysis proceeds in four linked stages. First, administrative damage and disruption records are compiled and validated through field verification. Second, these validated records are linked in a GIS environment to terrain, glacier, snow-cover, hydrographic, geological, and land-cover layers to characterize each station's local hazard-conditioning environment. Third, damage records are classified by hazard type and affected component, and a composite relative hazard-conditioning index is derived for each station. Fourth, K-means clustering combines repair burden, installed capacity, location, and hazard-conditioning into station groupings that summarize where disruption, capacity, and exposure coincide or diverge. A final, complementary analysis of snow-cover and seasonal generation data situates these findings within the region's hydrological seasonality. Throughout the study, we distinguish three conceptually separate elements: physical hazard conditioning, referring to the environmental setting; infrastructure exposure, represented by the location and installed capacity of hydropower assets; and observed consequences, represented by documented repair or disruption records and repair expenditure. The GIS-derived scores are interpreted as relative hazard-conditioning indicators rather than as absolute probabilities of failure or estimates of expected annual loss.

Hydropower inventory and damage records

Hydropower inventory and administrative damage records were obtained from the Water and Power Department of Gilgit-Baltistan (WPDGB)[19]. The inventory comprised 46 operational small- and medium-scale hydropower plants across Skardu, Shigar, Ghanche, and Kharmang, with a combined installed capacity of 65.319 MW. For each plant, records included installed capacity, location, documented repair or disruption entries, reported repair expenditure, outage information where available, and observed winter and summer operating output. The damage archive covers 2010–2019 and 2024–2025, the only periods with complete and internally comparable plant-level records; 2020–2023 was excluded owing to incomplete or inconsistent documentation across plants. The analytical unit is a documented repair or disruption record, which does not necessarily correspond

to an independent hazard event. Each record was coded by station, period, district, hazard category, affected component, repair expenditure, and outage duration where available. Because the number of operating plants increased over the study period, raw disruption counts are used to describe documented burden and spatial contrasts, not to infer temporal trends in hazard frequency.

Field verification and quality control

Field verification was conducted between 23 March and 30 April 2023 to verify the administrative repair archive and improve data quality. Field verification was undertaken at 26 hydropower stations distributed across Baltistan. Information was collected from 25 respondents, including hydropower engineers, plant operators, maintenance personnel, and technical staff responsible for the operation and maintenance of hydropower stations. Structured questionnaires and semi-structured interviews were used to verify the reported hazard category, affected infrastructure component, outage duration, repair information, and likely failure mechanism recorded in the administrative database. Field responses were used exclusively for verification and quality control, rather than as an independent statistical dataset. Their primary purpose was to validate administrative records, resolve inconsistencies among departmental files, maintenance documents, and operational accounts, and confirm the spatial location and characteristics of documented disruption events. Where discrepancies occurred between information sources, official departmental maintenance records were treated as the primary evidence, while field observations and interview responses were used to clarify event details and establish the most reliable record classification. Records that could not be confidently reconciled through documentary evidence and field verification were excluded from subsequent analyses. Interviews and questionnaires were limited to professional information related to infrastructure damage, hazard occurrence, and hydropower operation. No sensitive personal information was collected, and informed consent was obtained from all participants before the interviews. Formal ethical approval was not required under the research requirements of the University of Baltistan, Skardu, Pakistan.

Spatial datasets and preprocessing

With a validated damage-record archive established, each record was linked in a GIS environment to terrain, glacier, snow-cover, hydrographic, geological, soil, land-cover,

active-fault, and glacial-lake datasets. Station- and catchment-level variables included elevation, slope, local relief, upstream catchment area, distance to river channels, distance to glaciers, degree of glaciation, and snow-cover indicators. Degree of glaciation was calculated as the proportion of glacier-covered area within each station's upstream catchment. Elevation, slope, local relief, and upstream catchment area were derived from ASTER GDEM version 2. Glacier extent and glacier-proximity indicators were obtained from the Randolph Glacier Inventory version 6.0[20] , and snow-cover information from the MODIS/Terra Snow Cover 8-Day L3 Global 500 m product (MOD10A2 version 6.1)[21]. Additional hazard-conditioning layers comprised geology from the Global Lithological Map database[22] , soil from the Harmonized World Soil Database[23], land cover from the ESA Climate Change Initiative dataset, active faults from the USGS Quaternary Fault and Fold Database, river networks from HydroSHEDS, and a glacial-lake inventory. All administrative, field-verification, geospatial, cryospheric, hydrographic, and economic datasets are summarized in Supplementary Table S2. All spatial layers were projected to a common coordinate reference system, clipped to the study-area boundary, and resampled or harmonized as necessary before overlay and extraction. Hydropower-station coordinates were cross-checked against administrative boundaries, river networks, and field-verified locations.

Damage classification and repair-cost adjustment

Following spatial dataset assembly, each record was classified by hazard type and its associated cost quantified. Documented records were classified into six hazard categories: flash flood, landslide, heavy snowfall, rockfall, earthquake, and glacial lake outburst flood. Some disruption records involved overlapping or cascading processes and were assigned more than one hazard category; hazard-category counts are therefore non-exclusive and can exceed the total number of repair or disruption records. Infrastructure components were grouped into civil and electro-mechanical categories. Civil components comprised intake and diversion structures, headworks, channels, forebays, spillways, tailraces, penstocks, powerhouse structures, protective works, access roads, and bridges. Electro-mechanical components comprised turbines, generators, transformers, control equipment, and transmission or distribution

infrastructure. Nominal repair expenditures were converted into constant 2025 prices using the Consumer Price Index (CPI) published by the Pakistan Bureau of Statistics:

$$C_{\text{real}} = C_{\text{nominal}} \times \left(\frac{\text{CPI}_{2025}}{\text{CPI}_y}\right) \quad (1)$$

where C_{real} is the inflation-adjusted repair expenditure in 2025 constant prices, C_{nominal} is the original repair expenditure recorded in year *y*, CPI_{2025} is the Consumer Price Index value for the base year 2025, and CPI_y is the CPI value for year *y*. Descriptive statistics were subsequently used to summarize disruption frequency, component-wise damage distribution, repair-expenditure contributions, and district-level spatial patterns.

GIS-based multi-hazard exposure mapping

Building on the classified damage and cost data, which describe observed consequences, a GIS-based multi-criteria framework was applied to characterize the physical setting in which these consequences occurred and to map the spatial distribution of relative hazard-conditioning around hydropower assets. The selected environmental variables comprised elevation, local relief, slope, geology, soil, land cover, distance to active faults, distance to river channels, glacier proximity, and upstream glacial-lake influence.

Each conditioning layer was standardized to an ordinal scale from 1 to 10, where 1 represented the lowest and 10 the highest relative contribution to the composite score. Continuous variables were reclassified using predefined thresholds, and categorical variables were scored according to their relative association with runoff concentration, erosion, slope instability, seismic influence, or cryosphere-related exposure; reclassification thresholds and factor weights are provided in Supplementary Table S3. The composite hazard score for raster cell *x* was calculated as a weighted average:

$$H(x) = \frac{\sum_{i=1}^{n} w_i S_i(x)}{\sum_{i=1}^{n} w_i} \quad (2)$$

where $H(x)$ is the relative hazard-conditioning score for raster cell x; $S_i(x)$ is the standardized score (1–10) of the i^{th} conditioning factor at location x; w_i is the assigned weight of the i^{th} factor; and n represents the total number of conditioning factors included in the analysis. The resulting raster was classified into low, moderate, high, and very high

relative hazard-conditioning classes. Station-level scores were extracted at hydropower locations for comparison with documented disruption burden. District-level scores, derived using zonal statistics, are interpreted as broad landscape summaries rather than direct measures of asset-specific exposure.

Multivariate station grouping

Building on the station-level hazard-conditioning scores derived above, K-means clustering was used to test whether repair burden, installed capacity, location, and environmental setting jointly define distinct station groupings. Clustering was applied to 41 hydropower stations with complete and internally comparable repair-cost records for 2010–2019; five stations were excluded owing to incomplete or inconsistent repair-cost information. The 2024–2025 records were analysed separately, as recent events were not directly comparable with the longer-term cumulative disruption record. The clustering dataset comprised standardized variables representing repair burden, installed capacity, geographic location (latitude and longitude), local relief, upstream catchment characteristics, river and glacier proximity, and selected terrain-related indicators. Highly correlated or redundant variables were removed beforehand to minimize multicollinearity. All numerical variables were standardized using z-scores:

$$z = \frac{x-\mu}{\sigma} \qquad (3)$$

where z_i represents the standardized value of observation i, x_i represents the original value of observation i, μrepresents the mean value of the variable, and σrepresents the standard deviation of the variable. This is the commonly accepted equation format used in statistical analyses and machine-learning-based clustering methods such as K-means clustering.

Snow-cover context and seasonal generation analysis

To place documented hydropower disruption and capacity expansion within the region's pronounced hydrological seasonality, mapped snow-cover variability and seasonal operating output were examined. Snow-cover conditions for 2000–2025 were derived from the MODIS/Terra Snow Cover 8-Day L3 Global 500 m SIN Grid product (MOD10A2, Collection 6.1). The product represents the maximum snow extent observed during each

8-day compositing period at a spatial resolution of 500 m and is based on the Normalized Difference Snow Index.

Cloud screening followed the classification scheme of the Maximum_Snow_Extent layer and the MODIS Snow Products Collection 6.1 User Guide[24] . Pixels classified as cloud, missing data, no decision, night, lake, ocean, detector-saturated, or fill were excluded from the area calculation and were not treated as snow-free land. Only pixels classified as snow were used to calculate mapped snow-covered area. For each district and year, annual maximum mapped snow-covered area was defined as the largest valid snow-covered-area value among the available cloud-screened 8-day composites. Long-term district summaries were calculated as the mean of the annual maximum mapped snow-covered-area values over 2000–2025.

Temporal variability in annual maximum mapped snow-covered area was assessed for Skardu, Shigar, Ghanche, and Kharmang using Spearman's rank correlation to evaluate monotonic relationships with time without assuming normality. Simple linear regression was additionally used to estimate the direction and magnitude of temporal change. Trends were considered statistically significant at $p < 0.05$. Non-significant positive or negative slopes were interpreted as weak trends or interannual variability rather than established increases or decreases.

The 2025 operational dataset provided observed winter and summer hydropower operating output in megawatts. Because megawatts represent power at the time of observation rather than time-integrated energy production, these values were interpreted as seasonal operating output rather than seasonal generation totals. To compare stations and districts with different installed capacities, the output-to-installed-capacity ratio was calculated as

$$O_{s,i} = \left(\frac{P_{s,i}}{P_{\text{installed},i}} \right) \times 100 \qquad (4)$$

where $O_{s,i}$ is the output-to-installed-capacity ratio (%) for station or district i during season s, $P_{s,i}$ is the observed seasonal operating output (MW), and $P_{\text{installed},i}$ is the corresponding installed capacity (MW). For district-level calculations, the observed operating output and installed capacity of all stations within each district were summed before calculating the

ratio. This measure is not a conventional capacity factor, which would require time-integrated energy-generation data over a defined period.

Results

This section presents the documented hazard-related disruption record and repair burden across the Baltistan hydropower system. It examines disruption frequency, component-level damage, hazard-specific impacts, district-level spatial patterns, multivariate station groupings, hydropower expansion, and seasonal operating performance within the regional hazard-conditioning context.

Frequency and nature of documented hazard-related disruptions

During 2010–2019, 25 of the 46 analysed hydropower stations experienced at least one documented hazard-related disruption. Across the combined analysis periods (2010–2019 and 2024–2025), the administrative archive contained 150 repair or disruption records. These records represent documented administrative entries rather than independent hazard events. Because some events involved overlapping or cascading processes, individual records could be assigned to more than one hazard category; consequently, hazard-specific totals presented in Section 4.3 are non-exclusive and may exceed 150.

Documented disruption was episodic rather than uniformly distributed through time (Table 1). The highest numbers of records occurred during 2010–2011 (21), 2015–2016 (17), and 2017–2018 (22), whereas only five records were documented during 2012–2013. The 2024–2025 archive contained 28 records, indicating a substantial documented disruption burden. However, this value should not be interpreted as a long-term increase in hazard frequency because the archive is discontinuous and the hydropower inventory expanded over time. Shigar and Skardu recorded the largest numbers of documented disruption entries, followed by Ghanche and Kharmang. Several stations experienced repeated disruptions, indicating that documented damage was concentrated at a subset of hydropower facilities rather than being uniformly distributed across the regional network (Table 1).

Table 1. Temporal distribution of documented hydropower repair or disruption records across districts in Baltistan.

Period	Total repair/disruption records	Shigar	Skardu	Ghanche	Kharmang
2010–2011	21	6	6	8	1
2011–2012	10	2	4	3	1
2012–2013	5	2	1	1	1
2013–2014	7	2	2	2	1
2014–2015	12	2	2	4	4
2015–2016	17	5	5	2	5
2016–2017	12	4	2	3	3
2017–2018	22	8	9	3	2
2018–2019	16	6	5	4	1
2024–2025	28	9	8	5	6

Note. Values represent documented repair or disruption records rather than unique damaged stations. Some stations experienced multiple disruptions, and records involving cascading processes could receive more than one hazard assignment.

Component-level damage and repair burden

Damage was concentrated in a limited number of critical hydropower components (Table 2; Fig. 2). Power-generation units accounted for the largest share of documented component-level damage (25%), followed by headworks (18%), transformers (10%), penstocks and associated structures (8%), approach roads and bridges (7%), powerhouse structures (6%), supply, spillway, and tailrace structures (5%), intake structures (4%), and support or flood-protection works (3%). Other or mixed components accounted for the remaining 14%.

The distribution of repair expenditure broadly followed the damage pattern but differed among components. Power-generation units accounted for the largest share of inflation-

adjusted repair expenditure (20%), followed by headworks (15%), transformers (12%), penstocks and associated structures (10%), approach roads and bridges (8%), powerhouse structures (8%), supply, spillway, and tailrace structures (7%), intake structures (6%), and support or flood-protection works (5%), while other or mixed components contributed 9%. These results indicate that the most frequently damaged components were not always those associated with the highest repair costs.

Table 2. Component-wise shares of documented damage events and inflation-adjusted repair expenditure.

Component	**Share of documented damage events (%)**	**Share of total repair expenditure (%)**
Power generation units	25	20
Headwork structures	18	15
Transformers	10	12
Penstocks and associated structures	8	10
Approach roads and bridges	7	8
Powerhouse structures	6	8
Supply, spillway, and tailrace structures	5	7
Intake structures	4	6
Support and flood-protection works	3	5
Other or minor components	14	9
Total	**100**	**100**

Note. Values represent percentage shares of documented component-level damage and inflation-adjusted repair expenditure. Component categories were harmonized across administrative records and field verification.

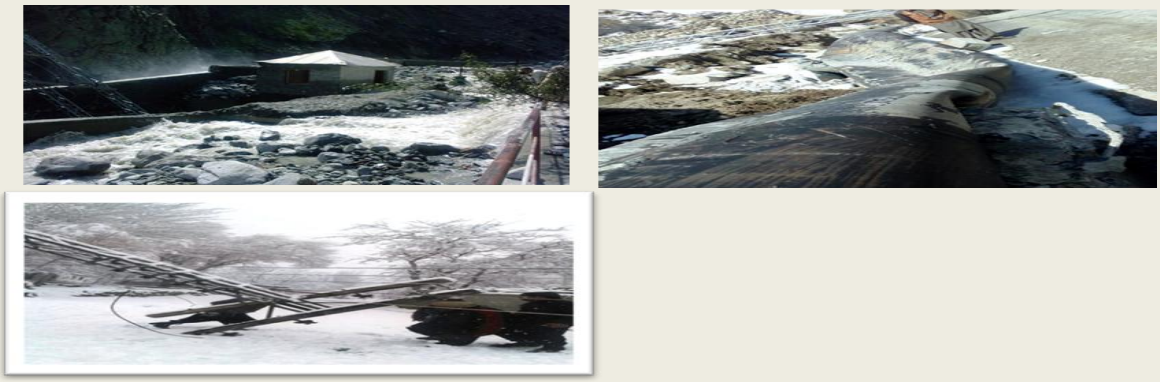


Fig 2. Representative hazard-related damage to hydropower infrastructure: (a) flash-flood damage to powerhouse structures; (b) heavy-snowfall damage to transmission and distribution lines in Shigar; and (c) rockfall damage to penstocks. Photographs by the authors.

Hazard-specific impacts

Hazard impacts differed markedly among hazard categories (Fig. 3). Flash floods were the most frequently assigned hazard, with 65 documented occurrences, accounting for 24% of total inflation-adjusted repair expenditure. Landslides were assigned to 45 occurrences and contributed 21% of repair expenditure, followed by heavy snowfall (30 occurrences; 15%), rockfall (20 occurrences; 12%), earthquakes (15 occurrences; 18%), and glacial lake outburst floods (GLOFs) (10 occurrences; 9%).

The total number of hazard assignments exceeded the 149 documented repair or disruption records because individual records involving overlapping or cascading processes could be assigned to more than one hazard category. Although flash floods and landslides accounted for most documented disruptions, earthquakes contributed a disproportionately high share of repair expenditure relative to their frequency, indicating greater damage severity per documented event.

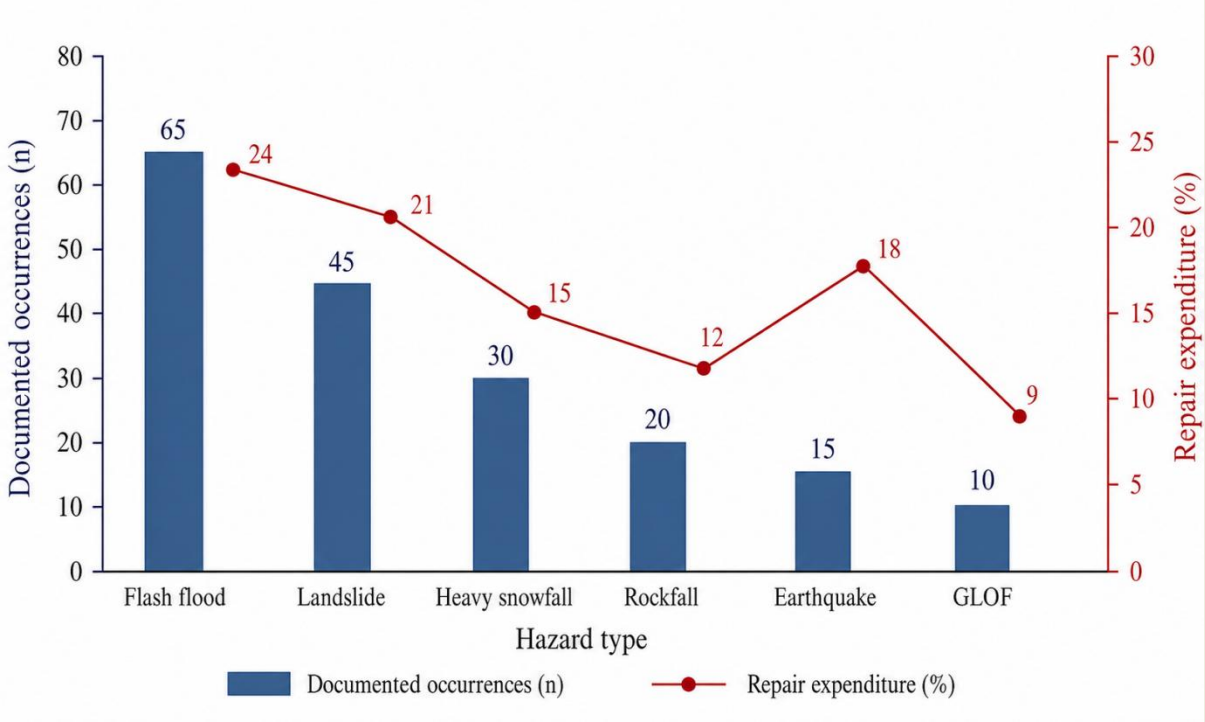


Fig 3. Number of hazard-category assignments and percentage share of inflation-adjusted repair expenditure. Hazard-category counts are non-exclusive because some repair or disruption records were assigned to more than one hazard category.

District-level contrasts in hazard burden and infrastructure concentration

District-level differences were evident in both documented disruption burden and relative hazard-conditioning (Figs. 4 and 5). Across 2010–2019 and 2024–2025, Shigar recorded the highest number of documented repair or disruption records (45), followed by Skardu (43), Ghanche (35), and Kharmang (26). Relative hazard-conditioning scores showed the same spatial pattern, with the highest value in Shigar (6.7), followed by Skardu (5.0), Ghanche (4.9), and Kharmang (2.8) (Fig. 4).

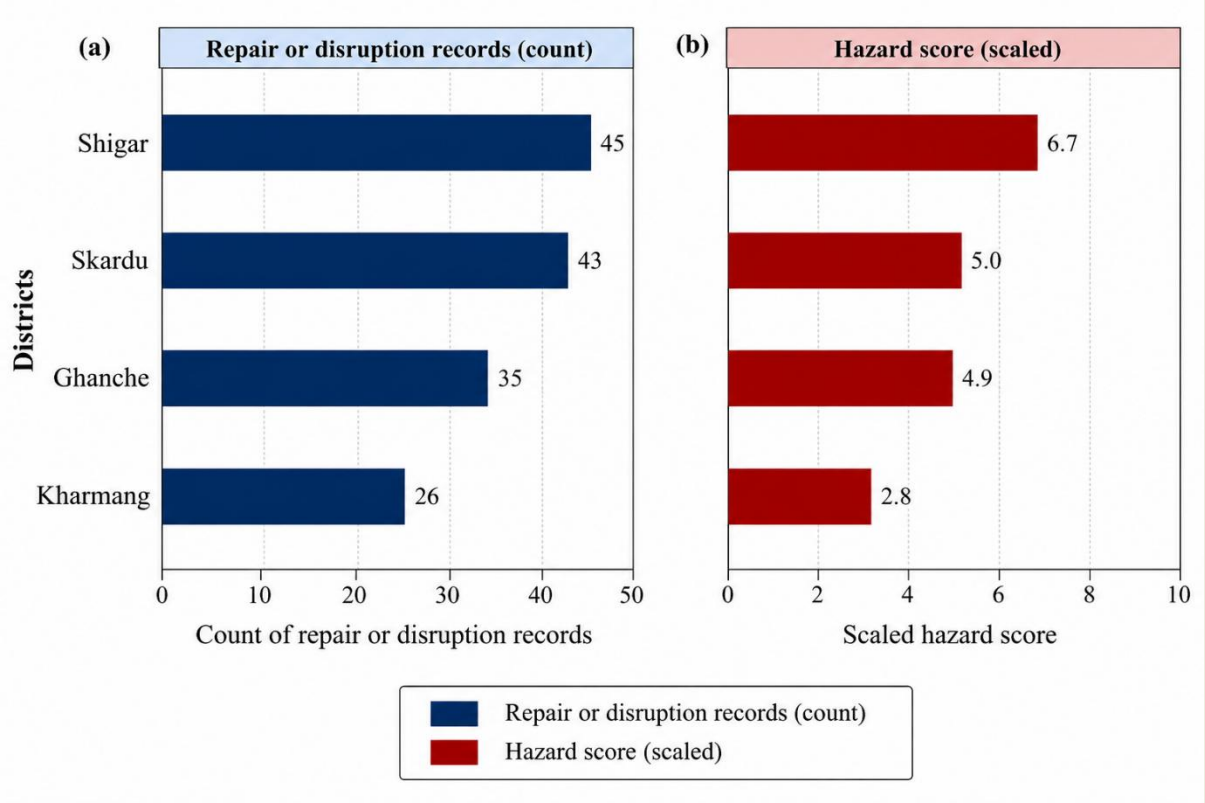


Fig 4. District-level comparison of documented hydropower repair or disruption records and relative hazard-conditioning scores in Baltistan. (a) Number of documented repair or disruption records during 2010–2019 and 2024–2025. (b) Scaled district-level relative hazard-conditioning score. Numerical values are shown at the end of each bar.

Installed hydropower capacity showed a contrasting distribution (Fig. 5). Skardu contained 50.8% of the regional installed capacity, followed by Ghanche (25.8%), Kharmang (16.1%), and Shigar (7.2%). Consequently, Shigar combined the highest documented disruption burden and relative hazard-conditioning with the smallest share of installed capacity, whereas Skardu contained the largest concentration of hydropower infrastructure despite a comparatively lower hazard-conditioning score. These results demonstrate a clear spatial mismatch between the distribution of installed hydropower capacity and documented hazard burden across Baltistan.

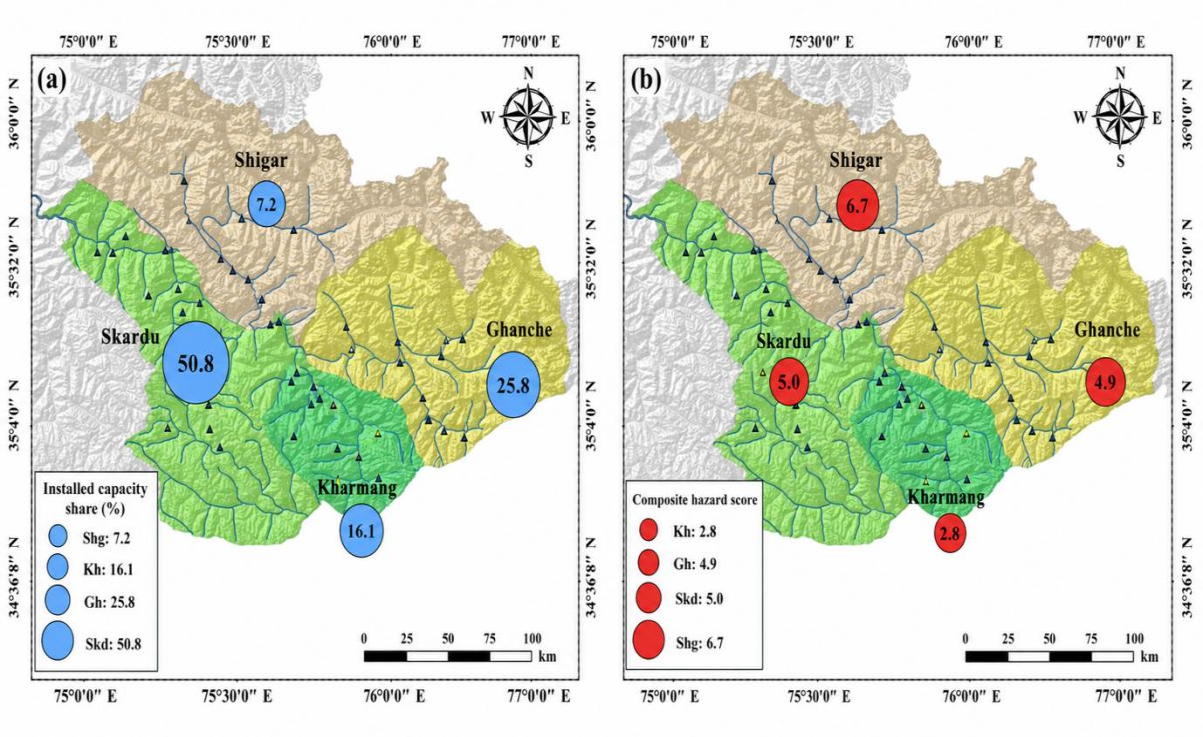


Fig 5. District-level distribution of installed hydropower capacity and relative hazard-conditioning in Baltistan. Panel (a) shows district shares of installed hydropower capacity, and panel (b) shows district-level relative hazard-conditioning scores.

Multivariate station grouping

K-means clustering was applied to 41 of the 46 hydropower stations with complete and internally comparable repair-expenditure records for 2010–2019. Five stations were excluded because their repair-expenditure information was incomplete or inconsistent. Records for 2024–2025 were analysed separately because they were not directly comparable with the longer cumulative dataset. A three-cluster solution ($\boldsymbol{k = 3}$) was selected based on the elbow method, silhouette coefficient, and interpretability of the resulting groups (Table 3; Fig. 6). The analysis integrated standardized repair expenditure, installed capacity, geographic location, and topographic and environmental variables. The resulting clusters therefore represent multivariate station profiles rather than repair-expenditure classes alone.

Cluster 0 comprised four stations and had the highest mean repair expenditure, at PKR 5,779,114, with values ranging from PKR 4,487,745 to PKR 6,935,600. These stations were distributed across Shigar, Ghanche, Kharmang, and Skardu. Cluster 1 contained 11

stations, with a mean repair expenditure of PKR 2,697,284 and a range of PKR 2,111,243–3,502,400. Cluster 2 included 26 stations, with a mean repair expenditure of PKR 2,428,790 and a range of PKR 1,502,500–4,021,527. Although the repair-expenditure ranges of Clusters 1 and 2 overlapped, the two groups differed in their combined spatial, topographic, environmental, and infrastructure characteristics. Overall, the analysis identified a small multivariate station group with comparatively high repair expenditure and two larger groups with lower, partly overlapping expenditure ranges. This pattern indicates that documented repair burden is unevenly distributed across the Baltistan hydropower network.

Table 3. Cluster-wise summary of hydropower stations based on K-means clustering of 41 stations with complete repair-cost records (2010–2019).

Cluster	Station count	Mean repair expenditure (PKR)	Minimum repair expenditure (PKR)	Maximum repair expenditure (PKR)
0	4	5,779,114	4,487,745	6,935,600
1	11	2,697,284	2,111,243	3,502,400
2	26	2,428,790	1,502,500	4,021,527
Total	**41**			

Note. Clustering was performed using standardized repair-cost, spatial, topographic, and environmental variables. The resulting clusters represent multivariate station profiles rather than repair-cost classes alone.

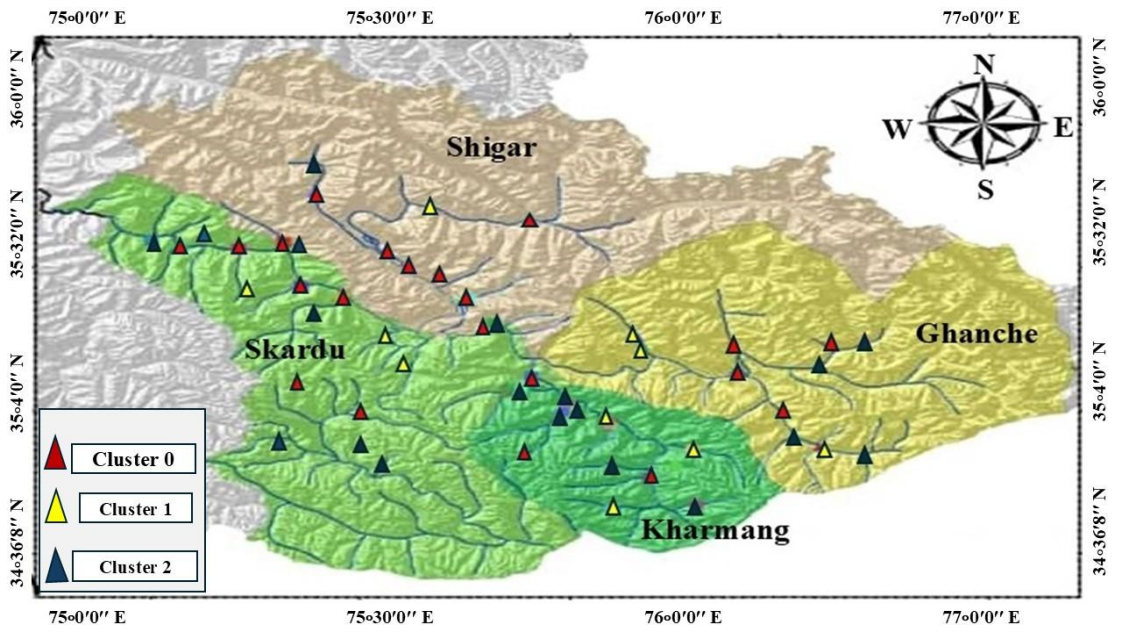


Fig 6. Spatial distribution of the three K-means station groups in Baltistan.

Expansion of installed hydropower capacity

Installed hydropower capacity in Baltistan increased substantially across the years for which comparable records were available (Fig. 7). Capacity rose from 17.18 MW in 2009 to 33.23 MW in 2019, nearly doubling over the first observation period. It increased further to 62.12 MW in 2024 and 65.319 MW in 2025. Because comparable annual records were unavailable for 2020–2023, these values represent documented observation years rather than a continuous annual time series. The expansion indicates a substantial increase in the amount of hydropower infrastructure and generation capability potentially exposed to mountain hazards.

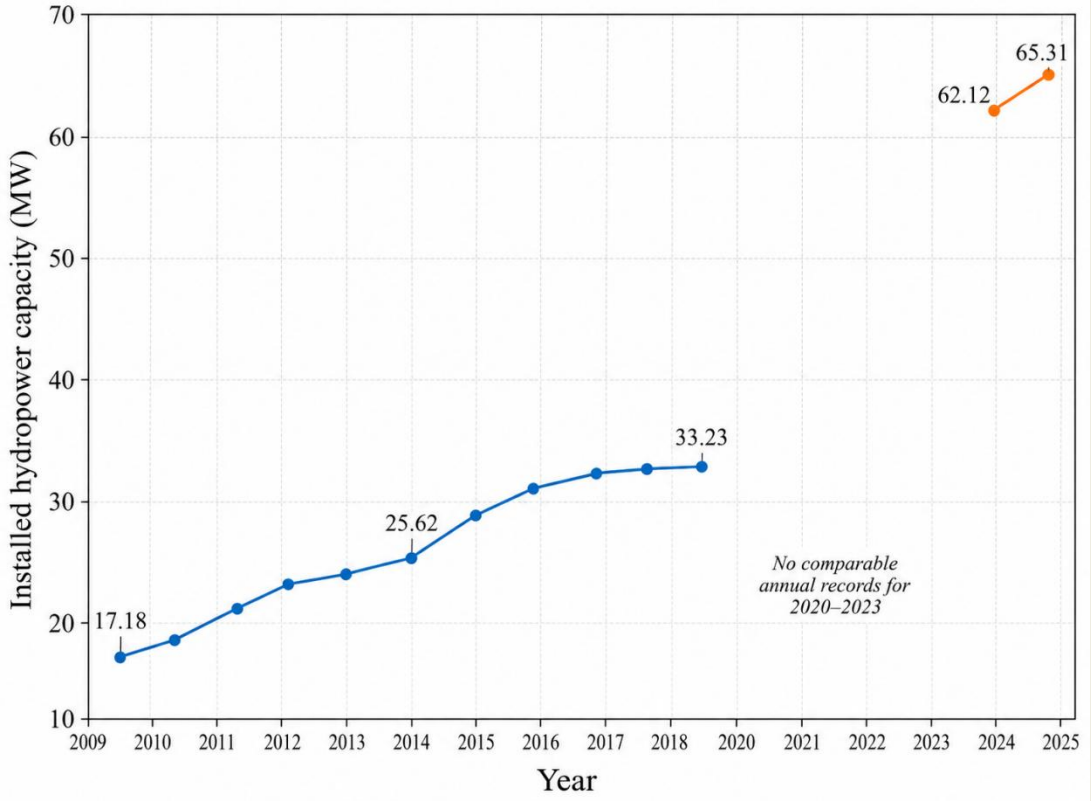


Fig 7. Installed hydropower capacity in Baltistan during the observed years (2009–2019 and 2024–2025). No comparable records were available for 2020–2023.

Installed capacity and seasonal operating output

The 2025 operational inventory included 46 small- and medium-scale hydropower stations with a combined installed capacity of 65.319 MW. Skardu contained the largest installed capacity, with 33.200 MW, followed by Ghanche with 16.900 MW, Kharmang with 10.524 MW, and Shigar with 4.695 MW (Tables 4 and 5).

Observed operating output differed substantially between winter and summer. Across the Baltistan hydropower system, winter output totalled 36.46 MW, corresponding to 55.8% of installed capacity, whereas summer output reached 51.24 MW, corresponding to 78.4%. At the district scale, Shigar recorded the highest observed output ratio in both winter and summer, while substantial station-level variability occurred within all four districts.

Detailed station-level values are presented in Table 4, and district-level totals and output ratios are summarized in Table 5. These data describe observed seasonal operating

output in 2025 and should not be interpreted as electricity generation, conventional capacity factors, or direct hazard-related energy losses.

Table 4. Station-level characteristics and clustering results for the hydropower stations included in the analysis.

S#	Power station	Installed capacity (MW)	Observed operating output (MW)	
			Winter	Summer
A. District Skardu				
1	WAPDA Ph-1	4.800	3.00	3.00
2	WAPDA Ph-2	8.600	6.00	6.00
3	WAPDA Ph-3	2.400	1.20	2.00
4	WAPDA Ph-4	1.400	0.00	0.00
5	Kachura-II	0.200	0.00	0.10
6	Kachura-III	3.000	1.40	2.80
7	Kachura-IV	2.000	0.90	1.80
8	Basho-II	0.500	0.24	0.45
9	Basho-III	0.500	0.24	0.45
10	Mendi	2.000	1.40	1.90
11	Tormik	0.800	0.50	0.75
12	Tallu	2.000	1.40	1.90
13	Nar	0.500	0.40	0.45
14	Sermik Ph-II	1.000	0.65	0.90
15	Sermik Ph-III	1.500	0.95	1.35

S#	Power station	Installed capacity (MW)	Observed operating output (MW)	
			Winter	**Summer**
16	Sermik Ph-IV	2.000	0.60	1.60
	Total	**33.200**	**18.88**	**25.45**
B. District Ghanche				
1	Keris Ph-II	0.500	0.40	0.25
2	Bordass	2.000	0.80	1.80
3	Thalley Ph-II	2.000	1.40	1.90
4	Thalley Ph-III	2.000	0.85	1.60
5	Balaygond Ph-I	1.200	0.65	0.90
6	Balaygond Ph-II	2.000	0.90	1.40
7	Dumsum Ph-I	1.200	0.54	0.85
8	Dumsum Ph-II	1.500	0.75	1.15
9	Kondus	2.000	1.60	1.90
10	Pion	1.000	0.35	0.85
11	Hassanabad	0.700	0.35	0.65
12	Kharkoo	0.800	0.24	0.56
	Total	**16.900**	**8.75**	**14.15**
C. District Shigar				
1	Shigar Ph-II	0.800	0.50	0.70
2	Shigar Ph-III	2.000	1.40	1.80

S#	Power station	Installed capacity (MW)	Observed operating output (MW)	
			Winter	**Summer**
3	Hashupi Ph-II	0.500	0.20	0.40
4	Hoo Shigar	0.580	0.30	0.48
5	Niaslo Shigar	0.250	0.14	0.21
6	Kayo Shigar	0.245	0.13	0.19
7	Testay Shigar	0.320	0.23	0.30
	Total	**4.695**	**2.90**	**4.08**
D. District Kharmang				
1	Mehdiabad Ph-II	1.300	1.00	1.10
2	Shamayul	1.000	0.68	0.75
3	Tolti Ph-II	1.000	0.70	0.85
4	Tolti Ph-III	1.500	0.85	1.20
5	Manthokha Ph-I	0.224	0.05	0.10
6	Manthokha Ph-II	1.500	0.80	1.20
7	Shiriting	0.500	0.12	0.25
8	Gabis	0.500	0.05	0.10
9	Hargosil	1.000	0.55	0.68
10	Kindrik	1.000	0.60	0.75
11	Ganokh	1.000	0.53	0.58
	Total	**10.524**	**5.93**	**7.56**

S#	Power station	Installed capacity (MW)	Observed operating output (MW)	
			Winter	Summer
	Grand total	**65.319**	**36.46**	**51.24**

Note. Values represent installed capacity and observed winter and summer generation for operational small- and medium-scale hydropower stations. District totals are shown at the end of each district section.

Table 5. District-level installed capacity, observed seasonal generation, and capacity utilization in the Baltistan hydropower system in 2025. Capacity utilization was calculated as observed seasonal generation divided by installed capacity. These values describe seasonal operational performance and do not represent direct disaster-related energy losses.

District	Installed capacity (MW)	Winter operating output (MW)	Summer operating output (MW)	Winter utilization (%)	Summer utilization (%)
Skardu	33.200	18.88	25.45	56.9	76.7
Ghanche	16.900	8.75	14.15	51.8	83.7
Shigar	4.695	2.90	4.08	61.8	86.9
Kharmang	10.524	5.93	7.56	56.3	71.8
Total	**65.319**	**36.46**	**51.24**	**55.8**	**78.4**

Note. Capacity utilization was calculated as observed seasonal generation divided by installed capacity. These values describe seasonal operational performance and do not represent direct disaster-related energy losses.

District-level hazard-conditioning and exposure profile

District-level indicators were compared to describe broad differences in the

environmental and infrastructure settings of hydropower development across Baltistan. The indicators included mean installed capacity, mean repair expenditure, hydrological conditions, precipitation, terrain relief, stream-power characteristics, and snow-cover conditions. Because these variables differ in units and physical meaning, they were min–max normalized across the four districts for visual comparison in Fig. 8. The resulting profiles represent relative district-level contrasts and should not be interpreted as absolute hazard probabilities or risk estimates.

Shigar showed the highest relative values for mean repair expenditure, flow, precipitation, stream power, and the snow-cover indicator. Skardu had the highest mean installed capacity and also showed comparatively high hydrological and precipitation values. Ghanche had the highest terrain-relief value, whereas Kharmang generally showed lower relative values for the hydrological, precipitation, repair-expenditure, and snow-related indicators.

These profiles provide broad environmental and infrastructure context for the plant-level disruption and clustering results. Detailed definitions, units, source data, and unnormalized district-level values are provided in Supplementary Table S5.

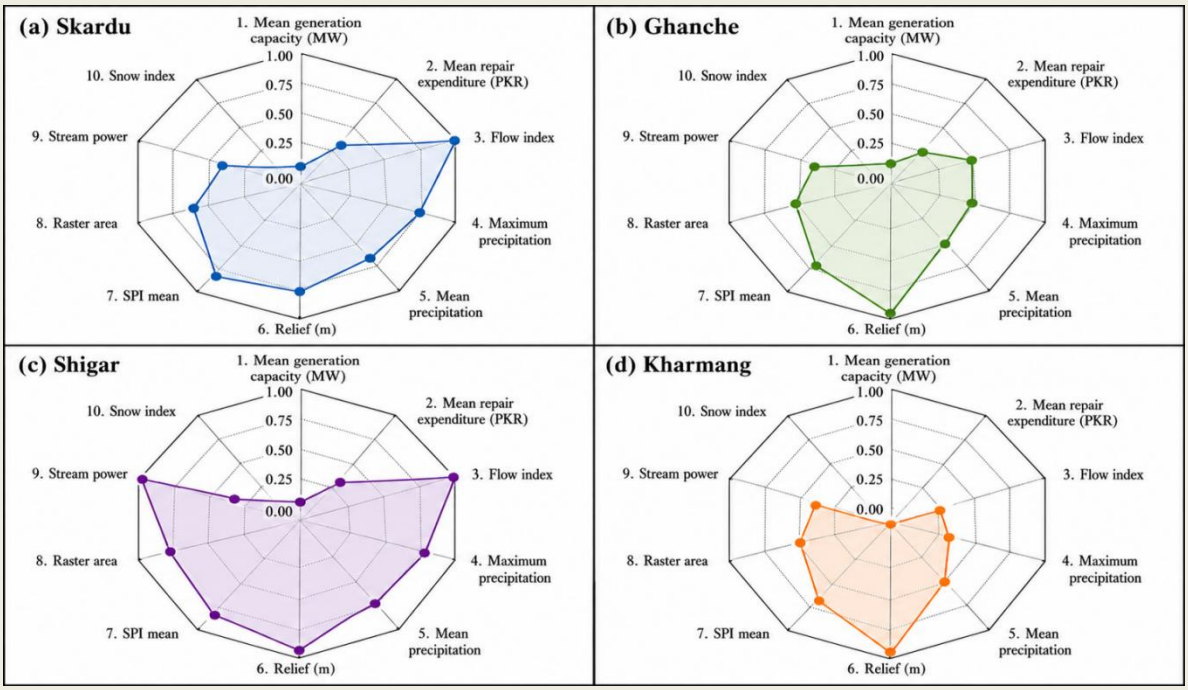


Fig 8. Normalized district-level environmental and infrastructure profiles for Skardu, Shigar, Ghanche, and Kharmang.

Radar axes show relative magnitudes of infrastructure, repair-burden, hydrological, precipitation, terrain, stream-power, and snow-cover indicators after min–max normalization across the four districts. Higher values indicate greater relative magnitude within this four-district comparison and do not represent absolute hazard probabilities or risk estimates.

Snow-cover variability across districts

Snow-cover observations for 2000–2025 showed persistent inter-district differences across Baltistan (Fig. 9). Shigar recorded the largest mean annual snow-covered area, approximately 7,805 km², followed by Skardu with approximately 6,199 km² and Ghanche with approximately 5,905 km². Kharmang recorded the smallest mean annual snow-covered area, approximately 2,330 km². Despite year-to-year variability, the relative ranking remained broadly stable throughout the study period. The maximum mapped snow-covered area occurred in 2017 in all four districts, reaching 8,069 km² in Shigar, 6,450 km² in Skardu, 6,208 km² in Ghanche, and 2,493 km² in Kharmang. Linear trend estimates indicated weak to moderate increases over 2000–2025, with the strongest increases in Shigar and Ghanche; given the substantial interannual variability in the record, these trends are interpreted cautiously. The snow-cover results provide broad cryospheric context for seasonal hydropower operation. However, total snow-covered area should not be interpreted directly as snowmelt contribution because district size, elevation distribution, snow water equivalent, melt timing, and runoff connectivity also influence hydrological response.

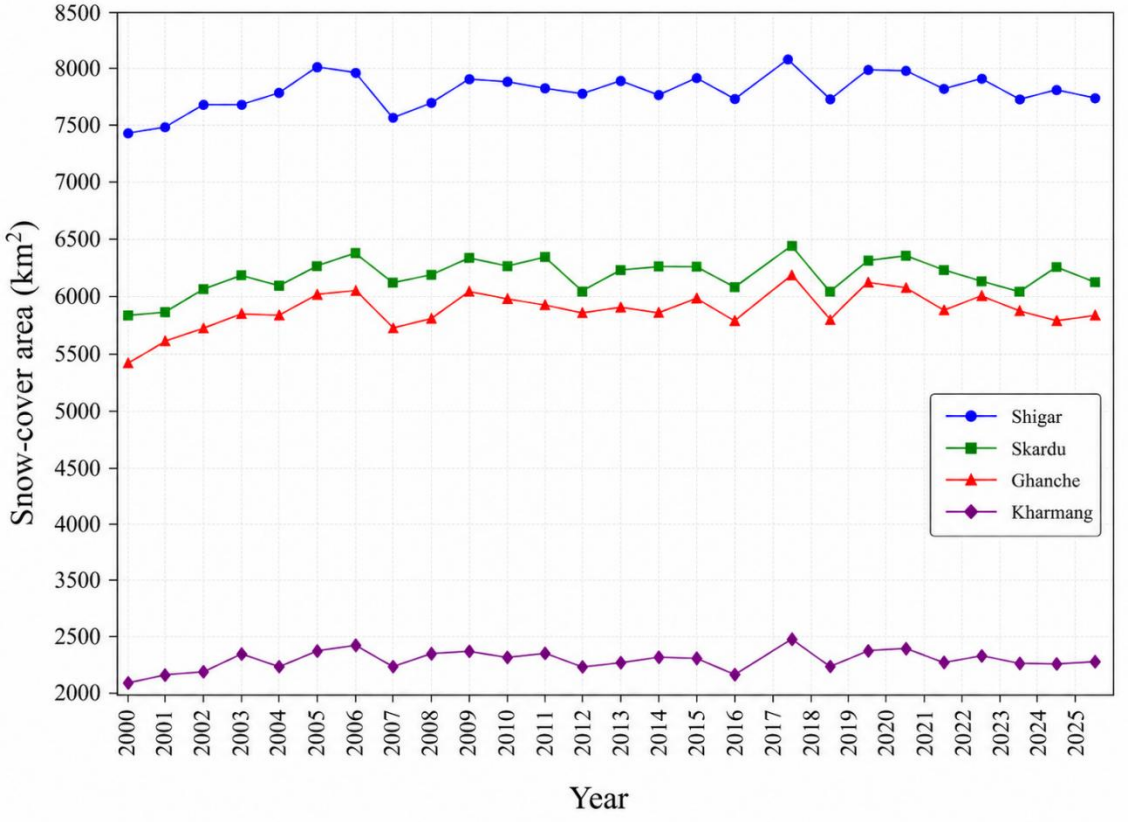


Fig 9. Annual maximum mapped snow-covered area in Shigar, Skardu, Ghanche, and Kharmang during 2000–2025, derived from MODIS/Terra snow-cover observations. The figure shows persistent spatial contrasts and interannual variability among the four districts.

Discussion

Multi-hazard disruption in an expanding high-mountain hydropower system

This study integrates plant-level repair or disruption records, inflation-adjusted repair expenditure, infrastructure characteristics, and GIS-based hazard-conditioning information for 46 hydropower stations in Baltistan. The archive contained 150 documented repair or disruption records during 2010–2019 and 2024–2025, while 25 of the 46 operational stations experienced at least one hazard-related disruption during the systematic 2010–2019 period. Flash floods, landslides, heavy snowfall, rockfall, earthquakes, and glacial lake outburst floods (GLOFs) affected different parts of the hydropower system. Infrastructure performance in Baltistan therefore reflects multiple interacting hazards rather than a single dominant process. Documented impacts arise from the coincidence of hazard occurrence, infrastructure exposure, and local

vulnerability, rather than from hazard magnitude alone. This interpretation is consistent with regional evidence showing that flood risk varies spatially according to combined patterns of hazard, exposure, and vulnerability[25]. In Baltistan, hydropower components are inherently exposed because they are located along active channels, steep slopes, sediment pathways, and snow- and glacier-influenced catchments. The temporal distribution of documented disruption was episodic rather than steadily increasing, with relatively high numbers of records during 2010–2011, 2017–2018, and 2024–2025. However, the discontinuous archive, the expansion of the operational station inventory, and the absence of comparable records for 2020–2023 prevent interpretation of this pattern as a long-term increase in hazard frequency. The recent records instead demonstrate a continuing disruption burden. A more robust change is the expansion of infrastructure exposure. Installed capacity increased from 17.18 MW in 2009 to 65.319 MW in 2025. Consequently, nearly four times as much generation capacity is now situated within active valleys and steep mountain terrain, irrespective of any change in hazard frequency. This distinction between changing hazard occurrence and increasing infrastructure exposure is important across High Mountain Asia, where hydropower development is expanding in environments influenced by glacier change, slope instability, sediment mobilization, and cascading geomorphic processes[5].

Dominance of flood- and slope-related disruption

Flash floods were the most frequently assigned hazard category, followed by landslides. This pattern is consistent with the location of run-of-river facilities along active channels, tributary junctions, alluvial fans, and confined valley floors. In these settings, disruption can result from high discharge, bank erosion, channel migration, sediment deposition, debris impact, scour, and blockage of intake and conveyance structures.

Short-duration intense rainfall in steep Himalayan and Karakoram terrain can generate rapid runoff and initiate linked flood, debris-flow, and landslide processes. Orographic effects, steep slopes, limited infiltration, and abundant unconsolidated sediment can transform localized rainfall into high-energy flows with substantial downstream consequences[26]. In Baltistan, these processes may also interact with seasonal snowmelt, glacier melt, and sediment stored within tributary channels. However, because the repair records do not identify the hydrometeorological trigger of every flash-flood event,

individual disruptions cannot be attributed specifically to rainfall, snowmelt, or glacier melt. Many records involved overlapping or sequential processes. A landslide may obstruct a channel, impound or redirect water, and subsequently generate downstream flooding and sediment pulses. A GLOF may mobilize large sediment volumes, destabilize riverbanks, damage access routes, and affect hydropower components far downstream from the source lake. Heavy snowfall may damage transmission infrastructure while simultaneously restricting access for inspection and repair. These interactions are consistent with studies showing that high-mountain hazards commonly develop as compound or cascading process chains rather than as isolated events [4-6,8]. Future disruption inventories should distinguish the initiating trigger, secondary processes, immediate damage mechanism, affected component, and final operational consequence. Such information would allow engineering and operational responses to target specific failure pathways rather than broad hazard categories.

Hazard frequency, repair burden, and component-specific vulnerability

Hazard frequency and repair expenditure represent different dimensions of infrastructure impact. Flash floods and landslides were assigned most frequently, whereas earthquakes and GLOFs accounted for relatively large expenditure shares despite fewer assignments. Recurrent hazards may therefore generate cumulative maintenance pressure, while less frequent events can cause disproportionately severe and costly damage. This distinction means that disruption frequency alone is insufficient for prioritizing resilience investment. A frequently affected station may experience repeated but relatively low-cost damage, while another station may be affected less often but incur much larger repair expenditure or prolonged operational interruption. Future assessments should therefore consider disruption frequency, repair expenditure, outage duration, unavailable generation capacity, and the system importance of individual facilities.

A similar pattern was observed at component level. Damage and expenditure were concentrated in power-generation units, headworks, transformers, and penstocks, demonstrating that both civil and electro-mechanical systems are vulnerable. River-facing structures, including headworks, intakes, channels, penstocks, and protective works, are exposed to erosion, debris impact, sediment accumulation, and channel instability. Damage to these components can interrupt water conveyance even when the

powerhouse remains intact. Generation units and transformers may be affected by inundation, sediment intrusion, electrical faults, vibration, or failure of connected civil structures. Transmission and distribution infrastructure is additionally exposed to snow loading, icing, rockfall, slope failure, and restricted maintenance access. The divergence between component-damage frequency and expenditure shares confirms that component criticality cannot be assessed from failure frequency alone. Future work should compare hazard–component combinations using expenditure per record, repair duration, and unavailable capacity. Comparison current regional datasets rarely resolve at plant level.

District-level contrasts in disruption burden and infrastructure concentration

The district-level results reveal a mismatch between recurring disruption burden and the concentration of generation capacity. Shigar recorded the highest number of disruption entries and the highest relative hazard-conditioning index despite containing only 7.2 % of regional installed capacity. Skardu contained 50.8 % of installed capacity but did not record the highest conditioning value. These districts therefore represent different resilience priorities. Repeated disruption of several relatively small stations in Shigar may create persistent maintenance requirements and affect local electricity reliability. In Skardu, disruption of one or more high-capacity facilities may have wider system consequences because a large proportion of regional generation is concentrated there. District-level comparisons should, however, be interpreted with caution because the number of hydropower stations and their commissioning periods differ among districts. Consequently, cumulative repair and disruption records represent the documented distribution of events within the existing hydropower infrastructure inventory rather than standardized measures of comparative hazard risk. Higher totals may therefore reflect greater infrastructure exposure and longer operational histories, in addition to differences in hazard occurrence.

District-average values should not, however, be interpreted as direct measures of station-level risk. Channel geometry, tributary connectivity, slope position, infrastructure condition, protective works, and component layout can produce substantial differences among stations within the same district. Such local heterogeneity is characteristic of the narrow and geomorphically complex valleys of High Mountain Asia [5].

The K-means analysis further identified a group of four stations with the highest mean repair expenditure, distributed across Shigar, Ghanche, Kharmang, and Skardu. High repair burden is therefore not confined to the district with the highest hazard-conditioning score. Local environmental and infrastructure characteristics may be as important as district-level location.

The clusters should be interpreted as multivariate station profiles rather than vulnerability, hazard, or repair-expenditure classes. Repair expenditure was included among the clustering variables, and the expenditure ranges of the two lower groups overlapped. The clustering is therefore exploratory rather than causal. A stronger future approach would classify stations using only pre-damage environmental and engineering characteristics and subsequently test whether disruption frequency, repair expenditure, or outage duration differs among the resulting station types.

Hydroclimatic and cryospheric context for seasonal operating output

Observed winter operating output corresponded to 55.8 % of installed capacity, compared with 78.4 % during summer. This seasonal contrast is consistent with the hydrology of run-of-river systems in the Upper Indus Basin, where snowmelt and glacier melt contribute substantially to warm-season discharge and where their relative contributions vary among sub-basins and seasons[11,27]. The available operational data cannot, however, attribute the winter–summer difference solely to meltwater availability. The observations are expressed in megawatts and represent operating output rather than seasonal energy generation or conventional capacity factors. Maintenance schedules, mechanical condition, sediment-related interruptions, water diversion, operational decisions, and transmission constraints may also influence output. The winter–summer difference should therefore be interpreted as an operational seasonal contrast rather than as quantified evidence of cryospheric control or hazard-related energy loss. The snow-cover analysis similarly provides regional cryospheric context rather than a direct measure of water availability. Shigar recorded the largest mapped snow-covered area, whereas Kharmang recorded the smallest. These values are influenced by district area, elevation distribution, terrain, cloud screening, and satellite-acquisition timing. They do not directly quantify snow water equivalent, meltwater production, runoff contribution, or hydrological connectivity to individual hydropower intakes. Snow and glaciers

nevertheless have a dual role in high-mountain hydropower systems. They store and release water seasonally, while snow loading, avalanches, glacial-lake failures, associated sediment mobilization, and changes in channel behaviour may threaten infrastructure. Given the spatial variability and uncertainty in future temperature, precipitation, glacier response, and runoff across Upper Indus sub-basins, hydropower planning should consider the cryosphere as both a source of seasonal water and a contributor to infrastructure hazards [28].

Implications for hydropower resilience

Adaptation should be differentiated by hazard, component, station, and district. At flood- and sediment-prone stations, priorities include strengthening hydraulic structures, improving sediment-management capacity, protecting exposed channels and penstocks, stabilizing riverbanks, and maintaining adequate flood conveyance. Regular post-event inspections should assess scour, channel migration, sediment accumulation, blockage, and deterioration of protective works. Facilities near unstable slopes require improved drainage, slope stabilization, rockfall protection, secure or flexible penstock supports, and reliable emergency access. Where complete stabilization is impractical, slope and channel monitoring may provide early warning of conditions that threaten critical infrastructure. Transmission systems in snow-prone corridors require attention to structural loading, route exposure, maintenance access, and redundancy. High-cost electro-mechanical components should be protected from inundation and sediment intrusion. Critical spare parts should be stored locally or made rapidly accessible where transport constraints could prolong outages. Emergency planning should also account for compound events that simultaneously affect hydropower structures, transmission routes, and access roads.

Adaptation priorities should reflect district-level differences. Shigar requires particular attention to recurrent flood, sediment, snowfall, and slope-related disruption. Skardu requires protection and contingency planning for its concentration of high-capacity assets. In Ghanche, steep terrain warrants closer evaluation of slope instability and access-related exposure. In Kharmang, resilience measures should focus on individual exposed stations rather than assuming uniformly low district-wide hazard. More broadly, mountain hydropower investments should be stress-tested against combinations of hydrological,

geophysical, operational, and financial uncertainty. Sedimentation, infrastructure condition, maintenance capacity, and project design may be as important as climatic uncertainty for hydropower performance[29]. The plant-level integration of disruption records, repair expenditure, infrastructure characteristics, and hazard conditioning used here provides a practical basis for such assessments in other glacier-fed mountain regions.

Limitations and future research

The archive consists of administrative repair and disruption records rather than a standardized engineering-loss database. Record completeness, terminology, and reporting practices may therefore differ among stations and periods. Some events may be represented by several repair entries, while smaller disruptions may be absent. The use of non-exclusive hazard labels also complicates the interpretation of hazard frequency and expenditure shares.

The expansion of the operational station inventory limits temporal comparison because raw record counts reflect both hazard occurrence and increasing infrastructure exposure. Plant commissioning dates and complete operational histories would allow disruption rates and expenditure to be normalized per station-year. Hazard-specific expenditure estimates are also sensitive to the procedure used to allocate costs among records assigned to multiple hazards. Although expenditure was adjusted to constant 2025 prices, variation in procurement conditions, labour costs, and emergency restoration practices introduces additional uncertainty.

The relative hazard-conditioning indices depend on factor selection, classification, standardization, and weighting. GIS-based multi-criteria results may change under alternative assumptions, making sensitivity analysis necessary to evaluate the stability of district and station rankings[30]. District averages also cannot represent all site-specific conditions affecting individual stations. The clustering analysis included only 41 stations and combined repair expenditure with infrastructure, spatial, topographic, and environmental variables. The resulting groups should therefore be treated as exploratory station profiles rather than predictive risk classes.

Finally, mapped snow cover and MW-based operating output provide contextual rather than process-based hydrological evidence. Stronger attribution would require snow-cover

duration, snow water equivalent, glacier area and mass change, glacial-lake evolution, streamflow, sediment concentration, energy generation in MWh or GWh, and complete outage-duration records. Integrating these observations with station-level engineering assessments would help distinguish cryospheric, hydrological, geomorphic, mechanical, and operational controls on hydropower performance. Despite these limitations, the study provides a rare plant-level evidence base for a data-limited high-mountain region. By integrating disruption records, affected components, inflation-adjusted repair expenditure, infrastructure characteristics, and environmental setting, it reveals differences among recurring hazard burden, repair severity, and infrastructure concentration that district- or single-hazard assessments cannot resolve. Hydropower resilience in Baltistan and comparable glacier-fed mountain regions therefore requires site-specific engineering protection, sediment and catchment management, cryosphere-related monitoring, emergency preparedness, and system-level contingency planning within an integrated multi-hazard framework.

Conclusion

Hydropower disruption in Baltistan is multi-hazard, spatially uneven, and shaped by interactions among infrastructure location, component sensitivity, cryosphere-influenced hydrology, and local hydrogeomorphic conditions. The archive contained 150 documented repair or disruption records during 2010–2019 and 2024–2025, while 25 of the 46 hydropower stations recorded at least one hazard-related disruption during the systematic 2010–2019 period. Flash floods were the most frequently assigned hazard category, followed by landslides, heavy snowfall, rockfall, earthquakes, and glacial lake outburst floods. This diversity demonstrates that single-hazard assessments are insufficient for hydropower systems in glacier-fed mountain environments.

Documented disruption burden did not correspond directly to the concentration of installed capacity. Shigar recorded the largest raw number of repair or disruption records and the highest relative hazard-conditioning score despite containing only a small share of regional installed capacity. Skardu, by contrast, contained more than half of the installed capacity but did not have the highest hazard-conditioning score. Because districts differ in station number and commissioning history, these raw totals should not be interpreted as directly comparable disruption rates. Nevertheless, the distinction

between districts characterized by recurrent disruption and those containing concentrated generation capacity is important for prioritizing maintenance, resilience investment, and future hydropower development.

Damage affected both civil and electro-mechanical infrastructure. Power-generation units, headworks, transformers, and penstocks accounted for substantial shares of documented damage and inflation-adjusted repair expenditure. The multivariate analysis also identified a small group of stations with comparatively high repair burden, indicating that important differences occur among individual facilities and are not confined to one district. The snow-cover and seasonal operating-output analyses provide cryospheric and operational context rather than direct hydrological attribution. Mapped snow-covered area varied among districts, and observed operating output was higher in summer than in winter. These findings are consistent with the seasonal hydrology of run-of-river systems, but they do not independently quantify snowmelt or glacier-melt contributions, conventional capacity factors, or hazard-related energy losses.

Overall, this study provides a spatially explicit, asset-level framework linking documented disruption, affected components, repair expenditure, infrastructure concentration, and relative hazard conditioning. The findings support greater emphasis on flood and sediment management, slope and rockfall protection, stronger civil and electro-mechanical safeguards, snow-resilient power-delivery systems, emergency access, and monitoring of upstream cryosphere-related hazards. This framework can support more resilient hydropower planning in Baltistan and other data-limited mountain regions where infrastructure is expanding under hydrological, geomorphic, cryospheric, and climatic uncertainty.

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PARTICIPANT RESEARCH PAPER

Gender-Responsive Disaster Risk Reduction and Climate Adaptation in Pakistan

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Abstract

Disasters do not affect everyone equally. The 2022 floods in Pakistan had an impact on 33 million people (World Bank, 2022), however this does not represent the distribution of impact between men and women. Women and girls are more at risk to disasters and less empowered in the decision-making process of disaster preparedness and response. This paper discusses the effects of gender inequality and sexist attitudes, including benevolent sexism, on disaster risk and institutional response in Pakistan. It applies a qualitative analysis of the secondary literature, policy documents and empirical case studies to examine the relationship between policy and practice. The review reveals that there have been tangible policy gains in Pakistan since the 2010 floods, including the establishment of the NDMA Gender and Child Cell, and the gender-responsive amendment of the National Disaster Management (NDM) Act. But lack of women in leadership and operational positions within the organization is proving to be a hurdle to this, as it is creating weak implementation. Paper also finds gaps in data, institutions and attitudes. It calls for gender disaggregated data, safe infrastructure, gender-inclusive early warnings, training of planners and responders and for the active participation of women in disaster risk reduction and climate adaptation.

***Keywords**:* climate adaptation, disaster risk reduction, gender equality, Pakistan floods, sexist attitudes

1. Introduction

Extreme weather and climate change poses increasing developmental and humanitarian challenge for the country of Pakistan. Approximately 30 million were impacted by flooding in 2010 and approximately 33 million were impacted in 2022 (World Bank, 2022). Women and girls face greater risks and vulnerabilities than men and boys during disasters; however, disaster risk management and climate adaptation planning are often seen as gender neutral (Sadia et al., 2016; United Nations Office for Disaster Risk Reduction [UNDRR], 2023). Gender-inclusive planning is not gender neutral. It diminishes women's decision-making authority and increases the risk for them of harm.

The following key terms help to frame the discussion. A hazard can be a phenomenon, substance, human activity or condition that could cause harm, injury or loss of life. Exposure – the population, livelihoods, infrastructure or economic assets located in hazard-prone areas. Vulnerability is the physical, social, economic and environmental characteristics or capacities that affect a person or community's ability to withstand the effects of a hazard. Risk is the product of hazard, exposure and vulnerability, which is the likelihood of a hazard occurring, in combination with its adverse effects. It is also important to have a sexist attitude. Like hostile sexism, benevolent sexism can exclude women from planning and response (Glick and Fiske, 1996), viewing women as persons to be cared for.

Data on women's vulnerability exists but women's role and agency in DRR in Pakistan is under-investigated. This paper explores this relationship between gender inequality and institutional structure and the effect of disasters. The idea is to discuss the role of gender and sexist attitudes in Pakistan's disaster vulnerability; review the lessons learned and gaps in disaster risk reduction and climate adaptation policies from 2010 and 2022 floods; and provide recommendations for gender-responsive DRR and climate adaptation policies. This is a secondary source review. It charts the gender provisions in the disaster laws of Pakistan, reviews empirical examples of large scale floods and looks at international frameworks like the Sendai Framework. There was no primary data collected.

2. Regional Context and Hazard Profile

PakistanPakistan faces various hazards like monsoon floods, earthquakes and glacial lake outburst flood (GLOF). As observed in the case of the Shishper GLOF in Hunza Valley, women and men are impacted in different ways (Khalid & Khan, 2021). The gender gap is also high at the regional level. According to Pakistan's score in the South Asia Women's Resilience Index (27.8) released in 2014 by ActionAid, Pakistan has been the worst performing country in the list of eight countries analysed.

The gender dimensions of floods are often mentioned in the Pakistani literature, especially in the health, shelter and recovery (Sadia et al., 2016). This paper focuses on women's agency in DRR, a topic which has received less focus. The social dimensions of a hazard and power relations have a significant influence on the event becoming a disaster. Approximately 30 million people were impacted by floods in 2010, and approximately 33 million people were impacted in 2022 (World Bank, 2022). These statistics illustrate the extent of flooding, but not who is bearing the brunt of the impact in the targeted households and communities.

3. Risk and Vulnerability Assessment

Disasters exacerbate the social and economic disparities among people and populations, and create new vulnerabilities for various groups. Risk is a function of hazard, exposure and vulnerability, and vulnerability is a function of unequal power and unequal access to resources. Women are less mobile and are more responsible for childcare and have less access to money and early warning information. These gaps slow down recovery, create shelter challenges, and hinder evacuation. Households lack sufficient income and access to food, and women are less able to control finances and assets, reducing their coping options (Sadia et al., 2016).

Women are less likely to be decision makers or the household head so they have less opportunity to be involved in household and community discussions around evacuation, relief and rebuilding.

Table 1 summarizes the evidence from studies of floods in Pakistan.

Table 1. *Gender Dimensions of Flood Impact and Recovery in Pakistan*

Area	Evidence	Why it matters

Area	Evidence	Why it matters
Household headship	In a study of 386 households in Nowshera, women made up 51% of the sample but only 5% of household heads (Sadia et al., 2016).	Women have less say in decisions on evacuation, relief and rebuilding.
Mobility, privacy and shelter	The 2010 UNIFEM assessment (253 respondents and 141 case studies) highlighted low mobility, lack of privacy and shelter, and the burden of water and sanitation needs for women.	Evacuation is delayed and shelter is harder to find.
Recovery housing	Gender standards were largely absent in recovery housing projects in Dadu and Thatta, Sindh (Shah, 2012).	Reconstruction can repeat existing gender gaps.
Relief camps	Overcrowding and displacement in relief camps are major drivers of violence against women (Ullah et al., 2024).	Women face a higher risk of harm after displacement.

Note. Based on Sadia et al. (2016), Shah (2012), Ullah et al. (2024) and the 2010 UNIFEM assessment.

There are multiple factors that enhance vulnerability. These range from unequal power distribution and male dominated household headship to sexist and even hostile attitudes towards women in the household, strictures on their mobility, on who owns and has access to transport and the lack of frontline and operational enforcement of gender

responsive policies (Glick and Fiske, 1996). All these factors indicate that these social conditions produce vulnerability in women and not women themselves.

4. Community Resilience Factors

However, in times of crisis, women are extremely resilient and capable of coping with the situation despite these restrictions. They are well known in their communities and in their families as providers of care, which helps to support the survival of their families and coping in the community during disaster events (Khalid & Khan, 2021). Established women's networks, such as local groups like the Girl Guides, enhance local preparedness and response when involved. They can be helpful and valuable because they exist, are local and trusted.

Community engagement also helps to ensure that any project for building resilience is grounded in what is happening at the grassroots level within the community. Women's leadership and meaningful participation in DRR is also included in the Sendai Gender Action Plan (UNDRR, 2024). But, there is a limit to resilience. It takes teamwork and the participation of both men and women to carry the burden of preparedness, and goodwill is not all that is needed. Formal support, inclusion and resources should be provided to enable women's capacity to be recognized and utilized, not relied on without support.

5. Scientific and Institutional Gaps

Results of institutional structures assessment indicate that there are obvious policy-ground relationship gaps. There has been an improvement in Pakistan after the floods in 2010 ;a flood during which women were unnoticed in most parts. The NDMA have a gender mainstreaming unit and, in 2014, they issued national guidelines on gender and vulnerable groups in disaster response, followed by Senate committee amendments to make the NDM Act gender-responsive in 2018, and the NDMA conducting pilot training on gender responsive implementation of the Sendai Framework in 2023 (National Disaster Management Authority [NDMA] 2023). The UNDRR developed worldwide the Sendai Gender Action Plan which sets the benchmark with 9 objectives and 33 actions (UNDRR, 2024).

But the execution of the policy is lagging up. Though policies are on paper and there is a relative dearth of women in the disaster management system. Gender provisions are seldom implemented in the absence of women at the front-and-firefighting level and in

leadership positions. The issues get compounded by attitudes. A paternalistic benevolent attitude as well as hostile attitude towards women keeps them passive and hinders their participation in planning and response (Glick & Fiske, 1996).

There also are areas of data and technology needs. The needs of women can be difficult to observe on disaster assessments and it is rare that there is a disaggregated approach by sex (UNDRR, 2023). The development of the tools and early warning systems, whether supported by analogue or artificial intelligence/machine learning depends on the quality and extent of available data. Gender-based data silos run the risk of perpetuating existing data blind spots with these tools.

6. Mitigation Strategies and Best Practices

Structural, social and institutional factors need to be part of mitigation and adaptation. Structural measures like the provision of private shelters and good sanitation facilities combined with violence prevention protocols, and psychosocial support (Ullah et al., 2024). Standards for Housing and Recovery Services must also be gender responsive (Shah, 2012).

Non-structural measures are gender-sensitive data collection and use of it in disaster planning and response; and gender-targeting in planning and responding and/or targeting of planning and responding skills in order to be gender-sensitive, as well as targeting debilitating gender biases, such as benevolent sexism. National practice should also reflect international frameworks to promote the Sendai Gender Action Plan (UNDRR, 2024).

There are a few good practices already in place. National level examples of how awareness, training and preparedness can be enhanced through institutional action include, for example, the national initiative on gender-responsive Sendai implementation in cooperation with UN Women (NDMA, 2016), the national pilot training on gender responsive Sendai implementation (NDMA, 2023), and the NDMA national dialogue on empowering women and girls (NDMA, 2024). The work of converting this into routine at all levels of the system..

7. Risk Communication and Early Warning

Effective risk communication requires a translation between warning by the technical and reaching vulnerable populations. Women’s access to communication technology is

limited, and their mobility is restricted; and early warning messages should be direct to them. (Sadia et al., 2016) Community channels and networks, such as women groups, should also be used for disseminating warnings to households that do not reach through the formal channels.

Women need to be actively involved in the dissemination of early warnings, and in local planning and in community responder teams. This renders EW people-centred and gender sensitive. Including women in the design and delivery of warnings increases the chances for this message to be trusted, understood and acted upon,.

8. Policy Recommendations

The evidence supports seven priority actions for the NDMA and its partners:

- **Gather and use gender-sensitive data.** Collect and apply sex-disaggregated data in all disaster assessments and planning frameworks (UNDRR, 2023).
- **Engage women in operational roles.** Involve women directly in early warning systems, local disaster planning committees and frontline responder teams.
- **Ensure safe infrastructure.** Provide private shelters and dedicated sanitation facilities with violence prevention mechanisms and psychosocial support (Ullah et al., 2024).
- **Sensitize planners and responders.** Train disaster management personnel to recognize and overcome gender biases, including benevolent and hostile sexism (Glick & Fiske, 1996).
- **Apply gender standards in recovery.** Enforce gender standards across housing design, reconstruction and post-disaster recovery services (Shah, 2012).
- **Use local knowledge.** Engage women's local knowledge and community groups, such as the Girl Guides, in resilience-building initiatives.
- **Strengthen institutions and integrate governance.** Link gender-responsive DRR with climate adaptation planning, and support the NDMA and provincial authorities with the resources and staff needed to carry out gender provisions at the frontline (UNDRR, 2024).

9. Conclusion

Gender gaps in disasters is not a natural thing that happens. They are influenced by the way power is distributed, and by society's attitude toward the role of women. Women are

more vulnerable to impacts before, during and after disasters because of unequal access to resources, less decision-making, and both negative and positive discrimination against women. Closing these gaps necessitates a shift in power toward women, giving them a seat at the table. The policies and frameworks are already in place in Pakistan and it is the institutional will to make them implementable. Resilience planning based on good data, social capital, local knowledge and appropriate technology can see to women as active rather than protected partners. These results should be tested in primary data from women in the affected communities in future studies.

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PARTICIPANT RESEARCH PAPER

GLOFs and Landslides in Gilgit-Baltistan: Climate Risk Assessment, Early Warning and Community Resilience

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Abstract

Gilgit-Baltistan (GB) is exposed to glacial lake outburst floods (GLOFs), rainfall-triggered landslides, debris flows and flash floods because settlements and infrastructure occupy steep, glacier-fed valleys. Climate change is altering glacier mass, snowmelt and precipitation, but disaster outcomes also depend on lake-dam stability, slope conditions, land use, infrastructure exposure and community preparedness. This desk-based paper assesses the connected risks of GLOFs and landslides, reviews early-warning arrangements and examines community resilience. Evidence shows that Pakistan has expanded glacial-lake monitoring and warning infrastructure, yet coverage, maintenance, communication and local response capacity remain uneven. The 2010 Attabad landslide and recent events in Ghizer show how slope failure and landslide-dammed water can cause prolonged or sudden damage. The paper recommends integrated hazard databases, locally maintained multi-channel warnings, inclusive evacuation planning, risk-sensitive land-use rules and formal integration of community knowledge with scientific monitoring. Resilience requires sustained institutions and investment, not technology alone.

Keywords: community resilience; early warning; Gilgit-Baltistan; glacial lake outburst flood; landslide

1. Introduction

Gilgit-Baltistan lies within the Hindu Kush, Karakoram and western Himalayan mountain system. Steep relief, glacier-fed rivers, active geomorphology and settlements concentrated on narrow valley floors create a distinctive disaster-risk environment. Roads, bridges, irrigation channels, hydropower assets, schools and homes often share the same constrained corridors as rivers and unstable slopes, so a single event can cause direct damage and also cut off markets, health care and emergency assistance.

A GLOF occurs when water stored in a glacier-associated lake is suddenly released, often after failure or overtopping of an ice or moraine dam. Landslides are downslope movements of rock, soil or debris triggered by rainfall, snowmelt, earthquakes, erosion or human disturbance. A landslide may also block a river and form a temporary lake that later breaches, linking the two hazards. Globally, glacial lakes have grown rapidly since 1990, increasing the number of people potentially exposed to outburst floods (Shugar et al., 2020).

Problem statement and rationale: Early-warning investment is growing, but system presence is often mistaken for system effectiveness. Little synthesis connects GLOF and landslide risk, warning performance and community capacity in a single GB-specific framework.

Objectives: The study aims to (1) characterise the combined GLOF and landslide hazard profile of GB; (2) assess exposure, vulnerability and livelihood risk; (3) examine community resilience and early-warning arrangements; (4) identify scientific and institutional gaps and the paper's novelty; and (5) propose policy, procedural and practical measures.

Scope and method: The paper is a desk-based synthesis of institutional climate projections, disaster-management reporting and published or publicly available case material, aligned with the Sendai Framework (United Nations Office for Disaster Risk Reduction [UNDRR], 2015). Reported figures are treated cautiously because inventories, event definitions and verification methods differ.

2. Regional Context and Hazard Profile

The Global Change Impact Studies Centre projects substantial warming across the Hindu Kush–Himalayan region. Under the high-emissions RCP8.5 scenario, projected warming

is about 2.2°C for 2006–2035 and 5.8°C for 2071–2100 relative to the study baseline, while precipitation changes vary by scenario and period (Global Change Impact Studies Centre [GCISC], n.d.). These are regional model projections, not forecasts for individual valleys; local outcomes depend on elevation, season, glacier characteristics and circulation patterns.

Warming can increase meltwater and alter the timing of snow and ice melt. Glacier retreat may expose depressions where lakes form, and rainfall or meltwater can raise lake levels or weaken dams. However, retreat does not mean every lake will outburst, and a warmer climate alone cannot predict the timing of a particular event. Site-specific assessment of lake geometry, dam material, slope hazards and downstream exposure remains essential.

The January 2010 Attabad landslide blocked the Hunza River, killed people and submerged sections of the Karakoram Highway, creating a lake that affected communities and transport for months (Khan, 2014). Slope failure initiated river blockage, while the lake and its later management created further risks. In August 2025, reporting from Ghizer described a landslide-associated sudden outburst that inundated farmland and damaged roads in the Roushan and Tildas area; some damage estimates came from local accounts and need independent verification (The Tribune, 2025).

Four terms are used throughout. *Hazard* is a potentially damaging physical process; *exposure* describes people, buildings and services in its path; *vulnerability* is the likelihood that exposed people or assets will be harmed, shaped by housing, income, mobility, health, information and institutional support; and *risk* emerges from their interaction rather than from the hazard alone.

3. Risk and Vulnerability Assessment

Risk is highest where a plausible high-impact event meets dense settlement, essential infrastructure and limited evacuation or recovery options. Valley-bottom villages face inundation, while road corridors cut into steep slopes face rockfall, debris flow and landslides. A road closure can magnify an otherwise local event by delaying ambulances, food, fuel and repair equipment, and damage to irrigation channels and farmland extends losses beyond the emergency.

Farming, livestock keeping and tourism are climate-sensitive livelihoods that can expose households to repeated shocks; a family that loses fields, animals or a guesthouse may have few savings or alternative income sources, which threatens food security. Women, children, older people, persons with disabilities and people without private transport may need tailored evacuation support. These vulnerabilities are not universal and should be assessed locally rather than assumed from demographic categories.

A practical assessment should combine an updated inventory of glacial lakes and unstable slopes with satellite imagery, digital elevation models, rainfall and river observations, event records, field validation and participatory mapping. Pakistan's reported 2026 assessment compiled 131 lakes and classified 35 as very high or high danger, 56 as medium and 24 as low, with field validation still needed (INP, 2026a). Such classifications aid prioritisation but cannot replace site investigation or downstream inundation modelling. A transparent risk matrix should score likelihood, magnitude, exposed population, critical infrastructure, vulnerability and warning lead time, and record uncertainty, because one village may face mainly flood exposure while another faces slope failure.

4. Community Resilience Factors

Community resilience is the capacity to anticipate, withstand, respond to and recover from disruption. Residents often hold detailed knowledge of seasonal stream behaviour, past landslides, glacier sounds, unusual water colour and changes in flow. Such observations add context that remote sensors cannot, while instruments detect changes that are hard to see. The strongest approach treats both as complementary and tests local indicators through documentation and joint learning.

Community disaster-risk committees can map evacuation routes, identify safe high ground, check on households needing help, maintain contact trees and run drills. In Tormik, Roundu, a community-based committee responded in the 2026 season even though the valley had no GLOF-II warning siren; no casualties were reported, although infrastructure was damaged (INP, 2026a). The case shows the value of preparedness, but one event cannot prove that committees alone suffice for a larger flood. Resilience also depends on recovery capacity: shelters, safe water, medical support, savings groups,

livelihood diversification and rapid road and irrigation repair, with women and marginalised groups taking part in decisions rather than only receiving relief.

5. Scientific and Institutional Gaps and Novelty

Pakistan has expanded satellite monitoring and automated warning infrastructure. SUPARCO has reportedly monitored 115 potentially dangerous glacial-lake locations (INP, 2026b), and the GLOF-II programme reportedly includes 286 early-warning systems across 24 valleys, 18 in GB and six in Khyber Pakhtunkhwa (INP, 2026a). These figures show investment, but not that every sensor works, that all exposed settlements are covered, or that residents receive enough lead time to evacuate.

Key gaps include harsh weather, power failures, weak mobile coverage, difficult repair access and few trained local operators; data fragmented among meteorological, space, disaster-management and water agencies; and incomplete or inconsistent landslide inventories and susceptibility maps. Artificial intelligence and machine learning can classify imagery and detect change, but depend on reliable training data and field verification, and should support rather than replace expert judgement and community reporting.

Novelty. Existing work tends to treat GLOFs, landslides, warning technology and community action separately. This paper contributes an integrated, GB-specific reading that (a) treats landslide-dammed outbursts and glacial-lake outbursts as one connected risk; (b) separates warning infrastructure from warning effectiveness through measurable outcomes; and (c) pairs institutional recommendations with a community-level preparedness checklist and procedural responsibilities.

6. Mitigation Strategies and Best Practices

Mitigation should combine structural and non-structural measures. Where technically and environmentally justified, options include slope drainage and stabilisation, protection of critical infrastructure, river training and controlled lowering of a dangerous lake. These need site-specific engineering, environmental review, downstream impact analysis and long-term maintenance, since poorly designed works can transfer risk or create false security. Nature-based measures, such as protecting vegetation, restoring suitable slopes and managing drainage, reduce some erosion and runoff but cannot prevent every high-magnitude event in steep high-altitude terrain.

Land-use planning is therefore essential: avoid new construction in mapped floodways and runout zones, site schools and health facilities more safely, and require hazard assessments for roads, hydropower and other major infrastructure. Preparedness measures can be implemented quickly: evacuation drills, marked routes, safe shelters, household plans, first-aid training and pre-positioned supplies. Public investment should prioritise high-risk sites and lifeline continuity, with funding for routine inspection and repair.

7. Risk Communication and Early Warning

An effective early-warning system connects four functions: risk knowledge, monitoring and forecasting, communication, and the capacity to act. A sensor is only one link. Warnings should state the threatened location, expected hazard, urgency, protective action and source of further information, in local languages and in audio and visual formats suited to different literacy and accessibility needs.

GB needs redundant channels because mobile networks and electricity may fail. Sirens attract attention, but residents must know what each signal means and where to go. SMS, voice calls, radio, mosque loudspeakers, community volunteers and official digital channels can reinforce one another, with protocols stating who verifies an alert, who authorises evacuation, who opens shelters and who confirms that vulnerable households were reached. Systems need routine testing, spare parts, maintenance budgets and public fault reporting, and each hazard season should be reviewed for missed events, false alarms, lead time, household reach and evacuation performance, while preventing unverified rumours from eroding trust.

8. Policy and Procedural Implications and Practical Recommendations

Policy implications. Policy should shift from counting installed systems to demonstrating protection: funding operation and maintenance as well as installation, embedding risk-informed land-use rules and climate-resilient infrastructure standards, and clarifying mandates among national, provincial and district bodies.

Procedural implications. NDMA, GBDMA, PMD, SUPARCO, WAPDA, district administrations, researchers and community committees need written protocols for data sharing, alert verification and authorisation, shelter activation, post-event review and public reporting of system status.

Practical recommendations:

a) Establish a shared, regularly updated GB hazard database integrating glacial lakes, landslide scars, rainfall, river gauges, exposed assets and community vulnerability, with uncertainty documented.
b) Prioritise warning coverage by downstream exposure and vulnerability, not ease of installation; publish which systems are functional and fund maintenance, local operators and backup power.
c) Require district-level, multi-hazard evacuation plans and annual drills with accessible routes, safe shelters, transport and named support for people needing assistance.
d) Formalise inter-agency collaboration with clear responsibilities for data sharing and alert authorisation.
e) Integrate local and Indigenous knowledge through participatory mapping, community observation logs and joint reviews, validating indicators and respecting local ownership.
f) Apply risk-informed land-use rules and review projects that may increase slope instability or place assets in floodways.
g) Evaluate programmes by warning lead time, share of at-risk households reached, system uptime, drill participation, evacuation time, and disaggregated losses and casualties.

9. Conclusion

GLOFs and landslides in Gilgit-Baltistan are linked hazards whose consequences are intensified by steep terrain, changing climate, concentrated infrastructure and uneven capacity to prepare and recover. Climate projections justify planning for changing melt and precipitation patterns but do not predict individual disasters. Reliable risk reduction depends on site-specific evidence, careful treatment of uncertainty and attention to the social conditions that determine who is harmed.

Pakistan's monitoring and early-warning investments are an important foundation, but their value depends on maintenance, broader coverage, clear communication and community capacity to act. The central priority is an integrated system that joins satellite and field science with local knowledge, risk-sensitive development and inclusive

preparedness. Technology can provide warning; sustained governance and community trust turn warning into protection.

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PARTICIPANT RESEARCH PAPER

Disaster Risk Financing and Climate Risk Insurance: Global Models and Pakistan's Opportunities

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Abstract

Pakistan's recurrent floods have turned disaster losses into a persistent fiscal risk. The 2022 floods caused damage of USD 14.9 billion and economic losses of USD 15.2 billion, with reconstruction needs of at least USD 16.3 billion, yet financing arrived largely after the event. This paper examines how disaster risk financing (DRF) and climate risk insurance (CRI) can pre-arrange funds for response, recovery and risk reduction. Through a desk review of government, multilateral and institutional sources, it reviews regional risk pools, parametric insurance and layered financing, and assesses Pakistan's vulnerability, community resilience, data and institutional gaps, and early warning links. The analysis finds that financing remains reactive, only 9.5 percent of farmers hold crop insurance, and parametric products depend on hydrometeorological data and trusted delivery channels. The paper recommends ex ante rules for disaster funds, a disaster finance classification in the budget, district-level parametric pilots through social protection and microfinance, investment in data and early warning, and a staged study of sovereign risk transfer coordinated by an inter-agency working group.

Keywords: climate risk insurance; disaster risk financing; early warning; Pakistan; parametric insurance

1. Introduction

Pakistan's floods have turned disaster losses into a recurring fiscal burden. The 2022 floods caused damage of about USD 14.9 billion and economic losses of about USD 15.2 billion, and estimated reconstruction needs were at least USD 16.3 billion (Ministry of Planning, Development and Special Initiatives [MoPDSI], 2022). Funding arrived mainly after the event, through budget revisions, borrowing and pledges. The International Monetary Fund (IMF, 2026) concludes that Pakistan cannot rely on after the event financing alone.

Disaster risk financing (DRF) pre-arranges funds before a disaster through a mix of retained funds, insurance and contingent finance. Climate risk insurance (CRI) is the part of DRF that transfers risk to insurers, including parametric (index-based) products that pay when an agreed trigger, such as rainfall or flood depth, is reached. Both support Priority 3 of the Sendai Framework, investing in disaster risk reduction for resilience (United Nations Office for Disaster Risk Reduction [UNDRR], 2015).

Problem statement: Pakistan's disaster financing remains reactive, rural insurance coverage is low, and no operational ex ante framework links funds to risk reduction.

Purpose and objectives: This paper (a) explains DRF and CRI, (b) reviews global models, (c) assesses Pakistan's vulnerability and gaps, and (d) proposes policy options.

Scope: It covers sovereign, provincial and household levels, and is a desk review of government, multilateral and institutional sources available to October 2026. No primary data were collected.

2. Regional Context and Hazard Profile

Definitions: Following UNDRR (n.d.), a hazard is a process or phenomenon that may cause loss; exposure is the situation of people and assets in hazard prone areas; vulnerability is the set of conditions that makes them susceptible to harm; and risk is the potential loss arising from their interaction. Financing decisions depend on all four terms, not on the hazard alone.

Context and historical events: Pakistan is projected to experience major shifts in rainfall patterns and more frequent extreme events (Green Climate Fund, n.d.). The 2022 floods affected 33 million people (United Nations Development Programme [UNDP],

2022). Agricultural losses from the 2025 floods have been estimated at more than PKR 302 billion (Khan, 2025).

Literature and trends: A World Bank-supported fiscal disaster risk assessment set out options for a national disaster risk financing strategy in 2016 (Global Facility for Disaster Reduction and Recovery [GFDRR], 2016), yet the IMF (2026) still calls for ex ante rules. Elsewhere, four regional pools, namely the Caribbean Catastrophe Risk Insurance Facility (CCRIF), African Risk Capacity (ARC), the Pacific Catastrophe Risk Insurance Company and the Southeast Asia Disaster Risk Insurance Facility, show that parametric cover can deliver fast liquidity (World Bank, n.d.). CCRIF, for example, paid USD 84.5 million to seven members after Hurricane Beryl in 2024 (CCRIF SPC, n.d.).

3. Risk and Vulnerability Assessment

Socio-economic impacts: The 2022 floods killed more than 1,730 people. Housing, agriculture and livestock, and transport and communications suffered the largest damage, at USD 5.6 billion, USD 3.7 billion and USD 3.3 billion (UNDP, 2022). The poverty rate was projected to rise by 3.7 to 4.0 percentage points, pushing 8.4 to 9.1 million more people below the poverty line (UNDP, 2022).

Livelihoods and food security: Agriculture contributes nearly one-fifth of gross domestic product and employs about 40 percent of the labour force, yet only 9.5 percent of farmers had any crop insurance in 2023 (Khan, 2025). Unaffordable premiums, slow claim assessment, products unsuited to smallholders and religious concerns about interest-based contracts explain the low uptake (Khan, 2025). Uninsured households absorb losses through asset sales and debt, which prolongs recovery.

Vulnerable groups and gender: Among those in need after the 2022 floods were more than 1.6 million women of reproductive age, including nearly 130,000 pregnant women needing urgent health services, and women and girls faced rising gender-based violence (United Nations Population Fund [UNFPA], 2022). A compensation or insurance scheme that registers only male household heads would repeat this exclusion.

Fiscal vulnerability: After 2022, a financing gap of about USD 8.2 billion was identified against the reconstruction need ("Pakistan Identifies $8.2b Flood Funding Gap," 2022). The federal allocation under the National Disaster Management Authority (NDMA) budget head has typically been below Rs1 billion and was revised to Rs2.97 billion for 2025-26

("Anticipatory Action Financing," 2026). The fiscal exposure is therefore large relative to the funds set aside in advance.

4. Community Resilience Factors

Household resilience in Pakistan rests largely on informal arrangements: kinship and community networks, remittances, borrowing and asset sales. These are quickly exhausted when floods affect whole districts at once. Formal instruments can build on existing community structures. Microfinance, social protection and agricultural credit programmes can carry parametric cover (Khan, 2025), and Shariah-compliant (takaful) products address the religious concerns that deter participation (Khan, 2025).

Community participation also improves design. Local knowledge of how rivers and hill torrents behave should be used to validate triggers and thresholds and so reduce basis risk, the mismatch between payouts and actual loss. Recharge Pakistan applies the same principle to ecosystems by combining nature-based flood management with community-based natural resource management in the Indus Basin (Green Climate Fund, n.d.). Evidence on how community knowledge has shaped insurance design in Pakistan is limited, which makes it a research priority.

5. Scientific and Institutional Gaps

Data and technology: Weather monitoring remains limited in rural and mountainous areas, which constrains index design and raises basis risk (Khan, 2025). Satellite imagery and remote sensors are already central to index design (Khan, 2025). Machine-learning flood mapping and impact forecasting could improve triggers further, but the sources reviewed identified no operational use in Pakistan's disaster insurance.

Regulation and markets: The Securities and Exchange Commission of Pakistan has introduced the concept of disaster insurance without loss assessment ("SECP Introduces Concept of Insurance in Disasters Without Assessment Claims," 2022), but clear standards for index design, disclosure and dispute resolution are still needed (Khan, 2025). Low awareness and affordability continue to limit demand (Khan, 2025).

Fiscal institutions: The IMF (2026) calls for ex ante rules and for linking federal co-financing to risk reduction. Budget tagging had covered more than 5,000 cost centres by 2024 ("Anticipatory Action Financing," 2026), but tagging is not yet a financing framework.

Capacity in finance ministries, provincial authorities and insurers to design and manage risk-transfer instruments remains thin.

6. Mitigation Strategies and Best Practices

Financial protection complements, and does not replace, structural and non-structural risk reduction. A layered approach retains frequent small losses in budgets and reserves, transfers less frequent severe losses through insurance and risk pools, and uses contingent credit and catastrophe bonds for rare extreme events (World Bank, n.d.; Annex A).

International practice offers four lessons. First, pre-agreed triggers deliver speed: ARC paid Malawi USD 14.2 million after the 2022 drought (Khan, 2025). Second, participation can narrow between membership and payout: of 34 African Union member states, 13 bought ARC policies and seven received payouts in 2020 (Climate Policy Initiative, n.d.), so products must match needs. Third, subsidies help: Fiji provided tax exemptions and subsidies for parametric cover (Khan, 2025). Fourth, regional pools build shared assets such as data, models and capacity, and have begun to coordinate their work (CCRIF SPC, 2025).

Nationally, Recharge Pakistan, a USD 77.8 million programme including USD 66 million from the Green Climate Fund, shows a route to international finance for nature-based flood risk management (World Wildlife Fund, 2023). Capacity building should target provincial and district disaster management authorities, finance officials, regulators and insurers, supported by awareness campaigns for farmers.

7. Risk Communication and Early Warning

Parametric triggers and early warning depend on the same hazard data, so investment in one strengthens the other. NDMA and the World Food Programme have agreed a three-year memorandum on anticipatory action, with a technical working group alongside the Balochistan provincial authority (World Food Programme [WFP], 2024). This is a natural platform for linking forecast triggers to pre-arranged funds.

People-centred and gender-sensitive design means that warnings and payouts must reach women and remote households. Messages should use local languages and trusted channels, and payouts should reach women directly through accounts or mobile wallets where possible. Digital finance and mobile payments can lower delivery costs in remote

areas (Khan, 2025). Community engagement on how products work, including takaful options, builds trust, and last-mile arrangements should be tested in pilot districts before scaling.

8. Policy Recommendations

The following measures are proposed. They are sequenced so that the first two can start within six months, the next three within 18 months, and the last two within 36 months.

I. **Ex ante rules:** Adopt written rules for the use of national disaster funds and link federal co-financing to measurable risk reduction (IMF, 2026).
II. **Fiscal framework:** Build on budget tagging with a disaster finance classification and update the fiscal disaster risk assessment (GFDRR, 2016).
III. **Parametric pilots:** Design pilots in two to three high-risk districts through social protection, microfinance and agricultural credit, with takaful options and subsidised premiums (Khan, 2025).
IV. **Data and early warning:** Invest in hydrometeorological networks, satellite data and data-sharing protocols, and test machine-learning support for trigger design.
V. **Governance:** Establish an inter-agency DRF working group of the Finance Division, NDMA, the Securities and Exchange Commission of Pakistan and provincial authorities.
VI. **Sovereign risk transfer:** Commission a staged feasibility study of pool membership and catastrophe bonds once pilots and data improvements are in place.
VII. **Risk reduction and international finance:** Develop a pipeline of nature-based flood and drought projects for international climate funds (World Wildlife Fund, 2023).

9. Conclusion

Pakistan's disaster financing is reactive, and the 2022 floods exposed a large gap between reconstruction needs and funds available. Global models show that pre-arranged finance works when it rests on reliable data, pre-agreed response plans and government ownership. In Pakistan, low insurance coverage, limited hydrometeorological data, unclear regulation and the absence of ex ante fiscal rules are the main obstacles.

Resilience will depend on combining science-based planning, strong community networks, local knowledge used to calibrate products, appropriate technology and an integrated approach across finance, disaster management and climate adaptation. The

recommended sequence of ex ante rules, district pilots and a staged study of sovereign risk transfer offers a realistic path from reactive spending to predictable, risk-informed financing that protects the most vulnerable, including women and rural households.

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77-8-million-funding-boost-from-the-green-climate-fund-united-states-agency-for-international-development-the-coca-cola-foundation-and-world-wildlife-fund

Annex A. Disaster risk financing layers and the situation in Pakistan

Layer	**Instruments**	**Situation in Pakistan (sources reviewed)**
Retain: frequent, smaller losses	Budget contingencies, reserve funds	Federal allocation under the NDMA budget head typically below Rs1 billion; revised to Rs2.97 billion for 2025-26
Transfer: less frequent, severe losses	Insurance, parametric cover, risk pools	Crop insurance covers 9.5 percent of farmers; parametric cover not yet at scale
Borrow or pool: rare, extreme losses	Contingent credit, catastrophe bonds, donor support	No sovereign catastrophe bond or pool membership identified; recovery relied on pledges and borrowing

PARTICIPANT RESEARCH PAPER

Fog, Dense Fog and Cloudburst Hazards in Pakistan: Impacts, Vulnerability, Early Warning and Disaster Risk Reduction

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Abstract

Pakistan deals with two very different weather hazards. Dense fog settles over the Indus plains every winter and slowly chokes roads, airports and daily life, while cloudbursts hit mountain valleys during the monsoon with almost no warning. This paper looks at both through the lens of Disaster Risk Management (DRM), drawing on studies by Pakistani and regional researchers, plans and guidelines of the National Disaster Management Authority (NDMA) and Provincial Disaster Management Authorities (PDMAs), Pakistan Meteorological Department (PMD) publications and news reports from 2012 to 2025. For fog, it examines impacts on transportation, aviation and public safety. For cloudbursts, it examines causes, vulnerability, early warning and disaster risk reduction (DRR), using the August 2025 Buner event as the main case. The review finds that contingency plans, fog thresholds and impact-based alerts now exist on paper, but sparse observation, short lead times, fragmented data and uneven last-mile delivery still turn hazards into disasters. The paper recommends stronger coordination, impact-based forecasting, land-use control and community-based early warning in line with the Sendai Framework.

Keywords: dense fog; cloudburst; early warning; disaster risk reduction; Pakistan

1. Introduction

Every winter, thick fog covers the plains of Punjab, Khyber Pakhtunkhwa (KP) and upper Sindh, and on bad nights visibility on national highways drops to between zero and 100 m (The News International, 2025). In the monsoon, a different hazard hits the northern mountains: the cloudburst, usually defined as more than 100 mm of rain in an hour over roughly 20–30 km² (Arab News, 2025a; Dawn, 2025).

The problem is that neither hazard is handled well. Fog does not destroy buildings, so its losses are scattered across crashes, delayed flights and illness. Cloudbursts are dramatic but still argued over. After the Buner floods of August 2025, the Pakistan Meteorological Department (PMD) said that technically no cloudburst had occurred, while the provincial authority said one had (Dawn, 2025). This paper therefore asks how well Pakistan's current DRM arrangements address both hazards. Its objectives are to (a) profile the two hazards; (b) assess impacts, exposure and vulnerability; (c) identify community capacities and scientific and institutional gaps; and (d) propose mitigation, early warning and policy measures. The scope covers the fog-prone plains and the mountainous north, with emphasis on 2012–2025. It is a desk-based review and no primary data were collected.

2. Regional Context and Hazard Profile

Fog. Pakistan lies in the western Indo-Gangetic Plain (IGP), where about 24% of the land and 86% of the population are found (Khokhar et al., 2016). Fog persists from November to March and is centred over northern Punjab (Muslehuddin et al., 2004). In Pakistani studies, visibility below 1,000 m is called shallow fog, below 500 m moderate fog and below 200 m dense fog (Khokhar et al., 2016). The Indus river system, irrigation and moist soils supply moisture, and winter inversions trap it near the ground (Khokhar et al., 2016; Syed et al., 2012). Smoke from crop-residue burning, traffic, industry and solid fuels adds condensation nuclei, so fog lasts longer. Satellite and ground data for 2012–2015 showed rising dense-fog incidents in Lahore and PM10 above the national standard on most days (Khokhar et al., 2016). Recent episodes show the same pattern. In November 2024, fog suspended flights at Lahore and was linked to three deaths in Lodhran (Aaj News, 2024). On 21 December 2025, Lahore's air quality index averaged

450 while sections of the M-2, M-3, M-4 and M-11 motorways were closed (The News International, 2025).

Cloudbursts. Pakistan's northern mountains, where the Hindu Kush, Karakoram and western Himalaya meet, receive pre-monsoon storms and monsoon moisture. Studies of the Indian Himalaya show that cloudbursts occur mainly in the monsoon along the mountain front, where moist air forced uphill forms intense convective clouds (Dimri et al., 2017; Das et al., 2006), and the 2010 floods in Pakistan involved monsoon moisture, mid-latitude disturbances and terrain together (Houze et al., 2011). In 2025, the season began with the Swat River tragedy on 27 June, when 13 of 17 tourists from one family died (Associated Press, 2025). On 15 August, Buner recorded more than 150 mm of rain in an hour, and by 17 August the NDMA reported at least 337 deaths across the mountainous north (Reuters, 2025a). By 19 August, 695 people had died across Pakistan since late June (Reuters, 2025b). A review by Shahid and Ali (2026) links the crisis to climate-amplified monsoon variability, land-use mismanagement, weak infrastructure and inadequate early warning.

In DRR terms, the hazard is the fog or extreme rainfall event, exposure is the people and assets in its path, vulnerability is the set of conditions that make them susceptible to harm, and risk is the likelihood of harmful consequences when these interact (United Nations Office for Disaster Risk Reduction [UNDRR], 2017). Annex A compares the two hazards.

3. Risk and Vulnerability Assessment

Fog impacts are indirect but add up. Very low visibility and fast traffic cause chain collisions, and authorities close motorways and divert vehicles onto the Grand Trunk Road, which carries mixed traffic (Aaj News, 2024). Dense fog has repeatedly suspended or delayed flights at Lahore's Allama Iqbal International Airport (Aaj News, 2024; The News International, 2025). The PDMA Sindh winter plan notes that low visibility also delays goods, relief and access to health care in remote areas (PDMA Sindh, 2025).

Health effects are real. A Lahore survey found that less educated people, older adults and those already living in polluted areas were more likely to develop respiratory symptoms during winter smog (Jabeen et al., 2021), and in a 2024–2025 outpatient sample, 98% reported at least one symptom, although that group was not representative of all residents (Ali et al., 2026).

Cloudburst impacts are more direct. In Buner, water, rocks and trees swept down the mountainside and buried homes (Reuters, 2025a). Shahid and Ali (2026) report more than 320 deaths in KP and severe losses of crops and infrastructure in Punjab. By 19 August, 941 houses in KP and 719 in Azad Jammu and Kashmir (AJK) were reported damaged or destroyed (Al Jazeera, 2025).

Vulnerability is uneven. For fog, motorcyclists, rickshaw drivers and pedestrians face the highest crash risk, while children, older adults and people with respiratory disease are most affected by smog. In the mountains, the poor, children, older adults, people with disabilities and tourists unfamiliar with the terrain are at greatest risk; the Swat case drew anger over slow response (Associated Press, 2025). Gender matters in both settings. Women travelling in the dark face added safety risks during fog, and in mountain households women and girls may have limited mobility and may receive warnings later because information often circulates in male-dominated spaces. The PDMA Sindh plan explicitly lists women, pregnant and lactating women, children, older adults and persons with disabilities as groups needing targeted winter support (PDMA Sindh, 2025).

Exposure is concentrated on the M-1 to M-5 and M-11 corridors for fog, and on alluvial fans, stream banks and riverside tourist sites for cloudbursts. Susceptibility rises with poor lane marking and speeding on roads, and with steep slopes, deforestation, fragile housing and encroachment on channels in the mountains. Poverty and weak enforcement of land-use and building rules sit behind both.

4. Community Resilience Factors

Communities already have useful knowledge. Drivers are told to use fog lights, reduce speed and avoid unnecessary night travel, and the Motorway Police helpline (130) is promoted for help (Aaj News, 2024). NDMA guidelines ask PDMAs and District Disaster Management Authorities (DDMAs) to involve local communities in monitoring, early warning feedback, awareness campaigns in schools, community centres and religious spaces, and mock exercises (PDMA Sindh, 2025). In mountain areas, kinship networks mean villagers are often the first rescuers, and places such as the hujra and the mosque already work as channels for passing on warnings.

Indigenous knowledge also matters. Residents who recognise the sound and colour of swollen streams, remember old high-water marks or avoid old channels can trigger

evacuation before formal alerts arrive. A Buner teacher described the thunder that day as sounding like the end of the world (Reuters, 2025a), a reminder that people sense danger before any message does. However, such knowledge is rarely documented or built into official risk assessments, and structured community participation in fog preparedness is hard to find in the literature reviewed.

5. Scientific and Institutional Gaps

Observation is the first gap. Station data give only point observations of fog, so researchers use satellite products to map it (Khokhar et al., 2016). Cloudburst conditions can develop over areas as small as 10 km across, which satellites struggle to detect (TNN English, 2025), and observation networks in Himalayan terrain are sparse (Dimri et al., 2017). A KP official argued that no system can predict the exact time and place of a cloudburst (Arab News, 2025a). That is true at point scale, but probabilistic nowcasting and impact-based forecasting, possibly supported by AI and machine learning, can still flag high-risk catchments.

Institutional gaps are just as serious. The National Disaster Management Act 2010 created the NDMA, PDMAs and DDMAs (Government of Pakistan, 2010), and fog is now covered in winter contingency plans with activation triggers, such as an alert when visibility stays below 200 m for more than three hours and a critical level below 50 m (PDMA Sindh, 2025). The weakness lies in delivery. The Post Monsoon Review 2025 notes progress in contingency planning and early action but also fragmented coordination and uneven data-sharing between provinces (Pakistan Post Monsoon Review, 2025). Reporting on the Buner event showed that a warning system existed but the downpour came before residents could be alerted (Arab News, 2025a), and commentators point to overlapping roles among SUPARCO, the PMD, the NDMA, PDMAs and DDMAs and to thin PMD staffing in northern flood zones (The Friday Times, 2025).

6. Mitigation Strategies and Best Practices

For fog, structural measures in PDMA plans include reflective road studs, fog lights, hazard beacons and visibility signage on motorways and rural links (PDMA Sindh, 2025). Non-structural measures include enforced speed limits, action against crop-residue burning (which prolongs fog), advisories through electronic signs, SMS and social media, school timing adjustments during heavy fog, and temporary limits on traffic and industry

in peak smog periods, all of which appear in NDMA smog guidelines (PDMA Sindh, 2025).

For cloudbursts, structural options include check dams and gabion walls on steep tributaries, properly sized culverts and bridges, slope stabilisation and catchment reforestation, designed for flash-flood and debris-flow loads. Non-structural options include hazard zoning, riverbank setbacks, building-code enforcement, tourist controls near rivers during alerts and relocation from the most dangerous sites, as the KP chief minister pledged after Buner (Reuters, 2025a). Capacity building should cover search and rescue, first aid and drills for PDMAs, DDMAs, Rescue 1122 and volunteers. Pakistan can build on its National Monsoon Contingency Plan, which NDMA prepares every year before the monsoon (NDMA, 2022), the National Disaster Management Plan 2025, which stresses climate risk, hazard analysis and provincial coordination (NDMA, 2025), and the Early Warnings for All framework (World Meteorological Organization [WMO] & UNDRR, 2022).

7. Risk Communication and Early Warning

A useful warning has to reach people in time and tell them what to do (WMO & UNDRR, 2022). The NDMA's National Emergencies Operation Center (NEOC) already issues impact-based alerts, including flash-flood and glacial lake outburst flood (GLOF) warnings (Arab News, 2025b). The next step is to make every alert say what will happen and where, for example that a motorway section will close or that flash floods are expected in named valleys, instead of debating whether an event counts as a cloudburst. Because cloudburst lead times may be minutes, formal alerts should be paired with simple local triggers: when intense rain starts, households near streams move uphill without waiting for instructions.

Channels should be people-centred and gender-sensitive: cell-broadcast SMS, the Pak NDMA Disaster Alert mobile application, radio, television, variable message signs, toll plazas, bus terminals, mosque and community loudspeakers, sirens in high-risk valleys and trained upstream volunteers. Messages should be in Urdu, Pashto, Sindhi and other local languages, reach women through schools, health workers and women's groups, and reach tourists through geo-targeted alerts.

8. Policy Recommendations

- Integrated governance: Adopt common hazard definitions and joint protocols among the PMD, NDMA, PDMAs, DDMAs, the National Highways Authority and the Civil Aviation Authority so that one authoritative message reaches the public.
- Climate adaptation: Treat fog and smog as a joint problem with enforceable controls on crop-residue burning and emissions, and mainstream flash-flood risk into climate adaptation plans for mountain districts.
- Technology integration: Install automated visibility sensors on high-risk motorways, expand rain gauges, Doppler radar and river sensors in mountain valleys, and pilot AI-supported nowcasting.
- Institutional strengthening: Enforce hazard zoning, building codes and riverbank setbacks, and build a unified database of fog crashes, rainfall intensity and disaster losses.
- Community participation: Support community-based early warning with trained volunteers, women's participation and documentation of indigenous knowledge.
- Evidence-based measures: Fund studies on fog trends, extreme sub-daily rainfall and economic losses, and use them to set thresholds and priorities in line with the Sendai Framework (United Nations, 2015).

9. Conclusion

Fog and cloudbursts look very different, but the evidence shows common causes of loss: exposed people and infrastructure, sparse observation, short or poorly communicated warnings and fragmented institutions. Fog comes from Indus basin moisture, stable air and heavy aerosol loads, and it disrupts the most productive part of the country. Cloudbursts interact with steep terrain and fragile settlements to cause mass-casualty events, as in Buner in 2025.

Pakistan has moved from relief-based response towards planning, with contingency plans, activation triggers and impact-based alerts. The task now is to make these work at the last mile. That needs science-based planning, better monitoring, control of pollution and land use, and real use of social capital and local knowledge, supported by coordination across meteorological, disaster management, transport and community institutions.

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Annex A: Comparative Hazard–Risk Matrix and Priority Actions

Component	**Fog and dense fog (plains)**	**Cloudburst (mountains)**
Hazard	Visibility < 200 m is dense fog; Nov – Mar; moisture, inversions and aerosols	Rain > 100 mm/h over ~20–30 km ^{2} ; flash floods, debris flows, landslides
Exposure	Motorways, highways, airports, commuters, freight	Homes on stream banks, riverside tourism, roads, bridges

Component	Fog and dense fog (plains)	Cloudburst (mountains)
Vulnerability	Motorcyclists, daily-wage workers, children, older adults, women travelling in the dark	Fragile housing, poverty, women, children, older adults, tourists
NDMA/PDMA tools	Winter contingency plans; fog triggers (< 500 m, < 200 m, < 50 m); smog guidelines	National Monsoon Contingency Plan; NEOC impact-based alerts; NDMP 2025
Priority actions	Visibility sensors; closure protocols; emission control; driver training	Radar and gauges; zoning and setbacks; community early warning; drills

Note. Fog thresholds follow PDMA Sindh (2025) and Khokhar et al. (2016). Synthesised by the author from the sources cited in this paper.

PARTICIPANT RESEARCH PAPER

Climate-Induced Migration and Displacement in Pakistan: Policy Challenges and Humanitarian Responses

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Certificate Course in Disaster Management

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Abstract

Pakistan contributes about one percent of global greenhouse gas emissions yet ranks among the countries most exposed to climate extremes (Arab News, 2026). This paper examines climate-induced migration and displacement in Pakistan, focusing on flood-driven mobility between 2010 and 2025, and asks why humanitarian response alone cannot address its core. Drawing on government assessments, United Nations and Red Cross reporting, attribution science and policy literature, it profiles hazards, assesses vulnerability, and reviews community resilience, institutional gaps, mitigation practice and early warning. Displacement proves recurrent rather than exceptional: roughly eight million people were displaced in 2022 and about three million at the 2025 peak. Pakistan has no national legal or policy framework for disaster-displaced people, climate policy treats migration only in passing, and recovery lags far behind relief. The paper recommends a rights-based displacement policy, integration of mobility into adaptation and DRR planning, anticipatory early warning, resilient housing with planned relocation, and sustained, gender-responsive finance.

Keywords: Climate adaptation, disaster risk reduction, displacement, humanitarian response, Pakistan

1. Introduction

Climate change is reshaping where people can live safely. In Pakistan, floods, glacial lake outbursts, drought, heat and coastal erosion repeatedly destroy homes and livelihoods, forcing households to move temporarily or permanently. The 2022 floods affected about 33 million people and caused damage exceeding USD 14.9 billion (Government of Pakistan et al., 2022). The 2025 monsoon affected nearly seven million more (Arab News, 2026). These are no longer exceptional shocks but a pattern that tests the national disaster management system.

The problem is that rescue, shelter and food assistance, delivered by the National Disaster Management Authority (NDMA), provincial authorities and humanitarian partners, leave displaced households in prolonged vulnerability, because Pakistan lacks a legal status, policy framework and long-term financing for people displaced by climate-related disasters (Amjadullah, 2023; CASSTT, 2022). Relief treats the symptoms of displacement rather than its structural causes.

The purpose of this paper is to analyse that gap. Its objectives are to profile the hazards driving displacement, assess vulnerability and resilience, identify scientific and institutional gaps, and propose actions consistent with the Sendai Framework (United Nations Office for Disaster Risk Reduction [UNDRR], 2015). The scope is internal displacement in Pakistan from 2010 to 2025, with emphasis on flooding, and the method is a desk-based analysis of secondary sources.

2. Regional Context and Hazard Profile

A hazard is a climate-related event or process, such as a flood or drought, that may cause harm; exposure describes the people and assets in hazard-prone areas; vulnerability is their susceptibility to harm; and risk emerges from the interaction of all three. Climate-induced displacement is the forced movement of people, mostly within national borders, in response to such hazards.

Flooding is the dominant driver. Attribution analysis found that peak five-day rainfall in the worst-hit areas of Sindh and Balochistan in 2022 was about 75 percent more intense under observed trends, although climate models suggested a smaller contribution of up to 50 percent, and the authors stressed that vulnerability magnified the disaster (World Weather Attribution [WWA], 2022). Mass displacement is recurrent: an estimated 11

million people were displaced in 2010 and four million in Sindh in 2011 (CASSTT, 2022), about eight million in 2022 (Shahzar, n.d.), and around three million at the September 2025 peak, falling to roughly 150,000 by late October as most evacuees returned (International Federation of Red Cross and Red Crescent Societies [IFRC], 2025).

Slow-onset change adds a second pathway. More than 3,000 glacial lakes have formed in Gilgit-Baltistan and Khyber Pakhtunkhwa, 33 of them assessed as prone to outburst (United Nations Development Programme [UNDP], 2022), and coastal erosion has reportedly displaced about 1.2 million people in the Indus Delta (Shahzar, n.d.). Table 1 summarises these pathways, synthesised from UNDP (2022), Shahzar (n.d.) and WWA (2022).

Table 1. Main Climate Hazards and Displacement Pathways in Pakistan

Hazard	**Main areas affected**	**Displacement pathway**
Monsoon and riverine floods	Indus basin provinces	Sudden mass evacuation; prolonged housing loss
Glacial lake outburst floods	Gilgit-Baltistan and Khyber Pakhtunkhwa	Local loss of homes, land and bridges
Coastal erosion	Indus Delta	Gradual loss of land and livelihoods
Drought and heat	Arid rural districts	Livelihood decline and migration

3. Risk and Vulnerability Assessment

The 2022 Post-Disaster Needs Assessment estimated damage of USD 14.9 billion, economic losses of about USD 15.2 billion and resilient reconstruction needs of at least USD 16.3 billion (Government of Pakistan et al., 2022). Agriculture and livestock suffered

heavily, women's livelihoods in these sectors were notably affected, and the losses spilled over into industry, trade and services, threatening rural incomes and food security.

Housing is the clearest measure of why displacement persists. About two-thirds of the more than eight million people displaced in 2022 were in Sindh, where 2.1 million houses were partially or fully damaged; a year later, reconstruction of a planned two million homes had advanced by less than eight percent (FairPlanet, 2023). Exposure and susceptibility were shaped by low-lying settlements, poor drainage and the absence of housing-rights legislation (FairPlanet, 2023). Displaced households that move to cities add pressure on urban services, and Karachi is expected to receive growing numbers of climate migrants (Shahzar, n.d.).

Vulnerability is unevenly distributed. In Khairpur, Sindh, women displaced by the 2022 floods faced layered vulnerabilities and gender-specific protection gaps (Amjadullah, 2023), and in 2025 women, children and other vulnerable groups were disproportionately affected (Arab News, 2026). Critically, official figures mostly count people evacuated or sheltered; those who remain in damaged homes, or migrate informally, are largely invisible, so the scale of lasting climate migration is probably underestimated.

4. Community Resilience Factors

Resilience depends on capacities that exist before a disaster. In northern Pakistan, community-based disaster risk management has built some of them: the GLOF-II programme reported 51 trainings for more than 1,600 participants and 71 mobilisation sessions reaching over 2,000 people (PreventionWeb, n.d.). Social capital, meaning kinship, neighbourhood and village networks, typically provides displaced households with first shelter, food and information, while local knowledge of river behaviour and safe ground can complement scientific forecasts. Such assets are rarely documented or built into official plans.

Resilience capacities are also unequal. Amjadullah (2023) shows weak service provision for displaced women, so participation structures must deliberately include them. Fiji's planned relocation guidelines require inclusive, gender-responsive consultation and recognition of indigenous knowledge (Government of Fiji, 2018), a standard Pakistan could adopt. Finally, resilience erodes when displacement is prolonged: families in temporary arrangements for over a year face mounting hardship (FairPlanet, 2023).

5. Scientific and Institutional Gaps

Four gaps weaken the response. First, data: estimates of 2022 displacement range from at least 7.9 million (CASSTT, 2022) to over eight million (Shahzar, n.d.), suggesting that no standardised system tracks who is displaced, where and for how long. Second, law and policy: no national legislation guarantees long-term protection for disaster-displaced people, the updated National Climate Change Policy launched in 2022 mentions climate-induced migration only briefly, and the national disaster risk reduction policy and risk management framework are similarly silent (CASSTT, 2022).

Third, institutional design: NDMA has described Pakistan's system as a three-tier devolved structure in which primary responsibility lies with provincial and district authorities (State of Children, 2025). Devolution can strengthen local ownership, but without displacement-specific mandates and funding it fragments accountability, a weakness Shahzar (n.d.) describes as institutional disarray. Fourth, technology and research: artificial intelligence and machine learning could improve flood forecasting, satellite damage mapping and displacement tracking, yet none of the sources reviewed documents their systematic use in managing displacement in Pakistan. Longitudinal evidence on what happens to households after relief ends is also scarce; Amjadullah (2023) offers a single district-level study that cannot be generalised nationally.

6. Mitigation Strategies and Best Practices

Structural measures include flood-resilient housing, improved drainage and protective infrastructure, such as the barriers and warning systems built under GLOF-II. The Post-Disaster Needs Assessment framed recovery around building back better on the principles of poor first, transparency, inclusion and climate resilience (Government of Pakistan et al., 2022). Non-structural measures include land-use planning, secure housing rights, training and preparedness. The National Adaptation Plan approved in July 2023 prioritises natural capital, urban resilience, human capital and disaster risk management (Press Information Department, 2023), but the sources reviewed do not show a displacement-specific protection mechanism within it.

International practice offers models. The Guiding Principles on Internal Displacement apply to people displaced by natural or human-made disasters and set rights-based standards for protection and durable solutions (United Nations Commission on Human

Rights, 1998). The African Union's Kampala Convention (2009) turned such standards into a binding regional treaty that covers disaster displacement. Fiji's 2018 Planned Relocation Guidelines created a national, participatory process for relocating communities (Government of Fiji, 2018). The Sendai Framework adds the call to build back better in recovery (UNDRR, 2015).

7. Risk Communication and Early Warning

Early warning is effective only when it reaches people and prompts action. Before GLOF-II, only two districts in the north had outburst warning systems and protection structures, serving about 14,000 people, and vulnerable households could not receive or respond to warnings (PreventionWeb, n.d.). Even now, the director general of the Gilgit-Baltistan Disaster Management Authority stresses that coverage is narrower than widely assumed: GLOF-II covered only 16 selected valleys and limited sites within them (Al Jazeera, 2026). Provincial authorities issue threat alerts and monsoon contingency plans (State of Children, 2025), and more than three million people were rescued or evacuated in 2025 (Arab News, 2026). Yet Khyber Pakhtunkhwa recorded 504 deaths that year, 256 of them in Buner district (State of Children, 2025), suggesting that alerts alone do not guarantee protective action. People-centred systems therefore need last-mile channels in local languages, community volunteers, and gender-sensitive messaging that reaches women directly.

8. Policy Recommendations

The analysis supports six evidence-based recommendations. First, adopt a national law or policy on disaster-induced displacement, aligned with the Guiding Principles, that defines status, rights and the duties of federal, provincial and district authorities (CASSTT, 2022; United Nations Commission on Human Rights, 1998). Second, integrate human mobility into the National Climate Change Policy, the National Adaptation Plan and NDMA and provincial disaster management plans (Press Information Department, 2023). Third, establish a national displacement data system disaggregated by sex and age, and pilot AI-supported flood forecasting and damage mapping (Shahzar, n.d.).

Fourth, extend anticipatory, people-centred early warning beyond pilot valleys and flood-prone districts, with gender-sensitive last-mile delivery (Al Jazeera, 2026; PreventionWeb, n.d.). Fifth, invest in resilient housing, secure housing and land rights, and national

planned relocation guidelines modelled on Fiji's (FairPlanet, 2023; Government of Fiji, 2018). Sixth, ring-fence recovery finance within adaptation budgets, build provincial and district capacity, and continue to press for international loss and damage funding, which Pakistan has urged developed countries to operationalise (Arab News, 2026). Because responsibility is devolved, provinces must co-own each reform.

9. Conclusion

Flood-driven displacement is a recurring feature of Pakistan's climate risk, not an exception. Humanitarian response saved millions of lives in 2022 and 2025, but it is designed to stabilise, not to resolve. Without legal recognition, durable housing and planned relocation, displaced households return to exposed places or settle informally in cities. Resilience therefore requires science-based planning, reliable data, social capital, local knowledge, appropriate technology and integrated governance across federal, provincial and district levels. This study is limited by its reliance on secondary sources and varying displacement estimates; field research on the long-term outcomes of displaced households is the priority for future work.

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PARTICIPANT RESEARCH PAPER

Community-Based Early Warning Systems (CBEWS): Successes and Limiting Factors — A Case Study of the GLOF-II Project

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Abstract

Community-based early warning systems (CBEWS) are widely promoted for glacial lake outburst floods (GLOFs), but installed equipment does not by itself produce protective action. This paper evaluates the warning chain of the GLOF-II project, which scales up GLOF risk reduction in 24 valleys of Gilgit-Baltistan (GB) and Khyber Pakhtunkhwa (KP), Pakistan. Using qualitative secondary research, it combines a thematic synthesis of the literature with analysis of project documents, organised by a four-pillar framework that separates outputs from outcomes. Technical and operational achievements are well documented, including 15 GLOF alerts and 84 warnings in 2026. Evidence on community outcomes is thin, and equipment theft, donor dependence, staffing shortfalls and weak last-mile communication threaten sustainability. Warning effectiveness depends on the whole chain, and community ownership is its most important and least-evidenced link.

Keywords: community-based early warning; glacial lake outburst flood; people-centred early warning; Gilgit-Baltistan; sustainability; Pakistan

1. Introduction

Northern Pakistan contains thousands of glaciers, and their retreat has enlarged and multiplied glacial lakes in high-mountain valleys (Wester et al., 2019; Rounce et al., 2017). Glacial lake outburst floods are among the most destructive cryosphere hazards because they release large volumes of water, ice and debris, often with little warning (Carrivick & Tweed, 2016; Kääb et al., 2005). The Shishper lake in Hunza illustrates the problem. Singh et al. (2023) document outbursts there in 2019, 2020 and 2022, and Ali (2024) shows the lake forming in 2018 and growing until the May 2022 event.

Early warning is the standard response, and CBEWS are promoted because they link technical detection to local action (Basher, 2006; Macherera & Chimbari, 2016). Sensors and sirens, however, do not show that people receive, understand and act on warnings. This paper tests that gap through GLOF-II, a Green Climate Fund (GCF) scale-up implemented in 24 valleys (UNDP, 2023). It asks what successes can be documented across the warning chain, what limits performance and sustainability, and which lessons transfer. It distinguishes outputs (equipment installed, alerts issued) from outcomes (warnings understood, protective action taken, losses reduced).

2. Background and Conceptual Framework

2.1 Literature Review

People-centred early warning systems are commonly described as four interacting elements: disaster risk knowledge, monitoring and warning services, dissemination and communication, and response capability (Basher, 2006; Macherera & Chimbari, 2016). The Sendai Framework calls for greater availability of, and access to, multi-hazard early warning systems (UNISDR, 2015). Warning research treats warnings as social processes in which messages must reach people, be believed and be translated into action (Mileti & Sorensen, 1990). Recent evidence from Lunana, Bhutan, shows the same pattern in a glacial setting. Sirens existed, but they were not activated in either the 2019 or the 2023 event, and residents learned of flooding mainly from environmental cues and informal phone calls (Rinzin et al., 2026).

Community knowledge is a second strand. Mercer et al. (2010) argue for integrating indigenous and scientific knowledge. Ahmed (2025) presents community-operated systems as sustainable when locals are trained to run them, but notes that trust erodes

after false alarms; as a synthesis of existing literature, its claims are plausible rather than established. Regional evidence is uneven. Carrivick and Tweed (2016) compiled 1,348 glacier outburst floods at 332 sites in 20 countries and called for standardised monitoring. Butt et al. (2025) report awareness and training gaps in the Upper Indus Basin, although their well-educated respondents limit generalisation to mountain households.

2.2 Conceptual Framework

Figure 1 adapts the four pillars into an evaluation framework and shows the cross-cutting conditions that moderate each pillar. Figure 2 traces the warning-to-action chain. Outputs can be verified at the first four stages, for example by counting stations or confirming that a siren sounded. Outcomes at the last three stages, such as comprehension, protective action and reduced losses, require evidence from the community itself. This distinction structures the analysis in Sections 5 and 6.

Figure 1. Conceptual framework for evaluating community-based early warning systems

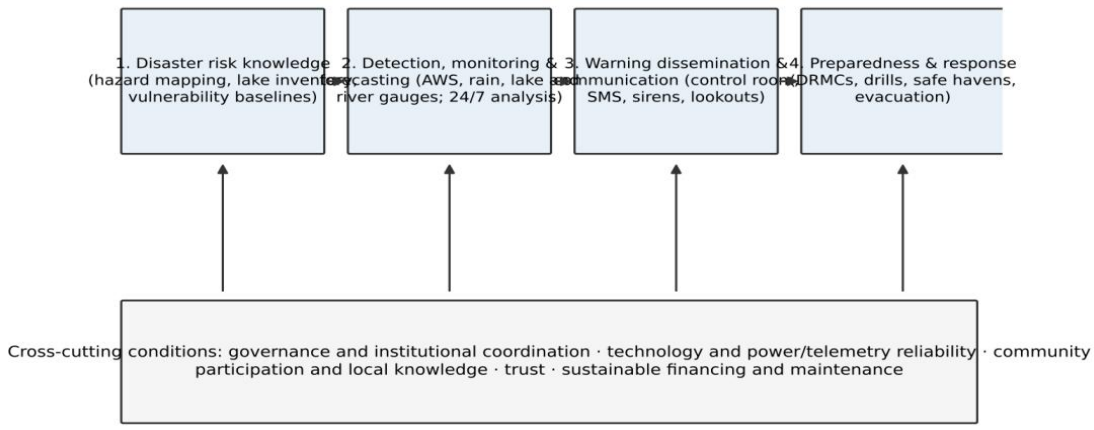
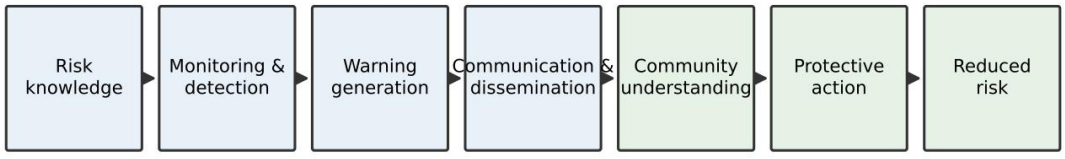


Figure 2. The warning-to-action chain (output stages are left; outcome stages are right)



Outputs are verifiable at the first four stages; outcomes require evidence at the last three.

3. Study Context: The GLOF-II Project

According to the UNDP project brief, the GCF financed about US$36.9 million, with US$0.5 million co-finance from the Government of Gilgit-Baltistan. The Ministry of Climate Change is the implementing partner and UNDP the funding partner (UNDP, 2023). Planned outputs include 24 early warning systems, 50 weather monitoring stations, community-based disaster risk management committees (CBDRMCs) in 24 valleys, and training for more than 150 officials. The expected result is that all households in target communities can receive and respond to warnings. The Pakistan Meteorological Department (PMD) runs the monitoring network, with about 20 staff working around the clock (PMD, 2026.). The predecessor GLOF-I project (2011–2015) reported a six-month start-up delay and no maintenance problems, but no operational early warning system (Adaptation Fund, n.d.).

4. Methodology

Design: The study is a qualitative secondary-research case study combining a literature review with a document-based analysis of GLOF-II. Evidence was synthesised thematically within the framework in Figure 1.

Search: Approximately thirty web searches combined the concepts community-based early warning, people-centred early warning, glacial lake outburst flood, Gilgit-Baltistan, Hindu Kush Himalaya, sustainability, risk communication and local knowledge, supplemented by citation tracing. Coverage spanned 2000 to 2026, prioritising Pakistan, Nepal, Bhutan and the Hindu Kush Himalaya (HKH). Bibliographic databases (for example, Scopus) were not accessible, so systematic completeness cannot be claimed.

Screening: Records were included if they were English-language peer-reviewed articles, academic books, academic or intergovernmental reports, or official project documents addressing CBEWS, GLOF warning or early warning in mountain settings. News items, commercial pages, unsourced web material and records whose citation details could not be verified were excluded. Eighteen sources were retained (Table 1).

Extraction and synthesis: Each source was coded for location, hazard, framework pillar, technology, community role, dissemination, response, sustainability and evidence strength, and themes were developed within the framework. Project documents were treated as self-reported. Where full texts were inaccessible, claims are drawn from

abstracts or repository summaries and flagged. Conflicting figures are reported rather than resolved (Section 5.3).

Table 1. Characteristics of the evidence base

Source category	Number	Evidential weight	Role in this paper
Peer-reviewed articles	12	High; several are reviews or single-site studies	Conceptual and regional evidence
Academic book	1	High	Regional HKH context
Academic (technical) report	1	Moderate to high	Warning-communication theory
Intergovernmental source	1	High for policy framing	Sendai Framework targets
Project documents and presentation	3	Low to moderate; self-reported and unaudited	GLOF-II and GLOF-I case data

Note. Total N = 18. PMD field reports(2025-2026); project documents are UNDP (2023) and Adaptation Fund (n.d.).

5. Findings

5.1 Documented Successes

The most clearly documented achievement is technological scale. The GLOF-II network comprises 279 units, including 38 automatic weather stations, 80 rain gauges, 48 warning posts and 113 water-level and discharge gauges (Awan, n.d.). Twenty staff monitor the system around the clock, and a satellite communication contract with Marlink reduces dependence on mobile networks. In 2026, the system generated 15 GLOF alerts, 27

siren activations and 84 warnings to communities and district administrations. Table 2 classifies these achievements; all are outputs, and none is yet verified as an outcome.

The deck does not report whether residents evacuated after the sirens sounded, so siren activations are an output with an unverified outcome. A post-event verification survey is listed, but no results are reported. The brief records mock drills for 2020 to 2022 and CBDRMC planning (UNDP, 2023). These are preparedness outputs and the strongest evidence of engagement in the record, though they say little about community understanding.

Table 2. Documented successes classified as outputs or outcomes

Achievement	Evidence	Classification	Interpretation
Hydro-meteorological network across 24 valleys	279 units (PMD, 2025)	Output	Technological scaling in 24 targeted valleys
Round-the-clock monitoring	GLOF Monitoring (PMD, 2026)	Output	Staffing sustainability unresolved
Alerts, sirens and warnings	15 alerts; 27 sirens; 84 warnings (PMD, 2026)	Output	No evidence of receipt, comprehension to all house holds or evacuation
Equipment repairs	147 stations repaired (PMD, 2025-2026)	Output	Shows maintenance capacity; community conflict
Community committees and drills	Mock drills 2020–2022 (UNDP, 2023)	Output	No outcome data on drill participation or response

Note. Classifications are the author's inference from the source type.

5.2 Limitations and Limiting Factors

The limitations concentrate in the operational and sustainability dimensions (Table 3). PMD reports that winter conditions cause battery failures, sensor degradation and telemetry dropouts, and that theft has removed solar panels, batteries and sensor wires at several sites (PMD, n.d.). It also identifies a short lead time, which it gives as a 30–60 minute siren warning. That figure is not sourced and may not hold across valleys. Institutional capacity is the second concern. Nine posts were recommended by the MS Wing, against 52 requested by PMD for sustainability (PMD, n.d.). GLOF data are viewed through two platforms: an operational system described as rigid and designed to the equipment vendor's requirements, and a PMD management portal described as flexible and usable by other departments (PMD, n.d.). Dependence on international climate finance then raises questions about post-project operation, spares and field costs.

Table 3. Documented limitations and limiting factors

Domain	Evidence	Interpretation
Technical / Communication	Battery and telemetry failure in winter; theft and damage at several sites. Mobile-network availability gaps and dead zones in some locations	Equipment is fragile without protection and maintenance budgets. Network limitations may disrupt timely warning dissemination and last-mile communication with households.
Operational	30 – 60 minute siren lead time; mobile dead zones cause dashboard–household gaps	Lead time may be insufficient for livestock and infrastructure; last-mile delivery is unverified
Institutional	Existing strength and capacity; rigid operational platform for additional scaling	Staffing and system design constrain sustainability and cross-department use

Domain	Evidence	Interpretation
Implementation	Project delays reported in independent evaluations (unnamed)	Cannot be checked against the deck; the evaluation must be obtained
Financial	Reliance on GCF and UNDP finance; needs listed for staff, vehicles, spares, fuel and communications	Post-project continuity is unfunded on current evidence
Community	Limited evidence of awareness, drills or household preparedness	Reach and comprehension are unmeasured

Note. Lead time and delay statements are reported in the presentation without source citations.

6. Discussion

6.1 Outputs Are Not Outcomes

GLOF-II's headline indicators (alerts, sirens, warnings issued, stations repaired) belong to the monitoring and dissemination pillars. They show that the chain functioned mechanically. They do not show that residents heard, understood or moved. Lunana demonstrates that a siren network can be ineffective when community awareness and drills are weak (Rinzin et al., 2026). The GLOF-II brief sets a target of universal household reach (UNDP, 2023), which is a plausible goal but one for which the current record offers no measurement. Treating the target as achieved would confuse outputs with outcomes.

6.2 Technical Performance and Social Ownership

The PMD field reports conclude that community ownership matters more than the sensors. This is consistent with Mercer et al. (2010), but the case cannot test it because community-level data are missing. The most consequential failures identified here, namely theft, damaged sensors and donor dependence, are also social and institutional.

Equipment that no one protects will fail, so a technically strong system can still fail at its last link.

6.3 Specific or Common

Most limitations are not unique to GLOF-II. Theft, winter power failure, mobile dead zones and staffing gaps recur across mountain CBEWS (Macherera & Chimbari, 2016; Rinzin et al., 2026), and Table 4 compares the cases directly. The Chamoli disaster demonstrates a further point. Shugar et al. (2021) show that a rock and ice avalanche can trigger a cascade of flooding without a glacial lake, so a lake-focused system must also monitor flash floods. The PMD reports indicates that GLOF-II detects flash floods, which is a strength. Lake dynamics, however, must also be tracked continuously. Ali (2024) shows that the Shishper lake grew from 2018 to 2022 before each outburst, so volume monitoring matters as much as event detection.

Table 4. Comparison with selected regional cases

Case	Setting	Documented warning performance	Transferable lesson
GLOF-II	GB and KP, Pakistan	Pillars 1–3 operating; pillar 4 unverified	Verify receipt and response; fund maintenance
Lunana, Bhutan (2019, 2023)	Glacial lake, Bhutan	Sirens not activated; informal channels dominated	Add redundant channels; run drills
Upper Indus Basin	Pakistan (survey)	Awareness and training gaps reported	Build training into the warning chain

Note. Comparisons identify transferable mechanisms. They do not imply equivalent performance.

7. Lessons Learned and Recommendations

Three lessons follow. First, a warning system should be judged by its last link, so evaluation must measure receipt and response rather than alerts issued. Second,

maintenance and staffing must be funded as part of the system, not treated as a project add-on. Third, local knowledge and drills should shape thresholds and procedures from the outset. Table 5 converts these lessons into recommendations, with the dimension responsible for each.

Table 5. Recommended improvements and responsible dimensions

Recommendation	**Evidence basis**	**Responsible dimension**
Fund spares, vehicles and communications	PMD (n.d.)	Government (PMD, Ministry of Climate Change)
Publish the verification survey and warning-receipt data	PMD (n.d.)	PMD and UNDP/PDMAs
Formalise redundant channels: SMS, radio, satellite phone, sirens	Rinzin et al. (2026); PMD	PMD, CBDRMCs, Telecomunication Authority
Institutionalise drills, schools programmes and household kit checklists	Rinzin et al. (2026)	District authorities and CBDRMCs
Protect equipment through community guardianship	PMD(n.d.)	Communities and CBDRMCs
Integrate local knowledge into threshold setting	Mercer et al. (2010)	PMD working with communities
Reconcile project figures	PMD	Ministry of Climate Change and UNDP

8. Conclusion

GLOF-II has built a substantial monitoring and warning network across 24 valleys and documented its operation in detail. The evidence supports the claim that the technical chain works, but not yet that the community warning system works. Outputs such as alerts, sirens and installed stations must not be read as outcomes such as understanding and protective action. Whether GLOF-II succeeds will depend on funding maintenance, staffing and community preparedness after donor support ends, which requires verified receipt data, reconciled project figures and an independent evaluation.

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PARTICIPANT RESEARCH PAPER

Availability of Clean Water in Karachi

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Abstract

Karachi, Pakistan's largest city faces two overlapping problems: water supply that falls far short of demand, and piped water whose safety is repeatedly questioned. This paper synthesizes peer-reviewed studies, official statements, and investigative reporting published between 2017 and 2026 to assess how available and safe the city's drinking water is. Official figures indicate that Karachi receives about 650 million gallons per day (MGD) against a demand of 1,300 MGD. Sample-based studies report that between 16.67% and 58.06% of samples were suitable for drinking across five districts in 2023, and that 90.7% of 118 samples were unsafe in a 2017 task-force sampling. Leaking pipes, sewage cross-connection, intermittent supply, and weak disinfection are the main contamination pathways, and the resulting health and financial burdens fall hardest on low-income households. Evidence on citywide water quality remains thin, responsibilities are split between bulk-supply and distribution agencies, and results of recent testing programs are not yet public. The paper recommends network rehabilitation, tail-end disinfection, regular public testing, and targeted support for underserved areas.

Keywords: Karachi, drinking water quality, water supply, contamination, water governance, public health

1. Introduction

Safe drinking water is a basic requirement for health, yet 2.1 billion people worldwide still lack safely managed drinking water services (World Health Organization [WHO] & United Nations Children's Fund [UNICEF], 2025). In Pakistan, a review of national evidence links water contamination to substantial health risks (Fida et al., 2023). Karachi illustrates the problem at city scale. With more than 14 million residents at the 2017 census, the city depends mainly on Keenjhar Lake, fed from the Indus River, with the Hub Dam as a secondary source (Khalid et al., 2023).

Clean water availability has two dimensions that are often discussed separately: quantity (is enough water delivered regularly?) and quality (is the water safe to drink when it arrives?). A household can receive water and still lack clean water. This paper therefore asks four questions: how large is the gap between supply and demand; how safe is the supplied water and how does it become contaminated; who bears the health and economic risks; and which scientific and institutional gaps stand in the way of improvement.

The paper is a narrative review. It draws on peer-reviewed studies of Karachi's water quality, official statements on supply and projects, and one investigative report on a government task-force sampling, supplemented by WHO guidance. Because most quality studies use small, area-specific samples, their results are treated as warning signals rather than as a citywide audit.

2. Karachi's Water System and the Supply Gap

Official figures show a persistent shortfall. In July 2025, Sindh's chief minister told the federal water minister that Karachi receives 650 MGD against a demand of 1,300 MGD (Chief Minister's Secretariat, 2025). Earlier estimates differ in size but not in direction: in 2017 a Karachi Water and Sewerage Board official put requirements at about 1,100 MGD and supply at 450–480 MGD (Ebrahim, 2017). These are administrative estimates rather than published metered data, so the exact gap should be treated cautiously, but supply has consistently covered only about half of demand.

The main bulk-supply response is the K-IV project, designed to eventually deliver 650 MGD from Keenjhar Lake, with Phase I intended to supply 260 MGD (Chief Minister's Secretariat, 2025). Funding has slowed progress. Physical progress stood at 63% in July

2025 (Chief Minister's Secretariat, 2025); in August 2026 the federal water minister reported about 66% completion, Rs86 billion spent, and a further Rs70 billion required, while WAPDA's chairman expected completion by June 2027, subject to funds (Ghumman, 2026). Delivery inside the city is a separate problem. WAPDA supplies water only up to Karachi, distribution infrastructure is a provincial responsibility estimated at about Rs200 billion, and the utility's chief executive expected the distribution system to be completed by December 2028, possibly April 2029 (Ghumman, 2026). New bulk water may therefore reach the city well before it reaches households.

Supply is also intermittent. A water board chemist reported in 2017 that some areas received water only after a week to ten days (Ebrahim, 2017). Intermittency matters for quality as well as quantity, as the next section shows.

3. Water Quality and Contamination Pathways

Khalid et al. (2023) collected 152 tap water samples from five districts and compared them with WHO guidelines. The share classified as suitable for drinking was 16.67% in Malir, 38.71% in Karachi West, 43.33% in Karachi South, 50% in Karachi East, and 58.06% in Karachi Central. Turbidity and chloride were elevated in all districts, mean residual chlorine was below the WHO range, and coliform and *E. coli* were detected in all five districts, with the highest mean counts in Karachi Central. Because Central combined the highest suitability share with the highest bacterial counts, the classification should be read alongside the microbiological results rather than as a simple ranking.

A 2017 task-force sampling by the Pakistan Council of Research in Water Resources collected 118 drinking water samples in Karachi, including supply points as well as taps. Of these, 104 (88.1%) exceeded WHO limits for coliform bacteria, 40 (33.4%) contained *E. coli*, and 107 (90.7%) were unsafe overall (Ebrahim, 2017). In Liaquatabad Town, 23 piped samples from 2022 showed *E. coli* in about 74% and faecal contamination in more than 70%; even where physico-chemical indicators looked acceptable, metal contamination made most samples unsafe by water quality index (Alamgir et al., 2024). The studies differ in year, method, and place, so their percentages are not directly comparable, but they point in the same direction.

Reported causes cluster into four pathways. First, leakage and sewage cross-connection: a council scientist said *E. coli* indicated mixing of sewage and drinking water (Ebrahim,

2017), and Alamgir et al. (2024) attribute contamination to untreated sewage and cross-contamination. Second, intermittent supply: a water board chemist explained that bacteria can multiply in dried-out pipelines and pipe biofilms, which continuous flow would limit (Ebrahim, 2017). Third, weak treatment and disinfection: treatment plants were described as ailing in 2017, with 200 MGD supplied unfiltered (Ebrahim, 2017). Fourth, poor management and planning, including leakages and ineffective management (Kumar et al., 2022).

4. Health, Economic and Equity Risks

Risk depends on hazard, exposure, and vulnerability. Kumar et al. (2022) link poor water sanitation in Karachi to typhoid, diarrhea, and other infections that burden the city's health system, and note low public awareness of safe drinking water and socioeconomic disparities that complicate access to care. A household survey combined with laboratory tests found that contamination raised, and filtration lowered, the prevalence of diarrhea, and estimated the direct health cost of untreated water use at PKR 80.7 million per month for Karachi's population (Jamil et al., 2022).

Vulnerability is unevenly distributed. Households that can pay buy tanker water, bottled water, or filters, while others depend on the piped supply. Ebrahim (2017) describes two related households in a squatter settlement that bought tanker water (PKR 4,000 a month for 45,400 litres) and bottled drinking water (a PKR 200 barrel stretched over two days). The World Bank–supported reform plan likewise lists intermittent supply that fails drinking-water standards, and poor service levels especially in katchi abadis, among Karachi's structural problems ("World Bank Likely," 2024). Because filtration lowers diarrhoea risk (Jamil et al., 2022) but costs money, protection is partly purchased, which makes the burden regressive.

5. Household Coping and Community Resilience

Residents compensate for unreliable public supply through defensive behavior. Documented strategies include buying tanker water, switching to bottled or sealed filtered water, and installing filters (Ebrahim, 2017; Jamil et al., 2022). Household storage is another buffer, but it can also become a contamination point: a water board chemist urged residents, high-rise buildings, mosques, and hospitals to clean their underground tanks regularly (Ebrahim, 2017).

These responses show adaptive capacity, yet three limits weaken resilience. They are costly, so protection is unevenly available; they depend on awareness, which Kumar et al. (2022) describe as low; and they treat symptoms, because filters and storage hygiene cannot repair leaking, cross-connected pipes. Community-level assets are under-documented: none of the sources reviewed here evaluates shared treatment points, neighborhood tank-cleaning schemes, or community monitoring in Karachi, which is itself a research gap. Resilience therefore depends mainly on whether the public system becomes reliable, not on household adaptation alone.

6. Scientific and Institutional Gaps

Scientific gaps. The evidence base is fragmented. Studies use different years, standards, and sampling designs (23 piped samples in one town, 152 samples across five districts, and 118 samples in a 2017 task-force exercise), and none provides continuous, citywide, publicly accessible monitoring. Khalid et al. (2023) used the 2011 WHO guidelines, which have since been updated (WHO, 2022), and sampling at the tap does not capture contamination in household storage. Supply and demand figures also vary by source and rest on administrative estimates (Chief Minister's Secretariat, 2025; Ebrahim, 2017).

Institutional gaps. Responsibility for the water chain is split. WAPDA delivers bulk water up to the city, whereas distribution is a provincial task that still needs financing (Ghumman, 2026). This creates timing risk: K-IV is targeted for June 2027, while distribution completion is projected for December 2028 or later (Ghumman, 2026). A committee member noted that K-IV's planning document dated from 2010 while implementation stalled for years (Ghumman, 2026), and in 2025 its annual allocation covered only Rs3.209 billion of Rs39.964 billion required (Chief Minister's Secretariat, 2025). Reform efforts exist: the World Bank–supported second phase of the Karachi water services project aims to deliver safely managed water and improve utility performance, and plans a centralized laboratory for biological and metals testing and water safety plans ("World Bank Likely," 2024). In a July 2026 review of the project, water quality testing was expected to begin by 30 July ("Sindh Govt," 2026), but the sources reviewed here report no results, so effectiveness cannot yet be judged.

7. Mitigation Strategies and Best Practices

WHO (2022) advocates a preventive approach built on health-based targets, water safety plans covering the system from catchment to consumer, and independent surveillance, with household treatment and safe storage where supply is not yet reliable. Applied to Karachi, the evidence supports five measures. First, rehabilitate leaking pipes and separate sewage from supply lines, starting where contamination is documented, such as Malir and Karachi West (Khalid et al., 2023) and Liaquatabad (Alamgir et al., 2024). Second, restore and monitor disinfection; with residual chlorine low in the 2023 samples (Khalid et al., 2023), chlorination and residual checks at tail ends deserve priority. Third, move toward continuous, pressurized supply in pilot zones, since drained and stagnant pipes encourage bacterial growth (Ebrahim, 2017). Fourth, match new bulk supply with distribution capacity so that K-IV water can be delivered (Ghumman, 2026). Fifth, support household treatment and safe storage as a bridge measure, because filtration lowers diarrhoea risk (Jamil et al., 2022) and clean tanks prevent recontamination (Ebrahim, 2017).

The sources reviewed offer no cost-effectiveness comparison for Karachi, so these priorities follow the contamination pathways documented in Section 4. They suggest that repairs and disinfection promise the fastest health return, whereas supply expansion helps only if the network can carry clean water.

8. Risk Communication and Monitoring

Risk communication links science to household decisions. Because the appearance of water cannot confirm microbial safety, residents need regular, location-specific information on test results and supply schedules. Three practices would help. First, publish sampling results by neighborhood with standard methods and dates, consistent with WHO's emphasis on independent surveillance (WHO, 2022). Second, issue prompt advisories, such as boil-water or tank-cleaning notices, when tests fail or the network is disrupted, and publish tail-end supply schedules so households can plan. Third, address the awareness gap identified by Kumar et al. (2022) through campaigns on safe storage and household treatment. Messages should state uncertainty plainly: sample-based findings such as those of Khalid et al. (2023) describe the samples tested, not every tap.

If the testing expected in July 2026 (“Sindh Govt,” 2026) releases results openly, it could anchor a public early-warning system.

9. Policy Recommendations

The following recommendations follow from the evidence above and are the author’s synthesis rather than findings of the cited studies.

I. Synchronize bulk and distribution investment by securing distribution financing early, so that K-IV water can reach households soon after completion (Ghumman, 2026).
II. Fund pipe repair and sewer separation first in areas with documented contamination (Alamgir et al., 2024; Khalid et al., 2023).
III. Report tail-end residual chlorine as a public performance indicator, supported by independent surveillance (WHO, 2022).
IV. Commission statistically designed, repeated citywide sampling covering microbes, metals, and household storage, using the planned central laboratory (“World Bank Likely,” 2024), and publish the results.
V. Protect low-income households through subsidized household treatment and tested public water points, because defensive spending is currently regressive (Ebrahim, 2017; Jamil et al., 2022).
VI. Reconcile and publish supply and demand figures based on metering, so that targets and progress can be audited (Chief Minister’s Secretariat, 2025).

10. Conclusion

Clean water in Karachi is limited by both quantity and quality. Officially reported supply covers about half of demand, and sample-based studies from 2017 to 2023 indicate that a large share of piped water is unsuitable for drinking, with contamination linked mainly to leaking and cross-connected pipes, intermittent supply, and weak disinfection. The costs fall unevenly, because those who can afford tankers, bottled water, and filters protect themselves while others cannot. Large projects such as K-IV can ease the quantity gap, but their benefit depends on a distribution system that is still being financed and on a monitoring regime that is not yet public. The most defensible priorities are therefore repair, disinfection, transparency, and targeted support for underserved neighborhoods. Future

research should provide representative, repeated, and publicly accessible measurements, including household storage, so that conclusions rest on more than isolated samples.

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PARTICIPANT RESEARCH PAPER

Risk Communication Strategies for Effective Disaster Preparedness

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Abstract

The ability of individuals to absorb, comprehend, trust, and act upon risk information is just as important to disaster preparedness as prediction accuracy. In Pakistan, where social and economic vulnerabilities intersect with floods, heatwaves, droughts, earthquakes, and landslides, this research investigates risk communication techniques for efficient disaster preparedness. The study examines how exposed populations are impacted by climate-related hazards and why warnings do not always result in preventative action using a qualitative desk-based assessment of government and institutional sources. The magnitude of possible losses is demonstrated by data from the 2022 floods: the national Post-Disaster Needs Assessment projected over US$14.9 billion in direct damage and US$15.2 billion in economic losses (Government of Pakistan et al., 2022). Language and literacy disparities, unequal access to digital channels, false information, a lack of local input, and inconsistent coordination are among the obstacles identified by the investigation. It makes the case that alerts need to be applicable locally, actionable, accessible to women and people with disabilities, and distributed via a variety of media. Community-led planning, more transparent institutional procedures, workplace and school drills, responsible use of digital tools and artificial intelligence, and assessment of people's ability to respond to signals are among the recommendations. Risk communication should be viewed as an ongoing public service that connects local trust, practical preparedness, and climate knowledge.

Keywords: climate change, disaster preparedness, early warning, Pakistan, risk communication

1. Introduction

Disasters pose a major threat to human lives, livelihoods, and economic development. Climate change is intensifying weather-related hazards, while Pakistan remains vulnerable to floods, heatwaves, droughts, earthquakes, and landslides. These risks are further increased by poverty, unplanned urbanization, and limited preparedness. Effective disaster management therefore requires not only accurate forecasting but also clear communication that enables people to take timely protective action.

The main problem addressed in this study is the gap between issuing warnings and enabling communities to respond effectively. Language barriers, misinformation, limited access to digital technology, and weak institutional coordination can reduce the effectiveness of risk communication. Even accurate warnings may fail if people cannot understand them, access assistance, or identify the appropriate protective measures.

Risk communication is therefore essential for bridging the gap between hazard information and practical action. This study is important because it highlights the need for timely, accessible, and inclusive warnings that build public trust, strengthen community preparedness, and support effective disaster response in Pakistan.

1.1 Objectives of the Study

- To examine risk communication in disaster preparedness.
- To identify communication gaps and challenges.
- To recommend effective and inclusive warning strategies.

1.2 Scope of the Study

This study focuses on risk communication in Pakistan, covering floods, heatwaves, and other hazards. It is based on secondary sources from government and institutional reports.

2. Regional Context & Hazard Profile

Communities in Pakistan are vulnerable to riverine and flash floods, heat waves, droughts, earthquakes, landslides, glacial lake outburst floods, and coastal hazards due to the country's topography. The effects of disasters are shaped by interactions between poverty, land use, drainage, water management, and settlement patterns. Exposure refers to people, homes, infrastructure, and livelihoods situated in areas where a danger may arise. A hazard is an event or activity that has the potential to cause harm. While

catastrophe risk represents the possible losses resulting from the combination of hazard, exposure, vulnerability, and capacity, vulnerability defines the circumstances that make those exposed elements more likely to experience harm. One such recent example is the floods of 2022. According to the Government of Pakistan et al. (2022), the Post-Disaster Needs Assessment calculated economic losses of around US$15.2 billion, recovery needs of at least US$16.3 billion, and direct damages exceeding US$14.9 billion. Transport, cattle, housing, and agriculture were some of the industries most severely impacted. These numbers demonstrate the need for disaster communication to cover livelihood preservation, safe water, health risks, recovery information, and immediate safety. Understanding risk, bolstering governance, investing in resilience, and enhancing readiness for a successful response are all key components of the Sendai Framework (UNDRR, 2015).

3. Risk & Vulnerability Assessment

Communities are not equally exposed to risk. Low-income households frequently reside in flood-prone locations, and farmers and unorganized laborers suffer losses to their livestock, crops, and earnings. Transportation, communication, healthcare, education, and market access can all be hampered by disasters. According to Pakistan's 2022 flood assessment, disasters inflict significant damage and financial losses (Government of Pakistan et al., 2022).

Access to knowledge and the capacity to react are also factors that determine vulnerability. Alerts may go unnoticed by those without phones, electricity, or access to warnings in their native tongue. Accessible shelters and additional evacuation assistance may be necessary for women, children, the elderly, individuals with disabilities, and displaced households (UNDRR, n.d.-a).

Effective risk assessment should combine hazard maps and forecasts with local knowledge to identify vulnerable communities, communication gaps, and evacuation barriers. Protecting personal data and considering differences in age, sex, and disability can help authorities develop more inclusive warnings and response plans.

4. Community Resilience Factors

Relationships, knowledge sharing, local leadership, and the capacity to plan group activities all contribute to community resilience. Neighbors may be aware of which

buildings can act as makeshift shelters, which roads flood first, and where senior citizens stay. Local volunteers, educators, medical professionals, religious and community leaders, and civil society organizations are able to locate those overlooked by digital channels and express warnings in plain language. They should support official forecasting and emergency services, not take their place.

When appropriately integrated with scientific data, indigenous and local knowledge can enhance readiness. Although they shouldn't be used in place of confirmed forecasts, locals' observations of river levels, rainfall patterns, heat conditions, or access routes can offer helpful local context. Participation also builds trust: people are more likely to use a plan they helped shape. Community meetings, school drills, household preparedness discussions, and post-event reviews can create practical habits before a crisis. Resilience is strongest when communities have both social networks and reliable institutional support.

5. Scientific & Institutional Gaps

Monitoring a hazard is not enough for early warning. Disaster risk awareness, monitoring and forecasting, warning distribution and communication, and preparedness to respond are the four interconnected pillars of the World Meteorological Organization's Early Warnings for All framework (WMO, 2023). Any weakness in one of the pillars can lower the system's overall worth. For instance, if exposure statistics are out-of-date or public messaging responsibilities are unclear, a technically correct forecast might not result in a helpful local warning.

Incomplete local risk data, unequal technical capability, restricted database interoperability, poor community feedback, and inadequate assessment of whether alarms result in action are examples of potential gaps. Weather, satellite, hydrological, and social data analysis may be aided by AI and machine-learning techniques, but they require accurate data and professional supervision. Models may generate false confidence, replicate data gaps, or be challenging to interpret. They should encourage community involvement and official judgment rather than take its place. Clear protocols should be published, people should be trained in plain English communication, systems should be tested frequently, and lessons learned from drills and disasters should be documented.

6. Research Gap and Novelty

A key gap exists between issuing warnings and enabling timely protective action. This paper proposes an integrated approach for Pakistan combining scientific forecasts, local knowledge, inclusive communication, community participation, and responsible AI use to improve disaster preparedness.

7. Mitigation Strategies & Best Practices

Both structural and non-structural risk reduction should be connected to risk communication. Safer roadways, drainage, flood protection, resilient shelters, and heat-safe public facilities are examples of structural interventions. Land-use planning, risk mapping, public education, building rules, evacuation preparations, insurance or social protection arrangements, and early warning systems are examples of non-structural interventions. Communication must be matched by expenditures that enable protective action because it cannot make up for the lack of safe shelters or impassable evacuation routes.

A helpful model is provided by international guidance. The Sendai Framework emphasizes risk awareness and readiness and encourages a whole-of-society approach (UNDRR, 2015). Early Warnings for All emphasizes the need for monitoring, communication, and response capacities to grow in tandem (WMO, 2023). Pre-monsoon community briefings, heat-health messages prior to excessive temperatures, district-level simulation exercises, and coordination between technical agencies, provincial and district authorities, media, and local organizations are examples of practical interventions that might be implemented in Pakistan. The location, anticipated time, degree of uncertainty, and precise action needed should all be included in the messages.

An innovative approach would be to combine location-specific digital alerts, local-language voice messages, community volunteers, and two-way feedback systems so that warnings reach people through accessible channels and authorities can assess whether the information has resulted in protective action.

8. Risk Communication & Early Warning

Effective risk communication is a two-way process in which communities share their concerns and questions while authorities provide reliable information. Warnings should use simple language, avoid unexplained technical terms, and be available in local

languages and accessible formats. Each message should explain the hazard, who may be affected, what actions to take, where to seek help, and when the next update will be issued. Being honest about uncertainty helps maintain public trust.

A multi-channel approach is essential to ensure warnings reach everyone, especially when electricity or mobile networks fail. Alongside SMS and official apps, radio, television, loudspeakers, community volunteers, and direct outreach remain important. Official social media platforms should promptly address rumours and provide regular updates. Authorities should also consult women and local organizations to ensure gender-sensitive communication, while considering phone access and safety concerns. Information must be accessible to people with hearing, visual, cognitive, or mobility impairments. Ultimately, early warnings are effective only when people receive them in time and can access the support needed to take protective action.

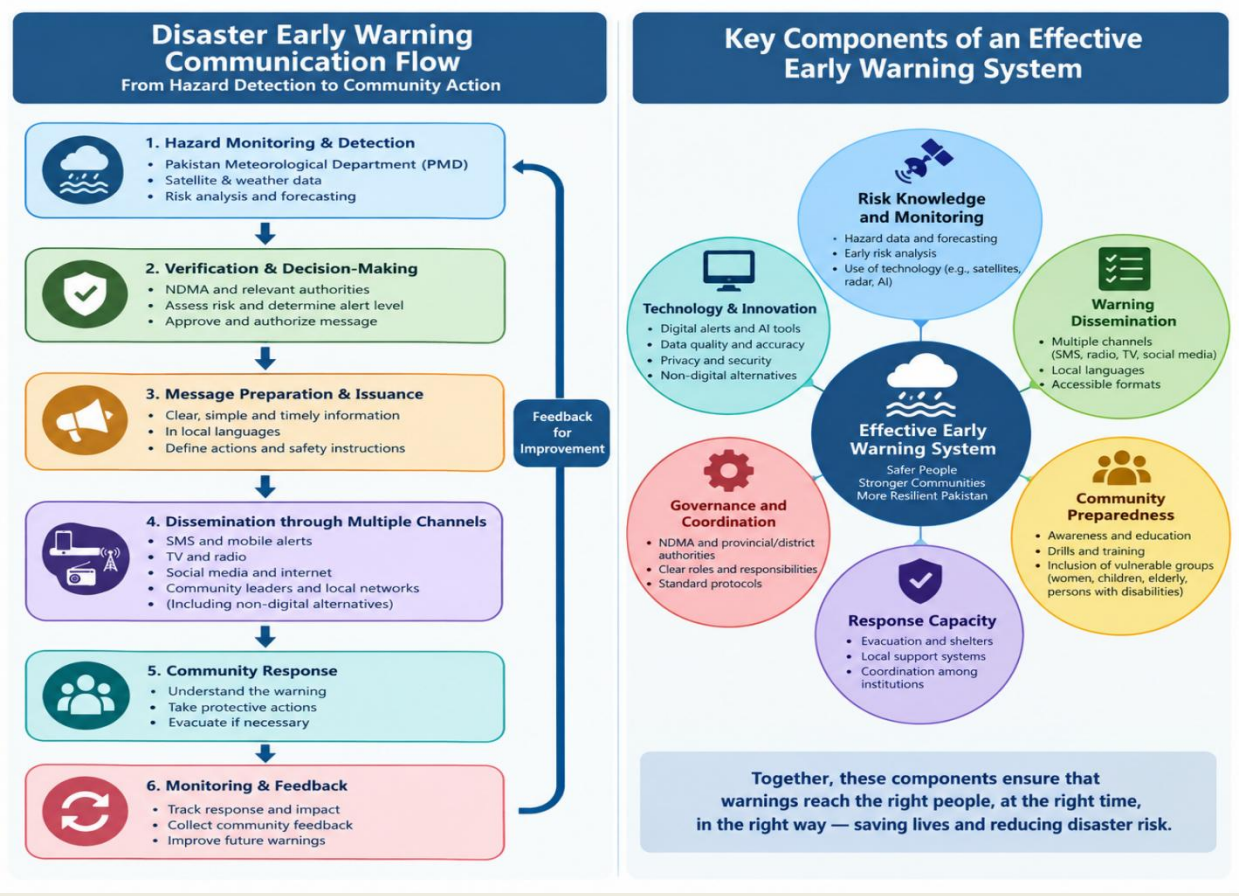


Figure 1. Disaster Early Warning Communication Flow & Key Components of Effective Disaster Early Warning System

9. Policy Recommendations

Effective risk communication requires clear procedures for verifying hazards, issuing and translating warnings, distributing alerts, and coordinating emergency responses. NDMA, provincial and district authorities, and technical agencies should have defined responsibilities. Regular drills and post-disaster reviews can help identify gaps and improve procedures.

9.1. Standardized Early Warning Protocols

- Establish standard warning protocols across NDMA and provincial and district authorities.
- Define responsibilities for verifying, issuing, and updating warnings.

9.2. Strengthening District Disaster Plans

- Identify high-risk communities and vulnerable households.
- Provide local-language alerts, accessible shelters, and evacuation support.

9.3. Community Participation and Feedback

- Establish regular feedback mechanisms.
- Include women, youth, older people, and persons with disabilities in planning.

9.4. Disaster Education and Preparedness

- Integrate disaster education into schools, workplaces, and communities.
- Conduct regular drills before high-risk seasons.

9.5. Digital Alerts and AI-Based Technologies

- Invest in digital alerts and AI-supported analysis.
- Ensure data accuracy, human oversight, privacy, and non-digital alternatives.

9.6. Monitoring and Evaluation

Assess warning delivery time, public understanding, drill participation, trust, and reach among vulnerable groups.

9.7. Climate Adaptation and DRR Funding

- Allocate adequate funding for climate adaptation and disaster risk reduction.
- Support local communication networks, forecasting, and resilient infrastructure.

These policy recommendations can strengthen disaster preparedness, improve early warning communication, and connect national policies with effective community-level action in Pakistan.

10. Conclusion

Risk communication is essential for disaster preparedness, connecting scientific information with actions that protect individuals and communities. Pakistan's 2022 floods and multi-hazard exposure highlight the need for timely, credible, and inclusive warnings. However, language barriers, limited technology, misinformation, unequal vulnerability, weak feedback mechanisms, and poor institutional coordination remain key challenges.

This desk-based review concludes that effective early warning requires an integrated system covering risk awareness, monitoring, communication, and response. Although AI and digital technologies can strengthen these processes, they cannot replace human judgment, public trust, local knowledge, and accessible emergency services. Community participation, multi-channel alerts, public education, gender-sensitive planning, and regular evaluation can help turn warnings into action.

By treating risk communication as a continuous public service, NDMA and its partners can strengthen disaster preparedness, support climate adaptation, and build safer, more resilient communities.

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PARTICIPANT RESEARCH PAPER

Nature-Based Solutions for Sustainable Urban Housing

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Abstract

Cities in Khyber Pakhtunkhwa face rising heat, an intensifying urban heat island and power cuts that expose households during heatwaves. This paper asks whether nature-based retrofits reduce that risk and how they would be paid for. Simulation of a representative 10-Marla house in Peshawar showed that rooftop and vertical gardening cut annual HVAC electricity use from 35,988 to 27,125 kWh, a 24.6% reduction, with carbon emissions and costs falling by the same share. Indoor peak temperature dropped by up to 1.2 °C in summer and simple payback was 3.45 years. A survey of 252 households found high stated willingness to adopt, tied strongly to income. The carbon-finance value of the avoided emissions was PKR 5,930 to 17,791 per dwelling per year, PKR 2,965 to 8,896 of it reaching households, and the public-sector share at 25% adoption was PKR 166 to 497 million annually. Carbon finance supplements but cannot replace upfront retrofit financing, which argues for an aggregated pilot with bridge financing.

Keywords: Nature-based solutions; Green roofs; Vertical gardens; Urban heat island; Household carbon finance

1. Introduction

Buildings produce roughly 37% of global energy-related greenhouse gas emissions (United Nations Environment Programme, 2024). In Pakistan the sector uses about 23% of national energy and 54% of electricity, and the housing stock is largely inefficient (NEECA, 2023). Peshawar combines high cooling demand, an unreliable grid and rapid urban growth, so households least able to afford cooling are the most exposed when heatwaves and outages coincide.

This paper merges a technical assessment of rooftop and vertical gardening on a representative 10-Marla house (Shah et al., 2026) with a household survey and carbon-finance analysis of who would adopt them and how they would be paid for (Shah & Shah, 2026). It asks how much energy, carbon and heat stress the retrofits remove, which households accept them and whether carbon finance can cover the upfront cost. The scope is one modelled dwelling, 252 surveyed households and scenario-based financing, framed through climate change adaptation, mitigation and disaster risk reduction (DRR).

2. Regional Context & Hazard Profile

Peshawar, the largest city of Khyber Pakhtunkhwa, lies in a semi-arid basin (ASHRAE Climate Zone 2B) where summer temperatures exceed 40 °C. Pakistan faces rising temperatures, glacial melt, extreme floods and recurrent heatwaves (UNDRR, 2019), and temperatures are projected to rise by 0.9 to 1.5 °C between 2020 and 2050, raising cooling demand (Shah et al., 2026). The IPCC (2022) identifies South Asian cities as hotspots of heat and flood risk, and the 2022 floods damaged housing stock nationwide (NDMA, 2025).

The standard DRR terms apply: a hazard is a potentially damaging event such as a heatwave or flood; exposure is the people and assets in harm's way; vulnerability is the propensity to suffer harm, shaped by income, building quality and access to services; and risk combines the three (UNDRR, 2015). Peshawar's risk chain runs from rising temperatures and the urban heat island through heavier cooling loads to grid overload, blackouts and households unable to cool their homes. The National Disaster Management Authority's strategy prioritises multi-hazard risk assessment, urban resilience and heatwaves among climate-driven hazards (NDMA, 2025).

3. Risk & Vulnerability Assessment

3.1 Building energy exposure

The technical baseline is a two-story, 10-Marla brick house in Hayatabad, Peshawar, modelled in Autodesk Revit and simulated in DesignBuilder with EnergyPlus using NASA POWER weather data (NASA, 2026; Shah et al., 2026). Under full air-conditioning it consumes 35,988 kWh per year, costs about PKR 1.51 million at the 2025 tariff of PKR 42/kWh and emits 17,202 kg of CO2 (Shah et al., 2026). This load strains the district grid in summer, and the bill rivals other essential household spending.

3.2 Socio-economic vulnerability and household income

The survey of 252 respondents (112 urban, 140 peri-urban) shows uneven capacity to act. Income was significantly associated with stated willingness to adopt ($\chi^2 = 133.78$, $p < 0.001$). Middle-income respondents had higher estimated odds of willingness than the lowest income group (OR = 2.74, p = 0.001), upper-middle respondents higher odds as well (OR = 1.89, p = 0.029), and every upper-income respondent was willing unconditionally (Shah & Shah, 2026). Willingness also took different forms by settlement: 43 of 112 urban respondents (38.4%) were willing unconditionally, 67 (59.8%) if costs were reasonable and 2 (1.8%) postponed or opposed, against 7 of 140 peri-urban, 123 conditional on cost and 9 postponed or opposed (Shah & Shah, 2026).

Distribution makes the pattern concrete. A carbon dividend of PKR 2,965 to 8,896 per year equals roughly 0.99 to 2.97% of monthly income for the lowest-income group but 0.06 to 0.19% for the highest, and it does nothing to help a low-income household fund the initial PKR 1.27 million retrofit (Shah & Shah, 2026). Vulnerable households face a double exposure: the highest heat and outage risk, and the least capacity to finance protection. Gender and tenure were not measured.

4. Community Resilience Factors

Stated demand is high. Taken together, 98.2% of urban and 93.2% of peri-urban respondents were willing to adopt in principle, with most peri-urban willingness conditional on cost. Advice-seeking is equally price-sensitive: 45 of 112 urban respondents (40.2%) would consult a professional engineer only if affordable, against 117 of 140 peri-urban respondents (83.7%) (Shah & Shah, 2026).

When eight retrofit options were scored in a multi-criteria decision analysis across energy saving, carbon reduction, social acceptability, affordability and technical feasibility, solar panels ranked first (8.70), rooftop gardening second (8.30) and vertical gardening third (7.40); rooftop gardening was preferred by 87.5% of urban and 85.2% of peri-urban respondents (Shah & Shah, 2026). Figure 1 summarises the pathway from household characteristics through adoption, outcomes and carbon finance to revenue sharing.

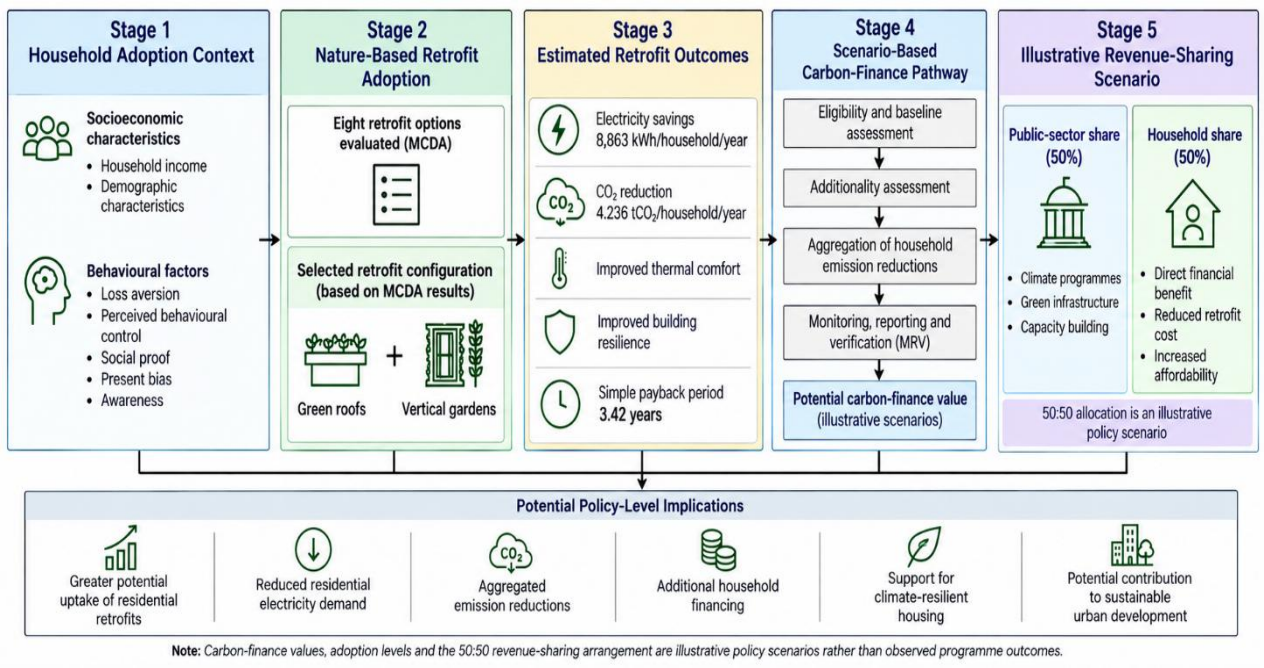


Figure 1. Analytical framework linking household adoption, retrofit performance and scenario-based carbon finance. (Source: Shah & Shah, 2026).

5. Scientific & Institutional Gaps

Four gaps temper the evidence. First, the performance results are simulations of one dwelling, not measured post-retrofit data, and should not be read as typical of the housing stock (Shah et al., 2026). Second, the survey achieved 252 responses against a planned 384 because security conditions limited field access, giving an approximate precision of ±6.2% at the 95% level, and it is not a probability sample of the district (Shah & Shah, 2026). Third, Pakistan has no household-scale carbon crediting method: baselines, additionality, monitoring, reporting and verification (MRV), aggregation and

double-counting safeguards are unresolved, so MRV and aggregation costs had to be treated as scenarios of 10 to 50% of gross revenue (Shah & Shah, 2026).

6. Mitigation Strategies & Best Practices

6.1 Retrofit performance

The package adds rooftop gardening and vertical gardening, each with a 50 mm expanded polystyrene layer, to the external envelope (Figure 2). Under HVAC operation, annual consumption fell from 35,988 to 27,125 kWh, a 24.6% reduction, with emissions and cost falling by the same share (Shah et al., 2026). June's peak operative temperature dropped from 31.24 to 30.01 °C, about 1.2 °C cooler, easing summer discomfort. Monthly discomfort hours fell by up to 38.72 hours in March. These are model results for one house, and gridded weather data likely understate urban heat island effects, so they are conservative estimates (Shah et al., 2026).



Figure 2. Autodesk Revit model of the representative 10-Marla house in Hayatabad, Peshawar. (Source: Shah et al., 2026).

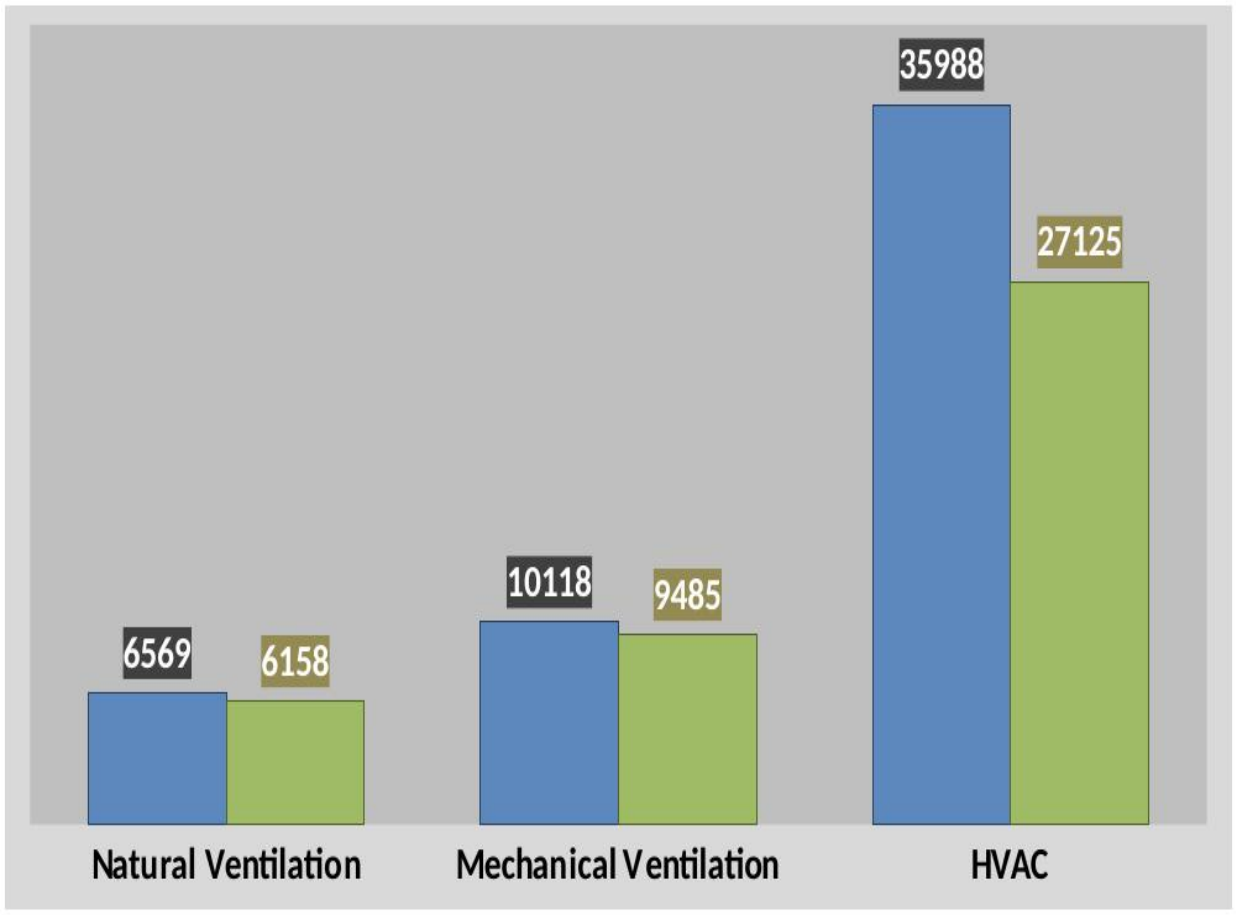


Figure 3. Baseline and optimised annual energy consumption under natural, mechanical and HVAC ventilation. (Source: Shah et al., 2026).

6.2 Costs, payback and comparison with other studies

The installed cost was about PKR 1.27 million at local market rates. Annual electricity savings of PKR 372,246 at PKR 42/kWh give a simple payback of 3.45 years as reported in the technical assessment (Shah et al., 2026); the household survey reports 3.42 years because of tariff rounding, and 3.45 is used throughout. This beats the 6 to 14 years reported for comparable packages in Mediterranean and hot-arid climates, mainly because of Peshawar's extended cooling season and higher tariffs (Shah et al., 2026). Table 1 consolidates the headline results.

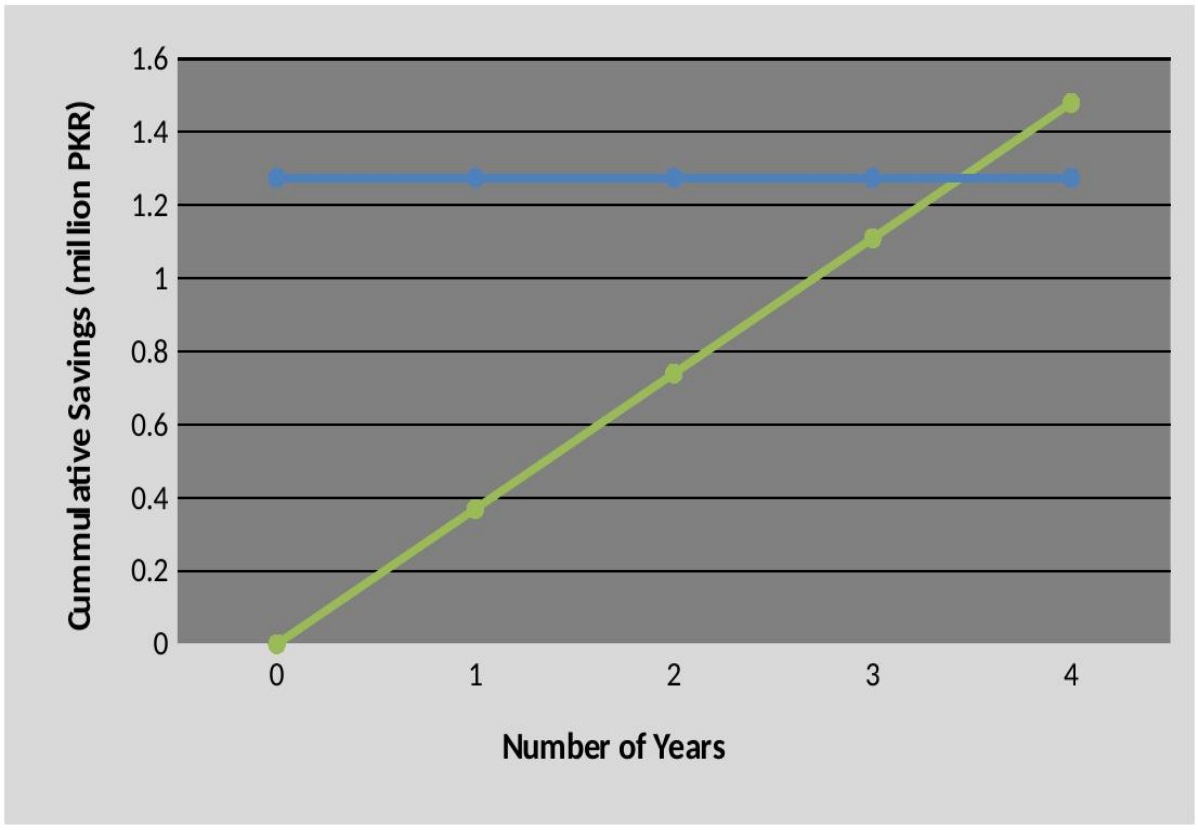


Figure 4. Cost recovery of the retrofit package against cumulative operational savings. (Source: Shah et al., 2026).

Table 1. Headline performance, payback and survey results. All performance values are EnergyPlus simulation results for one representative 10-Marla house; carbon-finance values elsewhere are scenarios, not realised income.

Indicator	**Baseline**	**With retrofits**
Annual HVAC electricity use (kWh)	35,988	27,125
Reduction in energy, CO2 and cost	–	24.6%
Annual CO2 emissions (kg)	17,202	12,966

Annual electricity cost (PKR)	1,511,496	1,139,250
June peak operative temperature (°C)	31.24	30.01
Simple payback (years)	–	3.45
Surveyed households willing to adopt	Urban: 110 of 112	Peri-urban: 130 of 140
Top-ranked options (MCDA score)	–	Solar 8.70; rooftop gardening 8.30; vertical gardening 7.40

6.3 Policy alignment

The measures sit inside an existing policy frame. The Energy Conservation Building Code 2023 sets envelope, insulation and retrofit requirements, and the Green Building Code of Pakistan 2023 adds environmentally responsive design provisions (NEECA, 2023; Pakistan Engineering Council, 2023); envelope measures are among the cheapest available savings in Pakistan's climates (Mehmood et al., 2025). The interventions also match the IUCN Global Standard for nature-based solutions (IUCN, 2020).

7. Risk Communication & Early Warning

The supporting evidence concerns what moves households to act: strong stated willingness and a preference for professional engineering advice when affordable, which makes engineers the effective last mile for technical risk messages (Shah & Shah, 2026). Incentives are the other supported channel: the Chief Minister Punjab Green Credit Programme, launched in 2024, pays citizens for verified climate-positive actions and shows that performance-based rewards can be administered at household scale (Government of Punjab, 2024).

8. Policy Recommendations

The findings point to a financing gap between a PKR 1.27 million retrofit and a carbon dividend of at most PKR 8,896 a year. Three measures follow.

Pilot an aggregated household programme. Most carbon finance operates through large projects because household-scale reductions are small and dispersed (World Bank, 2024). Aggregating verified reductions across many houses would spread MRV and transaction costs and could yield a public-sector share of PKR 166 to 497 million annually at 25% adoption (Shah & Shah, 2026). These values are scenarios and depend on an applicable crediting methodology.

Test bridge financing. The dividend arrives only after installation, so it cannot by itself pay the upfront cost. A pilot should test whether a lender would treat the expected dividend of PKR 2,965 to 8,896 a year and the modelled electricity saving of PKR 372,246 as supplementary repayment capacity for a small loan aligned with the 3.45-year payback. With electricity savings alone the ten-year net present value at a 12% discount rate is about PKR 829,000; the carbon dividend lifts it by 2.0 to 6.1% (Shah & Shah, 2026).

Support lower-income and peri-urban households first. Peri-urban willingness is almost entirely cost-conditional (123 of 140 respondents), so targeted subsidies, bundled technical guidance and phase-in by income group would convert stated demand into adoption where vulnerability is highest. The Punjab Green Credit Programme offers an administrative template (Government of Punjab, 2024), and alignment with the NDMA's DRR strategy would place housing retrofits inside the national risk-reduction agenda (NDMA, 2025).

9. Conclusion

Nature-based retrofits are a workable response to Peshawar's heat risk. For a representative 10-Marla house, rooftop and vertical gardening cut annual HVAC electricity use by 24.6%, cut costs by the same share, cooled the hottest month by about 1.2 °C and paid for themselves in 3.45 years. Households are willing: over nine in ten surveyed residents would adopt if costs allowed, and income shapes both willingness and the ability to act. Carbon finance adds value but does not close the gap; at most it returns PKR 8,896 a year against a PKR 1.27 million upfront bill. An aggregated pilot with bridge financing, aimed first at lower-income and peri-urban households and evaluated against measured rather than modelled savings, is the path from stated willingness to safer housing.

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Annexes

Annex A. MCDA criteria and weights: energy saving 0.30, social acceptability 0.25, carbon reduction 0.20, affordability 0.15, technical feasibility 0.10; eight alternatives scored 1 to 10 per criterion (Shah & Shah, 2026). Annex B. Household survey questionnaire, administered in KoboToolbox with informed consent; available on request subject to confidentiality safeguards (Shah & Shah, 2026). Annex C. Green roof and green wall layer specifications and embodied carbon assessment, 40 to 60 kg CO2-e per square metre (Shah et al., 2026).

PARTICIPANT RESEARCH PAPER

Urban Expansion in the Ravi River Floodplain: Flood Risk and Governance Response in Lahore, Pakistan

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Abstract

Lahore's built-up area more than tripled between 1973 and 2020, and growth is now pressing on the Ravi River floodplain. This paper examines how urban expansion has increased flood exposure along the Ravi and how effectively governance has responded. It uses a desk-based review of peer-reviewed land-use research, institutional assessments, court and policy reporting, and data on the August 2025 flood, organized around the hazard, exposure, vulnerability and risk framework. Findings show that farmland and floodplain land are being converted to housing through both a state-backed megaproject and private housing societies; that the August 2025 flood, the highest Ravi flow in nearly four decades, breached an embankment and flooded housing schemes, and that regulation exists while enforcement, relocation and early warning remain weak. Evidence on community resilience in the corridor is limited. The paper recommends enforcing no-build zones, halting approvals in high-risk areas, relocating the most exposed households, requiring independent flood assessments, steering growth to safer corridors, and building people-centered, gender-sensitive early warning.

Keywords: Disaster risk reduction, Floodplain management, Lahore, Ravi River, Urban expansion

1. Introduction

Floods are among Pakistan's most damaging hazards, and climate change is raising flood risk across Asia (IPCC, 2022). The 2022 floods affected 33 million people and caused damages above USD 14.9 billion and economic losses of about USD 15.2 billion, with housing the worst-hit sector (Government of Pakistan et al., 2022). Such events show that disaster risk is shaped not only by hazards but by where and how people build. The Sendai Framework therefore calls on states to understand risk in all its dimensions and to prevent the creation of new risk (United Nations Office for Disaster Risk Reduction [UNDRR], 2015).

Lahore illustrates this problem. The Ravi River runs along the northern edge of a district of 1,772 km² whose built-up land has grown about 3.4 times since 1973, largely at the expense of farmland (Nasar-u-Minallah et al., 2021). Housing is now spreading into a river corridor that floods, through both a state-backed riverfront city and private housing societies. The August 2025 flood, which reached housing schemes at the river's edge, turned this concern into evidence (Daily Pakistan, 2025a).

The purpose of this paper is to assess urban expansion in the Ravi floodplain as a disaster risk problem and to recommend risk-reduction actions. Its objectives are to (1) track how quickly built-up land has grown towards the Ravi. (2) test flood exposure using the August 2025 flood and (3) judge the governance response and recommend actions. The scope is the Lahore stretch of the Ravi from 1973 to July 2026. The study is desk-based and uses no primary data.

2. Regional Context and Hazard Profile

Four terms structure the analysis. *Hazard* is a potentially damaging physical event, here Ravi River flooding. *Exposure* is the presence of people, housing and assets in hazard zones. *Vulnerability* is the set of conditions that make exposed people and assets more susceptible to harm. *Risk* is the potential for loss that results when these combine (IPCC, 2022; UNDRR, 2015).

Lahore's population grew from 1.1 million in 1951 to 11.1 million in 2017. Between 1973 and 2020, built-up area rose from about 224 km² to 756 km², while agricultural land fell from about 1,213 km² to 825 km² (Nasar-u-Minallah et al., 2021; see Annex B). The same study identifies the Ravi and its floodplain as a constraint on northern growth and urges a

flood study before building across it. Pressure then increased. In 2020 the Ravi Urban Development Authority (RUDA) was created to build a riverfront city on about 100,000 acres (Profit, 2022). In January 2022 the Lahore High Court held the land acquisition beyond RUDA's authority and against environmental law, but six days later the Supreme Court suspended the ruling, allowing building only on land already acquired and paid for (Dialogue Earth, 2022). Private societies have also built at the river's edge (Dawn, 2026). The hazard materialized in August 2025, when the Ravi carried about 215,000 cusecs at Shahdara, the highest flow in nearly four decades (Daily Pakistan, 2025a). Across Punjab's river floods, about 1.5 million people were affected and over 213,000 homes were damaged (Reuters, 2025; The Express Tribune, 2026). The sources reviewed document the physical and legal history well, but corridor-level studies linking land conversion to flood exposure remain scarce.

3. Risk and Vulnerability Assessment

Exposure: In August 2025 floodwater breached a protective embankment at Park View City, and more than 100 homes near Shahdara were evacuated (Daily Pakistan, 2025a, 2025b). Embankments may also encourage further building behind them, so structural protection can raise exposure unless paired with land-use control.

Socio-economic and livelihood impacts: The 2022 national assessment found housing, agriculture and livestock, and transport and communications to be the most damaged sectors, at USD 5.6, 3.7 and 3.3 billion respectively (Government of Pakistan et al., 2022). In Lahore, the loss of about 388 km² of farmland removes income sources for farming households and reduces local production capacity, a long-term food-security concern (Nasar-u-Minallah et al., 2021). Displacement from flooded homes also carries psychological costs; the IPCC (2022) links climate extremes to mental-health harm, an impact rarely counted in damage figures.

Vulnerable groups and gender: Residents of the 44 housing schemes RUDA has declared illegal face a dilemma: they hold property in places the state says should not have been developed, which may weaken their claim to protection or compensation (The Express Tribune, 2026; author's inference). During the 2022 floods, the United Nations Population Fund estimated that almost 650,000 pregnant women needed maternal health services and warned of heightened risks to women and girls (UNFPA Pakistan, 2022).

Displaced women in the Ravi corridor could face similar risks, although no corridor-specific gender data were found.

Susceptibility: Low-lying land, weak enforcement and slow relocation keep susceptibility high. More than a year after the flood, no major flood-hit settlement had been permanently relocated, and 897 encroachments were reported uncleared to a Senate committee (The Express Tribune, 2026; Dawn, 2026).

4. Community Resilience Factors

The sources reviewed say little about community capacities in the Ravi corridor, which is itself a finding. Several resilience resources can nonetheless be identified, though they are inferred here rather than measured. *Social capital:* housing-society committees and neighborhood networks are likely first responders when water arrives, as the evacuation of homes near Shahdara suggests (Daily Pakistan, 2025a). *Indigenous and local knowledge:* long-settled riverside farming communities probably hold experience of the Ravi's seasonal behavior that residents of newer planned schemes lack, yet such knowledge is rarely used in planning. *Local coping:* staying with relatives and moving to higher ground are likely coping practices, but they are short-term and depend on advance notice. *Participation:* the court challenge to RUDA indicates that land-use decisions have been contested rather than co-designed (Dialogue Earth, 2022).

The 2022 national assessment urged recovery guided by the principles of poor first, transparency, inclusion and climate resilience (Government of Pakistan et al., 2022). Applying them here means involving residents, farmers and women in hazard mapping and relocation planning.

5. Scientific and Institutional Gaps

Data and technology: Land-use evidence for Lahore ends in 2020 and predates the 2025 flood (Nasar-u-Minallah et al., 2021). Punjab ordered updated floodplain boundaries using 2025 flood data only in July 2026, implying earlier maps were outdated (Associated Press of Pakistan [APP], 2026). Satellite change detection is established, but the sources reviewed do not document artificial intelligence or machine-learning tools for flood forecasting, inundation mapping or encroachment detection in the corridor. Such tools depend on good gauge data, open data sharing and trained staff.

Institutional weaknesses: The 2016 Flood Plain Regulation Act zones river land by risk, yet it predates the 2025 flood and encroachment cases kept rising (Abbasi, 2025; Dawn, 2026). The legal dispute over RUDA suggests environmental review was unsettled when the project advanced (Dialogue Earth, 2022). Responsibility is spread across development authorities, courts, irrigation and disaster-management bodies, so accountability is diffuse.

Research gaps: No household-level vulnerability survey, gender-disaggregated data or evaluation of past relocation was found for the corridor. Reliance on news and opinion sources for the 2025 events is a limitation that peer-reviewed post-flood studies should address.

6. Mitigation Strategies and Best Practices

Structural measures such as embankments remain necessary but are insufficient alone, as the Park View breach showed (Daily Pakistan, 2025b). The IPCC (2022) warns that poorly planned development can cause maladaptation, increasing long-term risk. Non-structural measures should therefore lead: risk-based zoning, no-build zones, independent flood and environmental assessment before approval, disclosure of flood-risk status to plot buyers, and funded relocation. Capacity building should train development-authority, revenue and enforcement staff to read hazard maps and apply them in approvals. Awareness campaigns should tell residents of floodplain schemes about their risk and evacuation routes, and scheme-level drills should test arrangements before each monsoon.

Relevant frameworks point the same way. The Sendai Framework's four priorities are understanding risk, strengthening governance, investing in resilience, and enhancing preparedness and building back better (UNDRR, 2015), and Pakistan's post-2022 assessment adopted the same logic (Government of Pakistan et al., 2022). Locally, the 2016 floodplain law and the July 2026 crackdown are consistent with these principles, but their value depends on enforcement (APP, 2026).

7. Risk Communication and Early Warning

Reporting from August 2025 describes residents in panic as water entered housing schemes (Daily Pakistan, 2025a) but does not show whether timely, understandable instructions reached them. An effective system should be people-centered and gender-

sensitive. First, river-flow thresholds at Shahdara should be translated into zone-specific messages in Urdu and Punjabi that say what to do, where to go and when. Second, several channels should be used: mobile alerts, mosque loudspeakers, scheme-level messaging groups and visits by community health workers, because women may not control phones or hear announcements made in male-dominated spaces. Third, trained focal persons, including women, should handle last-mile dissemination in every scheme, with evacuation routes, shelters and transport accessible to elderly, disabled and pregnant residents. Fourth, community meetings should provide feedback so warnings are tested and improved. These elements support the Sendai Framework target of substantially increasing the availability of multi-hazard early warning systems and risk information (UNDRR, 2015). Regular, honest communication of floodplain risk, including to buyers and renters, is the non-structural complement.

8. Policy Recommendations

The Lahore evidence supports seven measures:

I. Enforce no-build zones by applying the 2016 floodplain zoning with the updated 2025 hazard maps (Abbasi, 2025; APP, 2026).

II. Stop approvals in high-risk areas and act on the 44 schemes declared illegal (The Express Tribune, 2026).

III. Relocate the most exposed families, providing safe land and alternative housing rather than embankments alone (The Express Tribune, 2026).

IV. Require independent flood and environmental assessment before any riverfront project proceeds (Dialogue Earth, 2022; Nasar-u-Minallah et al., 2021).

V. Steer growth towards safer south-east and south-west corridors (Nasar-u-Minallah et al., 2021).

VI. Integrate governance and technology: one shared hazard map for RUDA, development authorities, irrigation and disaster-management bodies, with annual satellite monitoring and, where capacity allows, AI-assisted encroachment detection and flood forecasting.

VII. Embed community participation and climate adaptation: include residents, farmers and women in hazard mapping, relocation design and drills, and base approvals on climate-adjusted flood projections (IPCC, 2022).

Together this shift policy from responding to floods towards preventing new risk, which the Sendai Framework places at the core of disaster risk reduction (UNDRR, 2015).

9. Conclusion

Lahore's built-up land has more than tripled since 1973 and now presses on the Ravi floodplain. The August 2025 flood showed the cost: record flow, a breached embankment and flooded housing schemes. The governance response includes a 2016 law, declarations against illegal schemes and a 2026 crackdown, yet enforcement, relocation and early warning lag behind the risk. Resilience here depends on science-based planning that keeps development out of the floodplain, on social capital and local knowledge that are currently under-used, on technology that supports monitoring and warning, and on integrated governance linking planners, disaster managers and communities. The answer is enforcement, relocation and planning growth elsewhere, not building closer to the river. Future research should add household-level, gender-disaggregated vulnerability data to test and refine these findings.

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Annex A: Hazard, exposure, vulnerability and risk matrix for the Ravi floodplain, Lahore

Component	Ravi floodplain, Lahore	Evidence
Hazard	River flooding; about 215,000 cusecs at Shahdara in August 2025, highest in nearly four decades	Daily Pakistan (2025a)
Exposure	Housing schemes at the river's edge; embankment breach at Park View City; 100+ homes evacuated near Shahdara; 44 schemes declared illegal	Daily Pakistan (2025a, 2025b); The Express Tribune (2026)
Vulnerability	Weak enforcement; no major flood-hit settlement relocated after a year; 897 encroachments uncleared; unclear status of residents in illegal schemes; women ' s added risks	Dawn (2026); The Express Tribune (2026); UNFPA Pakistan (2022)
Risk	High and rising: built-up land 3.4 times larger than in 1973, with growth directed towards the river	Nasar-u-Minallah et al. (2021)

Annex B: Land use in Lahore, 1973–2020 (km²)

Year	Built-up area (km^2)	Agricultural land (km^2)
1973	223.96	1213.23

Year	Built-up area (km^2)	Agricultural land (km^2)
1980	273.29	1170.57
1990	352.75	1117.82
2000	445.12	1062.25
2010	517.43	1004.99
2020	756.44	825.23
Change 1973 – 2020	+532.48	−388.00

Source: Nasar-u-Minallah et al. (2021), Table 3. Totals for change were calculated from the table.

PARTICIPANT RESEARCH PAPER

El Niño and Sri Lanka's Water Security: A Proposed Framework for Seasonal Risk Integration, Impact-Based Preparedness, and Anticipatory Action

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Abstract

Sri Lanka's agriculture, water supply, hydropower generation and rural livelihoods depend heavily on rainfall. El Niño, the phase of the El Niño–Southern Oscillation (ENSO) can change regional air flow and affect the chances of rain; but El Niño effects in Sri Lanka vary by season, location and each event. This paper looks at the link between El Niño and Sri Lanka's water security on how seasonal rain changes and the drought of 2016–2017. The paper uses a literature- based idea drawing on peer- reviewed studies, official climate data, global climate advice and the 2017 FAO/WFP crop and food- security review. The studies show that El Niño influence must be read together with the Indian Ocean Dipole, monsoon air flow and local conditions. The 2016–2017 case shows that big drops in rain can hurt paddy growth reduce irrigation water, lower household earnings and threaten food security. Later flooding in parts of Sri Lanka shows that drought and flood danger can appear in the place or one, after the other. This paper suggests a Seasonal Risk- to- Action Framework that links climate watching seasonal predictions, water and farm impact checks, official decisions, local messages, early actions and learning after the season. The framework is an idea and has not been tried in real life. It is meant to add to the weather, irrigation, farm and disaster plans not to replace them. The paper calls for combined climate watching, better water planning, farm methods that survive drought risk messages and a review of the whole warning- to- action chain.

Keywords: El Niño; El Niño–Southern Oscillation; Sri Lanka; drought; water security; seasonal rainfall; Indian Ocean Dipole; food security; impact-based preparedness; anticipatory action.

1. Introduction

El Niño is a part of the El Niño–Southern Oscillation (ENSO) a natural climate event that occurs when sea temperatures change in the central and eastern equatorial Pacific Ocean. El Niño changes how air moves how wind blows, where heat goes and how much rain falls across parts of the world. Even though El Niño starts in the Pacific Ocean El Niño can spread beyond that area altering seasonal weather, crop growth, water supply and everyday life for millions of people. Nonetheless the strength and direction of El Niño vary from country to country, region to region and season, to season. El Niño should be seen as a sign of climate risk not as a guaranteed cause of drought El Niño touches.

Sri Lanka relies heavily on rainfall because Sri Lanka's agriculture, irrigation systems drinking water supplies, hydropower production and rural livelihoods all depend closely on water availability and distribution. Sri Lanka's rainfall pattern is shaped by four seasons: the First Inter-Monsoon, the Southwest Monsoon, the Second Inter-Monsoon and the Northeast Monsoon. These seasons spread rainfall unevenly across Sri Lanka, which creates differences in water availability between the Wet Zone, Intermediate Zone and Dry Zone. Therefore any change in the timing, intensity or distribution of rainfall can strongly affect Sri Lanka's agriculture, reservoir storage, river flows and domestic water supplies in areas where people depend heavily on irrigation and rainfall, for daily living.

The relationship between El Niño and Sri Lanka's rainfall is complex. Studies show that El Niño can change rainfall during seasons, such as the First Inter- Monsoon and later monsoon seasons. However El Niño's effects are not the same across Sri Lanka. Other climate forces, the Indian Ocean Dipole (IOD) plus local weather and the nature of each monsoon season can change how rainfall falls. Thus if we rely on El Niño to foresee drought we may make wrong evaluations and bad decisions about managing resources. A better plan would mix El Niño monitoring with forecasts for the season rainfall data, soil moisture status, how full reservoirs are and data, on how much water is needed.

When consider the 2016–2017 drought in Sri Lanka, the drought clearly showed what happens when dry conditions last long. The drought severely affected production, especially paddy cultivation and made food-security and livelihood difficulties worse for vulnerable communities. The Food and Agriculture Organization (FAO) reported that the forecast paddy production for 2017 was 2.7 million tonnes, nearly 40 % lower, than the

2016 output. The drought showed how climatic variability can turn into a socioeconomic challenge when water shortages meet agricultural dependence, when household resources are limited and when many people compete for water. The drought experience also highlighted how important it is for climate-monitoring institutions, water-management authorities, agricultural agencies and disaster-management organizations to coordinate well.

Water security is more than having water available. It means making sure people can dependably get clean water for drinking, farming, jobs and keeping nature healthy. It also means dealing with risks that come from water problems. When the climate changes water can become scarce. This can hurt food growing, strain reservoirs and irrigation systems break up people's ways of living and make life harder for those who are already struggling. To truly protect water security we need more, than building dams or pipes. We need climate data teams working together across different groups smart ways to share water and quick actions when problems arise. Water security must be handled with care and planning.

Even though forecasting and climate monitoring have gotten better there is still a big challenge in turning climate data into real decisions at the national, regional and local levels. Climate forecasts need to be looked at with what is happening on the ground. They should lead to actions like checking irrigation plans watching water levels, in reservoirs getting drinking water backup plans ready and sharing risk information with people who might be affected. These actions must come from evidence have clear responsibilities assigned and use decision thresholds that make sense. At the time it's important to remember that seasonal climate forecasts always carry some level of uncertainty.

Accordingly this research looks at the link between El Niño and Sri Lanka's water security. It focuses on drought risk the effects on farming and the lessons learned from the drought of 2016- 2017. The study proposes a Seasonal Risk- to- Action Framework. This framework connects climate monitoring and local interpretation with sector- specific impact assessment, coordinated decision- making, early action and later evaluation. The aim is to see how climate- risk data can be put into the existing systems for water management and disaster preparedness in a way. The proposed framework is

conceptual and would require consultation with relevant stakeholders, pilot implementation and systematic evaluation before being adopted as an operational mechanism.

Ultimately I believe this study helps us create a proactive and evidence-based approach to water-security planning in Sri Lanka. By recognizing the link between ENSO, regional climate conditions and local water demands decision makers can better prepare to predict potential risks prioritize limited resources protect vulnerable communities and build stronger resilience, against future droughts and other climate-related water challenges.

Background and Research Problem

El Niño is a scale ocean- atmosphere phenomenon in the tropical Pacific. Through changes in how air moves it can change weather patterns far away from the Pacific. The link between ENSO and Sri Lankan rainfall is complicated. The timing and strength of an El Niño event how fast it. How it mixes with conditions, in the Indian Ocean can change the direction and size of rainfall differences. Recent Sri Lanka-focused studies demonstrate that post-El Niño rainfall responses can differ substantially between events (Kajakokulan & Kumar, 2025; Ranaweera & Kamae, 2024). It is therefore inaccurate to assume that every El Niño event will cause drought throughout Sri Lanka.

Research Problem

The main problem that this paper looks at is how to turn facts about El Niño and seasonal rainfall into useful choices for water use, farming and helping the public get ready. Climate forecasts are not very helpful if they are not translated to the seasons and places linked to the real effects on each sector and given early enough to let people act. The challenge is not just that El Niño can change rainfall but how to show the uncertainty and the differences from one region to another, in ways that help people prepare.

Research Aim

To examine the influence of El Niño on Sri Lanka’s seasonal rainfall and water-security risks, and to propose a conceptual framework linking climate information with impact assessment, preparedness and anticipatory action.

Research Objectives

Research objectives of El Niño and Sr Lanka's water security are as follows:

- Review scientific literature on ENSO, the Indian Ocean Dipole and Sri Lanka's seasonal rainfall.
- Examine the reported impacts of the 2016–2017 drought on agriculture and food security.
- Identify implications of rainfall variability for irrigation, drinking water, hydropower and livelihoods.
- Propose a practical Seasonal Risk-to-Action Framework for translating climate information into sectoral preparedness.
- Recommend measures for improving forecasting use, water management, communication and future evaluation.

Research Questions

Research questions of El Niño and Sr Lanka's water security are as follows:

a) How does El Niño influence Sri Lanka's seasonal rainfall, and why do impacts differ by season and event?

   a. What lessons can be drawn from the 2016–2017 drought for water security and agricultural preparedness?

   b. How can climate outlooks be connected to impact-based decisions and anticipatory action?

   c. How could a proposed framework be evaluated without assuming that it has already been implemented or validated?

2. Background and Literature Review

El Niño and the Enso Climate System

ENSO is a connection between the ocean and the atmosphere that involves shifts in sea-surface temperatures, winds, pressure and rainfall in the Pacific. When El Niño happens the surface waters in parts of the eastern equatorial Pacific become warmer than normal. This change affects the Walker circulation, which in turn influences weather patterns around the world and in many regions. The World Meteorological Organization (WMO, n.d.) points out that the effects of ENSO are not the same. It also says that seasonal climate forecasts can offer information ahead of time for sectors that are sensitive to

climate changes. El Niño should be seen as a factor that shifts the odds, not as a prediction, for a specific area.

Sri lanka's Seasonal Rainfall and Regional Variation

Sri Lanka has four rainfall seasons: the first inter-monsoon from March to April the southwest monsoon from May to September the second inter-monsoon from October to November and the northeast monsoon from December to February. The importance of each season varies by region. The central highlands, the direction of the monsoon winds and the local geography all affect how rain is spread out. This leads to differences in water availability between the zone, the intermediate zone and the dry zone (ADB & World Bank 2020). Because of this a national seasonal forecast should be considered together with rainfall data the conditions of reservoirs the timing of crops and the situation, in each district.

Research on Enso and Sri Lankan Rainfall

Kamae in the year 2024 studied rain data from 114 stations between 1975 and 2019. They discovered a negative link between the Niño 3.4 index from the previous November to January and the first inter-monsoon rain at most of the stations. Their results also showed some areas where this pattern did not hold. This means that after an El Niño the rain is not the same. Kajakokulan and Kumar in 2025 looked at summer monsoon rain following El Niño events that ended quickly or slowly. They found that summers were wetter and cooler after endings. Summers were drier and hotter after slow endings. These two studies warn that it is not correct to say that El Niño always causes the kind of rain, in Sri Lanka.

The Role of the Indian Ocean Dipole

The Indian Ocean Dipole (IOD) is another climate pattern that can affect rainfall in Sri Lanka. Studies looking at the Maha season have found a link between positive IOD conditions and more rain (Rao et al., 2003). Since ENSO and IOD can happen at the time and each affects the atmosphere in different ways it's important to look at both when predicting seasonal risks. Relying on ENSO might miss part of the picture. How much each one matters can change depending on the season or specific weather event. Therefore, it's best to follow the seasonal forecasts, from national and international sources when giving practical advice.

The 2016–2017 Drought and Food-Security Impacts

The FAO/WFP Crop and Food Security Assessment Mission said that drought conditions in 2016 and early 2017 caused crop failures, especially for paddy. Paddy production in 2017 was expected to be 2.7 million tonnes, 40% lower than in 2016 and 35% lower than the average of the past five years. The assessment found that about 229,560 households or 900,000 people were borderline food insecure (Food and Agriculture Organization of the United Nations [FAO] & World Food Programme [WFP] 2017). Heavy rain in May 2017 then caused floods and landslides in parts of the southwest while water shortages remained in drought-affected eastern areas (FAO, 2017). Hazards show that uneven hazards across a region can overlap and that drought can affect more, than rainfall amounts, touching livelihoods, food costs and the ability to use irrigation. The drought continues to shape these outcomes.

Water Security and Climate Risk

Water security means making sure that people, their jobs, the environment and farming have good quality water. In Sri Lanka the way the rain falls can cause problems at the same time. Some places might get much rain and flood while other places might not get enough rain and have dry periods. The Sri Lanka Climate Risk Country Profile talks about both dry periods and flooding because of the way it rains and the shape of the land (ADB & World Bank 2020). Therefore, a plan for water security must link weather predictions with water storage watering crops providing water to drink the timing of farming activities and helping people who are, in need.

Research Gap and Proposed Contribution

Existing scientific literature explains ENSO rainfall relationships while disaster assessments document the consequences of the 2016 2017 drought. The practical challenge is to connect those knowledge streams in a seasonal decision process. This paper proposes a Seasonal Risk to Action Framework that links climate monitoring, regional interpretation, sectoral impact assessment, authorized decisions, public communication, anticipatory measures and post season learning. The individual components are established practices; the contribution is their synthesis, for examining Sri Lankas El Niño related water security preparedness. The framework is not claimed to be the first of its kind. Has not been operationally tested.

3. Research Methodology

Research Design

This paper uses a research design based on existing literature. It brings together studies that have been checked by experts, official reports and guidance about climate to find how ENSO, changes in rainfall, drought effects and being ready are connected. No new data about rainfall was looked at no model that uses numbers was created and no people were interviewed or experiments were done in the field. The idea that is suggested is therefore a thinking model, than something that has been tested and proven.

Source Selection

Sources were chosen because they relate to the research questions and because they come from official organizations. They include studies about ENSO and Sri Lankan rainfall that have been checked by experts, the FAO/WFP 2017 report on crops and food security information about climate risks from the Asian Development Bank and the World Bank and details about ENSO, from the WMO. The list of sources is focused and not complete. It is not a systematic review.

Analytical Approach

I compared the sources thematically across five areas. Those areas were ENSO and IOD influences, seasonal and regional rainfall patterns, drought impacts on agriculture and food security implications for water resources and livelihoods and practical links, between forecasts, decisions and anticipatory action. From the findings I derived a sequence of proposed stages.

Methodological Limitations

The analysis depends on available publications and reports. The cited studies use different time frames, data and methods so the findings cannot always be compared directly. The 2016–2017 assessment talks about drought impacts but does not prove that El Niño alone caused every impact. The paper does not check how well any forecasting or water- management system works. Analysis that uses long- term rainfall and reservoir data district- level agricultural facts and talks, with stakeholders would make the conclusions stronger.

4. Proposed Seasonal Risk-to-Action Framework

Framework Overview

The proposed framework aims to link climate information with real-world decisions, about water security and agriculture. It works alongside the efforts of agencies irrigation experts, agricultural groups and disaster management teams. It does not take over forecasts or replace formal decision-making processes.

Stage 1: Climate monitoring. Monitor ENSO indicators the Indian Ocean Dipole, climate outlooks, local rainfall observations and relevant hydrological conditions. Every information product must have a date. Must be linked to a specific geographic area and a specific time period.

Stage 2 : Seasonal and regional interpretation. Interpret global climate signals alongside national forecasts, regional rainfall climatology and current local observations. Identify the degree of confidence, likely range of outcomes and locations where the outlook has limited skill. Avoid converting a broad ENSO signal into a deterministic district-level prediction.

Stage 3 : Sectoral impact assessment. Translate rainfall scenarios into potential consequences for reservoir inflows, irrigation availability, drinking-water supply, crop calendars, livestock, hydropower and household livelihoods. Where possible, combine climate information with reservoir storage, crop stage, water demand, population exposure and vulnerability data.

Stage 4 : Authorized decision and trigger review. Relevant authorities should review official forecasts, sectoral thresholds, available resources and uncertainty before deciding on actions. Decision rules may include monitoring escalation, irrigation scheduling, water-conservation advice, agricultural extension support or targeted assistance. Responsibilities should follow existing mandates and approved procedures.

Stage 5 : Communication and anticipatory action. Communicate risk in clear, geographically relevant language. Explain what is expected, when it may occur, what remains uncertain and what people or institutions can do. Depending on local conditions, actions may include adjusting planting plans, prioritizing drinking-water needs, preparing water distribution, protecting livestock, or providing timely advice to farmers. Safety-critical advice should be reviewed by responsible authorities.

Stage 6 : Evaluation and learning. After each season, compare outlooks with observed rainfall, reservoir conditions, agricultural outcomes and reported impacts.

Review whether decisions were timely, messages reached intended audiences and planned measures were feasible. Use the findings to refine local triggers, communication plans and data requirements.

5. Data Quality and Uncertainty

The framework depends on data that are timely, sufficiently complete and suitable for the decision being made. Missing rainfall observations, outdated reservoir information or incomplete local crop data can lead to misleading impact assessments. Forecast uncertainty should be recorded rather than concealed, and decisions should consider alternative scenarios where consequences are serious.

6. Human Oversight and Institutional Responsibility

Climate models and decision-support tools should inform, not replace, the judgement of qualified officials and sector specialists. Forecast interpretation, public advice and resource allocation should remain with the responsible institutions. Documenting the evidence, assumptions, authority and reasons for decisions can improve accountability and support post-season learning.

7. APPLICATION TO KEY WATER-SECURITY SECTORS

Agriculture and Irrigation

Seasonal outlooks can support discussion of planting windows, crop choice, irrigation demand and water allocation. Such advice should be tailored to local crop calendars and actual reservoir and tank conditions. Drought-tolerant varieties, efficient irrigation and timely extension advice may reduce vulnerability, but no single intervention is appropriate for every farming system.

Drinking-Water Supply

Water-supply planning should monitor source reliability, storage, demand and the needs of communities with limited alternatives. Where a seasonal outlook indicates elevated drought risk, responsible authorities can assess contingency sources, prioritize essential services and communicate conservation measures before shortages become acute.

Hydropower and Energy

Reservoir inflows influence hydropower availability, but energy planning also depends on storage, competing water demands and the wider electricity mix. Seasonal climate

information can inform scenario planning, provided it is combined with current hydrological and operational data rather than treated as a direct prediction of generation.

Food Security and Vulnerable Households

The 2016–2017 experience demonstrates that crop losses can affect both food availability and household purchasing power. Monitoring should therefore include not only rainfall and production estimates but also local livelihood conditions, market prices and access to assistance. Where credible early indicators identify heightened risk, authorities and partners may consider targeted preparedness or anticipatory support within their mandates.

Flood and Drought Risks Occurring Together

The May 2017 floods and landslides alongside continuing water constraints in other regions illustrate the need for geographically differentiated risk management. National planning should not assume that a single climate condition produces the same hazard everywhere. Drought preparedness must coexist with flood readiness, and decisions should be based on local observations and official hazard information.

8. DISCUSSION

Main Findings

The literature supports three main conclusions. First, El Niño can influence Sri Lanka's seasonal rainfall, but the response depends on season, event characteristics and other climate drivers. Second, drought impacts are transmitted through water availability, irrigation, agricultural production, household income and food security. Third, the usefulness of climate information depends on how it is interpreted and connected to decisions and actions.

Why a Risk-to-Action Approach is Useful

A risk-to-action sequence can make the link between forecasts and sectoral decisions explicit. Rather than treating an ENSO index as an action trigger on its own, the approach asks what the climate outlook means for a particular region, water system, crop stage or vulnerable population. It also makes space for uncertainty and for evaluation after the season. These are anticipated benefits of the proposed framework, not measured outcomes.

9. Technical and Institutional Challenges

Challenges include uncertainty in seasonal forecasts, limited local observations, differences in data formats and update schedules, competing water demands, and unequal capacity among districts. Communication can also fail if information is too technical, arrives late or does not identify practical actions. Sustainable implementation would require coordination among the Department of Meteorology, Irrigation Department, Department of Agriculture, water-supply agencies, disaster-management authorities, local government and affected communities. This paper does not assess the internal procedures or performance of those institutions.

10. Contribution and Novelty Limitations

The paper's contribution is a Sri Lanka-focused conceptual synthesis connecting ENSO and seasonal rainfall knowledge with impact assessment and anticipatory water-security action. ENSO monitoring, seasonal forecasting, water planning and drought preparedness are not new concepts. The framework should therefore be regarded as a structured proposal for further review, not as a proven new method or a claim that comparable approaches do not exist.

11. Recommendations

Integrate climate indicators: Use ENSO and IOD information together with national seasonal forecasts and local observations. Provide clear explanations of uncertainty and avoid communicating global climate signals as guaranteed local outcomes.

Link forecasts to sectoral thresholds: Relevant agencies should review whether existing decision procedures define useful triggers for reservoir monitoring, irrigation planning, drinking-water contingencies, agricultural advice and targeted support. Any triggers should be based on local evidence and authorized protocols.

Strengthen water-resource planning: Monitor reservoir and tank storage, forecast demand where feasible, reduce avoidable losses and consider essential household needs alongside agricultural and energy requirements. Water-allocation plans should be transparent and adapted to local conditions.

Improve agricultural preparedness: Provide timely seasonal information to farmers, support suitable crop and planting decisions, promote water-efficient practices where appropriate and coordinate agricultural assistance with observed conditions and crop calendars.

Communicate actionable information: Warnings and advisories should specify the affected area, relevant time period, expected risk, uncertainty and recommended action. Communication should use accessible language and channels appropriate to local communities.

Evaluate the complete process: Evaluation should compare forecasts with observations and assess whether information reached decision-makers and communities, whether actions were timely and whether outcomes improved. A review should identify whether problems arose from forecast skill, data availability, decision processes, communication or response capacity.

Use a phased approach: Begin with a review of existing processes and available data. If justified, pilot the framework for a selected season or sector, define evaluation criteria in advance and consult the responsible institutions before considering wider adoption.

12. Proposed Future Evaluation Plan

Stage 1: Baseline review

Document existing seasonal forecast products, water-management processes, agricultural advisories and decision responsibilities for a selected district or basin.

Stage 2: Define indicators

Select the indicators, for the project like rainfall changes how much water is stored in reservoirs, how far in advance the forecast is made how many people get the advice, how much water is needed for farming what crops produce or when there is not enough water.

Stage 3: Retrospective assessment

When data exists compare past forecasts with what actually happened in terms of rain, water levels and farming results. The study must say when it looked at what was used as a starting point how sure it was and what method was used.

Stage 4: Stakeholder consultation

Consult meteorological, irrigation, agricultural, water-supply and local stakeholders to assess whether proposed decision links are technically feasible and institutionally appropriate.

Stage 5: Limited pilot and review

If approved by the relevant authorities, conduct a limited pilot with predefined objectives and safeguards. Compare results against the baseline and revise the framework before any wider application.

13. Conclusion

El Nino is a global climate driver that can affect the seasonal rain in Sri Lanka but the effects are not the same everywhere and are not always predictable. Research that has been checked by experts shows that the way rain responds depends on the time of year and whether El Nino fades quickly or slowly along with other factors like the Indian Ocean Dipole and the way the land is shaped. The drought that happened between 2016 and 2017 shows how less rain can harm the production of paddy the availability of water the way people earn a living and the security of their food. The floods that came after in some parts of the country also show the need for kinds of preparation based on where people live and the different types of dangers that can happen. This paper suggests a Seasonal Risk-to-Action Framework that connects monitoring the weather understanding what it means in areas looking at the effects on different industries making decisions that are allowed sharing information taking steps before the season ends and learning after the season is over. The framework is still an idea and has not been tested yet. Its usefulness should be checked by looking at data talking to people who know about it and trying it out in a planned test. In the end information, about the weather can help people be safer when it is turned into actions that happen on time are trusted and fit what is needed where people live.

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PARTICIPANT RESEARCH PAPER

Sea-Level Rise and Disaster Risk in Small Islands

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Abstract

Small Island Developing States (SIDS) face disproportionate risks from sea-level rise despite contributing relatively little to global greenhouse-gas emissions. Rising mean sea level increases the likelihood and severity of coastal flooding and erosion, while interacting with wave conditions, reef degradation, freshwater scarcity and concentrated coastal development. This paper examines these risks with particular reference to the Maldives, where low-lying coral islands, dispersed settlements and reliance on tourism and fisheries create interconnected vulnerabilities. Using a desk-based review of international assessments and institutional reports, the paper considers physical and socioeconomic exposure, unequal impacts on vulnerable groups, community resilience, and scientific and institutional capacity gaps. It argues that disaster risk is shaped not by the hazard alone but by exposure, vulnerability and the ability to prepare and respond. A transition from reactive response to anticipatory disaster management should combine locally relevant risk data, climate-informed land-use and infrastructure planning, ecosystem protection, appropriate engineered measures, accessible multi-hazard early warning, and pre-agreed action and financing. The paper recommends island-level risk profiles, stronger institutional coordination, community participation, improved monitoring and transparent adaptation finance. Long-term resilience in the Maldives and other SIDS depends on local preparedness and adaptation alongside urgent global emissions reductions and sustained international support.

Keywords: Sea-Level Rise; Small Island Developing States (SIDS); Coastal Vulnerability; Disaster Risk Reduction; Climate Change Adaptation.

1. Introduction

Small Island Developing States (SIDS) contribute a relatively small share of global greenhouse-gas emissions but face disproportionate consequences from climate change. Their small land areas, concentration of settlements and infrastructure along coastlines, dependence on marine ecosystems, and limited financial and technical resources can turn gradual environmental change into a national development challenge. Sea-level rise is especially serious because it increases the reach and frequency of coastal flooding, worsens erosion, and raises the baseline upon which storm surges and high waves act (Intergovernmental Panel on Climate Change [IPCC], 2022).

The Maldives illustrates this vulnerability. It is a dispersed archipelago of low-lying coral islands, with around 80% of its islands reported to lie less than one metre above mean sea level. Coastal communities, transport links, water supplies, public facilities, tourism assets and fisheries infrastructure are therefore exposed to overlapping risks (United Nations Development Programme [UNDP], n.d.; World Bank, 2024). The problem is not simply whether the sea will eventually cover land. Present-day risks include repeated wave overtopping, shoreline retreat, damage to homes and public infrastructure, saltwater intrusion into freshwater lenses, and disruption to livelihoods.

This paper examines how sea-level rise magnifies disaster risk in SIDS, using the Maldives as the principal case study. It aims to assess exposure and vulnerability, identify community and institutional resilience factors, and recommend an integrated shift from reactive response towards anticipatory disaster risk reduction (DRR). The analysis draws on international assessments and institutional publications. It is a desk-based review rather than primary field research; consequently, recommendations should be refined through island-level data and consultation with affected communities.

2. Regional Context and Hazard Profile

Sea-level rise is a slow-onset climate hazard, but its impacts can become sudden when high tides, monsoon waves, storm conditions and local drainage problems combine. The IPCC concludes that rising sea levels and changes in wave climate are expected to increase coastal flooding and erosion on small islands, with the frequency, extent and duration of flooding projected to increase further from mid-century (IPCC, 2022). The

exact outcome differs between islands because reef condition, island elevation, shoreline shape, sediment movement, rainfall and local construction all influence risk.

Four concepts help clarify the problem. A hazard is a potentially damaging process, such as a high-water event or coastal flood. Exposure refers to people, buildings, infrastructure and ecosystems located where the hazard may occur. Vulnerability is the degree to which those exposed are susceptible to harm, shaped by factors such as housing quality, income, health, access to services and preparedness. Disaster risk emerges from the interaction of hazard, exposure, vulnerability and capacity; it is not determined by sea level alone (United Nations Office for Disaster Risk Reduction [UNDRR], 2015).

For the Maldives, the World Bank's Country Climate and Development Report identifies sea-level rise and associated flooding as major economic threats and estimates substantial adaptation investment will be needed. It also stresses the importance of protecting coral reefs and integrating climate scenarios into island and infrastructure planning (World Bank, 2024). These findings underline that coastal risk is both physical and economic: damage to a harbour or freshwater system can interrupt services far beyond the immediate flooded area.

UNDERSTANDING COASTAL RISK: SEA-LEVEL RISE IN THE MALDIVES

ADAPTED FROM IPCC (2022), UNDRR (2015), & WORLD BANK (2024) REPORTS

A SLOW-ONSET HAZARD, SUDDEN IMPACTS



Sea-level rise combines with high tides, monsoon waves, storm conditions, and local drainage issues to cause sudden flooding.

IPCC FINDINGS: INCREASING RISK

Reef condition, island elevation, shoreline shape, sediment movement, and construction influence outcomes.



PROJECTED INCREASE IN COASTAL FLOODING FREQUENCY & EXTENT (FROM MID-CENTURY)



FOUR CONCEPTS OF DISASTER RISK (UNDRR)

1) HAZARD

Tidal surges, storm waves, coastal flood



Tidal; waves, coastal flood

2) EXPOSURE

People, buildings, infrastructure, ecosystems



Harbor

3.VULNERABILITY

Susceptibility to harm housing quality, income, health, preparedness



First aid

4) CAPACITY

Ability to cope, adapt, and respond



Community training

DISASTER RISK = HAZARD × EXPOSURE × VULNERABILITY / CAPACITY

MALDIVES: ECONOMIC IMPACTS & ADAPTATION (WORLD BANK)



Sea-level rise and flooding are major economic threats. Adaptation investment is essential.

Protect Coral Reefs & Ecosystems



Protect Coral Reefs & Ecosystems

Integrate Climate Scenarios into Planning

Build Resilient Infrastructure

3. Risk and Vulnerability Assessment

Physical and infrastructure impacts. Repeated flooding and erosion can damage houses, roads, seawalls, jetties, harbours, power and telecommunications assets, schools, health facilities and waste-management systems. Because islands have limited land and many essential assets occupy narrow coastal zones, there may be few alternative locations or routes. Dispersed geography also makes repair work, evacuation and delivery of supplies expensive and weather-dependent. Protective structures may be necessary in high-risk locations, but poorly designed coastal works can transfer erosion to neighbouring shorelines or disrupt sediment movement. Site-specific engineering and environmental assessment are therefore essential.

Freshwater and public health. Many island communities rely on rainwater storage and shallow groundwater lenses. Coastal inundation and saline intrusion can make these sources less usable, while flooding can contaminate water storage, damage sanitation systems and increase exposure to water-borne illness. Emergency water shipments and desalination can provide important safeguards, but they require energy, maintenance, transport and finance. Water security should consequently be treated as a core element of disaster preparedness, not merely a utility issue (Asian Development Bank & World Bank Group, 2021).

Livelihoods and economic security. Tourism depends on beaches, healthy reefs, reliable utilities, transport and the perception of a safe destination. Fisheries depend on accessible landing sites, functioning cold chains, marine ecosystems and predictable weather. Reef degradation can reduce natural coastal protection while also undermining tourism and fishing income. The World Bank (2024) identifies the country's reliance on tourism and fisheries as a major source of climate-related economic exposure. If households lose income at the same time that homes and assets are damaged, their capacity to recover is weakened and disaster impacts may persist for years.

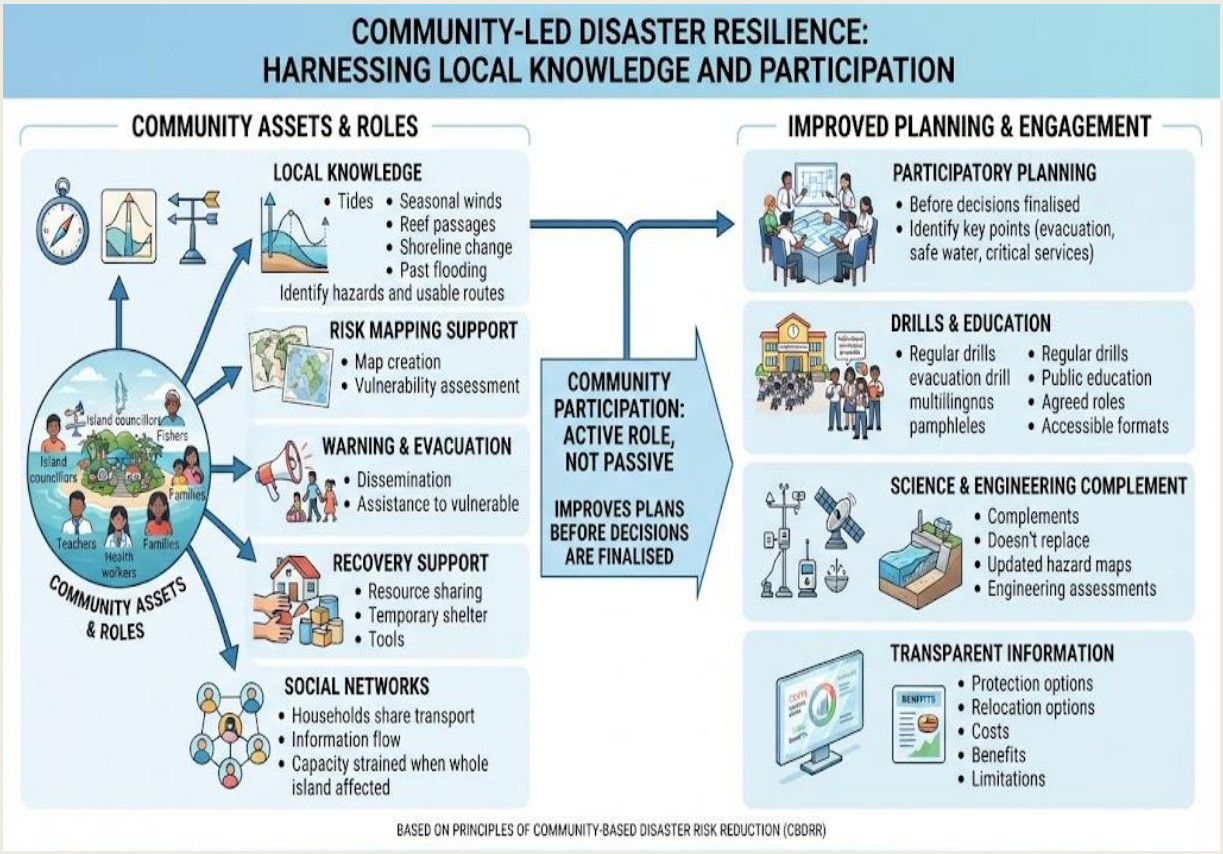
Unequal impacts. Risk is not shared evenly. Low-income households may be unable to elevate homes, buy insurance, relocate temporarily or replace damaged equipment. Older people, children, persons with disabilities, pregnant women and people with chronic illnesses may face additional barriers to evacuation and access to services. Women may carry disproportionate responsibility for caregiving and household water

management, while informal workers and small-scale fishers may have limited savings or social protection. Remote islands may experience longer delays in receiving technical assistance and supplies. Risk assessments should therefore disaggregate data by island, age, gender, disability, income and livelihood instead of relying only on national averages. Sea-level rise should be understood as a risk multiplier. It increases the starting water level, so an event that previously caused minor flooding may increasingly damage assets or interrupt services. Combined risks matter: coastal flooding during a power outage can affect desalination; erosion near a harbour can disrupt food and fuel supply; and reef decline can simultaneously reduce ecosystem protection and tourism income. Planning for each hazard or sector separately may therefore underestimate real-world consequences.

4. Community Resilience Factors

Communities are not passive recipients of disaster assistance. Local knowledge of tides, seasonal winds, reef passages, shoreline change and past flooding can help identify where hazards occur and which routes remain usable. Island councils, community groups, schools, health workers, fishers and local businesses can support risk mapping, warning dissemination, evacuation assistance and recovery. Existing social networks may help households share transport, tools, temporary accommodation and information, although their capacity can be strained when a whole island is affected.

Community participation improves plans when it occurs before decisions are finalised. Residents should help identify evacuation points, people requiring assistance, safe water locations and critical services that must remain operational. Drills and public education should be conducted in accessible formats and languages, with roles agreed in advance. Traditional knowledge is valuable, but it should complement rather than replace scientific measurements, updated hazard maps and engineering assessments. Communities also need transparent information about the costs, benefits and limitations of proposed protection or relocation options.

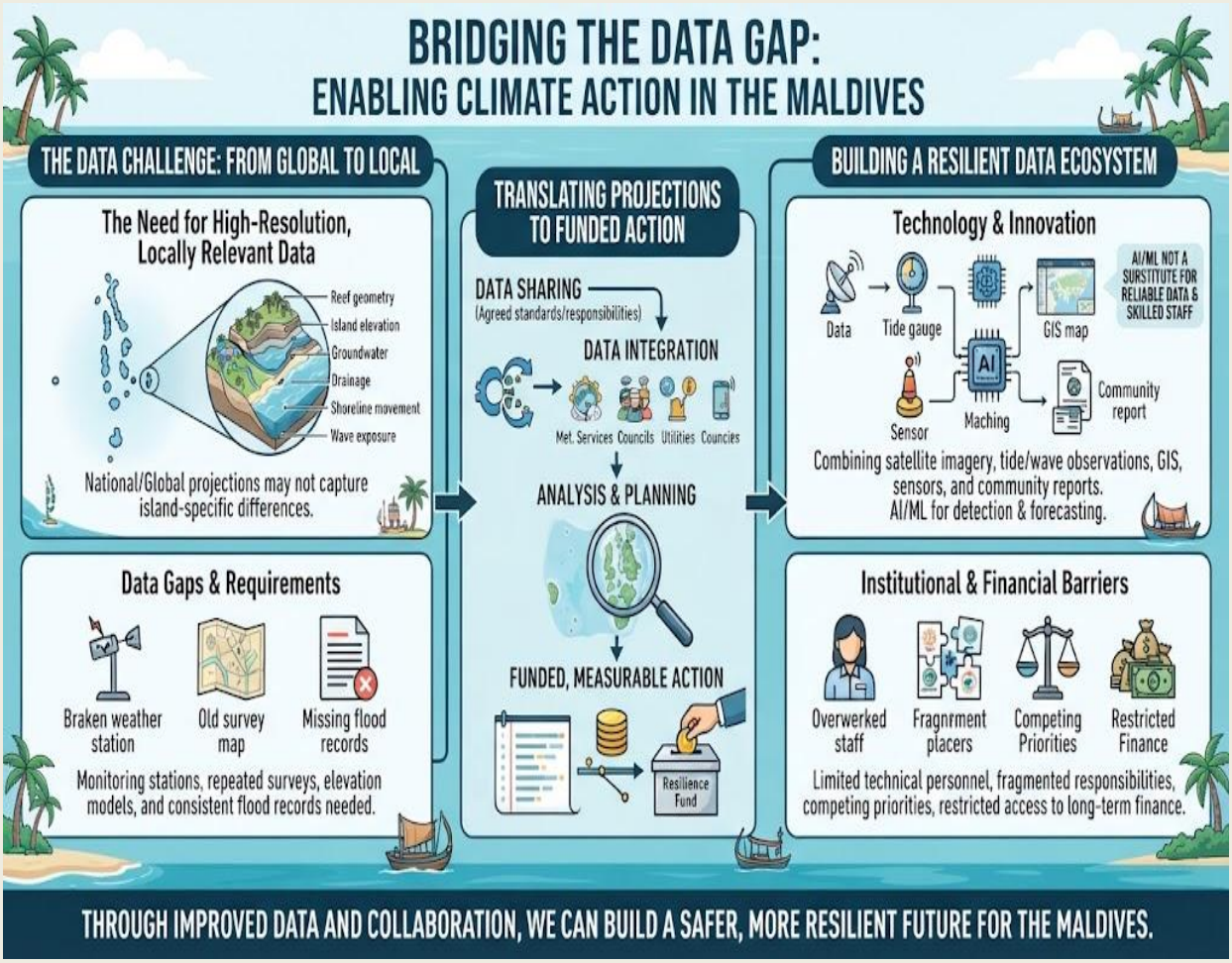


5. Scientific and Institutional Gaps

A major challenge is the availability of high-resolution, locally relevant data. National or global projections may not capture differences in reef geometry, island elevation, drainage, groundwater, shoreline movement and wave exposure between individual islands. Monitoring stations, repeat shoreline surveys, elevation models and consistent records of flood impacts are needed to improve planning. Data should be shared between meteorological services, disaster-management authorities, environment and infrastructure agencies, local councils, utilities and researchers through agreed standards and responsibilities.

Technology can help combine satellite imagery, tide and wave observations, geographic information systems (GIS), sensors and community reports. Artificial intelligence and machine-learning tools may support shoreline-change detection or impact forecasting, but they are not substitutes for reliable data, local validation, skilled staff or accountable decisions. Models can mislead when observations are sparse or when uncertainty is not communicated. Institutions also face practical constraints: limited technical personnel,

fragmented responsibilities, competing development priorities and restricted access to long-term adaptation finance. These gaps make it difficult to translate climate projections into funded, measurable action.



6. Mitigation Strategies and Best Practices

A balanced strategy should combine nature-based solutions, engineered protection, land-use planning and preparedness. Coral reefs dissipate wave energy and provide habitat that supports fisheries and tourism; mangroves, wetlands and seagrass can also contribute to coastal protection and ecosystem health where local conditions support them. The World Bank's guidance on natural coastal solutions recommends measuring and valuing the protection services of mangroves and coral reefs in coastal and development decisions (World Bank, 2016). Protection and restoration should be based

on ecological evidence and sustained management. Nature-based approaches are not universally suitable and cannot eliminate risk under all sea-level scenarios.

Where risk assessments justify it, engineered measures such as seawalls, revetments, raised critical facilities, improved drainage and elevated utilities may protect people and essential services. They should be designed for future rather than historical water levels, assessed for effects on neighbouring coastlines, and maintained over their full life cycle. Other measures include protecting freshwater storage, improving rainwater harvesting, safeguarding backup power for water systems, strengthening building standards, preventing development in high-risk areas and identifying safe land-use options. In some locations, planned relocation or retreat from the most exposed sites may need to be considered transparently and with community participation.

Climate mitigation remains essential. Adaptation can reduce harm, but it cannot fully offset continued global sea-level rise. SIDS should continue to advocate for rapid global emissions reductions while pursuing feasible domestic measures such as renewable energy, energy efficiency, resilient transport and lower-carbon public infrastructure. National best practice should be assessed by measurable outcomes—reduced service downtime, fewer people exposed, protected freshwater, healthier reefs and faster recovery—rather than by the number of projects completed.

7. Risk Communication and Early Warning

Early warning systems reduce risk only when warnings lead to timely action. UNDRR describes effective systems as a connected chain of risk knowledge; hazard monitoring and forecasting; warning dissemination; and preparedness to respond (UNDRR, 2017). A forecast that does not reach an exposed household, or a warning without clear instructions and transport arrangements, will have limited protective value.

For the Maldives, warnings should combine meteorological and ocean information with local exposure data and practical impact messages. Communication channels may include mobile alerts, radio, television, official digital channels, mosque and community announcements, and direct contact with households that may not receive digital messages. Messages should state the expected impact, affected locations, timeframe, actions to take and the official source. Redundant channels are important during power or telecommunications outages. People-centred systems should account for persons with

disabilities, older residents, visitors, language needs and households without reliable internet access.

Preparedness must be linked to pre-agreed action. Island-level plans should identify evacuation assistance, safe shelters, boat and harbour restrictions, protection of critical equipment, backup water, emergency supplies and responsibilities for checking vulnerable residents. Exercises should test the entire chain, from detection to public response, and after-action reviews should correct weaknesses. Forecast-based or anticipatory financing could release pre-agreed funds for protective action when credible thresholds are reached, rather than waiting for damage to occur (UNDRR, n.d.).

8. Policy Recommendations

No.	Policy area	Key recommendations
1	Island-level risk assessment	Develop and regularly update multi-hazard risk profiles combining elevation, shoreline, population, infrastructure, freshwater, ecosystems and livelihoods. Publish accessible summaries of key risks and uncertainties.
2	Climate-resilient development	Integrate future climate scenarios into major development decisions. Require climate-risk screening for infrastructure and public facilities, considering multiple sea-level and wave scenarios, maintenance costs and future upgrades.
3	Coastal protection and adaptation	Combine ecosystem restoration, engineered defences, improved drainage and water security. Assess lifecycle costs, social equity and environmental impacts while avoiding development that increases or transfers risk.
4	Community-led preparedness	Support island councils in maintaining evacuation and continuity plans, conducting regular drills and identifying residents requiring assistance. Ensure inclusive participation in decision-making.
5	Early warning and anticipatory action	Improve local observations and impact-based forecasts, standardise warning messages, maintain backup communication channels and link warnings to operational

		procedures and pre-arranged funding.
6	Coordination and accountability	Clarify institutional responsibilities, establish shared data standards and monitor indicators such as service interruptions, freshwater quality, shoreline change, warning reach and recovery time. Conduct independent post-event reviews and report progress publicly.
7	Predictable adaptation finance	Combine national budgets, concessional finance, international climate funds and appropriate private investment. Prioritise risk reduction, essential services and vulnerable groups, supported by transparent procurement and maintenance plans.
8	Mitigation and international advocacy	Advance domestic low-carbon development while advocating for ambitious global emissions reductions and accessible climate finance for SIDS, recognising that the challenge exceeds the capacity of individual islands.

9. Conclusion

Sea-level rise poses a serious and growing disaster risk to SIDS because it interacts with low elevation, coastal settlement patterns, fragile ecosystems and concentrated economic assets. In the Maldives, risks extend beyond land loss to freshwater security, public health, transport, infrastructure, tourism, fisheries and household income. These impacts are unevenly distributed and can compound when multiple services fail together.

The central finding is that vulnerability is not fixed. Although no island can eliminate sea-level rise through local action alone, risk can be reduced through better data, climate-informed planning, healthy coastal ecosystems, carefully designed infrastructure, inclusive early warning and prepared communities. The shift from reactive response to anticipatory disaster management requires institutions to act before losses occur, with clear responsibilities, sustained finance and measurable results. A resilient Maldives will

depend on integrating scientific evidence with local knowledge and ensuring that adaptation decisions protect people, essential services and livelihoods over the long term.

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PARTICIPANT RESEARCH PAPER

Integrated Water Resources Management for Drought Risk Reduction in Pakistan: A Review of Subsurface Dams as a Sustainable, Climate-Resilient Storage Solution

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Abstract

Pakistan faces recurring and intensifying drought, driven by climate change, population growth, over-extraction of groundwater and fragmented water governance. Drought is not only a shortage of rainfall: weak storage, unregulated pumping and sector-by-sector crisis relief turn a dry spell into a disaster. This review paper examines how Integrated Water Resources Management (IWRM) can move Pakistan from reactive drought response to proactive drought risk reduction, and assesses subsurface dams (SSDs) as a practical IWRM tool within that shift. Unlike conventional surface dams, SSDs store water inside the aquifer, which minimizes evaporation losses, reduces land displacement and avoids reservoir sedimentation. The paper organizes drought risk reduction around three pillars (monitoring and early warning, vulnerability and impact assessment, and mitigation, preparedness, response and recovery) and maps the contribution of SSDs to each IWRM principle. It highlights arid and drought-prone regions with severe groundwater depletion and limited surface water, such as the Pothohar Plateau, the Thar Desert, southern Kohat district in KPK and Balochistan. Global experience from Japan, East Africa and India, together with Pakistani pilot projects, shows that distributed groundwater storage is feasible in comparable climates. Successful implementation, however, requires thorough hydrogeological evaluation, community participation and policy integration. SSDs are not a panacea, but they are a critically underused layer of low-evaporation storage that supports Pakistan's large dams in drought years and strengthens climate resilience and sustainable agriculture.

Keywords: Integrated Water Resources Management, Drought Risk Reduction, Subsurface Dams, Groundwater Recharge, Aquifer Storage, Climate Resilience.

1. Introduction

Pakistan is classified as a water-stressed country, with per capita water availability falling from over 5,000 cubic meters in 1951 to less than 900 cubic meters today (PCRWR, 2022). In 2018 the IMF ranked Pakistan as the third most water-scarce nation. Contributing factors include rapid population growth, inefficient agricultural practices (agriculture consumes over 90% of water resources), glacier melt and erratic rainfall linked to climate change, and heavy reliance on an over-allocated and diminishing Indus River System (PCRWR, 2022; Qureshi, 2020; World Bank, 2019). Pakistan loses an estimated 30%–40% of its canal water to seepage and conveyance losses before it reaches farms (Shah et al., 2019), and groundwater abstraction is largely unregulated, causing over-extraction and declining aquifer levels, particularly in Punjab and Sindh (Qureshi, 2020; Shahid & Ashraf, 2018). Urbanization and industrial expansion add water pollution to the stress on freshwater resources. Water scarcity in Pakistan is therefore not merely physical; it is also the result of systemic mismanagement and the lack of integrated water resources planning (World Bank, 2019; Ahmed & Sohail, 2019).

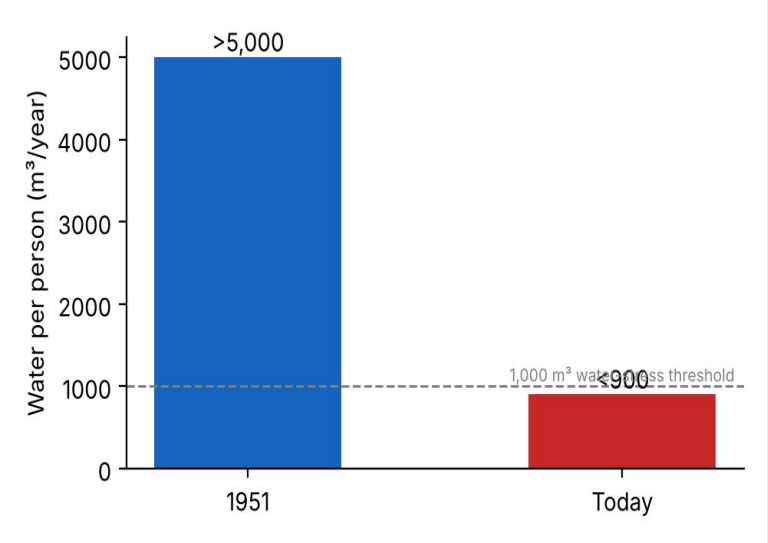


Figure 1. Decline in per capita water availability in Pakistan (PCRWR, 2022)

These weaknesses become most visible during drought. Between September 2024 and March 2025, rainfall across Pakistan was about 40% below normal, with a deficit of about 62% in Sindh, the worst-hit province. March 2025 was 2–3 °C above normal, and Tarbela and Mangla reservoirs reported acute storage shortages (PMD-NDMC, 2025). Responses to such events are still largely reactive: they begin after drought is declared,

rely on ad hoc restrictions, are handled sector by sector, and so repeat losses in every cycle (Wilhite et al., 2014; UNDRR, 2021).

National water security discourse has been dominated by large surface dams (e.g., Diamer-Bhasha, Kalabagh). They are important for flood control and hydropower, but involve large capital outlay, long gestation periods, displacement, rapid siltation and heavy evaporation losses, a critical drawback in a warming climate (FAO, 2010; Khan et al., 2020). There is an urgent need to diversify the storage portfolio and to manage it within an integrated framework. Subsurface dams offer such an option by storing water in the aquifer rather than on the surface, conserving water underground and enhancing groundwater recharge. They are widely used in countries such as Japan, Kenya and India, where they have proven low-cost, sustainable and adaptable to local communities (Lasage & Verburg, 2015; JICA, 2004; UNEP, 2016).

This paper therefore asks: can distributed groundwater storage move Pakistan from drought crisis response to drought risk reduction? Its objectives are to (i) explain IWRM as a framework for drought risk reduction, (ii) assess Pakistan's drought exposure and vulnerability, (iii) connect subsurface dam technology to IWRM practice, and (iv) recommend policy and institutional actions. The scope is Pakistan (Balochistan, Thar, Pothohar and southern KP), with lessons from Japan, East Africa and India.

2. IWRM and Drought Risk Reduction: From Crisis Response to Risk Management

IWRM is the coordinated development and management of water, land and related resources to maximize economic and social welfare in an equitable manner without compromising the sustainability of ecosystems (GWP, 2000). Its three guiding goals are efficiency, equity and sustainability. Applied to drought, IWRM replaces reactive crisis management with proactive risk management (Wilhite et al., 2014; Cap-Net et al., 2020), as contrasted in Table 1.

Table 1. Reactive crisis response versus proactive risk management

Aspect	Reactive crisis response	Proactive risk management
Timing	Acts after drought is declared	Monitors, forecasts and warns early

Aspect	Reactive crisis response	Proactive risk management
Planning	Ad hoc water-use restrictions	Plans storage and allocation ahead
Coordination	Relief handled sector by sector	Links water, land, agriculture and DRR
Outcome	Losses repeat each cycle	Builds resilience over time

2.1 Three pillars of drought risk reduction

Drought risk reduction rests on three pillars (Cap-Net et al., 2020; UNDRR, 2021), and IWRM is the glue that joins them across water, land, agriculture and disaster risk reduction.

Pillar 1: Monitoring and early warning. Rainfall, reservoir and drought indices, together with seasonal forecasts and advisories. In Pakistan, the National Drought Monitoring and Early Warning Centre (NDMC) issued advisories in December 2024 and January 2025 and a drought alert in March 2025 (PMD-NDMC, 2025).

Pillar 2: Vulnerability and impact assessment. Identifying who and what is exposed, assessing impacts on crops, livestock and drinking water, and guiding where to invest first.

Pillar 3: Mitigation, preparedness, response and recovery. Storage and recharge (such as subsurface dams), allocation rules and contingency plans, and recovery support for affected households.

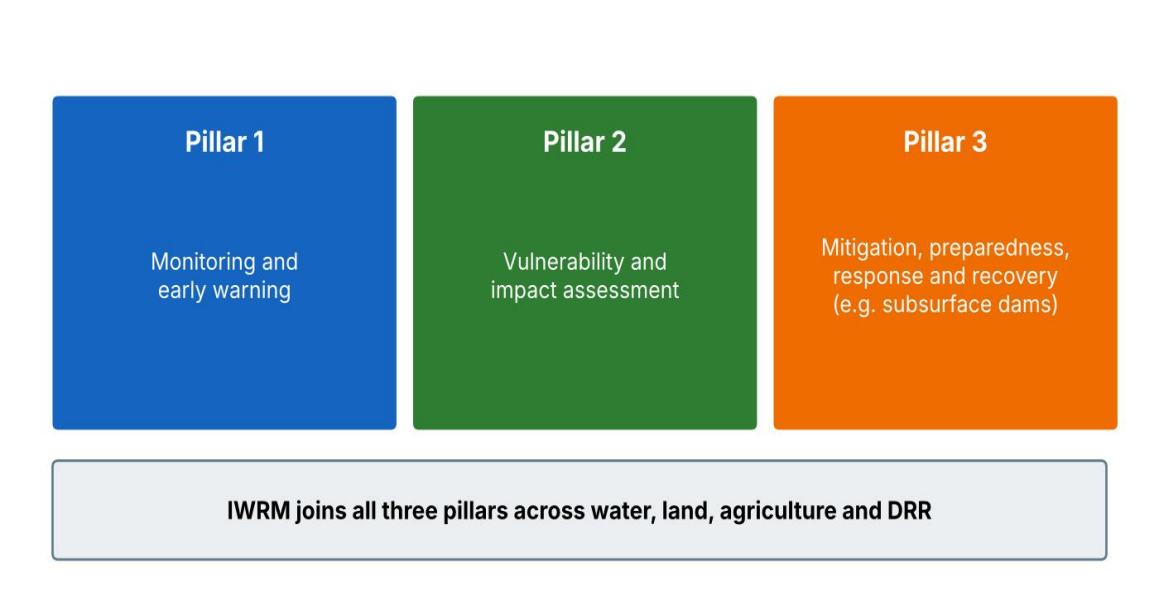


Figure 2. Three pillars of drought risk reduction joined by IWRM

2.2 Who is exposed in Pakistan

Drought risk is borne unevenly. Rain-fed farmers and herders in Thar, Balochistan and southern Punjab depend directly on rainfall. Women and children face longer trips to fetch water. Low-income rural households depend on water tankers, and groundwater users in Punjab and Sindh face falling water tables from over-extraction (Qureshi, 2020; Ahmed & Sohail, 2019; Ali & Hussain, 2021). Mapping this exposure (Pillar 2) shows where distributed, locally managed storage will matter most.

3. Subsurface Dam Background

A subsurface dam is an underground structure constructed across a subsurface valley, ephemeral stream, alluvial aquifer or groundwater flow path to intercept and store groundwater, creating an artificial aquifer or raising the water table of a natural one (Aziz et al., 2025; Chang et al., 2023). The dam wall, typically of impermeable material such as concrete, clay or masonry, is keyed into bedrock or low-permeability strata to prevent seepage (Nissen-Petersen, 2006). This raises the groundwater level upstream and creates a subsurface reservoir. The core principles are:

Impermeable barrier. A wall of concrete, clay, sheet piles or brick masonry is built down to an impermeable layer such as bedrock (Nilsson, 1988; Steenbergen & Tuinhof, 2009).

Groundwater impoundment. The barrier impedes natural subsurface flow, so water accumulates upstream, saturating the porous geological material and forming a stored reservoir.

Natural filtration. The overlying soil and aquifer material improve water quality by removing pathogens and contaminants as water infiltrates.

The technical design typically involves site investigation (geological surveys, boreholes and geophysical methods), cutoff wall construction using clay, masonry or reinforced concrete, keying into bedrock or low-permeability layers to minimize seepage, and water abstraction through wells, infiltration galleries or pumps. Construction is best undertaken in the dry season, using locally available materials where possible to reduce cost.

Table 2. Key design considerations

Parameter	**Recommended approach**
Cutoff depth	Into bedrock or clay lens (≥0.5–1.0 m)
Wall material	Clay, masonry, reinforced concrete
Suitable location	Narrow valleys with coarse alluvium
Abstraction	Infiltration wells, pump stations

The main types are: (i) Sand storage dams, built across seasonal riverbeds (wadis), where an impermeable wall captures sediment-laden flash-flood water and coarse sand settling behind the wall forms a high-porosity storage zone; (ii) Traditional subsurface dams, built entirely below the natural ground surface with no visible structure, with water abstracted by wells or pumps from the upstream saturated zone; and (iii) Weir-type subsurface dams, whose structure may be partially exposed in the dry season and functions like a weir to control the groundwater level.

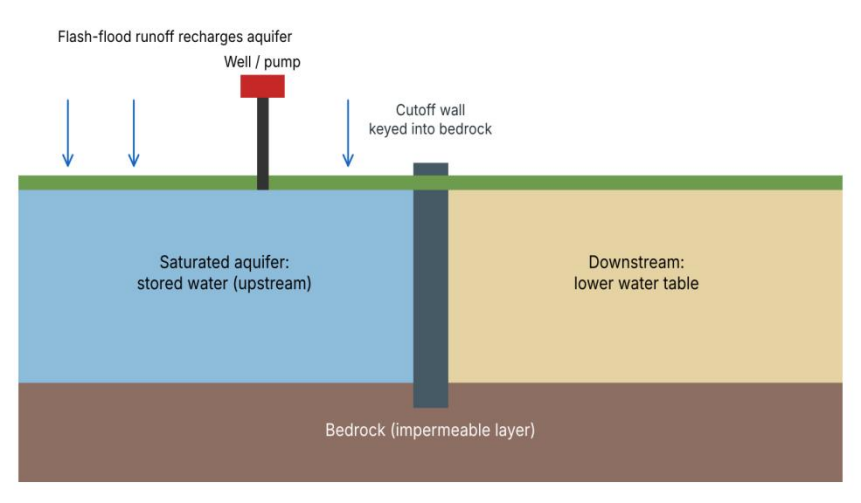


Figure 1. Schematic of a subsurface dam (author's illustration)

4. Advantages of Subsurface Dams for Drought Resilience

Subsurface dams reduce evaporation losses because stored water is shielded from high temperatures. No large surface reservoir is needed, so land displacement is minimal. Filtration through sand and gravel improves water quality by reducing turbidity and contamination (Hameed et al., 2025; Hwang et al., 2023). Costs can be reduced because materials are often locally available, and maintenance can be managed by the community. Unlike surface reservoirs, which are highly vulnerable to prolonged drought, SSDs stabilize groundwater tables and support year-round water availability (Lasage & Verburg, 2015). They also reduce land-acquisition conflicts because they do not inundate villages or farmland, making them more socially acceptable in densely populated areas (Ali & Hussain, 2021). Storing water below ground shields it from animals and surface pollutants, reducing treatment costs for domestic use (Boelee et al., 2013). As nature-based solutions, they enhance groundwater recharge, biodiversity support and soil moisture retention (UNEP, 2016; Steenbergen & Tuinhof, 2009).

Table 3. Comparison between surface dams and subsurface dams

Parameter	**Surface dam**	**Subsurface dam**
Evaporation loss	Very high	Negligible
Land submergence	Extensive	Minimal

Parameter	Surface dam	Subsurface dam
Construction cost	High	Low to moderate
Environmental impact	Significant	Relatively low
Maintenance	Centralized	Community-based

Three drought-related problems are addressed in particular. First, evaporation: with some of the highest evaporation rates globally (up to 2,500 mm per year), Pakistan loses large volumes from surface reservoirs, whereas losses from subsurface storage are negligible (Sharma & Goyal, 2020). Second, siltation: unlike surface dams, which lose capacity to sediment, sedimentation is integral to sand storage dams and can enhance their storage over time (Sainov & Talalaev, 2024; Tokunaga, 2023). Third, climate extremes: SSDs capture intense, erratic rainfall, store water in wet periods for use in drought, and are less vulnerable to climate-related damage than surface infrastructure.

5. Subsurface Dams as an IWRM Tool

Table 4 links IWRM principles to what subsurface dams contribute and to the drought risk reduction pillar each supports. The result is a low-evaporation storage layer that supports Pakistan's large dams in drought years rather than replacing them.

Table 4. Subsurface dams mapped to IWRM principles and drought pillars

IWRM principle	What subsurface dams contribute	Drought pillar
Integrate water and land	Capture flash-flood runoff in nullahs and recharge aquifers (Steenbergen & Tuinhof, 2009)	Pillar 3: mitigation
Diversify storage	Distributed groundwater storage with negligible evaporation complements Tarbela and Mangla	Pillar 3: preparedness

IWRM principle	What subsurface dams contribute	Drought pillar
Local participation	Local labor, materials and upkeep; pilots by PCRWR and NGOs in Pothohar, Balochistan and Tharparkar	Pillars 2 – 3: resilience
Equity and environment	Little land submergence or displacement; natural filtration protects water quality	Pillar 2: vulnerability

5.1 Environmental and socio-economic impacts

Environmentally, SSDs reduce land submergence, cause less ecological disruption than large dams, promote natural groundwater recharge and protect water quality (Steenbergen & Tuinhof, 2009). Socio-economically, construction costs are a fraction of those for surface dams, and simple technology allows local labor and materials, fostering ownership and simplifying maintenance. Reliable drinking water reduces the time women and children spend fetching water and improves health outcomes, while reliable supply enables more crop cycles, livestock rearing and kitchen gardens, which supports livelihoods and helps reduce poverty and dependence on water tankers (Ahmed & Sohail, 2019; Ali & Hussain, 2021). Potential risks include localized waterlogging, reduced downstream flows and inequitable distribution, which can be mitigated through proper planning and community engagement.

6. Global Evidence and Pakistani Pilot Projects

6.1 Global experience

Subsurface dams have been implemented successfully in diverse climates (Imaizumi, 2024; Liu, 2023). Japan has more than 1,500 SSDs for water supply, including large underground dams in Okinawa that store millions of cubic meters of freshwater for agriculture on islands with few surface sources (Sainov & Talalaev, 2024; Tokunaga, 2023). Kenya, Tanzania and Ethiopia have thousands of community-built sand dams that supply drinking and irrigation water to arid-land communities (Mumma & Lane, 2021; Boelee et al., 2013). In India, subsurface barriers in Maharashtra and Rajasthan have raised groundwater levels and improved drought resilience.

Table 5. Global experience with subsurface dams and lessons for Pakistan

Country/region	Type of subsurface structure	Purpose	Key lessons
Japan (Okinawa)	Large underground dams	Agricultural water supply	High storage capacity from advanced engineering
Kenya & Tanzania	Sand dams	Rural water supply, irrigation	Community management, low cost, scalable
India (Maharashtra, Rajasthan)	Subsurface barriers	Drought resilience, groundwater recharge	Effective in arid and semi-arid zones

6.2 Hydrogeological suitability in Pakistan

Pakistan's diverse geography offers many suitable sites. The alluvial piedmont plains (Bars/Bhits) of Punjab, KP and Balochistan, with unconfined aquifers and defined subsurface gradients, are well suited to larger SSDs that augment groundwater recharge. Seasonal rivers (Rods/Nullahs) in Balochistan, KP and the Pothohar Plateau are crossed by ephemeral streams with high-intensity, short-duration flash floods, making them natural locations for sand storage dams that capture otherwise wasted runoff. In the Indus Delta and parts of Thar, SSDs can create localized freshwater lenses above saline groundwater and buffer against saltwater intrusion (Hussain & Siwar, 2017). Hydrogeological assessment, including grain size distribution, bedrock depth and aquifer transmissivity, is essential for site selection.

6.3 Local pilot projects

Although not yet mainstream, several NGOs and government departments have initiated promising pilots. PCRWR has constructed subsurface and sand storage dams in the Pothohar region (e.g., Pind Dadan Khan) and in Balochistan, improving water availability

and quality for local communities (PCRWR, 2022). Practical Action and other NGOs have built sand dams in Tharparkar, providing a reliable drinking water source and reducing the burden of water collection, particularly for women. BARANI (Rainfed) Area Development Projects have included check dams and subsurface structures in watershed management. These projects, though small, provide proof of concept and lessons for scaling up.

7. Scientific and Institutional Gaps

Scientific and technical gaps: incomplete hydrogeological data (bedrock depth, transmissivity); limited local design expertise and long-term monitoring; underuse of GIS, remote sensing and geophysics for site mapping; and the absence of artificial intelligence and machine learning for forecasting and site screening.

Institutional gaps: subsurface dams are absent from national and provincial water policy; groundwater governance is weak and pumping largely unregulated; there are no clear rules for equitable sharing between users; and few engineers, hydrologists and community organizers are trained in SSD planning and construction.

Risks to be managed through planning and community engagement include localized waterlogging, reduced downstream flow and unequal access.

8. Policy Recommendations and Institutional Integration

Despite their potential, subsurface dams remain largely absent from Pakistan's water policy. Pilot projects should demonstrate feasibility and then be scaled through government programs, public-private partnerships, donor funding and community initiatives. Five actions are recommended (Government of Pakistan, 2018):

A. Mainstream. Add subsurface dams and managed aquifer recharge to the National Water Policy and to provincial drought and climate adaptation plans.

B. Plan for risk, not relief. Adopt a national drought plan built on the three pillars, with clear roles for PMD, the provinces and PDMAs.

C. Map and pilot. Screen sites with GIS, remote sensing and geophysics, and pilot in Thar, Balochistan, Pothohar and southern Kohat, scaling successful pilots into government-led programs.

D. Build people and skills. Promote community-managed schemes, with community participation from planning through maintenance, and train engineers, hydrologists and community organizers in site selection, design and participatory construction.

E. Warn the last mile. Turn NDMC advisories into gender-sensitive, local-language alerts, and monitor dam performance over the long term.

9. Challenges and Research Needs

Key challenges for SSD adoption in Pakistan are limited local expertise and research, incomplete hydrogeological data, institutional gaps in groundwater governance, and social acceptance and equitable water sharing. Future research should focus on mapping potential sites with GIS and remote sensing, piloting in diverse hydrogeological settings, long-term monitoring of performance and socio-economic outcomes, applying AI and machine learning to forecasting and site screening, and integrating SSDs with managed aquifer recharge and climate resilience planning.

10. Conclusions

Drought in Pakistan is systemic: it reflects weak storage, over-extraction and fragmented governance as much as missing rain, and so it needs integrated, risk-based management rather than crisis relief (Ali & Hussain, 2021; FAO, 2010; Wilhite et al., 2014). Subsurface dams are not a panacea, but they are a critically underused tool in Pakistan's drought toolkit. By storing water in aquifers with negligible evaporation, improving water quality, recharging groundwater and empowering rural communities, they diversify storage and complement Tarbela and Mangla in drought years. Their success, however, depends on people and policy: community ownership, better hydrogeological data, careful site selection and integration into national and provincial plans. With targeted research and pilot projects, a distributed network of subsurface dams can help Pakistan move from drought crisis response to drought risk reduction and secure its water future.

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PARTICIPANT RESEARCH PAPER

Urban Flood Risk in Rawalpindi District: A Case Study of Nullah Lai, Vulnerability and Risk-Reduction Measures

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Abstract

Urban flooding is a recurring disaster risk in Rawalpindi, where intense monsoon rainfall, rapid runoff, development in flood-prone areas and pressure on drainage systems can combine to produce damaging floods. Nullah Lai is a central part of the city's drainage network and has a documented history of severe flooding, including the major event of July 2001. This paper reviews published research and official material on flood hazards in the Lai basin, with attention to exposure, social vulnerability, early warning and risk-reduction options. It uses a literature-review approach and does not present new field data or a new hydrological model. The reviewed evidence indicates that heavy rainfall is the immediate trigger, while urban growth, encroachment, waste and drainage constraints, and unequal household capacity can increase the consequences. Studies also show that warnings are most useful when they reach communities in accessible language and are linked to clear actions. The paper recommends strengthening rainfall and water-level monitoring, improving drainage maintenance and land-use enforcement, protecting vulnerable communities, using impact-based warnings, and coordinating agencies before the monsoon season. Flood risk in Rawalpindi should therefore be managed through a combination of infrastructure, environmental and community-based measures rather than relying only on emergency response.

Keywords: urban flooding; Nullah Lai; Rawalpindi; early warning; disaster risk reduction; monsoon

1. Introduction

Urban flooding occurs when rainfall and runoff exceed the capacity of natural channels, drains and other parts of the urban drainage system. In Rawalpindi, the risk is strongly associated with monsoon rainfall and the Nullah Lai basin. The Pakistan Meteorological Department describes Nala Lai as a natural stream that plays an important role in the city's drainage system and notes that rapid urbanisation and encroachment contribute to flood risk (Pakistan Meteorological Department [PMD], n.d.).

The July 2001 flood remains a major example of the consequences of extreme rainfall in the Lai basin. Published accounts describe severe loss of life, damage to homes and infrastructure, and impacts on lower-income communities living close to the stream (Kamal, 2004; Mustafa et al., 2015). Research also describes flooding in the basin as a recurring problem rather than an isolated event. The scale of damage depends not only on rainfall but also on where people live, the condition of drainage infrastructure, access to warnings, and the resources available to households before and after a flood.

The purpose of this paper is to review urban flood risk in Rawalpindi District, focusing on Nullah Lai and the surrounding communities. It considers the hazard profile, risk and vulnerability, community resilience, institutional and scientific gaps, and practical options for reducing future losses.

1.1 Objectives of the Study

1. To describe the main factors contributing to urban flood risk in Rawalpindi, particularly in the Nullah Lai basin.
2. To review the exposure and vulnerability of communities and urban infrastructure.
3. To examine the role of early warning and community preparedness.
4. To recommend practical measures for flood-risk reduction and disaster management.

1.2 Scope and Methodology

This study is a desk-based literature review. It draws on published academic studies, official information from the Pakistan Meteorological Department, and disaster-management reports available from public sources. No household survey, interview, field measurement or original GIS analysis was conducted for this paper. Findings are therefore a synthesis of existing sources, and site-specific conditions should be checked through current official records and field assessment.

2. Regional Context and Hazard Profile

Nullah Lai drains parts of the Islamabad–Rawalpindi urban area and passes through densely developed parts of Rawalpindi before joining the Soan River. Its catchment includes natural drainage channels and heavily urbanised land. The basin's topography can allow runoff from higher ground to reach lower-lying urban areas quickly during intense rainfall. Published case studies identify steep slopes, rapid runoff, dense settlement and limited drainage capacity as important elements of the flood problem (Kamal, 2004; Siddiqui et al., 2023).

The July 2001 event is widely cited as a severe flood in the basin. A flood-management case study describes it as a turning point in efforts to improve flood management in the twin cities (Kamal, 2004). Historical accounts also show that flood impacts are not limited to one event; flooding has affected communities along the Lai at different times. These records support the need for long-term risk management, not only temporary measures taken during an emergency.

Heavy monsoon rainfall is the immediate trigger for many urban floods, but the impact of a rainfall event is shaped by local conditions. Encroachment along channels can restrict the flow path, waste can block drains, and hard urban surfaces reduce the amount of rainwater absorbed into the ground. Where drainage systems are poorly maintained or undersized, water may accumulate in streets and low-lying neighbourhoods. These factors can operate together, making flood risk a combined environmental, planning and governance issue.

3. Risk and Vulnerability Assessment

3.1 Physical Exposure

Homes, shops, roads, bridges, utilities and public services located near Nullah Lai or in low-lying areas may be exposed to fast-rising water. Floodwater can damage buildings and household belongings, interrupt transport and access to schools or health facilities, and affect electricity, water supply and sanitation. When roads are submerged or damaged, emergency services may also find it harder to reach affected neighbourhoods.

3.2 Social and Economic Vulnerability

Flood losses are often heavier for households with limited savings, insecure housing, few transport options or livelihoods that depend on daily wages and small businesses. People

living in informal or poorly constructed housing may have fewer options for protecting property or relocating quickly. Older people, children, persons with disabilities and people with illness may need additional support during warnings and evacuation. Women may face specific barriers if warnings do not reach them directly or if evacuation centres do not provide safe, accessible and private facilities.

Research on flood warning in Pakistan emphasises that social inequalities influence whether people receive, understand and act on risk messages (Mustafa et al., 2015). Vulnerability should therefore not be measured only by distance from the stream. It also includes access to information, trust in institutions, household resources, mobility, and the ability to recover after the event.

3.3 Environmental and Urban-Planning Factors

Urban development changes how rainfall moves across a catchment. More paved surfaces can increase runoff, while construction or encroachment near drainage channels may reduce the space available for floodwater. Solid waste in drains and streams can further obstruct water movement. These issues require coordinated planning, regular maintenance, enforcement of land-use rules and public participation. Structural works alone cannot fully manage risk if development continues to increase exposure.

4. Community Resilience Factors

Community networks can support early action and recovery. Neighbours may help older residents, share transport, move belongings to safer places and pass warnings to people who do not have reliable phone access. Local organisations, schools, health workers, mosque committees and volunteers can help communicate risk and identify people who may need assistance.

Community participation is important when authorities prepare hazard maps, evacuation routes and local response plans. Residents often know which streets flood first, where water collects, and which routes remain passable. This knowledge should complement rainfall and water-level information rather than replace scientific monitoring. Community plans should include safe meeting points, contact arrangements, support for people with limited mobility, and guidance on avoiding floodwater.

5. Scientific and Institutional Gaps

A key challenge is connecting forecasts to action at neighbourhood level. Rainfall forecasts may indicate a risk, but households and local officials need clear information about which areas may be affected, how quickly water may rise, and what steps should be taken. Research on the effectiveness of flood early-warning systems in Pakistani cities has highlighted communication and institutional challenges alongside the importance of community understanding (Rana et al., 2021).

Another challenge is coordination. Flood management may involve meteorological services, disaster-management authorities, municipal bodies, development authorities, drainage agencies, police, rescue services and community organisations. If responsibilities are unclear or information is not shared promptly, warning and response can be delayed. Data gaps, limited monitoring in some locations and insufficient public awareness can further weaken preparedness.

The evidence reviewed here does not establish the current condition of every drain, embankment or warning instrument in Rawalpindi. These should be assessed through updated inspections, official records and consultation with affected communities. Future research could combine GIS-based mapping, rainfall and water-level records, household surveys and interviews with local officials to identify priority locations.

6. Mitigation Strategies and Best Practices

6.1 Drainage Maintenance and Infrastructure

Municipal and relevant agencies should inspect and clear drains and culverts before and during the monsoon season, remove accumulated waste safely, and repair damaged drainage structures. Flood-protection works should be designed using current hydrological information and assessed for possible effects on communities downstream. Infrastructure should be maintained over time, not only constructed as a one-time project.

6.2 Land-Use Planning and Environmental Management

Authorities should identify flood-prone zones, discourage new construction in high-risk areas, and enforce restrictions on encroachment along natural drainage channels. Where relocation is considered necessary, it should be planned fairly and with appropriate consultation and support. Urban planning should preserve drainage corridors and increase green or permeable spaces where feasible, helping reduce rapid runoff.

6.3 Household and Community Preparedness

Households in exposed areas should know their local warning channels and evacuation routes, keep essential documents and medicines in a waterproof bag, and avoid crossing fast-moving water. Community volunteers can help prepare neighbourhood risk maps, support drills and identify people who may need assistance. Public awareness campaigns should explain that floodwater can be deep, fast and contaminated, even when it appears shallow.

6.4 Nature-Based and Catchment Measures

Measures such as protecting vegetation, improving soil infiltration where appropriate, maintaining open drainage corridors and restoring suitable green spaces can complement engineered drainage. Their effectiveness depends on local terrain and design, so they should be selected after technical assessment rather than treated as a substitute for essential flood infrastructure.

6.5 Coordination Before the Monsoon

Before each monsoon, agencies should agree on responsibilities, thresholds for action, communication channels, evacuation arrangements and the location of emergency supplies. A joint seasonal review can identify blocked drains, high-risk crossings, vulnerable facilities and areas requiring public awareness. After each flood or near-miss, agencies should record what happened and update their plans.

7. Risk Communication and Early Warning

An early-warning system is effective only when warnings reach the people at risk in time and provide understandable advice. PMD's information on Nala Lai describes flood-management work that includes strengthening warning capacity and improving the preparedness of local authorities and communities (PMD, n.d.). Research on the Lai basin also highlights the importance of people-centred warnings and the unequal ability of different groups to receive and respond to messages (Mustafa et al., 2015).

Warnings should be shared through multiple channels, including SMS, radio, television, official social media, mosque announcements and community focal persons. Messages should use plain Urdu and, where useful, local languages. They should identify the likely hazard and affected locations, explain the level of urgency, and provide specific actions such as moving away from the channel, avoiding underpasses, protecting essential items

and following official evacuation instructions. Backup channels are important when electricity or mobile networks fail.

Warning systems should be tested before the monsoon through drills and community feedback. Authorities should assess not only whether a message was sent, but whether people received it, understood it, trusted it and were able to act.

8. Policy Recommendations

Improve monitoring and forecasting: Maintain rainfall and water-level monitoring, share timely information between PMD and response agencies, and communicate uncertainty in plain language.

Prioritise high-risk locations: Use updated hazard maps, field inspections and community reports to identify exposed settlements, crossings, schools, health facilities and critical infrastructure.

Maintain drains and protect channels: Schedule pre-monsoon cleaning and inspections, address waste blockages, and enforce rules against unsafe encroachment on drainage corridors.

Make warnings inclusive and actionable: Use multiple communication channels and accessible language; ensure women, older people, persons with disabilities and low-income households can receive and act on alerts.

Strengthen local preparedness: Prepare evacuation routes, safe assembly points, volunteer networks and practical drills before the monsoon season.

Improve coordination and accountability: Clarify agency responsibilities, establish shared response triggers, publish post-event reviews and track whether agreed actions were completed.

Support further research: Combine GIS mapping, rainfall records, water-level data and community surveys to evaluate local exposure and intervention effectiveness.

9. Conclusion

Urban flood risk in Rawalpindi is shaped by the interaction of intense rainfall, the physical characteristics of the Nullah Lai basin, urban development, drainage conditions and social vulnerability. The 2001 flood demonstrates the potential for severe consequences, while later research confirms the continuing importance of forecasting, warning communication and preparedness. Flood risk cannot be reduced through emergency

response alone. It requires reliable monitoring, well-maintained infrastructure, land-use enforcement, environmental planning and community participation.

The most practical approach is to connect scientific information with local action. Agencies should prepare together before the monsoon, communicate warnings in accessible ways, and learn from each flood season. Community knowledge should be included in planning, with particular attention to residents who have fewer resources or face barriers during evacuation. Since this paper is based on existing literature rather than new fieldwork, further local assessment is recommended to identify specific neighbourhood priorities and evaluate the effectiveness of current measures.

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Appendix A: Summary of Urban Flood Risk and Priority Actions

Risk factor	Possible consequence	Priority action
Intense monsoon rainfall	Rapid rise in stream and surface water	Timely forecasts, monitoring and evacuation advice
Encroachment or reduced channel capacity	Water overtopping into nearby settlements	Land-use enforcement and protection of drainage corridors
Blocked or poorly maintained drains	Localised street and neighbourhood flooding	Pre-monsoon inspection, cleaning and maintenance
Limited warning access	Delayed protective action	Multi-channel, local-language, actionable alerts
Low household resources or mobility barriers	Higher injury, displacement and recovery burden	Inclusive preparedness and targeted assistance

PARTICIPANT RESEARCH PAPER

La Niña Impact on Pakistan: Monsoon Variability, Floods, Droughts and Agriculture

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Abstract

La Niña, the cool phase of the El Niño–Southern Oscillation, is often linked with Pakistan's most damaging hydrometeorological extremes, yet its effects are uneven. In some summers it coincides with intensified monsoon rainfall; in other seasons it brings dry winters and drought. This paper reviews how La Niña shapes monsoon variability, flooding, drought and agriculture in Pakistan, and assesses the resulting risk, vulnerability and resilience, with attention to gender and to mountain communities such as those of Gilgit-Baltistan. Drawing on published climate science and post-disaster assessments, it argues that La Niña acts as a risk amplifier rather than a sole cause, interacting with warming, weak infrastructure and poverty. The key findings are that forecasting skill is not yet matched by local action, that data and institutional gaps limit anticipatory planning, and that social capital and indigenous knowledge remain underused. The paper recommends building ENSO outlooks into seasonal planning, adopting people-centred and gender-sensitive early warning, strengthening basin-level governance, and combining AI-supported forecasting with community knowledge.

Keywords: agriculture; disaster risk reduction; drought; floods; La Niña

1. Introduction

Pakistan sits on the western edge of the South Asian monsoon system and relies on it, together with snow and glacier melt in the Indus basin, for most of its water. Agriculture contributes roughly a fifth of national output and employs more than a third of the labour force (Government of Pakistan, Ministry of Finance, 2023), so a shift in seasonal rainfall rarely stays a purely climatic matter. La Niña, marked by cooler-than-average sea-surface temperatures in the central and eastern equatorial Pacific (Trenberth, 1997), is one of the large-scale drivers behind such shifts.

The problem is that the country's two most destructive recent floods, in 2010 and 2022, both happened in La Niña years and together affected tens of millions of people. Yet La Niña also tends to bring dry cool seasons and drought, and the relationship is probabilistic, not guaranteed. Planning in Pakistan has therefore remained largely reactive: the hazard is recognised only after the water arrives, or after it fails to.

The purpose of this paper is to synthesise what is known about La Niña and Pakistan and to turn it into practical guidance. Its objectives are to (a) explain the mechanisms linking La Niña to monsoon variability, floods and drought; (b) describe impacts on agriculture and livelihoods; (c) assess vulnerability and community resilience; and (d) identify gaps and recommend policy responses. The scope is national, with examples from Punjab, Sindh, Balochistan and Gilgit-Baltistan, concentrating on events from roughly 1998 to 2023. The study is a literature-based review and uses no primary data.

2. Regional Context and Hazard Profile

Most of Pakistan receives the bulk of its annual rainfall between June and September, while the north and west also depend on winter westerly disturbances. Textbook accounts say El Niño weakens and La Niña strengthens the South Asian monsoon, but that link has weakened in recent decades (Kumar et al., 1999). For Pakistan the evidence is best read as a shifting of odds. In 2010, a strong La Niña coincided with extreme rainfall, but a blocking pattern over Europe and a wave train across Eurasia were decisive in steering moisture into the region (Houze et al., 2011; Lau & Kim, 2012; Webster et al., 2011). In 2022, the third consecutive La Niña year, rainfall far above normal fell over Sindh and Balochistan (Nanditha et al., 2023), and attribution work found that human-caused warming made the heaviest rainfall more intense (Otto et al., 2023).

The opposite side of the hazard profile receives less attention. La Niña has been associated with below-normal cool-season precipitation across southwest Asia, and with the severe drought of 1998–2002 (Ahmad et al., 2004; Barlow et al., 2002; Hoell et al., 2014). Different “flavours” of La Niña produce different patterns, which is one reason simple rules fail.

Four terms are used throughout, following IPCC (2012) and UNDRR (2015). A *hazard* is a potentially damaging physical event; *exposure* is the presence of people, assets and livelihoods in places where a hazard can strike; *vulnerability* is the predisposition to be adversely affected; and *risk* arises from the interaction of the three. La Niña modifies the hazard. Exposure and vulnerability decide whether the hazard becomes a disaster.

The historical record shows how severe that outcome can be. The 2022 floods affected about 33 million people, caused more than 1,730 deaths and produced estimated damages of USD 14.9 billion and losses of USD 15.2 billion, with Sindh bearing nearly 70 percent of the total (Government of Pakistan, 2022). Exposure is concentrated in the Indus floodplain and the low-lying delta, drought risk in arid Balochistan and Thar, and landslide and glacial-lake hazards in the northern mountains.

Not every damaging season fits the pattern. The 2025 monsoon unfolded under ENSO-neutral conditions yet had killed more than 800 people by late August (Arab News, 2025; NOAA Climate Prediction Center, 2025), a reminder that La Niña is one driver among several.

The timing of this review also matters. By September 2026 an El Niño advisory was in force, with a very strong event likely through the 2026–27 winter, after the 2025–26 La Niña faded early in the year (NOAA Climate Prediction Center, 2026). El Niño generally favours a weaker monsoon (Kumar et al., 1999), so drought and heat stress are the nearer risk. Historically, however, strong El Niño episodes have often given way to La Niña, which keeps the flood lessons below relevant for 2027.

3. Risk and Vulnerability Assessment

Floods destroy standing crops, stored grain, irrigation channels and livestock in a single season. The 2022 assessment recorded its heaviest agricultural losses in Sindh, where cotton, rice and vegetable crops were submerged and wheat sowing was delayed on flooded land (Government of Pakistan, 2022), and women lost livelihoods in agriculture

and livestock in particular (Government of Pakistan, 2022). Drought works more slowly but just as deeply: the 1998–2002 episode reduced crop yields, killed livestock and pushed households out of Balochistan and parts of Sindh (Ahmad et al., 2004). Both extremes interrupt incomes, raise food prices and erode the assets poor households would otherwise sell or borrow against, so food insecurity outlasts the event itself.

Vulnerability is not evenly spread. Tenant farmers and landless labourers, who depend on others' land and have no insurance, lose income without any claim on compensation. Children, older people and persons with disabilities face higher risks during evacuation and displacement. Gender is central. Globally, disasters kill more women than men where women's status is low (Neumayer & Plümper, 2007), and case evidence shows that women's unpaid work in livestock, kitchen gardens and post-harvest handling is often invisible to relief systems (Enarson, 2012). Restricted mobility, limited phone access and the lack of privacy in shelters add to the risk.

Exposure and susceptibility reinforce one another: mud-brick houses near riverbanks, encroachment on drainage paths, poor road access, low literacy, thin savings and limited access to credit. Together they explain why similar rainfall can produce very different losses in different places.

4. Community Resilience Factors

Communities are not passive recipients of aid. Social capital, meaning trust, reciprocity and networks, consistently emerges as one of the strongest predictors of recovery (Aldrich & Meyer, 2015). In Pakistan it takes familiar forms: kin networks that host displaced relatives, village and mosque committees that pool money and food, and shared boats, tractors and pumps. These networks act faster than formal relief and cost almost nothing, but they weaken when everyone in a village is affected at once.

Indigenous and local knowledge also matters. Traditional ecological knowledge can function as a form of adaptive management (Berkes et al., 2000), and disaster risk reduction works better when it is combined with scientific information (Mercer et al., 2010). Examples include raised house plinths, local reading of snow, stream and cloud signs, adjusting sowing dates, and traditional water-harvesting systems in dry areas. Mountain communities, in particular, often keep close watch on slopes and streams. The resilience of a place depends on its absorptive, adaptive and transformative capacities (Cutter et al.,

2008), and these grow when communities take part in planning instead of being informed afterwards.

5. Scientific and Institutional Gaps

Scientific gaps are considerable. Most studies treat 2010 and 2022 as individual cases; far fewer examine how different La Niña types or the Indian Ocean affect Pakistan season by season (Hoell et al., 2014). Seasonal outlooks are coarse over complex terrain, and rain gauges are sparse in the north and in Balochistan. Sex-disaggregated loss data are rare, which makes gender impacts hard to prove and easy to ignore.

Artificial intelligence and machine learning offer real promise. Deep-learning models have forecast ENSO conditions well in advance (Ham et al., 2019), and data-driven methods are increasingly useful for Earth-system science, though interpretability and data limits remain concerns (Reichstein et al., 2019). In Pakistan, adoption is held back by limited long-term data, computing capacity and trained staff, and few models are validated at district level.

Institutional weaknesses are just as important. Responsibilities are shared among meteorological, disaster management, irrigation, agriculture and provincial bodies, and forecasts seldom become farm-level advisories. District staff often lack training and budgets for anticipatory action. Closing these gaps requires data, but also clear mandates and people able to act on the information.

6. Mitigation Strategies and Best Practices

Structural measures include embankments, spillways, drainage improvements, flood-resilient housing and raised hand pumps. They need careful design, since embankments can simply move risk downstream. Nature-based options deserve more weight: watershed management in the uplands, wetland protection, and restoration of mangroves in the Indus delta, which buffer storm surges and store carbon.

Non-structural measures are often cheaper and quicker. These include land-use zoning, crop insurance, ENSO-informed crop calendars, drought-tolerant and short-duration varieties, and rainwater harvesting. Capacity building should reach farmers, local volunteers and officials through training, school programmes and regular drills. Preparedness means pre-positioned food, seed and fodder, and agreed evacuation routes before the season begins.

International practice offers useful models. Bangladesh's Cyclone Preparedness Programme relies on trained local volunteers to carry warnings door to door, and the Sendai Framework calls for understanding risk, strengthening governance, investing in resilience and improving preparedness (UNDRR, 2015). Pakistan can adapt these ideas rather than start from scratch.

7. Risk Communication and Early Warning

A warning is useful only if it is understood and acted upon. The World Meteorological Organization (2022) has set a goal of universal early-warning coverage by 2027, built on four elements: risk knowledge, detection and forecasting, warning dissemination, and preparedness to respond. For La Niña, this means translating "La Niña watch" into plain statements, such as a higher chance of heavy monsoon rain in named districts, together with advice for farmers on sowing, storage and livestock.

Last-mile delivery is the weakest link. Messages should use Urdu and local languages such as Sindhi, Pashto, Balochi, Shina and Burushaski, and travel by radio, mosque loudspeakers, SMS and community volunteers. Gender-sensitive systems also use women's networks, health workers and women's groups, because women may not receive messages sent through male channels. Shelters need to be safe, private and accessible. Communities should also report back on what failed, so that warnings improve each season.

8. Policy Recommendations

First, integrate governance: ENSO outlooks from the meteorological service should feed directly into agriculture, irrigation and disaster management calendars each season, with clear provincial and district responsibilities. Second, mainstream climate adaptation into agricultural policy through resilient seed systems, efficient irrigation, index-based insurance and cash support for tenant farmers.

Third, make community participation routine. Village organisations, women's groups and local knowledge-holders should help to design risk maps and response plans. Fourth, invest in technology wisely: densify gauge networks, downscale seasonal forecasts, pilot AI-supported tools with local validation, and collect sex-disaggregated loss data. Fifth, strengthen institutions with district-level training, predictable budgets and anticipatory-action funds released on forecast triggers.

Finally, base policy on evidence. Post-event assessments should be published, compared and used to update standards for infrastructure, land use and relief, so that each La Niña season leaves the country better prepared than the one before.

9. Conclusion

La Niña does not cause Pakistan's floods and droughts by itself, but it shifts the odds, and the country's exposure and vulnerability determine the human cost. The review shows that science can now provide seasonal warning, that communities already hold valuable networks and knowledge, and that the main shortfall lies in connecting the two. Science-based planning, social capital, indigenous knowledge, appropriate technology and integrated governance, taken together, offer the most realistic route to resilience. Treating each La Niña outlook as a prompt for early action, not a prelude to emergency response, would save lives and livelihoods.

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Annex A: La Nina Hazard Matrix for Pakistan (summary)

Season / phase	Likely hazard	Most exposed areas	Sectors at risk	Priority action

Monsoon (Jun–Sep), La Niña year	Heavy rain, riverine and flash floods	Indus floodplain, Sindh, southern Punjab, Balochistan	Crops, housing, livestock, roads	Seasonal outlook advisories; drainage and shelter readiness
Cool season (Oct–Mar)	Below-normal rain, drought	Balochistan, Thar, rain-fed Punjab and Khyber Pakhtunkhwa	Rabi wheat, livestock, drinking water	Drought-tolerant seed; water harvesting; fodder stocks
Warm spells and melt	Glacial-lake outburst, landslides	Gilgit-Baltistan, Chitral	Communities, roads, hydropower	Lake monitoring; community watch; local warning

Note. Summary prepared by the author from the sources cited in Sections 3 and 4.

PARTICIPANT RESEARCH PAPER

Comparative Analysis of the 2005 Kashmir Earthquake and the 2023 Türkiye–Syria Earthquakes

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Abstract

This paper presents a comparative analysis of two of the most destructive seismic events of the 21st century: the Mw 7.6 Kashmir earthquake of October 2005 and the Mw 7.8 Türkiye–Syria earthquake doublet of February 2023. Drawing on published seismological studies, United Nations agency reports, and World Bank damage assessments, the paper examines the geophysical characteristics, human and economic consequences, disaster response mechanisms, and governance failures associated with both events. It further situates the findings within the Sendai Framework for Disaster Risk Reduction 2015–2030. The analysis reveals that despite occurring 18 years apart and in geologically distinct settings, both disasters were shaped by inadequate enforcement of building codes, limited preparedness investment, and political constraints on humanitarian access. The paper concludes with evidence-based policy recommendations for disaster-prone nations, with particular relevance for South Asia and Pakistan.

Keywords: Build Back Better, disaster risk reduction, East Anatolian Fault, earthquake, Kashmir, seismic vulnerability, Sendai Framework

1. Introduction

Earthquakes are among the most sudden and devastating natural hazards on Earth. They strike without warning, collapse infrastructure in seconds, and leave communities struggling to recover for years. Despite advances in seismology and disaster risk governance over recent decades, major earthquakes continue to produce catastrophic losses not primarily because they are unforeseeable, but because the societies they strike remain unprepared. Two events, separated by 18 years, illustrate this painful reality with particular clarity.

The first is the Mw 7.6 earthquake that struck the Kashmir region of northern Pakistan and India on 8 October 2005, killing nearly 88,000 people and displacing over 3.3 million. The second is the devastating earthquake doublet of 6 February 2023, in which a Mw 7.8 event was followed nine hours later by a Mw 7.7 earthquake on the East Anatolian Fault Zone in southeastern Türkiye, collectively killing more than 59,000 people across Türkiye and Syria and causing over $34 billion in direct physical damage in Türkiye alone (World Bank, 2023).

Comparing these two events offers more than a chronicle of destruction. It reveals structural patterns in how seismic risk is produced, how institutional responses succeed or fail, and what reforms are necessary to reduce future losses. The purpose of this paper is to conduct an evidence-based comparative analysis of the two events across five dimensions: seismological and geophysical characteristics, human and economic impacts, vulnerability factors, disaster response effectiveness, and policy implications for disaster risk reduction (DRR). The research draws exclusively on published academic literature, peer-reviewed seismological studies, and official government and United Nations agency reports.

2. Regional Context & Hazard Profile

2.1 The Kashmir Region: A Himalayan Convergent Zone

The Kashmir region sits at one of the most seismically active convergent boundaries on Earth. The Indian Plate moves northward into the Eurasian Plate at approximately 40 mm per year, generating enormous compressional stress along a system of thrust faults that defines the Himalayan arc (Avouac et al., 2006). On 8 October 2005, this accumulated strain was released in a Mw 7.6 earthquake that ruptured a 75-kilometre segment of the

Balakot–Bagh fault part of the broader Hazara–Kashmir Syntaxis at a depth of approximately 26 kilometres (Avouac et al., 2006). The shallowness of the rupture, combined with its compactness in both time and space, meant that seismic energy reached the surface with minimal dissipation, producing ground shaking of Modified Mercalli Intensity X (Extreme) at Balakot (Parsons et al., 2006).

The Kashmir region had experienced significant seismic activity previously, including a Mw 6.2 event in 1974 and a destructive event in 1935 near Quetta. However, the 2005 earthquake was the most powerful in the region in over a century, and its occurrence on a fault that had not been extensively studied meant that building design and land use planning had not adequately accounted for the level of hazard present (Parsons et al., 2006).

2.2 Southeastern Türkiye: A Long-Dormant Transform Boundary

The tectonic setting of the 2023 events is fundamentally different. The East Anatolian Fault Zone (EAFZ) is an approximately 700-kilometre left-lateral strike-slip fault system that forms the boundary between the Anatolian and Arabian microplates. Palaeoseismological evidence indicates that the EAFZ had not experienced a major earthquake rupture since approximately 1789 a seismic gap of over 230 years that had accumulated substantial elastic strain energy (Melgar et al., 2023). On 6 February 2023 at 04:17 local time, a Mw 7.8 event nucleated on a previously unmapped fault segment before transitioning onto the main East Anatolian Fault, ultimately rupturing approximately 350 kilometres bilaterally. A second Mw 7.7 event followed at 13:24 the same day on the adjacent Sürgü fault, rupturing approximately 160 kilometres with supershear velocities reaching 4.8 km/s on its western segment (Melgar et al., 2023). The dual-rupture sequence, occurring on a cold winter night when most inhabitants were asleep, dramatically amplified the humanitarian consequences.

3. Risk & Vulnerability Assessment

Understanding why both earthquakes produced such catastrophic outcomes requires moving beyond seismology to examine the social, economic, and institutional factors that transform geophysical hazards into humanitarian disasters. The concept of disaster risk encompasses not only physical hazard but also exposure the distribution of people and

assets in hazard zones and vulnerability, the susceptibility of those people and assets to harm (United Nations Office for Disaster Risk Reduction [UNDRR], 2015).

3.1 Building Stock and Structural Vulnerability

In the Kashmir case, the built environment was overwhelmingly composed of non-engineered masonry structures stone and mud-brick construction with no seismic reinforcement. Such buildings are highly susceptible to even moderate ground shaking, and the Mw 7.6 event at close range produced catastrophic structural failure. The World Bank (2005) estimated that over 600,000 buildings were damaged or destroyed. The destruction of Balakot, a town of approximately 30,000 people located near the fault trace, was virtually complete. Critically, the earthquake struck at 08:50 local time on a school day, when approximately 8,500 schools were occupied. This timing is estimated to have contributed significantly to the death toll of approximately 88,000 with schoolchildren representing a disproportionate share of fatalities (United Nations Office for the Coordination of Humanitarian Affairs [OCHA], 2006).

In Türkiye, the structural vulnerability problem manifested differently but with equally lethal consequences. Türkiye had introduced seismic building codes following the devastating 1999 Mw 7.6 Kocaeli (Marmara) earthquake, which killed over 17,000 people. However, widespread non-compliance with these codes facilitated by construction amnesties that legalised code-violating buildings meant that modern multi-storey reinforced concrete apartment blocks collapsed in the characteristic 'pancake' mode, burying sleeping residents under tonnes of rubble. The World Bank (2023) estimated direct physical damage at $34.2 billion from the February 2023 events in Türkiye alone, with the heaviest damage concentrated in Hatay, Kahramanmaraş, and Adıyaman provinces, which together accounted for 81% of estimated losses.

3.2 Geographic and Socio-Economic Exposure

Both events struck regions characterised by relative poverty, limited public infrastructure, and geographic isolation. In Kashmir, mountainous terrain not only amplified ground shaking through topographic effects but also severed road access to hundreds of villages for days, severely delaying emergency response. In southeastern Türkiye, the affected provinces had poverty rates significantly above the national average and hosted over 1.7 million Syrian refugees, representing approximately half of all Syrian refugees in Türkiye

(World Bank, 2023). This pre-existing vulnerability compounded the earthquake's impact, as marginalised populations had less social protection, fewer resources for recovery, and greater dependence on fragile housing stock.

In Syria, the compound nature of the crisis was even more severe. Active armed conflict, mass displacement, and the deterioration of health and infrastructure systems meant that the earthquake struck a population already in acute humanitarian need. Affected areas in northwestern Syria had been heavily damaged by years of conflict, with pre-existing structural damage making buildings more susceptible to collapse. UN estimates suggested that up to 8.8 million people across Syria were affected (OCHA, 2023), with humanitarian access severely constrained by political factors discussed below.

Table 1. Comparative Summary: 2005 Kashmir and 2023 Türkiye–Syria Earthquakes

Parameter	**Kashmir 2005**	**Türkiye–Syria 2023**
Magnitude	Mw 7.6 (single event)	Mw 7.8 + Mw 7.7 (doublet)
Fault Type	Oblique thrust (convergent)	Left-lateral strike-slip (transform)
Focal Depth	26 km	17.9 km (first event)
Date & Time	8 Oct 2005, 08:50 local	6 Feb 2023, 04:17 local
Confirmed Deaths	~88,000	~59,000+ (likely undercounted)
Injured	207,000+	107,000+
Displaced / Homeless	~3.3 million	~3.3M (Turkey) + 5.4M (Syria)
Direct Economic Loss	$6.7 billion	$34.2 billion (Turkey; GRADE)
Countries Affected	Pakistan, India, Afghanistan	Türkiye, Syria

Parameter	Kashmir 2005	Türkiye–Syria 2023
International Response	86 countries; UN Flash Appeal	90+ countries; UN Flash Appeal

Note. Sources: Avouac et al. (2006); Melgar et al. (2023); OCHA (2006, 2023); World Bank (2005, 2023); UNDRR (2015).

4. Community Resilience Factors

In both disasters, community-level actors neighbours, local volunteers, and indigenous knowledge networks played a critical role in the initial life-saving response before formal emergency services could reach affected areas. In mountainous Kashmir, where road networks were severed within minutes of the earthquake, local communities conducted rescue using basic tools and traditional knowledge of terrain and shelter. Studies conducted in the aftermath noted that survivors consistently credited community solidarity as the primary survival mechanism in the critical first 72 hours (OCHA, 2006).

In Türkiye, the organised civilian rescue association AKUT (Search and Rescue Association) deployed teams rapidly and played a significant role in early interventions in urban areas. Social media platforms unavailable in 2005 enabled survivors to broadcast their locations from under rubble, directing rescuers with unprecedented precision. This digital dimension represents a qualitative shift in community-level resilience capacity between the two events, though it came with a significant caveat: the digital divide in conflict-affected Syria meant that this technology-enabled resilience was largely inaccessible to Syrian communities who arguably needed it most.

Indigenous and local knowledge also played a role in community resilience in Kashmir's rural areas, where communities had traditional practices for constructing walls that partially dissipated lateral seismic forces. The Earthquake Reconstruction and Rehabilitation Authority (ERRA) subsequently incorporated elements of this vernacular knowledge into its Build Back Better guidelines for owner-driven reconstruction (ERRA, 2006).

5. Scientific & Institutional Gaps

Both events exposed significant gaps in seismic monitoring, early warning, and institutional capacity. The 2005 Kashmir earthquake occurred on a fault the Balakot–Bagh fault that had not been recognised as capable of producing a Mw 7.6+ event (Avouac et al., 2006). The absence of a dense seismographic network in northern Pakistan and Azad Kashmir meant that ground motion data were insufficient for rapid damage assessment and emergency resource deployment. Following the earthquake, the Pakistan Meteorological Department (PMD) expanded its seismic monitoring network, but coverage of the highest-hazard zones in Azad Jammu and Kashmir and Khyber Pakhtunkhwa remains incomplete as of 2024.

In Türkiye, the institutional gap was less about scientific knowledge the hazard posed by the EAFZ was well documented and more about governance failures in translating that knowledge into protective policy. The post-1999 building code reforms were substantively sound, but the issuance of 'construction amnesties' that retroactively legalised non-compliant buildings fundamentally undermined the code's protective value. In the immediate aftermath of the 2023 earthquake, Turkish authorities arrested several hundred construction contractors on criminal negligence charges an acknowledgment that enforcement failures had directly contributed to mass casualties.

At the international level, both disasters exposed gaps in the global humanitarian system's capacity to deliver aid across political boundaries. In Kashmir, the political sensitivity of the Line of Control between India and Pakistan initially slowed cross-border cooperation, though a temporary agreement was eventually reached. In Syria, the United Nations Security Council's deliberations over authorising additional border crossings for humanitarian access consumed critical hours while survivors remained alive under rubble a systemic gap that the UNDRR (2015) Sendai Framework sought to address through its emphasis on humanitarian access principles.

6. Mitigation Strategies & Best Practices

The responses to both disasters generated important lessons for mitigation policy. Pakistan's establishment of the Earthquake Reconstruction and Rehabilitation Authority (ERRA) following the 2005 Kashmir earthquake represented a significant institutional innovation. ERRA adopted an owner-driven reconstruction model in which affected

households received phased cash grants to rebuild their own homes, with technical support to ensure seismic compliance. Independent evaluations found that this approach produced significantly higher compliance rates with seismic construction standards than contractor-led models, and the programme has since been cited as a global best practice by the United Nations Development Programme (ERRA, 2006).

A further innovation emerging from the 2005 response was the systematic use of military helicopters for logistical support in mountain environments. NATO's deployment of rotary-wing assets to Kashmir demonstrated that helicopter-based supply chains could serve as a force multiplier for ground operations where road access was unavailable a lesson that has been incorporated into subsequent disaster response planning for Himalayan regions.

In Türkiye, the 2023 disaster accelerated existing plans for urban renewal and building retrofitting. The government announced a comprehensive programme to demolish and replace earthquake-risk buildings in affected and high-risk provinces, with a target of 1.5 million units over five years. However, analysts noted that the success of such programmes depends critically on sustained political commitment and enforcement capacity precisely the governance dimensions that had failed before 2023. Japan's experience with mandatory seismic retrofitting of older buildings, introduced following the 1995 Great Hanshin earthquake, offers a model for how such programmes can be structured to achieve high compliance rates over time.

7. Risk Communication & Early Warning

Earthquake early warning (EEW) systems represent a mature and cost-effective technology that neither Pakistan nor Türkiye had fully deployed at the time of these disasters. EEW systems detect the initial P-wave of an earthquake and transmit alerts to exposed populations before the more destructive S-waves arrive, providing between 10 and 90 seconds of warning depending on proximity to the epicentre. Japan's nationwide EEW system, managed by the Japan Meteorological Agency, has demonstrably saved lives by triggering automatic safety responses stopping high-speed trains, opening fire station doors, and activating emergency broadcasts in the seconds before shaking arrives.

In the context of the 2023 Türkiye–Syria earthquake, the 04:17 AM timing of the first event meant that even a few seconds of warning would have been insufficient to facilitate

physical evacuation. However, EEW could have automated safety responses such as opening prison and hospital doors, triggering gas line shutoffs, and alerting emergency services that might have reduced secondary casualties and accelerated response. The development of a South Asian early warning network, building on existing seismographic infrastructure in Pakistan, India, and Afghanistan, represents a high-value investment that falls squarely within the UNDRR (2015) Sendai Framework's Priority 3 actions for investing in disaster risk reduction.

Risk communication in both events was hampered by limited public awareness of appropriate earthquake response behaviours. Surveys conducted in Pakistan following the 2005 event found that a significant proportion of the rural population had never received any earthquake safety education. Post-event programmes delivered through schools and community networks improved awareness, but longitudinal studies showed that retention of safety knowledge diminishes rapidly without periodic reinforcement underscoring the need for sustained, institutionalised public education programmes rather than one-off post-disaster initiatives.

8. Policy Recommendations

Drawing on the comparative evidence presented above and situated within the Sendai Framework for Disaster Risk Reduction 2015–2030, this paper advances the following policy recommendations for disaster-prone nations, with particular relevance for South Asian governments and international DRR partners:

A. Enforce seismic building codes through independent oversight and penal accountability. The construction of non-compliant buildings must be treated as a criminal matter, not merely an administrative one. The Turkish precedent of prosecuting contractors following the 2023 earthquake, while representing a post-hoc measure, establishes an important deterrent precedent. Pakistan should strengthen NDMA's building code enforcement mandate and resource independent inspection capacity in all seismic Zones 2B and above.

B. Establish a regional seismic monitoring and early warning network across South Asia. Given the transboundary nature of Himalayan seismic hazard, a SAARC-mandated seismographic network building on bilateral agreements between Pakistan, India, Nepal, and Afghanistan would provide the data infrastructure for both scientific

hazard assessment and operational early warning. This aligns directly with Sendai Framework Priority 1 (understanding disaster risk) (UNDRR, 2015).

C. Pre-position humanitarian response capacity near highest-hazard zones. NDMA and provincial disaster management authorities should pre-position Urban Search and Rescue (USAR) teams, field hospitals, emergency shelter materials, and water purification units within 100 kilometres of the highest-hazard districts in Khyber Pakhtunkhwa and Azad Jammu and Kashmir, reducing the critical first-72-hour response lag experienced in 2005.

D. Negotiate and ratify humanitarian access agreements that function independently of political relations. The Syria experience in 2023 demonstrated with tragic clarity that politicised delays in humanitarian access cost lives. Bilateral and multilateral humanitarian access frameworks modelled on the 2005 India–Pakistan cooperation, despite its limitations should be formalised as standing agreements that are activated automatically upon declaration of a major disaster.

E. Institutionalise earthquake safety education in school curricula in all seismic risk zones. Given that school-age children represented a disproportionate share of the 2005 Kashmir death toll partly due to the timing of the earthquake and partly due to weak school construction, mandatory, annually reinforced earthquake safety education should be treated as a public health intervention equivalent to fire safety training.

9. Conclusion

The 2005 Kashmir earthquake and the 2023 Türkiye–Syria earthquake doublet are separated by geography, tectonic setting, and nearly two decades of technological and institutional development. Yet both disasters reveal a persistent and troubling pattern: seismic hazard was known, building regulations existed, and international frameworks for disaster risk reduction were in place. The deaths of nearly 150,000 people across the two events were not inevitable; they were the product of governance failures; failures to enforce building codes, invest in preparedness, and protect humanitarian access from political interference.

The Sendai Framework for Disaster Risk Reduction 2015–2030 articulates the global community's commitment to substantially reducing disaster mortality and losses by 2030 (UNDRR, 2015). The evidence from these two earthquakes makes clear that achieving

those targets requires not merely the adoption of frameworks but their rigorous implementation at national and local levels. For Pakistan and other seismically exposed countries in South Asia, the lessons are particularly urgent: the next major earthquake in the Himalayan arc is a matter of when, not if. The question is whether the governance systems, physical infrastructure, and community preparedness will be adequate when it comes.

This paper has argued that they can be if the political will to prioritise lives over short-term economic and electoral interests is sustained. Building that will is ultimately a social and political task as much as a technical one, and it begins with ensuring that the lessons of 2005 and 2023 are not forgotten in the next period of relative calm.

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PARTICIPANT RESEARCH PAPER

Assessing Disaster Response Capability and Resilience: Kay Findings from the Sri lanka Army's Response to 'Cyclone Ditwah' in Mullaitivu District in Sri lanka

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Abstract

Cyclone “Ditwah” exposed significant operational, logistical and social challenges associated with disaster response in Sri Lanka, including in low lying and flood prone areas of Mullaitivu District (Disaster Management Centre [DMC], 2025; Sri Lanka Army, 2025). This paper analyses the disaster response experience documented in the supplied operational assessment prepared by the Sri Lanka Army‟s 0A Infantry Division. It examines early warning and situational awareness, preparedness, command and control, logistics, civil–military coordination, technology, protection of vulnerable groups and the transition from emergency response to recovery. Official Sri Lanka Army reporting describes the establishment of a Special Disaster Operations Centre and the coordination of relief activities with government institutions, while the Government of Sri Lanka‟s post disaster needs assessment documents the extensive displacement and protection challenges associated with Cyclone Ditwah (Sri Lanka Army, 2025; Government of Sri Lanka, 2026).

The supplied operational assessment indicates that the response benefited from rapid mobilization, an established chain of command, community assistance and cooperation with civilian authorities, while identifying weaknesses relating to specialist equipment, dedicated disaster response training, resilient communications, geospatial awareness and village level preparedness (0A Infantry Division, 2026). The paper adopts a qualitative document analysis approach, drawing primarily on the supplied operational assessment and using relevant official Sri Lankan publications for contextual support. It deliberately excludes exact deployment details, unit locations and the specific distribution of Battalions, brigades or Divisions. The analysis concludes that future effectiveness would benefit from area specific disaster plans, trained response teams, pre-positioned equipment, interoperable communications, inclusive evacuation arrangements and a shared civil–military information system. As the supplied assessment does not provide complete bibliographic details for every warning, agency record or official communication it mentions, these underlying records are not treated as independently verified publications unless supported by an accessible official source.

Keywords: Cyclone Ditwah; disaster response; Sri Lanka Army; Mullaitivu; Civil–military coordination; preparedness; resilience; lessons learned.

1. Introduction

Cyclone Ditwah exposed the operational, logistical and social challenges associated with disaster response in Sri Lanka, including in low-lying and flood prone areas such as Mullaitivu District. Sri Lanka‟s National Disaster Management Policy recognizes floods, cyclones, coastal flooding and other natural hazards as significant threats, emphasizing the need for early warning, preparedness, coordinated emergency response and long-term recovey. Natural disasters place immediate pressure on public authorities to protect life, evacuate exposed communities, maintain essential services and restore access to affected areas. In Sri Lanka, the Disaster Management Act No. 13 of 2005 provides the legal and institutional framework for disaster risk management, while the Disaster Management Centre coordinates preparedness, emergency response, relief and postdisaster activities with relevant stakeholders (Government of Sri Lanka, 2005; Disaster Management Centre, n.d.-b). During Cyclone Ditwah, the Sri Lanka Army and other armed forces supported disaster relief through search and rescue operations, civilian evacuation. The provision of temporary shelters and food supplies and the restoration of essential infrastructure. However, the effectiveness of military assistance depends not only on rapid mobilization but also on advance preparedness, appropriate equipment, reliable communications, inter-agency coordination, respect for civilian leadership and the timely transition from emergency response to recovery. These requirements are consistent with Sri Lanka‟s national disaster management framework, which emphasizes clear institutional responsibilities, effective coordination, equitable assistance to affected communities and the restoration of essential services.

Cyclone Ditwah exposed the operational, logistical and social challenges associated with disaster response in the low-lying coastal environment of Mullaitivu District, Sri Lanka. The operational assessment supplied for this paper describes the effects of Cyclone Ditwah in Mullaitivu District and records the Sri Lanka Army‟s support for rescue, evacuation, relief distribution, route clearance, medical assistance and restoration activities. These observations are consistent with official Sri Lanka Army reports documenting relief distribution by the 0A Infantry Division in Mullaitivu and the restoration of the Nayaru Bridge on the Mullaitivu–Kohombagas Handiya Road following the cyclone (Sri Lanka Army, 2025a; Sri Lanka Army, 2025b). The district‟s exposure to flooding is

also illustrated by the national Post-Disaster Needs Assessment, which identifies damage and safety concerns associated with the Muththiyankaddu Kulam Reservoir in Mullaitivu District following exceptionally heavy rainfall and high inflows (Disaster Management Centre, 2026a). The assessment further characterises the district as a low-lying area comprising coastal and inland settlements, water bodies and rural road networks vulnerable to heavy rainfall and flooding. The report records disruption to transport, power and communications, damage to homes and livelihoods and pressure on public services. These impacts are consistent with the wider national assessment of infrastructure damage, service disruption and emergency response requirements following Cyclone Ditwah (Disaster Management Centre, 2026a; Ministry of Defence, 2025).

This paper examines what the assessment indicates about the strengths and limitations of the response and develops practical recommendations for future preparedness. It is an analysis of the supplied document, not an independent verification of every incident or statistic in it. To protect operational security, it omits exact deployment information and does not disclose the deployment of specific battalions, brigades or divisions.

Aim: To assess the disaster response experience recorded during Cyclone Ditwah in Mullaitivu District and identify measures that could improve future military support to civil disaster management.

Objectives:

a. Assess the contribution of early warning, situational awareness and preparedness.
b. Examine command and control, communications, logistics and civil–military coordination.
c. Identify capability gaps affecting rescue, relief, protection and recovery.
d. Recommend short-, medium- and long-term improvements while maintaining civilian primacy and operational security.

Research questions:

a. What factors supported the response and what constraints limited its effectiveness?\

b. What lessons emerge regarding equipment, training, information sharing and community preparedness?

c. What institutional measures could improve resilience and the transition from response to recovery?

2. Methodology and Source Limitations

This paper employs qualitative document analysis of the supplied document titled Operational Assessment and Lessons Learnt by the Sri Lanka Army during Disaster Response Operations during „Ditwah‟ Cyclone in 0A Infantry Division Area of Responsibility. The document serves as the primary source for examining the Sri Lanka Army‟s disaster response experience. The analysis is organised into early warning and situational awareness, preparedness, command and control, execution of operations, logistics, inter-agency cooperation, technology, protection of affected communities, recovery and recommendations. This thematic approach is consistent with Sri Lanka‟s disaster management framework, which emphasises preparedness, coordinated emergency response, institutional responsibilities and post-disaster recover (Government of Sri Lanka, 2005; Disaster Management Centre, n.d.-a).

The primary source is an internal operational assessment containing both descriptive observations and recommendations. It does not provide a complete bibliography identifying the full titles, publication dates, links or document numbers of all meteorological warnings, Ministry of Defence communications, higher headquarters correspondence or agency records mentioned. Accordingly, this paper treats the operational assessment as its principal source and uses other official records only when their original publications can be independently identified and verified. This approach is consistent with sound documentary research practice, which requires transparent source attribution and verification of evidence. The document also contains apparent date and wording inconsistencies, therefore, statistics, operational timelines and event chronology should be cross checked against original incident logs and relevant official records before inclusion in formal external publication. Where independent corroboration is unavailable, the paper identifies information as reported in the supplied assessment rather than presenting it as independently verified fact.

3. Disaster Context and Operational Environment

The assessment describes a district environment in which low-lying terrain, lagoons, wetlands, inland water bodies and limited rural access routes can intensify the consequences of heavy rainfall. Flooded roads, muddy ground, damaged bridges and waterlogged pathways impeded access for emergency teams and the delivery of aid. These conditions meant that a response plan relying on normal road access could become ineffective precisely when rapid movement was most important.

The reported impacts extended beyond immediate flooding. The assessment records damage to homes and agricultural land, disruption to fishing and other livelihoods, power and communications failures and pressure on schools and health services. It also identifies post-disaster risks such as contaminated water, waterborne disease, psychological stress and the need for continued assistance to displaced households. This broad impact profile demonstrates that cyclone response must combine lifesaving action with infrastructure restoration, public health, welfare support and recovery planning.

4. Analysis of the Response

4.1 Early warning and situational awareness

The assessment records that warnings were monitored through meteorological and disaster management channels and communicated to military elements, civil authorities and communities. It notes that public messaging helped raise awareness and support preparedness, while field reporting and liaison with relevant authorities informed decisions. The document also describes local reconnaissance by officials, security personnel and community volunteers as a key source of ground-level information.

Nevertheless, warning information does not automatically translate into protective action.

The assessment's conclusion identifies limited village-level preparedness, inadequate evacuation planning, insufficient awareness of safe shelters and minimal community drills as weaknesses. It also notes communication gaps after power failures. This suggests a need to connect forecasts to clearly assigned actions: who issues the warning, who verifies local risk, how residents are contacted if mobile networks fail, and when evacuation begins.

An improved system should combine official forecasts with local risk maps, shelter capacity information, vulnerable-person registers and pre-agreed warning thresholds. Warnings should be issued in accessible languages and through multiple channels,

including local leaders, radio, loudspeakers and door-to-door notification where necessary. The effectiveness of the system should be measured by the time between warning and protective action, not simply by whether a warning was issued.

4.2 Planning, training and readiness

The report indicates that response personnel could be mobilized at short notice and that lifesaving teams and alert arrangements supported initial action. It also records previous training in rescue, evacuation, first aid and coordination. At the same time, it states that personnel specifically and formally trained exclusively for disaster response were limited, and that village-level rehearsals and community preparedness were insufficient.

This is a distinction between general readiness and specialist competence. General-purpose personnel can provide valuable immediate assistance, but flood rescue, swift water operations, casualty evacuation, shelter management and mass-casualty response require task-specific skills and recurrent practice. Training should be assessed through practical performance, not attendance alone. Joint exercises with local administration, police, health services, disaster-management authorities and community representatives can test warning dissemination, evacuation, communications, triage, relief distribution and handover.

Area specific plans are particularly important in locations where water bodies, embankments and damaged crossings can isolate communities. Plans should identify alternative access routes, safe assembly points, evacuation priorities and arrangements for people who cannot move independently. Exercises should test scenarios involving power failure, mobile network loss, night operations and the simultaneous closure of multiple routes.

4.3 Command, control and decision making

The assessment identifies clear command relationships, regular situation reporting, timely orders and the use of command intent as positive features. It states that subordinate leaders were able to act within assigned responsibilities as conditions changed, while coordination mechanisms helped maintain an overall picture of the emergency. These observations point to the importance of a command system that combines clear priorities with decentralised initiative.

Disaster environments are fluid: roads may become impassable, communications may fail and the scale of need may change rapidly. A sound command arrangement should therefore define decision authority in advance, use concise reporting formats and establish triggers for requesting specialist assistance. The source‟s emphasis on mission command is relevant because local leaders need freedom to adapt to ground conditions while remaining aligned with the overall humanitarian objective

However, command efficiency should not be confused with military control of the whole emergency. Civil authorities retain essential responsibilities for public administration, welfare, health and recovery. Military command arrangements should support a unified response, clarify responsibilities and avoid parallel systems that compete with civilian coordination.

4.4 Equipment, mobility and logistics

Resource availability is one of the clearest limitations recorded in the assessment. It identifies shortages or limited availability of boats, rescue equipment, generators, engineering tools, medical supplies and equipment suited to difficult terrain. It also describes delays associated with impassable roads, poor visibility and communications failures. The logistics sections highlight the need to sustain personnel and equipment during prolonged operations, including fuel, food, water, maintenance and troop rotation. These findings support a risk-based approach to equipment planning. Rather than relying mainly on improvised solutions or emergency borrowing, authorities should maintain a districtlevel inventory of serviceable rescue and relief assets, identify equipment gaps and pre-position essential stores according to hazard exposure and access constraints. Equipment should be inspected, tested and recorded in a common readiness register. Stockpiles should include personal protective equipment, life jackets, rescue ropes, lighting, portable power, water purification, firstaid and trauma supplies, and basic shelter materials.

Mobility planning should consider more than the number of vehicles available. It should assess whether vehicles can operate on flooded or damaged routes, whether alternative transport can reach isolated settlements, and how fuel and maintenance will be sustained. Pre-agreed arrangements with civilian engineering, transport and water service agencies can reduce duplication and speed up restoration.

4.5 Communications and technology

The report describes the importance of military communications when commercial networks were disrupted, while also noting that weather, power failure and network outages reduced the reliability of some systems. It identifies limited use of unmanned aerial vehicles and geospatial tools, insufficient real-time data integration and a need for additional digital capability and training.

A resilient communications plan should include interoperable radio procedures, backup power, designated liaison personnel, tested alternate channels and clear reporting priorities. Digital tools can improve the common operating picture, but they should not be treated as substitutes for reliable basic communications or local verification. Geospatial mapping can help identify inundated areas, vulnerable infrastructure, shelter capacity and route status. Aerial imagery may add value where legally authorized, safe and operationally appropriate; its use should follow established privacy, airspace and information security rules.

The most important technology requirement is integration. A map or digital form is useful only when its information is timely, accurate, shared with the right decision makers and updated as conditions change. A common data format for incident reports, displaced person registration, damage assessment and resource requests would reduce inconsistent reporting and support prioritization.

4.6 Civil–military and inter agency coordination

The assessment describes cooperation among military personnel, disaster-management authorities, district and divisional administration, police, health services, utility providers, road authorities, non-government organizations, private-sector actors and community volunteers. It credits information sharing and coordination with helping to organize rescue, relief, medical support and restoration activities.

Such cooperation is essential because no single organization holds all the capabilities or local information needed for disaster response. Coordination is strongest when responsibilities are agreed before an emergency, contact points are known, resource requests follow a shared procedure and information is exchanged regularly. Joint

exercises and district level coordination mechanisms can establish these relationships before roads are flooded or communications fail.

The source also records concerns among some community members about the extent and visibility of military involvement, despite generally positive accounts of assistance. This is a reminder that operational effectiveness includes legitimacy, transparency and public confidence. Military support should be proportionate to the need, undertaken in support of civil authorities, and accompanied by respectful communication and clear explanations of roles.

4.7 Protection, inclusion and community trust

The assessment identifies additional risks for women, children, older people and persons with disabilities, particularly where shelter privacy, sanitation, mobility and access to health services are limited. It recommends gender sense planning, child protection measures, culturally aware engagement and Tamil language capability.

Inclusive response must be designed before the emergency. Evacuation plans should identify residents who may need assistance, while shelters should provide safe sanitation, privacy, accessible routes, lighting, medical support and appropriate arrangements for families. Consultation with community leaders and service providers can improve cultural sensitivity and help identify groups who may otherwise be missed. Community members should be treated as partners in preparedness and recovery, rather than only as recipients of aid.

4.8 Recovery and disengagement

The source records joint damage and needs assessments, restoration of access and essential services, continued relief, debris clearance, support for repairs and the gradual reduction of military involvement as civilian capacity improved. It also highlights the importance of clear endstate conditions and structured handover to civil authorities.

Recovery should be planned from the start of the response. Otherwise, emergency tasks can continue without a clear transition, or support may be withdrawn before essential services and local administration are ready. A recovery framework should define responsibilities for household verification, infrastructure repair, public health, livelihood assistance and the replenishment of emergency stocks. Disengagement criteria should

be based on service restoration, safe access, functioning relief mechanisms and the capacity of civilian agencies to manage outstanding needs.

5. Key Findings

a) Rapid mobilization and a functioning command structure supported immediate rescue, relief and restoration activities.
b) Early warnings were available, but village-level evacuation planning, shelter awareness and community drills were not sufficiently developed.
c) Specialist rescue equipment, medical resources, power-generation capacity and equipment for difficult terrain were identified as gaps.
d) Communications redundancy and local reconnaissance were important, while network and power failures demonstrated the need for resilient information systems.
e) Coordination with civilian authorities and community actors was a major strength, but roles, data-sharing and joint exercises should be formalized.
f) Women, children, older people and persons with disabilities require explicit protection and access measures in evacuation and shelter plans.
g) Recovery and disengagement should be planned early, with clear handover criteria and continued civilian ownership.

6. Recommendations

Immediate priorities

a) Conduct an equipment audit and close the most critical gaps in rescue, personal protection, lighting, backup power, water purification and emergency medical stores.
b) Prepare and validate village level evacuation plans, safe routes, shelter capacity lists and arrangements for people requiring assistance.
c) Create a tested communication contingency plan covering power loss, mobile network failure and disrupted road access.
d) Establish a shared incident reporting format for affected households, route status, medical needs, relief stocks and urgent requests.
e) Conduct joint tabletop and field exercises with civil authorities, police, health services, disaster management officials and community representatives.

Medium term priorities

a) Develop dedicated disaster response teams with recurring practical certification in flood rescue, first aid, evacuation, casualty handling and shelter support.

b) Build a district level geospatial risk database showing flood-prone areas, critical infrastructure, evacuation routes, shelters and essential resources.

c) Improve interoperability through joint communications drills, liaison arrangements and tested backup power and radio equipment.

d) Establish planned maintenance, storage and replenishment arrangements for equipment and consumables used during extended operations.

e) Provide language, cultural-awareness, gender sensitivity and child-protection training for personnel likely to support disaster operations.

Long-term institutional priorities

a) Adopt cyclone and flood response procedures tailored to local terrain, population needs and likely infrastructure failures.

b) Maintain a central disaster knowledge repository containing verified incident data, after action reviews, resource inventories and updated plans.

c) Establish permanent civil-military coordination arrangements at district level while preserving civilian leadership of disaster management and recovery.

d) Integrate disaster management education into training and leadership development, supported by regular joint exercises and lessons-learned reviews.

e) Support community resilience programs, public education and local emergency response groups in partnership with civilian agencies.

f) Use measurable readiness indicators, including equipment serviceability, time to disseminate warnings, exercise performance, shelter readiness and time to restore essential services.

7. Conclusion

The Cyclone Ditwah experience recorded in the supplied assessment demonstrates both the value of military support during a major emergency and the limits of relying on rapid mobilization alone. Command arrangements, personnel, local reconnaissance and cooperation with civil authorities supported lifesaving and recovery tasks. Yet the report

also identifies persistent vulnerabilities in specialist equipment, dedicated training, community preparedness, resilient communications, technology integration and inclusive shelter planning.

The principal lesson is that disaster response capability must be built before a cyclone occurs. Forecasts need to trigger practical local action; trained teams need suitable equipment; communications need tested alternatives; agencies need agreed procedures; and communities need safe routes, shelters and trusted information. Recovery and disengagement must also be linked to clear measures of civilian capacity. Implementing these measures would help turn the operational lessons recorded in the assessment into a more resilient, coordinated and accountable disaster response system.

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PARTICIPANT RESEARCH PAPER

Multi-Hazard Risk in Jamshoro District: Assessing Riverine Flooding and Extreme Heat Impacts on Communities and Infrastructure

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Abstract

Jamshoro district occupies a precarious geographic and environmental position at the tail-end of the Indus River system, characterized by a fast-growing population of 1.12 million residents. This research paper evaluates the multi-hazard dynamics of Jamshoro, focusing on concurrent and compounding exposures to severe riverine flooding and extreme seasonal heatwaves. Utilizing empirical insights from the 2023 Population Census, Pakistan Meteorological Department (PMD) advisories, and Provincial Disaster Management Authority (PDMA) Sindh situation reports, the study investigates vulnerabilities across its four talukas—Kotri, Sehwan, Manjhand, and Thano Bula Khan. Key findings highlight that structural flood events, such as the 2022 record monsoon rains combined with Indus backwater effects and Manchar Lake breaches, alongside recurring April–June heatwaves reaching 43\text{--}48\text{ }^\circ\text{C}, severely threaten regional communities, particularly a young and rural demographic. The paper identifies critical infrastructure vulnerabilities—including the Kotri Barrage, thermal power plants, and the Indus Highway—and proposes actionable, phased policy recommendations centered on multi-hazard contingency planning, resilient infrastructure, and integrated early warning systems.

Keywords: Jamshoro District; Riverine Floods; Extreme Heat; Multi-Hazard Risk; Disaster Risk Reduction; Kotri Barrage.

1. Introduction

Jamshoro district represents a critical administrative and economic node in Sindh, featuring a population of 1.12 million, of which 53% reside in rural settings and 41.7% comprise children under the age of 15. Home to pivotal national infrastructure—such as the Kotri Barrage, major thermal power plants (Jamshoro, Lakhra, and Kotri), the Indus Highway, and the SITE Kotri industrial estate—the district is highly vulnerable to systemic disruptions induced by climate change.

The rationale for this research stems from the traditional siloed approach to disaster management, which treats floods and heatwaves as isolated seasonal events. In Jamshoro, these hazards interact in compounding ways; stagnant floodwaters exacerbate heat-related health crises, while grid failures during peak heatwaves paralyze drainage and water supply systems. The purpose of this study is to comprehensively assess riverine flood and extreme heat hazards, analyze their socio-economic impacts on vulnerable communities, and map risks across interdependent critical assets. The scope encompasses Jamshoro's four talukas, utilizing secondary institutional data to formulate a comprehensive framework for sustainable regional resilience.

2. Regional Context & Hazard Profile

Regional Context and Literature Review

Jamshoro's topography spans from the Kirthar hill-torrent paths in the west to the Indus River corridor in the east. Literature from the Federal Flood Commission and PDMA Sindh highlights that as a tail-end district, Jamshoro experiences prolonged flood inundation periods because receding waters face bottlenecks before discharging downstream. Simultaneously, pre-monsoon and summer thermal profiles show regular spikes, placing severe stress on human health, agriculture, and power infrastructure.

Vulnerability Profile and Historical Events

Historical data underscores the recurring severity of multi-hazard shocks in the district:

- **2010 and Historical Floods:** The Kotri Barrage, possessing a design flow capacity of 875,000 cusecs, has been repeatedly tested, with historical flows exceeding design limits notably in 1956 and 2010.

- **2022 Mega Flood and Rain Crisis:** A combination of unprecedented provincial rainfall anomalies (province-wide rains surging +426%) and Indus backwater effects submerged approximately 500 villages across 10 Union Councils, forcing four controlled breaches at Manchar Lake and cutting off the Indus Highway link to Sehwan.
- **2024–2025 Heatwave Emergencies:** PMD and PDMA advisories recorded temperatures 5\text{--}7\text{ }^\circ\text{C} above normal (43\text{--}48\text{ }^\circ\text{C}), prompting the Sindh Health Department to declare province-wide heatwave hospital emergencies explicitly naming Jamshoro.
- **2025 Riverine Flood Surges:** Medium flood classifications were triggered at Kotri Barrage (such as inflows reaching 421,100 cusecs in September 2025), necessitating extensive evacuations across riverine *katcha* settlements.

Core Definitions

- **Hazard:** A dangerous phenomenon, human activity, or condition that may cause loss of life, injury, property damage, social disruption, or environmental degradation (e.g., Indus riverine floods, extreme heatwaves).
- **Exposure:** The presence of people, livelihoods, infrastructure, and economic assets in places subject to potential adverse impacts.
- **Vulnerability:** The physical, social, economic, and environmental factors that increase the susceptibility of a community to the impact of hazards.
- **Risk:** The combination of the probability of an event and its negative consequences, resulting from the interaction between natural hazards and vulnerable exposed systems.

3. Risk & Vulnerability Assessment

Socio-Economic Impacts and Livelihood Disruption

Disaster impacts in Jamshoro disproportionately affect marginalized rural populations. According to the 2022 Post-Disaster Needs Assessment (PDNA), approximately 70% of total national damage and losses were concentrated in Sindh, pushing millions of additional citizens into poverty. Livelihood disruptions follow the dual hazard trajectory:

floods destroy standing crops, livestock, and mud-brick housing in *katcha* zones, whereas extreme heat compresses outdoor labor hours, reduces agricultural productivity, and spikes mortality rates among vulnerable groups.

Vulnerable Groups and Demographic Exposure

Vulnerability is amplified by demographic structures: 41.7% of Jamshoro's population consists of children under 15, and 53% live in rural households with high exposure to outdoor thermal stress and floodwaters. During the September 2025 flood threats, 360,777 individuals were relocated across Sindh, including 121,769 displaced directly from riverine *katcha* areas, straining local shelter capacities and increasing susceptibility to waterborne diseases.

4. Community Resilience Factors

Local resilience in Jamshoro is sustained through informal social mechanisms and traditional adaptation strategies:

- **Community Coping Networks:** Indigenous riverine communities utilize traditional river transport and informal warning networks to evacuate livestock and vulnerable family members prior to official administrative alerts.
- **Local Architecture and Sheltering:** Rural households rely on elevated earthen platforms and traditional mud-plastered structures designed to withstand moderate environmental shocks, though extreme events like the 2022 backwaters overwhelmed these coping capacities.

5. Scientific & Institutional Gaps

Institutional preparedness in Jamshoro faces several systemic constraints:

- **Siloed Hazard Management:** Existing disaster management frameworks treat floods and heatwaves as independent, single-hazard phenomena, neglecting the compounding feedback loops between extreme temperatures and hydrological flows.
- **Infrastructure Monitoring Deficits:** Gaps persist in real-time sensor coverage for hill-torrent tracking in the Kirthar range and localized urban heat island monitoring across rapidly growing municipal centers.
- **Data and Resource Gaps:** Limited availability of granular, gender-disaggregated vulnerability data and delayed emergency response logistics caused by compromised road links (such as the inundation of the Indus Highway).

6. Mitigation Strategies & Best Practices

Mitigation in Jamshoro requires integrating structural defenses with proactive health and administrative measures:

- **Structural Interventions:** Strengthening and heightening protective bunds around Manchar Lake and the Kotri Barrage perimeter; upgrading the resilience of the Indus Highway transport corridor.
- **Non-Structural Measures:** Establishing synchronized Standard Operating Procedures (SOPs) linking PMD heat advisories with irrigation flow management; implementing mandatory work-hour restrictions during peak summer months.
- **Best Practices:** Drawing lessons from the 2015 Karachi heatwave response analogue, establishing pre-positioned cooling centers and hospital emergency wards across Jamshoro's health facilities.

7. Risk Communication & Early Warning

Effective risk communication in Jamshoro requires bridging the gap between technical forecasting agencies and grassroots communities. Because over half the population is rural, early warning dissemination cannot rely solely on digital channels.

A people-centred and multi-channel early warning system must integrate meteorological heat alerts and barrage inflow data with localized communication tools—such as community radio, mosque announcements, and mobile SMS advisories in local languages—ensuring that outdoor laborers, pastoralists, and riverine residents receive actionable lead times to secure livestock and seek shelter.

8. Policy Recommendations

Aligned with the PDNA 2022 "build back better" principles, a phased policy roadmap is proposed for Jamshoro District:

Timeline	Strategic Action	Lead Agency	Verification Metric
0–6 Months	Link PMD heat advisories and Kotri barrage flow data into a unified district multi-hazard SOP.	PDMA Sindh / District Administration	Formal adoption and operationalization of unified district SOPs.
0–6	Execute pre-monsoon technical	Irrigation	Completion rate of pre-

Months	inspections of protective bunds and establish clear Manchar Lake breach protocols.	Department Sindh / PDMA	monsoon structural audits.
6–24 Months	Develop a comprehensive District Multi-Hazard Risk Atlas incorporating vulnerable *katcha* settlements.	PDMA Sindh / District Disaster Management Authority	Publication of the district-specific multi-hazard risk atlas.
6–24 Months	Install backup solar power systems for rural health clinics and community water supply points.	Health Department / Local Government Sindh	Number of rural health facilities equipped with reliable solar backups.
2–5 Years	Implement comprehensive river-space management downstream of Kotri Barrage and raise vulnerable road infrastructure.	Irrigation & Works and Services Departments	Kilometers of flood-proofed highway and regulated river corridors.

9. Conclusion

Jamshoro District faces complex, compounding risks from structural riverine flooding at the tail-end of the Indus system and recurrent seasonal heatwaves. With a young and predominantly rural population dependent on vulnerable infrastructure, single-hazard planning is no longer sufficient. By adopting an integrated multi-hazard management framework, upgrading critical assets like the Kotri Barrage and Indus Highway, and prioritizing community-level early warning systems, Jamshoro can successfully build long-term resilience against escalating climate shocks.

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PARTICIPANT RESEARCH PAPER

Urban Flooding in Karachi: Causes, Impacts and Sustainable Solutions

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Abstract

Urban flooding is a regular disaster risk in Karachi because of the combination of heavy monsoon rains and rapid urban expansion, together with impermeable surfaces, modified drainage routes, inadequate drainage infrastructure, the build-up of solid waste, and pressure on land use (Iftikhar & Iqbal, 2023). The rainfall incident in August 2020 illustrates how serious this risk is: the Pakistan Meteorological Department [PMD] recorded 231 mm of rainfall at Karachi-Faisal on 28 August 2020 within 24 hours (PMD, 2020). This research examines the primary causes and impacts of urban flooding in Karachi, focusing on its impact on residents, infrastructure, the economy, and public health. Additionally, it highlights major vulnerabilities and systemic deficiencies in disaster management and suggests sustainable structural, nonstructural, and community-based solutions. Evidence from meteorological data, academic research, and organizational reports indicates that rainfall is the direct hazard, but the severity of the flooding also depends on exposure, vulnerability, drainage efficiency, land use, and preparedness. Reducing risk goes far beyond just widening the drains: it is necessary to maintain the drainage network, protect natural drainage paths, improve waste management, community-focused early warning systems, and introduce nature-based solutions (Jha et al., 2012). The paper recommends a step-by-step method consisting of risk mapping, targeted interventions, pilot testing and evaluation, and scaling, in line with the specific, timelimited flood-resilience objectives set out in Karachi's Climate Action Plan (United Nations Development Programme [UNDP], 2025).

Keywords: Climate adaptation; Disaster management; Karachi; Resilience; Urban flooding

1. Introduction

Urban flooding occurs when the amount of rainwater reaches a level higher than the rate at which it can soak into the ground or be removed by the drainage systems. In Karachi, intense monsoon rains may combine with the city's large urban areas, the presence of impermeable surfaces, and the lack of sufficient drainage routes, leading to extensive waterlogging and flooding (Hasan, 2020; Iftikhar & Iqbal, 2023).

Karachi has endured persistent flooding for decades, but due to urban growth and changes in land use, its Susceptibility and exposure have increased, and the way in which rainfall turns into surface runoff has changed. A study of the Malir Basin indicates that urbanization has modified the region's hydrological and drainage patterns (Zafar & Zaidi, 2019).

The August 2020 episode indicates the city's Defenselessness to climate extremes. On August 28, 2020, the Pakistan Meteorological Department noted that 231 mm of rain fell in Karachi-Faisal over 24 hours, thus exceeding the station's earlier record of 164 mm, which had been established in 1979 (PMD, 2020). As stated in recent assessments, the event led to serious disruptions and effects on both people and infrastructure (Human Rights Commission of Pakistan [HRCP], 2020).

This paper argues that it is wrong to blame Karachi’s flooding entirely on rainfall. Although rainfall is the direct cause, the extent of the damage is greatly affected by factors including exposure, vulnerability, drainage systems, land use, waste management, environmental conditions, and preparedness (Iftikhar & Iqbal, 2023; Jha et al., 2012).

This paper aims to:

1. Explore the major causes of urban flooding in Karachi.
2. Evaluate its impacts on people, infrastructure, the economy, and health.
3. Identify key vulnerabilities and gaps in disaster management.
4. Suggest sustainable structural, non-structural, and community-based solutions.

The paper focuses on rainfall-driven (pluvial) urban flooding in Karachi, using the August 2020 event as its main example and relying on meteorological data, academic studies, and institutional reports.

2. Regional Context and Hazard Profile

Karachi is a large coastal city which has seen considerable urban development. This development has turned the natural environment into buildings, roads and paved surfaces, thereby decreasing the capacity of rainwater to soak into the ground and increasing the quantity of water that runs over the surface. Consequence of this is that the risk of flooding may be seen as resulting from natural hazards, the fact that people and property are situated in susceptible areas, and the degree of susceptibility to damage (Jha et al., 2012). In the present paper, hazard means the heavy rainfall itself, exposure refers to the people and property in areas prone to flooding, vulnerability means their susceptibility to damage, and risk refers to the combined effect of these three factors.

It is shown in historical records that flooding has for a long time been a common problem in Karachi; nevertheless, the impact of heavy rainfall becomes more severe when the drainage systems are blocked, the infrastructure is inadequate or not properly maintained, and development takes place in areas which are already prone to flooding (Iftikhar & Iqbal, 2023).

The 2020 flooding is a clear example of this. Together with rainfall figures provided by the Pakistan Meteorological Department, the Human Rights Commission of Pakistan's 2020 report pointed out issues concerning drainage, infrastructure, and urban planning. On a national scale, the floods of 2022 in Pakistan impacted about 33 million people and resulted in damages and losses that went beyond $30 billion, thus showing the country's general vulnerability to flood emergencies (Asian Development Bank et al., 2022; World Bank, 2022). It is important not to understand these national figures as representing losses that are solely connected with Karachi.

The Climate Action Plan for Karachi also states that the increasing frequency and intensity of extreme rainfall in recent years indicate that the risk of urban flooding is likely to rise, and therefore demands substantial improvements in drainage and adaptation (United Nations Development Programme [UNDP], 2025, p. 52).

Intense rainfall

The heavy rain is the direct trigger of pluvial urban flooding; if it rains over a short period then the runoff can go beyond the capacity of the drains and channels. The amount of

231 mm recorded at Karachi-Faisal in 24 hours in August 2020 shows how great the extent of this risk is (PMD, 2020).

Rapid urbanization and impermeable surfaces

Cities are growing quickly. As more people move in, builders cover more land with concrete and asphalt. These hard surfaces do not let water soak into the ground. Instead, rain runs off into drains and streams. This can cause flooding during heavy storms. It also washes pollutants into rivers and lakes. As cities keep growing, these problems may get worse.

Urban development involves replacing the soil and vegetation with concrete, asphalt, and buildings, which in turn decreases absorption and increases runoff. Zafar and Zaidi (2019) not only highlighted but also recorded the changes in basin hydrology caused by urbanization in the Malir Basin. More recent studies that have used remote sensing have likewise identified land-use and land-cover change together with the growing amount of impermeable surfaces as important factors for flood-risk management in Karachi (Iqbal et al., 2025).

Altered natural drainage

Natural drainage channels, streams, and other waterways act as routes for stormwater. The development of urban areas can restrict, block, or modify these routes, which in turn increases the likelihood that water will pool in built-up regions. It follows that preserving the existing drainage corridors is an important part of reducing risk. A study concerning North Karachi also found a connection between flooding and poor drainage as well as encroachment close to the Lyari River and Gujjar Nala (Ejaz et al., 2024).

Inadequate drainage and maintenance

Drainage systems can become less effective because of their limited capacity, the presence of bottlenecks, sedimentation, old infrastructure or because they are not properly maintained. A case study carried out in DHA Karachi found that poorly maintained drainage networks and land encroachment were factors that contributed to the flooding that occurred in 2020 (Iftikhar & Iqbal, 2023).

Solid waste and land-use pressures

Solid waste has the potential to clog drainage systems and decrease their effective capacity when there is heavy rainfall. The evaluation carried out by the HRCP in 2020 highlighted concerns regarding drainage and waste management during the flooding that took place in 2020. As a result, flood management must include effective solidwaste management.

Building in low-lying areas and along natural flood paths can also increase vulnerability, so it is essential to carry out risk-informed land-use planning in order to prevent the creation of further flood risks (Iftikhar & Iqbal, 2023; Jha et al., 2012).

3. Risk and Vulnerability Assessment

Urban flooding has a wide range of effects on humans, infrastructure, the economy, and public health. It can result in drowning, electrocution, injuries, and damage to buildings; it can also damage people's homes, transportation systems, electrical grids, and other important infrastructure (HRCP, 2020).

The flooding has disrupted transport and has blocked access to workplaces, schools, and healthcare centres. It has been necessary for some businesses to close down, and families who depend on daily wages have then found it difficult to get back on their feet. Representatives of the Karachi trade estimated that the losses would amount to about Rs 5 billion (approximately US$30 million) on the first day of the flooding, which was on 25 August 2020 (Arab News, 2020a), and this had increased to an estimated Rs 10 to 12 billion (around US$71 million) by the end of the week, although property losses had not yet been counted at that time (Arab News, 2020b).

Floodwater, which contains sewage and solid waste, can also heighten public-health risks and make it more difficult to access healthcare (HRCP, 2020; Taseen et al., 2022).

The impact of flooding is not the same for all. People in low-income areas, those who live in informal settlements, and individuals residing near drainage channels may have limited means with which to evacuate and recover. Children, the elderly, people with disabilities, and families who do not have their own vehicles may face further difficulties. The HRCP (2020) report also observed that stateless people, who do not have national identity cards, were left out of the relief lists. According to the Karachi Climate Action Plan, approximately 6.85% of the city's population is susceptible to flooding, the South and

East districts being the most at risk (UNDP, 2025). It therefore follows that a proper disaster-risk assessment should take into account not only where flooding occurs but also who is exposed to it and why they are vulnerable (Hasan, 2020; Jha et al., 2012).

4. Community Resilience Factors

Community involvement is of great importance in terms of getting ready for disasters. People are able to identify areas that are often flooded, drains that are blocked, unsafe paths, and houses that need more help; in the case of Karachi, the local communities were aware of the spots where the flooding was worst and where the smaller drains had vanished (Hasan, 2020). The HRCP (2020) also suggested getting residents who know where the drains become blocked, pointing out that many settlements already possess the skills needed for mapping in order to evaluate the drainage issues. Involving the community can aid in local hazard mapping, planning for evacuations, carrying out drills, providing first aid, and disseminating warning information (National Disaster Management Authority [NDMA], 2007). Examples such as the Pakistan Life Savers Programme, which trains citizens in CPR and control of bleeding, demonstrate how first-aid capacity can be developed at the community level (Aga Khan University Centre of Excellence for Trauma and Emergencies [AKU-CETE], n.d.). Even so, community involvement should serve to strengthen rather than take the place of government responsibility for infrastructure, sanitation, emergency services, and responsible urban development (HRCP, 2020; Jha et al., 2012).

5. Gaps in the scientific and institutional fields

There is a significant gap in our scientific knowledge when it comes to combining spatial and temporal flood-risk data. Geographic Information Systems (GIS) and remote sensing technology are capable of integrating data on elevation, rainfall, drainage systems, land use and land cover, and past flood zones. Iqbal et al. (2025) pointed out the effectiveness of flood-risk assessment based on remote sensing in Karachi.

The fact that there are institutional weaknesses contributes to the existing gaps.

According to the HRCP in 2020, Karachi's 19 land-control and management authorities lack coordination and operate under different by-laws, leading to conflicts in city planning. Technologies such as artificial intelligence and machine learning have the potential to speed up and improve the accuracy of flood predictions, but many cities still do not have

the necessary data, sensors, and systems to make use of them. Such technology can only fulfill its role when it is connected with city planning, emergency response systems, and input from the community (Anik et al., 2025). The essential chain is therefore:
Data, analysis, warning, decision, action.

6. Mitigation Strategies and Best Practices

A comprehensive strategy for Karachi should incorporate conventional infrastructure together with environmental, technological, and community-driven measures.

The first step should be to map the drainage networks and assess them in the light of the present rainfall and runoff conditions; the main bottlenecks should be given priority and the regular maintenance carried out both before and after the monsoon should be recorded (HRCP, 2020).

Second, when planning land use regard should be given to the risks involved and natural drainage routes should be protected. In the case of new development attention should be paid to the amount of runoff produced, to flood paths and to the capacity of the adjacent drainage systems (Iftikhar & Iqbal, 2023; Zafar & Zaidi, 2019).

Thirdly, Karachi should improve on its existing grey infrastructure by integrating green and blue infrastructure, such as permeable surfaces, rain gardens, green roofs, vegetated areas, retention spaces, and restored drainage channels. With regard to this, Iqbal et al. (2025) offer a spatial framework for mapping flood risk in conjunction with nature-based interventions, and Soni et al. (2025) identify the main institutional, technical and financial obstacles to implementing a sponge-city model in Karachi.

Fourth, solid-waste management should be coordinated with stormwater management since blocked drainage reduces the efficiency of the infrastructure (HRCP, 2020).

Fifth, when granting approvals for major developments flood risk should be taken into account in order to avoid creating new exposure (Jha et al., 2012).

The Climate Action Plan for Karachi already includes such specific targets, for example incorporating nature-based measures to mitigate floods in 100 parks located in areas prone to flooding by 2027 (UNDP, 2025, p. 50).

7. Communication on risk and early warning

Early-warning systems should indicate not just the current level of rainfall but also where the risk lies, when the effects will take place, and what action residents should take; the

warnings have to be specific to the area, easy to understand, and sent out by a number of different communication methods (United Nations Office for Disaster Risk Reduction [UNDRR] & World Meteorological Organization [WMO], 2024).

Early-warning systems that are oriented towards the community should connect rainfall monitoring with local alerts, instructions for evacuation, and emergency responses (UNDRR & WMO, 2024).

8. Policy Recommendations

A practical implementation framework is:

Map → Fix → Pilot → Evaluate → Scale.

This approach allows officials to identify the main flood-affected areas, deal with urgent matters, assess sustainable solutions, and improve those strategies which have proven to be successful (Jha et al., 2012). The HRCP (2020) suggests that Karachi's metropolitan corporation should be placed under a single administration since responsibility is shared among a number of agencies.

9. Conclusion

The problem of urban flooding in Karachi is a regular disaster risk which cannot be attributed solely to rainfall. While heavy rainfall—such as the 231 mm that fell in 24 hours at Karachi-Faisal in August 2020—is what sets off the flooding, it is rapid urbanization, the presence of impermeable surfaces, changes to natural drainage, poor maintenance and the blocking of drains by solid waste that decide how severe the flooding becomes. The effects of this are felt by people (through drowning, electrocution and injury), as well as in relation to infrastructure and transport, livelihoods and public health because of contaminated floodwater and the disruption of access to medical care; trade representatives had estimated business losses of Rs 10 to 12 billion in just one week in 2020 (Arab News, 2020b). These burdens affect low-income communities, informal settlements, children, the elderly and people with disabilities most severely. Major shortcomings remain, such as inadequate drainage maintenance, a lack of coordination among institutions, landuse planning that fails to take flood risk into account, limited use of GIS and remotesensing data, and early warning systems that are not tailored to specific areas.

Sustainable solutions therefore have to include three elements: structural measures (such as drainage that is mapped and properly maintained and green and blue infrastructure), non-structural measures (including risk-informed planning, integrated waste management and community-focused early warning), and community-based preparedness which makes use of local knowledge and support, without, however, replacing the responsibility of the government. By adopting the Map → Fix → Pilot → Evaluate → Scale approach, Karachi can reduce the risks that currently exist and prevent the creation of new ones.

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PARTICIPANT RESEARCH PAPER

The Role of International Organizations in Disaster Risk Reduction and Response

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Abstract

Disaster risk reduction and emergency response require national leadership supported by effective international cooperation. International organizations contribute technical expertise, humanitarian coordination, emergency supplies, financing and recovery assistance. Their effectiveness, however, depends on whether these contributions are aligned with national priorities, provincial capacities and community needs. This paper examines the roles of international organizations across the disaster management cycle, with particular reference to Pakistan. It uses secondary research from official institutional reports and international policy frameworks, including evidence from the 2010 and 2022 floods. The analysis finds that international support can expand response capacity and help assess recovery needs, but it cannot substitute for domestic preparedness, risk informed development or accountable public institutions. Pakistan's experience also highlights the importance of reliable data, clear coordination arrangements, predictable financing and meaningful participation by local actors. The paper recommends that the National Disaster Management Authority strengthen pre disaster partner mapping, establish clear procedures for international assistance, improve shared information systems, promote anticipatory action and build stronger links between humanitarian response and long term recovery. International cooperation is most valuable when it reinforces national leadership and leaves local institutions better prepared for the next emergency.

Keywords: Climate adaptation; Disaster risk reduction; Humanitarian coordination; International organizations; Pakistan.

1. Introduction

Disasters can reverse development gains, damage essential infrastructure, interrupt livelihoods and place additional pressure on public finances. In Pakistan, exposure to riverine and flash floods, earthquakes, drought, extreme heat and glacial hazards intersects with poverty, settlement patterns, infrastructure weaknesses and uneven access to services. Climate change adds further pressure to an already complex risk environment. No single international organization can address these challenges alone, and external assistance is not a substitute for the state's responsibility to protect its population.

The central issue is how international expertise, finance and operational support can complement Pakistan's own disaster management system without creating fragmented reporting arrangements or bypassing national and local institutions. The Sendai Framework for Disaster Risk Reduction 2015–2030 recognizes that the state has the primary role in reducing disaster risk while responsibilities are shared with local government, the private sector and other stakeholders (United Nations Office for Disaster Risk Reduction [UNDRR], 2015).

This paper examines the roles of international organizations in disaster risk reduction (DRR), preparedness, emergency response and recovery. It asks how these organizations support Pakistan, what limitations emerge during major disasters, and what practical steps the National Disaster Management Authority (NDMA) can take to improve international collaboration. The study is based on secondary analysis of official reports, policy frameworks and documented disaster assessments. It does not claim to include original fieldwork or interviews.

2. Regional Context and Hazard Profile

Pakistan faces multiple, sometimes overlapping hazards. Heavy monsoon rainfall can trigger riverine and urban flooding, while steep terrain contributes to flash floods and landslides in mountainous areas. The country also faces significant seismic risk, drought and extreme heat. In the northern mountains, glacial lake outburst floods pose additional risks to settlements, roads and water infrastructure. The impact of any hazard depends not only on its physical intensity but also on exposure, vulnerability and the capacity to prepare and respond.

For practical analysis, disaster risk can be understood as the potential for loss arising from the interaction of a hazard with exposed people and assets, their vulnerability, and the capacities available to reduce harm. This is consistent with the Sendai Framework's emphasis on understanding risk in its multiple dimensions and strengthening governance, investment in resilience and preparedness (UNDRR, 2015).

The 2022 floods illustrate the scale of Pakistan's exposure. The government led Post-Disaster Needs Assessment (PDNA), supported by the Asian Development Bank (ADB), the European Union, United Nations agencies and the World Bank, estimated damage of more than US$14.9 billion, economic losses of about US$15.2 billion and resilient recovery and reconstruction needs of at least US$16.3 billion. It reported that 33 million people were affected and more than 1,700 people lost their lives (Government of Pakistan et al., 2022). These figures show why international cooperation matters, but they also underline the need to reduce risk before disasters occur. The World Bank's Pakistan Country Climate and Development Report likewise argues for stronger investment in climate adaptation and resilience as part of the country's development pathway (World Bank, 2022).

3. Risk and Vulnerability Assessment

Disaster impacts are unevenly distributed. Households with insecure housing, limited savings, weak access to health services or livelihoods dependent on agriculture often have fewer options for evacuation and recovery. Women, children, older people, persons with disabilities, displaced households and people living in informal settlements may face additional barriers to warnings, transport, shelter, documentation and assistance. These vulnerabilities are shaped by social and economic conditions, not simply by the hazard itself.

International organizations can help authorities assess needs, provide emergency health services, restore water and sanitation, support food security and livelihoods, and protect displaced or otherwise at-risk populations. Multilateral development institutions can also support post-disaster assessments that estimate damage, economic losses and reconstruction requirements. The 2022 PDNA is an example of joint assessment involving Pakistan's government and international partners; it helped establish a shared evidence base for recovery planning (Government of Pakistan et al., 2022). At the same

time, the UN and Government of Pakistan revised the 2022 Floods Response Plan to seek US$816 million for urgent humanitarian needs, illustrating the scale of the gap between immediate relief and longer-term reconstruction (United Nations Office for the Coordination of Humanitarian Affairs, 2022).

However, assessments are only useful when their findings inform decisions. Needs data should be timely, disaggregated where possible, shared through agreed systems and linked to transparent criteria for assistance. NDMA and provincial authorities should ensure that external assessments complement national information rather than produce competing estimates or separate reporting processes.

4. Community Resilience Factors

Communities are often the first to respond when a disaster occurs. Neighbours, local volunteers, community organizations and local authorities may provide initial rescue, shelter, information and mutual assistance before external teams arrive. Local knowledge can also help identify safe routes, seasonal hazards, vulnerable households and practical coping strategies.

International support is more likely to build lasting resilience when it strengthens these existing capacities. The Sendai Framework calls for an all of society approach and recognizes the importance of local level action (UNDRR, 2015). In practice, international organizations can support community based disaster risk management, locally appropriate preparedness plans, volunteer training, inclusive early warning arrangements and community participation in recovery decisions.

A 2023 independent review of the Grand Bargain found continued efforts to strengthen local actors, while identifying localization and the quality of funding as areas requiring sustained attention (Metcalfe-Hough et al., 2023). Localization should not mean transferring responsibilities to communities without resources. Local organizations need predictable funding, access to coordination forums, technical support and clear accountability arrangements. NDMA and provincial institutions should encourage international partners to work through capable local actors wherever appropriate, while ensuring that safeguarding, financial oversight and quality standards are maintained.

5. Scientific and Institutional Gaps

International organizations bring expertise in risk assessment, satellite based mapping, emergency logistics, public health, food security and recovery planning. These capabilities can strengthen national decision making, particularly when a disaster affects several provinces or overwhelms local response capacity. Yet technology alone does not guarantee effective action. Forecasts and risk maps must be reliable, understandable, shared promptly and connected to decisions that authorities and communities can implement.

Important challenges include fragmented datasets, inconsistent assessment methods, limited technical capacity at local levels, unclear information sharing arrangements and gaps between early warnings and protective action. The 2010 floods affected more than 20 million people; the United Nations response plan was later revised to more than US$1.9 billion as the scale of humanitarian needs became clearer (United Nations Office for the Coordination of Humanitarian Affairs, 2010). the World Bank and ADB's assessment estimated losses and damage at approximately US$9.7 billion (Asian Development Bank & World Bank, 2010). The scale of the event exposed the difficulty of matching response capacity and coordination to a nationwide emergency.

AI, machine learning, remote sensing and predictive analytics may help identify emerging risks, but their use should be based on tested methods, transparent assumptions and accessible data. NDMA should prioritize interoperability and operational usefulness over technology procurement alone. Any shared platform should identify who owns the data, who updates it, how uncertainty is communicated and how information informs decisions.

6. Mitigation Strategies and Best Practices

International assistance should support the full disaster management cycle rather than concentrate mainly on emergency relief. Before disasters, organizations can assist with risk assessments, contingency planning, resilient infrastructure, training, preparedness and early warning systems. During emergencies, they may provide specialist personnel, supplies, logistics, technical coordination and sector specific services. After disasters, they can support recovery planning, reconstruction, livelihood restoration and measures to reduce future risk.

The Sendai Framework identifies four priorities: understanding disaster risk; strengthening disaster risk governance; investing in disaster risk reduction for resilience; and enhancing preparedness for effective response while building back better in recovery, rehabilitation and reconstruction (UNDRR, 2015). These priorities offer a useful basis for aligning international support with Pakistan's own plans.

The 2022 PDNA recommended resilient reconstruction and estimated at least US$16.3 billion in recovery and reconstruction needs (Government of Pakistan et al., 2022). The lesson is that recovery should not simply replace damaged assets with the same level of vulnerability. Infrastructure standards, land use decisions, maintenance arrangements and community needs should be considered together. International partners can provide technical and financial support, but national institutions must set priorities and oversee implementation.

7. Risk Communication and Early Warning

Early warning is effective only when people receive a credible message, understand what it means and can act on it. Communication therefore requires more than forecasting technology. It depends on clear responsibilities, timely public information, trusted messengers, accessible formats and practical instructions. Messages should reach remote communities, people with disabilities, older people and households without reliable internet access.

International organizations can support technical capacity, communication planning, preparedness exercises and the exchange of good practice. NDMA, provincial authorities, meteorological and hydrological services, local administrations, media and community networks need agreed procedures for turning forecasts into protective action. Messages should specify the expected hazard, likely timing and location, recommended actions and where people can obtain verified updates.

Lessons from major floods also show the importance of linking warning systems to evacuation routes, safe shelters, health services and protection of essential water and sanitation infrastructure. Warning coverage should therefore be evaluated not only by the number of messages issued but also by whether at risk groups receive, understand and can act on them.

8. Policy Recommendations

8.1 Establish a standing international partner map. NDMA should maintain an updated register of international organizations, their mandates, technical capabilities, geographic presence, emergency contacts and available resources. The register should be reviewed before each hazard season.

8.2 Agree procedures for international assistance in advance. Relevant federal and provincial institutions should clarify requirements for registration, visas, customs clearance, permissions and field access. Pre-agreed procedures can reduce avoidable delays while preserving national oversight and security requirements.

8.3 Strengthen shared operational information. NDMA should work with provincial authorities and international partners to agree common formats for needs assessments, situation reports, geospatial information and funding data. Each dataset should have a designated owner, update schedule and clear method for communicating uncertainty.

8.4 Invest in preparedness and anticipatory action. Where forecasts and triggers are sufficiently reliable, NDMA and partners should develop pre-agreed actions that can be activated before a hazard reaches its peak. These arrangements should identify trigger thresholds, responsible institutions, funding sources and measurable protective actions.

8.5 Make localization practical. International partners should involve capable local organizations in planning, coordination and implementation, provide appropriate funding and technical support, and report transparently on resources reaching local actors. Community participation should be meaningful rather than limited to consultation after priorities have already been set.

8.6 Link relief to resilient recovery. Recovery plans should use post-disaster assessments to prioritize safer infrastructure, climate adaptation, livelihood restoration and maintenance. NDMA should encourage periodic reviews of whether international assistance has reduced risk, not only whether relief items were delivered.

8.7 Measure coordination performance. After major emergencies, NDMA and relevant partners should conduct joint reviews covering response timeliness, coverage of vulnerable groups, data quality, funding delivery, local participation and implementation of lessons. Findings should inform revised procedures and future training.

9. Conclusion

International organizations are important partners in disaster risk reduction and response because they can mobilize technical expertise, humanitarian assistance, financing and recovery support. Pakistan's experience, particularly the floods of 2010 and 2022, demonstrates both the scale of need during major emergencies and the value of coordinated international engagement. The 2022 PDNA provided a shared assessment of damage, losses and recovery needs, while the Sendai Framework offers a common basis for moving from response alone towards risk-informed development.

Nevertheless, international assistance cannot replace effective national institutions, local preparedness or sustained investment in risk reduction. Its value depends on whether support is coordinated, evidence based, inclusive and aligned with Pakistan's priorities. NDMA can improve results by preparing partner arrangements before emergencies, strengthening shared information systems, supporting anticipatory action, enabling capable local organizations to participate and linking relief to resilient recovery. The strategic objective should not simply be to attract more international assistance, but to ensure that every partnership strengthens Pakistan's ability to anticipate, withstand and recover from future disasters.

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PARTICIPANT RESEARCH PAPER

Climate Change and Emerging Public Health Risks: Disaster Management Perspectives

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Abstract

Climate change is altering the health risks that disaster managers must anticipate, yet health is often treated as a downstream sector rather than a core element of disaster risk management. It is increasingly shaping public-health risk through extreme heat, floods, drought, changing rainfall, food-system disruption and damage to essential services. This article reviews global evidence and uses Pakistan as a case study to examine how climate-related hazards translate into health outcomes, why risks are unequally distributed, and how disaster-management systems can reduce preventable harm. It is assessed through evidence that recent global warming has already affected some health outcomes. Evidence indicates that health impacts are both direct such as heat illness, injury and respiratory stress and indirect, including unsafe water, vector-borne disease, malnutrition, displacement and psychosocial distress. Pakistan's 2022 floods affected approximately 33 million people, illustrating how hazards interact with poverty, infrastructure exposure and disrupted health services. The review argues for health-centred disaster-risk reduction: climate-informed surveillance and early warning, resilient primary care, safe water and sanitation, continuity of medicines, locally led preparedness, and disaggregated risk data. Climate change should therefore be treated as a public-health and development risk, not solely an environmental issue.

Keywords: Climate change; Disaster risk reduction; Pakistan; Public health; Resilience

1. Introduction

Climate change is no longer a distant threat to health. The Intergovernmental Panel on Climate Change (IPCC) concluded with very high confidence that it has already harmed physical health worldwide and mental health in the regions assessed (IPCC, 2022). The 2025 Lancet Countdown, produced with the World Health Organization (WHO), found that 12 of 20 indicators tracking health threats had reached record levels, and that heat-related mortality had risen 23% since the 1990s to an average of 546,000 deaths a year (World Health Organization [WHO], 2025). The central problem is not simply that climate hazards occur, but that exposure and the ability to recover are unequally distributed. People living in informal settlements, floodplains, heat-prone workplaces or areas with weak water and health infrastructure often face greater risk while having fewer resources to adapt. Disaster management can reduce harm when health protection is built into preparedness, response and recovery; it can fail when health is treated as a secondary concern after infrastructure damage.

Pakistan contributes little to global emissions but is acutely exposed. The 2022 Post-Disaster Needs Assessment (PDNA) described the floods as evidence of the country's high vulnerability to climate change (Government of Pakistan, 2022), and UNICEF's Children's Climate Risk Index ranks Pakistan 14th of 163 countries, in the "extremely high risk" category (UNICEF Canada, 2022).

2. Methodology and Conceptual Framework

This is a structured narrative review of secondary evidence. It follows the transparency principles of the PRISMA 2020 statement (Page et al., 2021) but is not a systematic review: no protocol was registered, no bibliographic databases were searched, one reviewer screened sources, and no formal risk-of-bias tool was applied. No PRISMA flow diagram is presented and PRISMA compliance is not claimed. Table 1 reports what was done.

Table 1. Review Methods as Performed

Element	Description
Review type	Structured narrative review of secondary evidence. Not a systematic review.

Reporting guidance	PRISMA 2020 (Page et al., 2021), applied as a transparency guide only; full PRISMA compliance is not claimed.
Search date	11 October 2026.
Search platform	General web search engine. No bibliographic database (e.g., PubMed, Scopus, Web of Science) was searched.
Searches run (n = 7)	2022 flood damage and needs; WHO flood-related disease; Lancet Countdown 2025; UNICEF child impact; Karachi 2015 heatwave; authorship check (Akthar & Reid, 2024); National Adaptation Plan 2023.
Eligibility: included	Intergovernmental, government, or peer-reviewed sources on climate-related hazards, health outcomes, or disaster-management response; global or Pakistan scope.
Eligibility: excluded	Unattributed statistics, social-media content, and items lacking an identifiable issuer or date.
Sources retained	15 (2 journal articles; 1 IPCC assessment; 9 WHO, UN, UNICEF, World Bank or Government of Pakistan publications; 3 policy commentary or news items).
Not performed	Registered protocol; dual screening; risk-of-bias appraisal; PRISMA flow diagram; review of primary NDMA situation reports (NDMA figures are cited as reproduced by WHO and the PDNA).

3. Climate Change: A Global Hazard Profile

Vulnerability reflects poverty, age, livelihood and the state of local services, not exposure alone. Children: about 16 million children were affected by the 2022 floods and more than three million needed humanitarian help; 40% already had stunting beforehand, and 30% of water systems in affected areas were damaged (UNICEF Pakistan, 2022). Low-income and less-educated households: in Karachi, residents earning under PKR 20,000 a month and those with less than fifth-grade education faced significantly higher heat-death risk (Ghumman & Horney, 2016). Women: the PDNA reported notable livelihood losses among women, particularly in agriculture and livestock (World Bank, 2022). Displaced people: around 8 million were displaced (Akthar & Reid, 2024), and WHO identified

camps with damaged sanitation as outbreak hot spots (WHO EMRO, 2022). Sindh bore about 70% of damages and losses (World Bank, 2022).

Extreme Heat and Air Quality

Extreme heat can cause dehydration, heat exhaustion and heatstroke, and can worsen underlying cardiovascular, renal and respiratory conditions. Outdoor workers, older adults, infants, pregnant people and people without reliable cooling or water are particularly exposed. Heat can also affect sleep, mental well-being and the ability to work or attend school. Climate change interacts with urban heat-island effects and air pollution; the resulting burden depends on housing, occupational protections, health status and access to warnings and care. A public-health response therefore requires heat-health action plans, accessible cooling and hydration, worker protections and clear clinical guidance not warnings alone.

Floods, Water, Sanitation and Infectious Disease

Flooding produces immediate injury and drowning risk and can damage clinics, roads, electricity and supply chains. Contaminated water and interrupted sanitation raise the risk of diarrhoeal illness and other water-related infections. Standing water, rainfall and temperature may alter mosquito breeding conditions, but disease transmission also depends on housing, mobility, vector control, immunity and surveillance; climate should not be treated as the sole cause of an outbreak. In Pakistan, research on Karachi describes how precipitation extremes and heat have been associated with health concerns including dengue, malaria and gastroenteritis, while emphasising the role of existing urban vulnerabilities (Impact of Climate Change on Health in Karachi, Pakistan, 2021).

Drought, Nutrition and Psychosocial Consequences

Drought, crop losses, livestock stress and disrupted transport can reduce food availability and household income, increasing the risk of undernutrition and food insecurity. After a disaster, children may lose access to school meals and routine health services; pregnant people may face additional nutritional and care barriers. Displacement, bereavement, uncertainty and loss of livelihoods can also contribute to psychological distress. These indirect effects may persist after floodwater recedes or an acute emergency is declared

over. The IPCC identifies food insecurity and malnutrition as important climate-related health pathways, with impacts shaped by socioeconomic conditions (IPCC, 2022).

Exposure and Historical Context: Pakistan

Pakistan's geography creates multiple, overlapping hazards: extreme heat and urban heat stress, riverine and flash floods, drought, water scarcity, glacial lake outburst floods in northern areas, and coastal risks. Climate hazards act on a large population with uneven access to safe housing, water, sanitation and healthcare. The 2022 monsoon floods provide a stark example. UNDP's summary of the Post-Disaster Needs Assessment reports that the disaster affected approximately 33 million people; estimated damages exceeded US$14.9 billion, economic losses reached about US$15.2 billion, and resilient rehabilitation and reconstruction needs were at least US$16.3 billion (Government of Pakistan et al., 2022). The Provincial Disaster Management Authority (PDMA) in Sindh alone distributed over 800,000 tents and more than 3.7 million mosquito nets (WHO Pakistan, 2022), and WHO worked with the health ministry to expand surveillance for diarrhoeal disease and cholera (WHO EMRO, 2022). These are disaster-impact and recovery figures, not estimates of health outcomes alone, but they show the scale of disruption to the conditions that sustain health.

Health-System and Community Consequences

Floods can contaminate wells and water networks, damage latrines, crowd displaced households into temporary shelters and make clinics unreachable. These conditions can increase exposure to diarrhoeal disease and vector-borne infections, worsen maternal and child nutrition, interrupt vaccination and chronic-disease treatment, and increase protection and psychosocial needs. UNICEF's reporting on the 2022 floods describes severe effects on children, including damaged homes, schools, health infrastructure, food systems and safe-water access. Its 2025 flood updates again documented deaths, injuries and multisectoral needs, demonstrating that preparedness must account for recurrent events rather than treating each disaster as exceptional (UNICEF, 2025).

Vulnerability and Unequal Risk

Hazard exposure alone does not explain who becomes ill. Poverty can constrain evacuation, safe shelter, transport to clinics and the ability to replace lost medicines or income. Women and girls may face privacy, menstrual-health, maternal-care and safety

barriers in temporary accommodation. Children are physiologically vulnerable to heat and dependent on adults for protection; older people and people with disabilities may require accessible warnings and evacuation assistance. Outdoor workers face occupational heat exposure, while people in informal urban settlements may lack drainage, cooling and reliable water. UNDP's climate and development work in Pakistan highlights the disproportionate burden borne by poorer and marginalized groups, including women and children (UNDP Pakistan, n.d.). These are not inherent weaknesses of communities; they reflect unequal access to resources and decision-making.

4. Public Health Risks and Vulnerability Assessment

Extreme Heat

Globally, heat-related deaths are rising (WHO, 2025). Pakistan's deadliest recorded heatwave struck Karachi in June 2015, when about 65,000 heatstroke patients were treated and an official reported 1,233 deaths; chronic power outages forced many residents to sleep outdoors (Christian Science Monitor, 2015). A death-certificate review found residents were roughly 17 times as likely to die of a heat-related cause as in June 2014, and the authors judged deaths to be almost certainly under-counted (Ghumman & Horney, 2016).

Vector- and Water-Borne Disease

In August 2022 WHO warned that floods would aggravate malaria, dengue and acute watery diarrhoea, especially in camps with damaged water and sanitation (World Health Organization Eastern Mediterranean Regional Office [WHO EMRO], 2022). Over 540,000 malaria cases were reported between July and early October 2022, with an outbreak across 32 districts (UN News, 2022), and malaria numbers nearly doubled in some areas (WHO, 2022). By December, malaria, cholera, diarrhoeal disease and dengue were declining in most districts, although 70 suspected diphtheria cases were reported in November (WHO Pakistan, 2022).

Nutrition and Service Disruption

Severe acute malnutrition with complications was rising in affected provinces, and fewer than half of those needing care could reach a health facility in mid-September 2022 (WHO, 2022). About 2,000 facilities, roughly 10% nationally, were damaged or destroyed, and 13,074 km of roads and 392 bridges were washed away (WHO, 2022).

Mental Health

Global assessment links climate change to mental-health harm (IPCC, 2022), but no Pakistan-specific evidence on this was retrieved; it is treated as an evidence gap.

Table 2

Evidence Snapshot: Selected Pakistan Indicators

Indicator	Reported value	Source
People affected, 2022 floods	33 million	Government of Pakistan (2022)
Deaths and injuries (NDMA, as of 18 Nov 2022)	1,739 deaths; 12,867 injured	WHO Pakistan (2022)
Damages and economic losses	USD 14.9 billion and about USD 15.2 billion; Sindh about 70%	World Bank (2022)
Health facilities damaged or destroyed	About 2,000 (10% of national total)	WHO (2022)
Malaria cases, July to early Oct 2022	Over 540,000; outbreak in 32 districts	UN News (2022)
Children affected by the floods	About 16 million	UNICEF Pakistan (2022)
Water systems damaged in affected areas	30%	UNICEF Pakistan (2022)
Reported heatwave deaths, Karachi, June 2015	1,233	Christian Science Monitor (2015)
Heat-related death risk, June 2015 vs June 2014	RR = 17.68 (95% CI 13.87 to 22.53)	Ghumman & Horney (2016)

Note. Values are as reported by each source at the time of publication and may have been revised.

5. Community Capacities

Local networks, community health workers, women's groups, teachers, volunteers and trusted religious or civic organisations can help translate warnings into action, identify people needing assistance and share locally credible information. Indigenous and local

knowledge can complement technical forecasting by identifying recurrent flood routes, water sources, seasonal livelihood patterns and safe evacuation locations. However, community participation should not substitute for government responsibility or transfer the cost of preparedness to households that lack resources. Community-led plans need budgets, accessible communication, safe shelters, transport and links to health facilities.

6. Scientific, Data and Institutional Gaps

Climate and health data are often collected by different agencies, at different geographic scales and with different reporting periods. Weather data may not be linked routinely to emergency-department visits, disease surveillance, water quality, nutrition screening or service outages. This makes it difficult to evaluate which warnings prevented illness or where resources should be pre-positioned. Digital tools, geographic information systems and machine-learning models may improve forecasting, but their usefulness depends on reliable data, transparent validation, local interpretability and human oversight. Models can reproduce gaps when rural, informal-settlement or marginalised populations are underrepresented. NDMA's e-Library provides a relevant institutional starting point through disaster-management plans, contingency plans, risk assessments, guidelines and research compendia; these materials should be connected more directly to health-sector preparedness and local implementation (NDMA, n.d.).

7. Disaster-Management Implications

Preparedness, response and recovery should be treated as a continuous cycle. Before an event, authorities can map health facilities and vulnerable populations, define heat and flood triggers, pre-position essential medicines and water-treatment supplies, and agree on referral and communication protocols. During an event, rapid surveillance should track injuries, diarrhoeal disease, vector risks, nutrition, maternal and neonatal needs and interruptions to routine care. Recovery should restore resilient clinics, water and sanitation systems, mental-health support and livelihoods rather than simply replacing damaged assets in the same risk locations. UNDP's Pakistan flood-recovery and climate-resilience programmes emphasise multi-sectoral recovery and integration of resilience into development planning (UNDP Pakistan, n.d.).

8. Evidence Gaps

(a) Counts moved rapidly; for example, damaged health facilities were reported as 888 in late August (WHO EMRO, 2022) and about 2,000 by October (WHO, 2022), so single figures should be treated cautiously.

(b) Pakistan-specific evidence was not found for mental health, outdoor workers' heat exposure, or air quality.

(c) Most evidence is descriptive or institutional grey literature; there are few studies that attribute specific outcomes to climate change.

(d) Evidence centres on two events, 2015 and 2022, which may under-represent slower risks such as drought and food insecurity.

9. Institutional Gaps

The sources suggest weak formal links between the health ministry, NDMA, provincial authorities and climate planners. How far the National Adaptation Plan has been operationalised in health could not be established.

Limitations

This is a single-reviewer web-based review, not a database-driven systematic review. Primary NDMA situation reports were not consulted, so NDMA figures come through secondary reproductions.

10. Disaster Management Perspectives and Mitigation Strategies

Retrieved evidence on community-level resilience is thin. Frontline community health infrastructure was heavily affected: plans were drawn up to rebuild all 7,878 health houses used by Lady Health Workers at a reported cost of PKR 9.879 billion (WHO Pakistan, 2022). The PDNA recovery principles emphasise putting the poor first, transparency, inclusion and climate resilience (World Bank, 2022). Community early-warning systems and volunteer networks are plausible entry points but were not evidenced in the sources reviewed; they appear below as recommendations, not findings.

Three messages emerge. First, health risks cascade: floods and heat act through damaged infrastructure, unsafe water, displacement and strained services, so health outcomes depend on how well other sectors are protected. Second, vulnerability is socially produced: the same hazard posed very different risks to low-income, displaced and undernourished people, which argues for targeting by vulnerability, not geography alone. Third, much of the response was reactive: surveillance and supply drives scaled

up after the floods began (WHO EMRO, 2022), whereas heat deaths can be reduced only if warning and cooling measures exist beforehand.

11. Risk Communication and Early Warnings

Early warning protects health only when a forecast becomes a clear message, the message reaches the people at risk, and those people have the means to act on it. Both of your papers show Pakistan falling short at different points in that chain. In the Karachi heatwave of June 2015, about 65,000 heatstroke patients were treated and 1,233 deaths were reported. Chronic power outages forced many residents to sleep outdoors (Christian Science Monitor, 2015). Residents were roughly 17 times as likely to die of a heat-related cause as in June 2014, and deaths were probably under-counted (Ghumman & Horney, 2016). A warning is of little use if people cannot cool down or keep their power on. In 2022, WHO warned in August that floods would aggravate malaria, dengue and diarrhoeal disease (WHO EMRO, 2022). Even so, fewer than half of those needing care could reach a health facility by mid-September (WHO, 2022). Surveillance and supply drives scaled up after the floods began, which shows that the response was largely reactive.

An effective warning system links meteorological alerts to health-sector action. Heat alerts from the Pakistan Meteorological Department should be tied to defined heat and flood triggers, power-outage contingency plans and public cooling spaces, with priority for low-income neighbourhoods. At the first flood warning, authorities should activate surveillance for malaria, dengue and diarrhoeal disease and release pre-positioned nets, water-treatment supplies and diagnostic tests (WHO, 2022; UN News, 2022). Warnings alone are not enough. They need to come with accessible cooling and hydration, worker protections and clear clinical guidance.

How a message is delivered matters as much as what it says. Messages should be sent in multiple languages and accessible formats, through local organisations and health workers. Children, pregnant people, older adults and people with disabilities may need accessible warnings and evacuation assistance, and women may face privacy and safety barriers in temporary shelters. Trusted local messengers help here, such as community health workers, women’s groups, teachers and religious or civic organisations. These channels are themselves vulnerable. Plans were drawn up to rebuild all 7,878 health

houses used by Lady Health Workers after the 2022 floods (WHO Pakistan, 2022). Community participation should also not replace government responsibility, and community-led plans need budgets, transport and links to health facilities.

Gaps remain in data and coordination. Weather and health data are collected by different agencies and rarely linked to hospital visits, disease surveillance or service outages, so it is hard to tell which warnings actually prevented illness. The 2023 National Adaptation Plan calls for stronger early warning, but how far it has been put into practice in the health sector could not be established. Sri Lanka's Climate Change and Health Unit offers a coordination model (Akthar & Reid, 2024). Any AI-supported forecasting tool should be independently validated and should not replace local expertise. Finally, community-level early-warning evidence was thin in the sources reviewed, so these measures are recommendations rather than established findings. Repeated flooding, including in 2025 (UNICEF, 2025), makes preparedness a recurring need rather than a response to exceptional events.

12. Recommendations

Heat-health action plans for high-risk cities. Link Pakistan Meteorological Department heat alerts to health-sector action, power-outage contingency plans and public cooling spaces, prioritising low-income neighbourhoods (Christian Science Monitor, 2015; Ghumman & Horney, 2016).

Pre-positioned flood-health packages. Stock mosquito nets, water-treatment supplies and rapid diagnostic tests in high-risk districts before the monsoon, and activate surveillance for malaria, dengue and diarrhoeal disease at the first flood warning (WHO, 2022; UN News, 2022).

Climate-resilient health facilities and supply chains. Map the flood exposure of clinics and Lady Health Worker health houses, and plan alternative routes and cold chains for essential services (WHO, 2022; WHO Pakistan, 2022).

A standing climate-and-health coordination mechanism. Establish a unit or focal group connecting NDMA, PDMAs, the health ministry and the climate ministry, informed by Sri Lanka's example, and align the National Adaptation Plan with disaster-risk-reduction strategy (Akthar & Reid, 2024; UNEP LEAP, n.d.).

Targeting children, women and displaced people. Pre-position nutrition screening and treatment capacity, protect maternal and immunisation services during emergencies, and design camps with safe water and sanitation (UNICEF Pakistan, 2022; WHO EMRO, 2022; World Bank, 2022).

Data and research. Disaggregate health-surveillance data by age, sex and income; mine NDMA's primary situation reports; and commission a database-driven systematic review plus studies on mental health and outdoor-worker heat exposure.

Inclusive risk communication and evacuation planning. Communicate through multiple languages and accessible formats; involve local organisations and health workers; and plan specifically for children, pregnant people, older adults and people with disabilities.

Integrate nutrition and psychosocial support into disaster response. Maintain maternal, infant and young-child feeding support, screening for acute malnutrition, continuity of routine care and practical psychosocial support during displacement and recovery.

Make risk assessments actionable. Use NDMA hazard and vulnerability assessments alongside district health profiles to prioritise investments. Monitor whether actions reduce service interruptions and prevent illness, not only whether plans were produced.

13. Conclusion

Climate change is a public-health risk multiplier: it intensifies hazards and disrupts the water, food, housing, livelihood and health systems that protect people from illness. Global evidence shows multiple connected pathways, while Pakistan's floods and recurring heat and water stresses demonstrate how exposure combines with inequality and service fragility to produce avoidable harm. Disaster management must therefore place health protection at the centre of risk assessment, early warning, emergency response and recovery. The most useful strategy is not a single technology or emergency intervention, but a coordinated system: reliable climate and health data, resilient primary care, safe water and sanitation, inclusive community participation, and sustained investment in the people most exposed. A structured review such as this can help

organise the evidence, but stronger future assessments require reproducible searches, systematic local surveillance and transparent evaluation of what works.

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PARTICIPANT RESEARCH PAPER

Flood and Drought Risk in Khairpur District: Implications for Water Security, Agriculture, and Climate Resilience

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Abstract

This assessment examines flood and drought risk in Khairpur District, Sindh, with particular attention to water security, agriculture, rural livelihoods, and community resilience. Khairpur's reported hot, semi-arid climate and low long-term average rainfall create a relevant climatic context for drought assessment, while the district's connection to the Indus River and monsoon system creates exposure to riverine and rainfall-related flooding. These hazards differ in onset and mechanism but can affect overlapping households, agricultural assets, livestock, infrastructure, and local services.

The District Disaster Management Plan (DDMP) identifies drought risk across union councils and reports a range of meteorological and agricultural drought hazard/risk classes. The PDMA Sindh provincial disaster profile, however, lists drought in Khairpur as infrequent and low severity. These classifications should be treated as different assessment outputs rather than directly interchangeable results. For flood impacts, PDMA's 2022 Sindh report records 356,582 acres of damaged crops in Khairpur (reported as 42.61%), 54,820 partially damaged houses, and 224,346 fully damaged houses. These flood figures are not measures of drought impact.

A central finding is that climate-related drought exposure cannot responsibly be quantified by reusing heatwave exposure estimates from the earlier assignment. A robust drought exposure estimate would require data on rainfall anomalies, soil moisture, crop calendars, irrigation reliability, groundwater, water supply, and affected households. The report therefore distinguishes verified district-level statistics from risk classifications, regional evidence, and data gaps. It recommends integrated flood and drought monitoring, improved water management, climate-resilient agriculture, community preparedness, and stronger institutional coordination.

Keywords: Khairpur District; flood risk; drought; water security; agricultural resilience; disaster risk reduction

1. Introduction

Climate hazards become disasters when physical events interact with exposed people, livelihoods, infrastructure, ecosystems, and limited coping capacity. Khairpur District in Sindh is exposed to riverine and monsoon flooding and is also identified in official district planning material as being at risk from meteorological and agricultural drought. These hazards should be assessed together because the same rural households may depend on agriculture, livestock, irrigation, and local water systems, while the timing and pathways of flood and drought impacts are different.

The original district profile describes Khairpur as hot and semi-arid, with a reported average annual rainfall

DISTRICT KHAIRPUR
AT A GLANCE

GEOGRAPHY

District area in Sq	16,076
Km Coordinates	26° 07' 57" N to 27° 44' 09" N 68° 10' 20" E to 70° 10' 58" E
Surrounding districts	Sukkur and Shikarpur in North Larkana in North West Sanghar in South India in East Naushahro Feroze in West Shaheed Benazirabad in West
Climate	Hot & Semi-Arid
Coldest and hottest	January May

Seasonal temperature	Max. Mean Temp. (°C)	Min. Mean Temp. (°C)
Spring (March and April)	37.88	20.91
Dry Summer (May and June)	44.66	28.84
Wet Summer (July to September)	41.39	28.41
Autumn (October and November)	35.20	19.50
Winter (December to February)	26.63	11.01

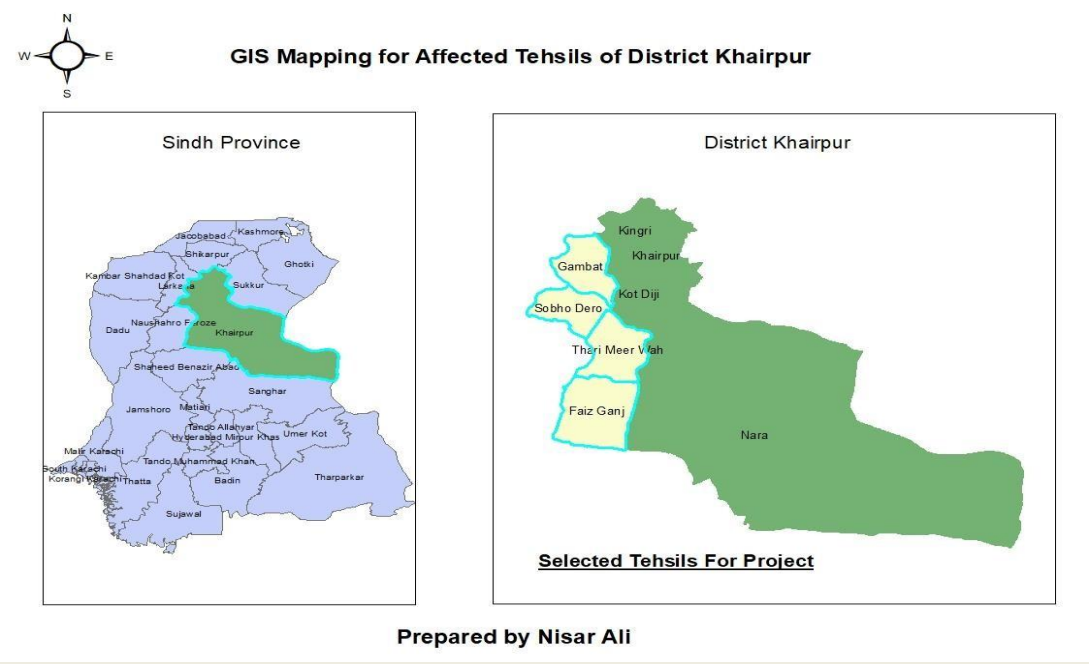
Average annual	127.65 mm/yr
Physiographic	Khuth Bakri Waro Lake



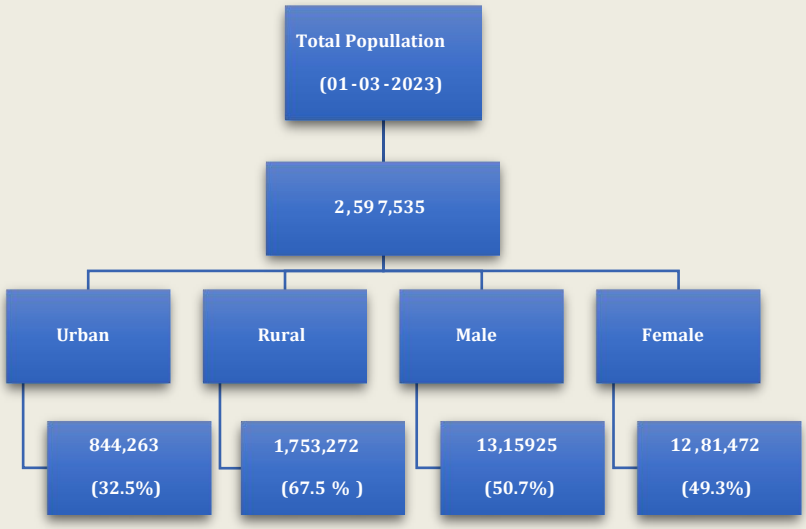
of 127.65 mm and a district area of 16,076 km². These figures provide context, but average rainfall alone cannot establish whether a drought occurred in a given year or which communities experienced losses. Drought assessment requires comparison of observed rainfall and water availability against a suitable baseline, and attention to the timing of deficits relative to crop and household water needs (District Disaster Management Authority Khairpur [DDMA Khairpur], 2022).

The 2022 floods illustrate the scale of flood-related impacts on homes and agriculture. At the same time, drought-related risk is not adequately represented by flood-loss records. The purpose of this assessment is to compare the two hazards, identify the sectors and conditions that shape exposure and vulnerability, examine the implications for water security and agriculture, and outline practical measures that can strengthen community resilience.

The assessment uses a qualitative, evidence-based district risk approach. It draws on the Khairpur DDMP, PDMA Sindh records, the Pakistan Bureau of Statistics' 2024 Agricultural Census for Sindh, and relevant disaster-management information. It does not claim to have completed new GIS modelling or calculated a district drought index. Where a precise drought-impact estimate is not supported by available evidence, that limitation is stated.



Demography



2. Regional Context and Hazard Profile

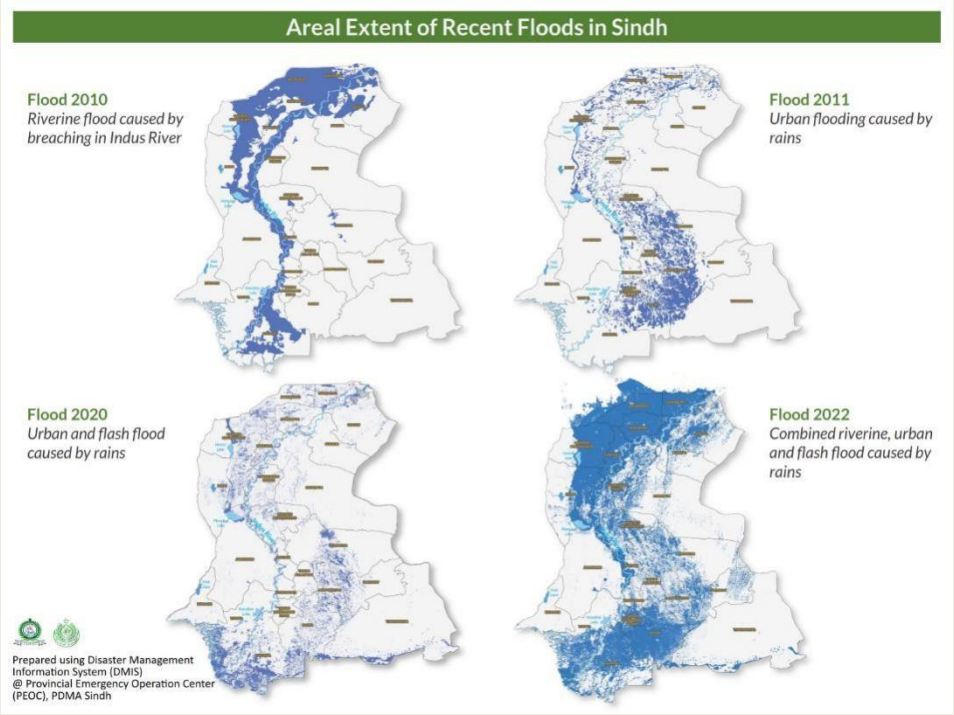
2.1 District context

The original district profile reports an area of 16,076 km², a hot and semi-arid climate, and average annual rainfall of 127.65 mm. The profile also reports a population of 2,597,535 as of 1 March 2023; this should be cited to the original demographic source if retained in any final externally submitted version. Agriculture and livestock are important to rural livelihoods, and the district's water and agricultural systems are shaped by canal irrigation, local water access, and seasonal climate conditions.

The Pakistan Bureau of Statistics' Agricultural Census 2024 Sindh report lists 187,955 farms in Khairpur, a farm area of 645,284 acres, cultivated area of 597,253 acres, and cropped area of 1,082,110 acres. These measures describe different agricultural concepts: farm area and cultivated area are land measures, while cropped area can count land planted across seasons and therefore may exceed cultivated area. They should not be treated as estimates of drought-damaged land (Pakistan Bureau of Statistics [PBS], 2026).

2.2 Flood hazard

Khairpur is listed by PDMA Sindh as having high riverine-flood severity, with historical flood years including 2010, 2011, 2012, 2014, and 2022. Monsoon rainfall can contribute to flooding and drainage pressure, while proximity to river and canal systems influences the geography of exposure. Actual flood risk varies by location, elevation, drainage, embankments, settlement patterns, and the condition of infrastructure (Provincial Disaster Management Authority Sindh [PDMA Sindh], n.d.-a).



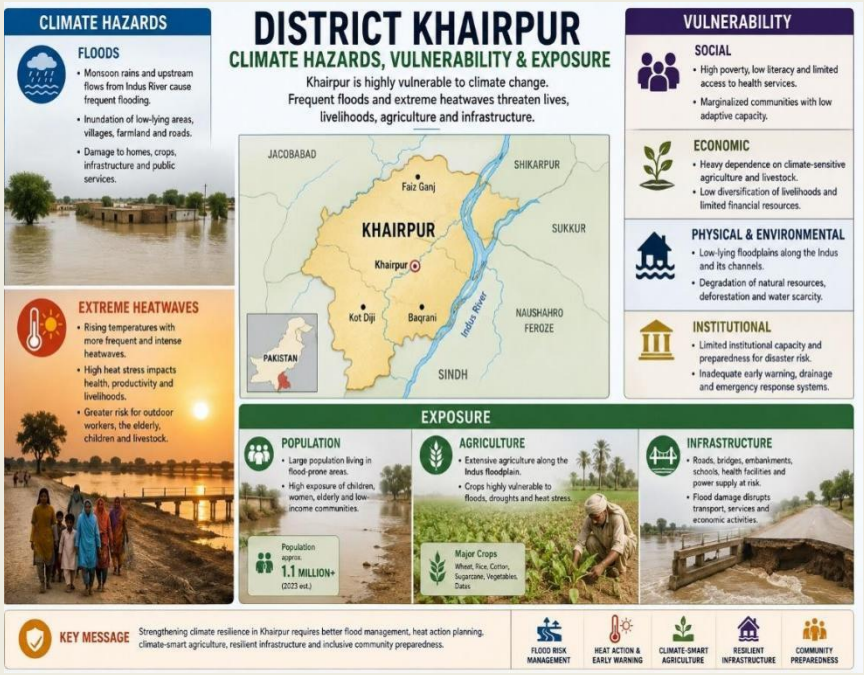
According to PDMA Sindh's report on the 2022 floods lists 356,582 acres of damaged crops in Khairpur, reported as 42.61%, 54,820 partially damaged houses, and 224,346 fully damaged houses. These are the figures reported in the PDMA district table and should be cited to that report. Because unusually large housing figures may be interpreted differently across datasets, the exact table definitions and reporting period should be checked against the source before submission. The numbers must not be silently merged with estimates from other reports (PDMA Sindh, 2023).

2.3 Drought hazard

Drought is a prolonged deficit in water availability relative to normal conditions and needs. Meteorological drought refers to below-normal precipitation; agricultural drought occurs when soil moisture is insufficient for crops and vegetation; hydrological drought refers to reduced water availability in rivers, reservoirs, or groundwater. These forms can overlap, but they do not necessarily begin at the same time or affect every location equally.

The Khairpur DDMP's MHVRA-informed assessment identifies all union councils as being at risk of drought. It reports meteorological drought hazard as "Extreme," meteorological drought risk as "Medium to Extreme," agricultural drought hazard as "Mild to Extreme," and agricultural drought risk as "Low to Extreme." The plan's drought section also identifies a hot, semi-arid setting, low average rainfall, and the importance of monitoring rainfall, temperature, potential evapotranspiration, soil moisture, streamflow, groundwater, lakes, and reservoirs (DDMA Khairpur, 2022).

The provincial disaster profile provides a different classification: it lists drought in Khairpur as "Infrequent" with "Low" severity and notes historical drought years 1999–2002. PDMA's separate drought information page also lists Khairpur among districts exposed to a very severe drought hazard class. These outputs are not necessarily measuring the same concept, period, or spatial scale. The contrast is important: the district plan provides a range of MHVRA risk classes for specific drought types, while the provincial profile summarizes frequency and severity. The sources should be reported transparently, not collapsed into a single score (PDMA Sindh, n.d.-a, n.d.-b).



3. Conceptual Framework of Risk Assessment

The assignment retains the simplified conceptual relationship: Risk = Hazard × Exposure × Vulnerability. Hazard refers to a potentially damaging event or process; exposure describes the people, assets, livelihoods, and services located where the hazard may occur; vulnerability describes the conditions that make exposed elements more

susceptible to harm. This expression is a conceptual aid, not a complete quantitative model unless its variables and rating method are operationalized.

Flood and drought risks should be assessed separately before being compared. Flood risk is shaped by inundation, rainfall, river flows, drainage, embankments, settlement location, and evacuation or recovery capacity. Drought risk is shaped by rainfall deficits, soil moisture, crop water demand, irrigation reliability, groundwater availability, and household capacity to manage prolonged water shortages. In both cases, poverty, dependence on climate-sensitive livelihoods, weak infrastructure, and limited access to timely information can increase vulnerability.

4. Drought Exposure Assessment in Khairpur District

The former heatwave exposure estimates in the original assignment—approximately 2.5 million people and 3.7 million acres—cannot be relabelled as drought exposure. Heat exposure and drought exposure are different concepts, and a defensible drought estimate requires drought-specific data. The available district plan identifies drought risk across all union councils and provides hazard/risk classifications, but the reviewed evidence does not establish a single verified number of residents or acres actually affected by drought in a specified year.

Sector	Drought exposure assessment	Main exposure drivers	Evidence and limitations
Population households	Potentially significant in communities dependent on agriculture, livestock, and local water systems; no verified district-wide affected population total identified.	Household water access, livelihood dependence, location, income and coping resources.	DDMP identifies all UCs at risk; this is a risk classification, not a count of affected people.
Agriculture	Large agricultural sector potentially sensitive to water deficits; 2024 census reports 1,082,110	Rainfall timing, soil moisture, crop water requirements,	Cropped area is not drought affected acreage; no verified district wide drought-

	acres of cropped area.	canal reliability and groundwater access.	loss estimate used here.
Livestock	Exposure may arise where water and fodder become less available during dry periods.	Drinking-water access, feed/fodder supply, pasture condition and household resources.	No verified Khairpur-specific drought livestock-loss count established from the sources reviewed.
Water resources	Drought risk concerns rainfall, surface water, groundwater, storage and the reliability of supply.	Precipitation deficit, demand, irrigation scheduling, groundwater extraction and water management.	The DDMP recommends monitoring these variables; no new district hydrological analysis was performed.
Infrastructure and services	Water supply and irrigation systems may be stressed by prolonged deficits.	Storage, conveyance losses, maintenance, electricity, monitoring and institutional coordination.	Exposure is a qualitative assessment unless infrastructure inventories and service data are analyzed.

The table therefore presents a sector-based exposure assessment rather than a fabricated numerical estimate. A future quantitative study could overlay georeferenced drought indicators with cultivated land, crop calendars, canal command areas, settlement locations, groundwater data, and household survey results. Until those data are analyzed,

the appropriate conclusion is that drought risk is recognized in official planning, while the number of people and acreage actually affected during a specific drought remains unquantified in this assessment.

5. Water Security and Irrigation Challenges

Water security concerns reliable and equitable access to adequate water of acceptable quality for household needs, agriculture, livestock, and ecosystems. In Khairpur, drought-related rainfall deficits may combine with the timing and reliability of canal deliveries, local storage, groundwater availability, and rising water demand. A climatic drought can therefore intensify an existing water-access problem, but not every water shortage is caused by drought.

The DDMP identifies agriculture as depending primarily on canal irrigation, supplemented by river water and tube wells, and recommends improving irrigation efficiency, monitoring groundwater and other water indicators, and regulating sustainable groundwater extraction. These recommendations point to the need for water management that addresses both supply and demand. Efficient irrigation, suitable scheduling, maintenance of distribution infrastructure, soil-moisture conservation, and careful groundwater monitoring can help reduce water stress. Measures must be designed locally and should not assume that all households or farmers have equal access to irrigation or pumping equipment (DDMA Khairpur, 2022).

Water scarcity also has a governance dimension. Unequal distribution, infrastructure constraints, water quality, storage limitations, and competing domestic and agricultural needs can influence who experiences shortages and how severe those shortages become. Claims about tail-end disparities or groundwater depletion should be supported by location-specific irrigation or groundwater evidence before being quantified.

6. Implications for Agriculture, Livestock, and Rural Livelihoods

6.1 Flood impacts

Flooding can damage standing crops, inundate fields, disrupt planting and harvesting, damage roads and irrigation infrastructure, and cause livestock losses. Floodwater and prolonged waterlogging can also delay agricultural recovery and create additional pressure on household income. The 2022 PDMA cropdamage figure for Khairpur

demonstrates the significance of flood impacts, although it should not be used as a proxy for drought losses.

6.2 Drought impacts

Drought can reduce soil moisture and crop water availability, particularly when rainfall deficits coincide with sensitive crop-growth stages or unreliable irrigation. Potential consequences include lower yields, higher irrigation costs, reduced fodder availability, stress on livestock, and pressure on farm income. The severity of these impacts depends on crop type, planting calendar, soil conditions, access to canal water or groundwater, and the duration of the deficit. These are plausible pathways of impact; this assessment does not claim a measured district-wide percentage reduction in wheat, cotton, or sugarcane yields.

6.3 Shared livelihood consequences

Floods and droughts can both disrupt agricultural income and household food security, but through different mechanisms. Floods may cause rapid physical damage and displacement; drought can create a slower-onset accumulation of crop stress, higher water costs, reduced livestock condition, and prolonged income pressure. Households with limited savings, narrow livelihood options, or weak access to assistance may have less capacity to absorb either shock. However, impacts are not uniform across Khairpur: they vary with location, water access, assets, crop choices, and institutional support.

7. Vulnerability and Community Resilience

Dimension	Flood vulnerability	Drought vulnerability	Resilience priorities
Social	Settlements in flood-prone areas; limited warning access or evacuation resources.	Household water insecurity and dependence on climate sensitive livelihoods.	Accessible warnings, preparedness, inclusive community planning and targeted support.
Economic	Crop, livestock, home and asset	Reduced production,	Diversified livelihoods, savings where feasible,

	losses can interrupt income.	increased irrigation costs and fodder pressure may reduce income.	social protection and recovery support.
Environmental	Riverine flooding, intense rainfall, inundation and drainage constraints.	Rainfall deficit, soil-moisture stress and reduced water availability.	Risk monitoring, soil and water conservation, ecosystem-sensitive management.
Infrastructure	Embankments, drainage, roads, housing and irrigation may be exposed.	Canals, groundwater access, drinking-water supply and storage may be stressed.	Maintain infrastructure, improve storage and service reliability, monitor water systems.
Institutional	Forecasting, evacuation, coordination and recovery capacity matter.	Drought monitoring, water allocation, agricultural extension and relief matter.	Coordinate district administration, PDMA, irrigation, agriculture and local institutions.

7.1 Community resilience and adaptive capacity

Community resilience is the capacity of people and institutions to anticipate hazards, reduce harm, maintain essential functions, and recover. It is shaped by more than awareness: water access, household assets, local knowledge, livelihood diversity, functioning infrastructure, social networks, public services, and institutional response all matter. Resilience should therefore be assessed across communities and social groups rather than assumed to be uniform throughout the district.

For flood risk, resilience priorities include credible early warnings, evacuation planning, protection of essential assets, safer infrastructure, and recovery support. For drought,

priorities include seasonal rainfall and drought monitoring, water conservation, efficient irrigation, locally appropriate crop choices, soil-moisture management, fodder planning, and support to households whose income depends heavily on farming or livestock. Both hazards require clear communication, inclusive planning, and coordination between district authorities and communities.

8. Comparative Flood–Drought Risk Matrix

Hazard	Main characteristics	Exposed sectors	Evidence available	Priority measures
Riverine/monsoon flood	Rapid or seasonal inundation; rainfall, river flows and drainage influence impacts.	Settlements, crops, livestock, roads, homes and irrigation infrastructure.	PDMA reports 356,582 acres of damaged crops in Khairpur in 2022 (reported as 42.61%) and house damage figures.	Forecasting, drainage and embankment maintenance, preparedness, evacuation, resilient infrastructure and recovery support.
Meteorological drought	Below-normal precipitation over a period; impact depends on duration and season.	Households, rain- fed areas, livestock, water systems and agriculture.	DDMP MHVRA classification: hazard Extreme; risk Medium to Extreme. Provincial profile separately reports infrequent/low.	Rainfall monitoring, drought indicators, preparedness, water demand planning and clear risk communication.

Agricultural drought	Insufficient soil moisture for crop and vegetation needs.	Crops, farmers, farm labourers, livestock and food supply.	DDMP MHVRA classification: hazard Mild to Extreme; risk Low to Extreme.	Soil-moisture conservation, crop diversification, suitable drought-tolerant varieties, efficient irrigation and agricultural extension.

The matrix is qualitative and does not assign a new numerical risk score. Risk classes reported by official sources are retained as reported and should not be compared as if they were produced by one identical method.

9. Climate Data, Assessment Methods, and Evidence Gaps

The sources reviewed provide useful risk classifications and documented flood impacts, but they do not provide a complete, harmonized district-level drought impact dataset. A stronger quantitative assessment would require consistent time series and spatial data. Relevant sources and their appropriate uses include:

Source/data	Potential use	Geographic/temporal caution
Khairpur District Disaster Management Plan / MHVRA	District hazard and risk classifications, elements at risk, monitoring priorities.	Check report date, assessment method, map scale and page for each statistic.
PDMA Sindh provincial disaster profile and drought page	Provincial hazard profile and historical classification.	These summary categories differ from the DDMP MHVRA classifications; do not combine without explanation.

PDMA Sindh Flood 202: report and flood maps	Documented flood impacts and flood extent products.	Use the specific reporting date, definitions, and district table; flood data do not measure drought losses.
Pakistan Bureau of Statistics Agricultural Census 2024 (Sindh report)	Farm counts, farm area, cultivated area and cropped area.	The published census is a structural/agricultural baseline, not a drought damage assessment.
PMD rainfall and temperature records; satellite rainfall products such as CHIRPS; drought indices such as SPEI	Potential analysis of rainfall anomalies, dry spells, and meteorological drought.	No new time-series extraction, droughtindex calculation or spatial analysis was completed for this report.
Sindh irrigation, groundwater and agriculture records	Irrigation delivery, groundwater, crop production and water availability.	Confirm whether records are districtspecific and whether the period aligns with the hazard assessment.

The main evidence gaps are: (1) a consistent district-level time series of rainfall and drought indicators;
(2) geospatial linkage between drought intensity, crop type, cultivated area and irrigation command areas; (3) reliable district-specific records of drought-affected households, livestock, and crop losses; (4) local evidence on drinking-water access and groundwater conditions; and (5) household-level evidence about coping strategies and recovery capacity. These gaps limit numerical claims about drought exposure and impact, but they also identify clear priorities for future research.

10. Integrated Flood and Drought Risk-Reduction Strategy

10.1 Risk information and early warning

Strengthen flood forecasting and drought monitoring through accessible rainfall, river, soil-moisture, and water-availability information. Communicate warnings in locally understood formats and connect them with practical advice for farmers, livestock owners, and households. Community preparedness should include clear responsibilities and procedures for response.

10.2 Water security and management

Improve irrigation efficiency and maintenance, support appropriate water storage, monitor groundwater use and quality, and promote soil-moisture conservation. Water-allocation decisions should consider household drinking-water needs, agricultural demand, and the needs of livestock. Interventions should be designed around local water conditions and equitable access rather than relying on a single technical solution.

10.3 Climate-resilient agriculture and livestock

Promote locally suitable crop varieties, crop diversification, efficient irrigation where feasible, soil-health management, and agricultural extension. Drought-tolerant seed varieties should be selected according to local agronomic evidence and market conditions. Livestock measures may include reliable drinking-water access, fodder planning, animal-health services, and protection during floods.

10.4 Community resilience and livelihood protection

Support community-based preparedness, farmer information services, livelihood diversification, and targeted assistance for households with limited recovery resources. Ensure that women, older people, people with disabilities, small farmers, and landless agricultural workers can access warnings and support.

Recommendations should be adapted to local priorities and available resources.

10.5 Institutional coordination and governance

Coordinate the district administration, PDMA, irrigation and agriculture departments, meteorological services, local government, and community organizations. Link risk information to practical decisions on irrigation, crop advisories, emergency response, and recovery support. A shared district risk-information system could help compare flood and drought priorities while retaining the different indicators required for each hazard.

11. Conclusion

Khairpur District faces distinct but potentially overlapping flood and drought risks that matter for water security, agriculture, livestock, and community resilience. Official district planning material identifies drought risk across union councils and provides a range of meteorological and agricultural drought classifications. PDMA's provincial disaster profile uses a different frequency/severity classification, underscoring the need to explain assessment methods and scales rather than assume that all official risk categories are directly comparable.

Flood losses recorded for 2022 demonstrate substantial documented impacts on crops and houses, but those figures cannot be used to quantify drought impacts. Likewise, the population and acreage estimates previously used for heatwave exposure cannot be transferred to drought without drought-specific evidence. The current evidence supports a qualitative drought exposure assessment and identifies the data needed for a defensible quantitative estimate.

An integrated resilience approach should combine flood preparedness and infrastructure maintenance with drought monitoring, water conservation, efficient and equitable irrigation, climate-resilient agriculture, livelihood protection, and institutional coordination. Improving district-level data—especially rainfall and drought indicators linked with crop, irrigation, household, and groundwater information— would strengthen future planning and help direct resources toward the communities and sectors most at risk.

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PARTICIPANT RESEARCH PAPER

The Paris Agreement and Its Linkages with Disaster Risk Reduction

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Abstract

The Paris Agreement and the Sendai Framework for Disaster Risk Reduction 2015–2030 were adopted within months of each other, yet they are often implemented through separate institutions and measured against different indicators. This paper examines how the Paris Agreement links with disaster risk reduction (DRR) through adaptation (Article 7), loss and damage (Article 8) and mitigation (Article 4), using Pakistan's 2022 floods as the case. Drawing on ten core sources, including IPCC assessments, official post-disaster assessments and peer-reviewed studies, it analyses risk and vulnerability, community resilience, scientific and institutional gaps, mitigation measures, and early warning. It finds that climate change amplifies existing vulnerability, that climate and disaster planning remain only partly integrated, and that community knowledge is underused. It recommends integrated governance, finance before disasters, gender-responsive local planning, better data and technology, stronger institutions, and proven preventive measures.

Keywords: Adaptation; Climate change; Disaster risk reduction; Early warning; Paris Agreement

1. Introduction

Weather- and climate-related hazards remain the leading source of disaster losses worldwide. The World Meteorological Organization (WMO, 2021) recorded more than 11,000 disasters attributed to weather, climate and water hazards between 1970 and 2019, with about two million deaths and US$3.64 trillion in economic losses. The Intergovernmental Panel on Climate Change (IPCC, 2022) concludes that climate risks are rising and fall hardest on the most vulnerable regions and people.

Two landmark agreements were adopted in 2015. The Paris Agreement seeks to hold warming well below 2°C while pursuing 1.5°C, and Article 2.1(b) commits Parties to strengthening adaptive capacity and fostering climate resilience (United Nations Framework Convention on Climate Change [UNFCCC], 2015). The Sendai

Framework recognises climate change as a driver of disaster risk (United Nations Office for Disaster Risk Reduction [UNDRR], 2015). Yet the 2015 frameworks emerged from separate negotiating processes, and Aitsi-Selmi et al. (2015) argue that their success depends on coherence between them.

Problem and purpose: Despite shared goals, climate and disaster agendas are frequently managed by different institutions and tracked against different targets, which invites duplication and gaps. This paper examines the linkages between the Paris Agreement and DRR. A simple chain frames the argument: climate change strengthens hazards, and hazards become disasters where people are exposed and vulnerable. The Paris Agreement works mainly on the first links of this chain, and DRR on the last. The objectives are to map the links between the two regimes; to assess risk, vulnerability and resilience using Pakistan's 2022 floods as the case; and to recommend integrated policy measures. The scope covers global frameworks and national implementation and relies on secondary sources. The rationale is practical: states such as Pakistan must serve both agendas with limited institutional capacity.

2. Regional Context and Hazard Profile

Definitions: Following the IPCC (2022), risk arises from the interaction of hazard (a potentially damaging physical event), exposure (people, assets and ecosystems in harm's way) and vulnerability (the propensity to be adversely affected, shaped by sensitivity and limited capacity to cope and adapt).

Regional context and historical events: South Asia combines dense populations, monsoon-dependent agriculture, glacier-fed river systems and rapid urbanisation, and the IPCC (2022) projects intensifying heat, flood and glacier-related hazards across Asia. Pakistan illustrates the risk. The 2022 floods affected more than 33 million people and caused damages of US$14.9 billion and losses of US$15.2 billion, with recovery and reconstruction needs of about US$16.3 billion (Government of Pakistan, 2022). Pakistan's Updated Nationally Determined Contribution (NDC) targets a 50 per cent reduction in projected emissions by 2030, of which 15 per cent is unconditional and 35 per cent conditional on international support, and it also sets adaptation priorities (Government of Pakistan, 2021).

The Sendai Framework as the DRR benchmark: Sendai organises action through four priorities: understanding disaster risk, strengthening disaster risk governance, investing in resilience, and enhancing preparedness with "build back better" in recovery. It also sets seven global targets (UNDRR, 2015). Priority 1 needs the risk knowledge that climate science supplies, while Article 7 adaptation needs the governance and investment described in Priorities 2 and 3.

Literature review: Paris–DRR linkages: Three strands connect the agreements. First, adaptation: Article 7 states that adaptation action should be gender-responsive, participatory and informed by the best available science and by traditional and indigenous knowledge (UNFCCC, 2015), principles that mirror community-based DRR. Second, loss and damage: Article 8 lists early warning systems, emergency preparedness, comprehensive risk assessment and management, risk insurance and community resilience as areas for cooperation (UNFCCC, 2015), all of which are core DRR tools. Third, mitigation under Article 4 limits future hazard intensity, since the IPCC (2022) finds that risk rises with every increment of warming. Scholars add a caution: climate change is better treated as one driver that interacts with vulnerability than as the sole cause of disasters (Kelman et al., 2015).

3. Risk and Vulnerability Assessment

Socio-economic impacts and livelihoods: The 2022 floods generated recovery and reconstruction needs of about US$16.3 billion, with housing, agriculture and livestock, and transport heavily affected (Government of Pakistan, 2022). Loss of standing crops,

livestock and productive assets disrupts incomes and food supply at the same time, and such damage can reduce the fiscal space available for prevention.

Food security: Rural households that depend on crops, livestock and daily wage labour see flood damage turn directly into income loss, debt and food insecurity.

Because agriculture and livelihoods were among the hardest-hit sectors in 2022 (Government of Pakistan, 2022), the impact falls hardest on households without savings or insurance.

Vulnerable groups and gender: Risk is distributed unequally. The poor, women, children, older persons, persons with disabilities, informal settlers and remote mountain communities face higher exposure and lower capacity to respond. Crossnational evidence shows that disasters kill more women than men on average, and that the gap widens where women's socio-economic status is low (Neumayer & Plümper, 2007). Article 7.5 asks Parties to take vulnerable groups and communities into consideration in adaptation (UNFCCC, 2015).

Exposure, susceptibility and vulnerability factors: Exposure rises as settlements expand into floodplains and unplanned urban areas. Susceptibility is increased by weak housing, rain-fed agriculture and limited insurance. Underlying factors such as poverty, insecure land tenure and weak local governance determine whether a hazard becomes a disaster, which is why Kelman et al. (2015) place vulnerability at the centre of DRR. This is also why Article 8's attention to the resilience of communities and livelihoods (UNFCCC, 2015) is directly relevant. These factors also compound one another: a poor household in a floodplain, with a weak house and no insurance, faces far greater loss than a neighbour with none of these disadvantages.

4. Community Resilience Factors

Community resilience emerges from social capital, local knowledge and the capacity for collective action. In Pakistan, kinship, faith-based and neighbourhood networks routinely provide first response through shelter, food and information before formal agencies arrive. The IPCC (2022) identifies community-based approaches and Indigenous and local knowledge as important to effective adaptation, and Article 7.5 of the Paris Agreement endorses their use (UNFCCC, 2015).

Local coping mechanisms, such as raised plinths, seasonal migration, grain storage and reading of river and weather signs, embody knowledge accumulated over generations. DRR is most effective when this knowledge is combined with scientific information rather than displaced by it. Meaningful participation of women, youth and marginalised groups in planning strengthens absorptive, adaptive and transformative capacities. Participation also builds trust, which improves the uptake of warnings and the legitimacy of adaptation measures.

Resilience also has limits. Communities cannot substitute for public investment, and over-reliance on self-help can shift responsibility away from governments. Community strengths are best treated as a foundation that formal climate and DRR programmes build on, not a replacement for them.

5. Scientific and Institutional Gaps

Scientific and data gaps: Article 7 calls for adaptation informed by the best available science (UNFCCC, 2015). Where observation networks and locally downscaled projections remain thin, as they often do in mountain and remote areas, risk assessment is constrained. Artificial intelligence and machine learning offer promise for flood forecasting and impact-based forecasting, but their value depends on data quality, computing capacity and trained personnel.

Institutional gaps: Responsibilities for climate change, disaster management and development planning are spread across federal, provincial and district bodies, and coordination is uneven. Where climate and DRR plans are prepared in isolation, investments can overlap or work against each other, a risk the IPCC (2022) describes as maladaptation. Finance is a further gap: the IPCC (2022) finds that current adaptation finance is insufficient.

Critical analysis: separate measurement: The two regimes measure progress differently. Paris implementation is communicated through NDCs and national reporting (UNFCCC, 2015), while Sendai implementation is tracked against its seven global targets (UNDRR, 2015). Aitsi-Selmi et al. (2015) stress the need for coherence across the 2015 frameworks. Without shared indicators, one flood-protection project may be counted twice or not at all, and neither regime shows clearly whether risk has actually fallen. Aligning indicators would reduce the reporting burden and improve accountability.

6. Mitigation Strategies and Best Practices

Structural and non-structural measures: Structural measures include flood-resilient housing and infrastructure, improved drainage and embankment maintenance, and nature-based solutions such as wetland and watershed restoration; the IPCC (2022) recognises ecosystem-based approaches among effective adaptation options. Nonstructural measures, including risk-sensitive land-use planning, enforcement of building codes, social protection and risk insurance, address vulnerability directly. Sendai Priority 3 calls for investment in both kinds of measure (UNDRR, 2015).

Capacity building and best practices: Awareness campaigns, school and community drills, and training of local officials and volunteers build preparedness. Sendai Priority 4, which promotes preparedness and "building back better" in recovery (UNDRR, 2015), is the clearest operational link to adaptation. At the national level, Pakistan's Updated NDC pairs an emissions-reduction target with adaptation priorities (Government of Pakistan, 2021), which offers an entry point for aligning climate and DRR planning. Mitigation under Article 4 then complements these measures by limiting how severe future hazards become. Best practice therefore combines prevention before the hazard, preparedness during it and recovery that reduces future risk.

7. Risk Communication and Early Warning

Early warning is the point where the Paris Agreement and the Sendai Framework converge most directly. Article 8 names early warning systems as an area of cooperation (UNFCCC, 2015), and Sendai Target G calls for a substantial increase in the availability of and access to multi-hazard early warning systems and risk information (UNDRR, 2015). The United Nations' Early Warnings for All initiative aims to protect everyone through early warning systems by the end of 2027 (WMO, 2022).

Effective systems are people-centred. Warnings must be translated into impact-based, actionable messages in local languages and delivered through trusted last-mile channels, such as community radio, mobile messaging and local civic and religious institutions. Gender-sensitive design is essential: because disasters can kill more women than men where women's status is low (Neumayer & Plümper, 2007), women volunteers and household-level communication should be built into dissemination. Community feedback keeps systems credible and improves them over time.

Multi-hazard coverage matters in South Asia because floods, heatwaves, landslides and glacier-related hazards (IPCC, 2022) can occur in the same season, and a warning that covers only one hazard leaves communities exposed to the others.

8. Policy Recommendations

Based on the analysis above, six measures are recommended. The first two are enabling conditions on which the others depend.

I. **Integrated governance:** Align the NDC, national adaptation planning under Article 7 and disaster management plans under a single coordination mechanism with shared risk data and common targets.

II. **Finance before disasters:** Direct adaptation and loss and damage finance towards anticipatory financing, risk transfer and resilient infrastructure, and report results against both Paris adaptation goals and Sendai targets.

III. **Gender-responsive local planning:** Make risk planning participatory and recognise indigenous and local knowledge, consistent with Article 7.5.

IV. **Data and technology:** Expand observation networks and open data, and pilot AI-assisted, impact-based forecasting with investment in skilled personnel and data governance.

V. **Stronger institutions:** Build provincial and district capacity, maintain a unified loss and damage database and clarify mandates to reduce overlap.

VI. **Proven preventive measures:** Prioritise nature-based solutions, enforceable building codes and risk-sensitive land-use planning, and evaluate interventions to avoid maladaptation.

9. Conclusion

The Paris Agreement and the Sendai Framework are mutually reinforcing: the adaptation, loss and damage, and early warning provisions of the former are the practical content of the latter. Evidence from Pakistan’s 2022 floods shows that climate change amplifies risks rooted in poverty, exposure and weak governance. Reducing risk therefore requires science-based planning, strong social capital, respect for indigenous knowledge, appropriate technology and integrated institutions rather than isolated climate or disaster

programmes. If these are aligned, reporting under both regimes can become a single, coherent effort to build resilience.

This paper relies on ten core sources and a single country case, so its findings are indicative rather than statistically generalisable. Future research could test the proposed integration through provincial case studies, examine whether Paris adaptation reporting and Sendai targets can be reported jointly, and evaluate AIassisted forecasting in Pakistan's mountain catchments.

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PARTICIPANT RESEARCH PAPER

Integrated Flood Risk Assessment in Dera Ghazi Khan: Hill Torrents, Riverine Flooding, and Climate-Resilient Infrastructure

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Abstract

Dera Ghazi Khan (DG Khan) located in South Punjab, sits between the Indus River and the Koh-e-Suleiman range. Because of this position the city faces two flood hazards at once: hill-torrent (Rod-Kohi) flash floods and riverine flooding. This paper looks at the compound risk by using the hazard, exposure, vulnerability and risk framework taught in the C2DM handbook. It draws on peer-reviewed studies, federal flood reports and the 2022 Post-Disaster Needs Assessment and adds a short clearly labelled field observation by the author. The evidence shows that ungauged torrents, vulnerable roads and bridges canal-torrent conflicts and unequal social vulnerability for women and shape losses as much as rainfall itself. Because district-level vulnerability data are scarce national figures are not treated as findings and conclusions rely only on published sources and informal observation. The paper recommends that torrent gauging and early warning be introduced that crossings and drainage be designed with climate in mind that spate management be compatible, with Rod-Kohi, that community preparedness be gender-responsive and that a district flood risk atlas be produced.

Keywords: Climate-resilient infrastructure; Dera Ghazi Khan; Flood risk assessment; Hill torrents; Rod-Kohi

1. Introduction

I believe Flooding is the frequent disaster in Pakistan as the National Disaster Management Authority (NDMA, 2026) states. In 2022 Flooding affected 33 million people. The damage cost than USD 14.9 billion. Economic losses were USD 15.2 billion. Reconstruction needs will be at USD 16.3 billion according to the Ministry of Planning, Development & Special Initiatives (MoPD&SI, 2022).

The problem in DG Khan is that risk is managed hazard by hazard. Torrents, canals, roads and rivers are handled by agencies. Yet the people in DG Khan feel all of this as a Flooding event. This paper aims to: (a) profile the hazards; (b) assess exposure and vulnerability; (c) identify resilience capacities and gaps; and (d) recommend measures. The scope covers the DG Khan district and division with the 2022 Flooding, as the reference event. The method is a desk review of academic, government and international sources; no primary data were collected.

2. Regional Context and Hazard Profile

In this paper a hazard represents a damaging event. Exposure refers to the people and assets that are located in places where the hazard can strike. Vulnerability describes how susceptible those people and assets are to harm. Risk is the result of hazard, exposure and vulnerability (NDMA, 2026).

DG Khan lies between the Suleiman range to the west and the right bank of the Indus to the east (Federal Flood Commission [FFC] 2025). 200 Hill torrents flow from the range through DG Khan and Rajanpur toward the Indus and 13 of these torrents are considered major (Ahmed et al., 2021). The FFC (2025) plan lists seven torrents and more than 26 minor torrents in one irrigation division; therefore the number of torrents changes with jurisdiction and how they are defined. Torrents create fast floods that erode channels and drop silt; canals can break when the water flow is higher than the capacity of cross-drainage works (Ahmed et al., 2021). Munir and Iqbal (2016) note that flash floods from the Wador torrent impact every part of DG Khan city.

In August 2022 a federal situation report predicted very high to high flooding in the DG Khan torrents and mentioned that pressure was moving to control structures downstream of Taunsa (Ministry of Water Resources 2022). Press reports described the destruction of the Bela Vidor Bridge and the deliberate breaching of the Kachhi Canal to

divert water from DG Khan city (Ismail, 2022). A Landsat-based study of the district estimated that flood lasted for five weeks (Sajjad et al. 2023). Attribution research shows that intense rainfall in Pakistan has become heavier as the country has warmed with some models indicating, up to 50 % higher five-day rainfall; however the overall contribution could not be. The study focused on the Indus basin, Sindh and Balochistan instead of DG Khan (Otto et al. 2023).

3. Risk and Vulnerability Assessment

Livelihoods. I have seen how floods both bring danger and help. Households, canals and farms in the piedmont (Pachad) zone lie on torrent routes. Floodwater also keeps livelihoods alive: farmers grow sorghum, millet, wheat, gram and oilseeds using irrigation (Ahmed et al. 2021). Floods are therefore both a danger and a resource something that a protective approach ignores.

Evidence limits. Loss figures at the district level that appear in grey literature cannot be checked against documents so this paper does not use them. For scale the national assessment found the damage in housing, agriculture and livestock and transport and communications (USD 5.6 3.7 and 3.3 billion respectively) (MoPD&SI, 2022). These are totals; their local spread in DG Khan must be verified with NDMA and Provincial Disaster Management Authority (PDMA) district data.

Access. UNFPA (2022) estimated that 650,000 pregnant women lived in flood-affected areas across the country warned that the risk of gender-based violence is higher and pointed out that damaged roads and bridges cut women and girls off from health facilities. This is evidence but it shows a mechanism loss of crossings that makes sense in torrent-cut districts.

Anthropological lens. Vulnerability comes from processes like who owns land how much money people have, how they move and how much political voice they have not just from exposure (Oliver-Smith, 2002; Wisner et al., 2004). A district assessment should therefore ask: who lives on torrent paths, who owns transport and who can reach services when a crossing fails.

Authors field observation (not systematic research data). On the road from DG Khan to Choti Zareen, the author. Video-recorded a missing section of a bridge. It is not known if

flooding caused it. The observation is used to show how a failed crossing can cut access for settlements, beyond it.

4. Community Resilience Factors

Published evidence shows that Pachad farmers have long built bunds, called gandas and diversion bunds to capture torrent flows. Local knowledge of shifting channels underpins maintenance as Ahmed et al. Show in 2021. Rod-Kohi practice is thus an adaptation, not merely a vulnerability. However disputes over upstream-priority water rights make new structures contentious as Ahmed et al. Note in 2021.

I saw that when floods approach announcements are made from mosques. Biradari members help one another. Some households move livestock in advance although some damage still occurs. I observed that women face the hardship, including during evacuation and recovery.

These practices match the community-based approach in the C2DM handbook. The C2DM handbook stresses community flood mapping, evacuation planning and small mitigation structures as NDMA notes in 2026. Solidarity networks can also be unequal in who's reached first. I think resilience should be assessed with attention, to diversity within communities than assumed.

5. Scientific and Institutional Gaps

Hydrological data are thin. Saleem et al. (2023) Note effort to quantify rainfall and runoff in ungauged catchments, their HEC-HMS modelling of ten Koh-e-Suleiman torrents estimated Indus inflows of 0.5 to 0.8 million acre-feet for 25- to 200-year rainfall but these are modelled, not observed, values. Earlier torrent-management efforts reportedly failed because they relied on data and ignored whole-catchment behaviour (Ahmed et al. 2021 citing a 1996 feasibility study so this is dated evidence).

Institutional responsibility is divided: the FFC (2025) plan for the DG Khan construction division excludes surface drains hill-torrent works and the Taunsa and Ghazi Ghat structures, which sit with bodies. No source reviewed documents an AI or machine-learning forecasting system for DG Khans torrents; this is a gap in the evidence reviewed not proof of absence. Satellite and GIS mapping studies (Munir & Iqbal 2016; Sajjad et al. 2023) show feasibility but not operational use. Finally DG Khan-specific gender-disaggregated vulnerability data are lacking.

6. Mitigation Strategies and Best Practices

Structural. Munir and Iqbal (2016) modelled two dam sites storing about 27 million metres on the Wador torrent with channels to the DG Khan Canal. Saleem et al. (2023) Identified storage options with retention potential of 0.14 to 1.14 million acre-feet to support irrigation and flood control. Ahmed et al. (2021) Proposed distributors that spread flows across the fan and protect the canals bank. The handbook adds buildings, drainage, levees and rainwater harvesting (NDMA, 2026). These are design proposals; none is shown here to have been implemented or tested.

Climate-resilient design. Bridges, causeways and culverts should be sized using climate-informed hazard, exposure and vulnerability screening than historical records alone following the handbooks climate risk assessment steps (NDMA, 2026). Infrastructure can also shift risk: diverting water from DG Khan city (Ismail, 2022) protected one population while sending floodwater elsewhere which my interpretation suggests needs risk-sharing and compensation.

Non-structural and international practice. Integrated flood risk management emphasises collaboration, sustainability, adaptive management and holistic assessment (NDMA, 2026) consistent with the Sendai Frameworks priority on understanding disaster risk (United Nations Office for Disaster Risk Reduction [UNDRR] 2015).

7. Risk Communication and Early Warning

Federal forecasts reached administrators ahead of the August 2022 peaks (Ministry of Water Resources 2022). I found no documentation of how warnings reach households in torrent paths. The authors observation is that mosque announcements are a local channel.. Early warning should combine gauge-based triggers with these trusted channels use languages such as Saraiki and Balochi and reach women inside households through female volunteers and health workers. Evacuation routes must account for crossings that may fail and anticipatory action -positioning resources, before forecast floods is a handbook priority (NDMA, 2026).

8. Policy Recommendations

The following recommendations are my take on the evidence above.

I. Put rain and flow gauges on the torrents. Then make a district flood risk map that shows danger, who is exposed and how vulnerability differs by gender.

II. Design bridges, culverts, causeways and canal crossings using climate data and risk checks.

III. Work with farmers to plan management that fits Rod-Kohi farming but first fix any water rights conflicts.

IV. Set up one district coordination group that connects Irrigation, Highways, PDMA, Rescue 1122 health services and local communities.

V. Give money for community-led preparedness that treats women fairly and sends warnings to the person in remote areas.

VI. Plan compensation and fair sharing of risk when redirecting floods affects communities.

VII. Try out satellite or AI-based flood mapping. Check how accurate it is before using it widely.

9. Conclusion

DG Khan's flood risk is complex. Torrents, the Indus River, weak crossing points and social inequality all mix together. The evidence shows that better data, infrastructure and local knowledge must all be planned at once. Why? Because protecting one area can push risk to another.. Warnings that miss women or faraway villages don't really reduce risk. There are still gaps in data at the district level. The observations in this paper are examples, not full proof. The best way forward is a joined-up people-centered and flexible approach. Matching the Sendai Framework and the handbook's IFRM principles. That's the likely path, to real resilience.

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PARTICIPANT RESEARCH PAPER

Artificial Intelligence for Multi-Hazard Early Warning Systems in Pakistan: A Proposed Framework for Risk Integration, Impact-Based Warnings, and Anticipatory Action

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Abstract

Pakistan faces multiple natural hazards, including riverine and flash floods, glacial lake outburst floods (GLOFs), landslides, heatwaves, droughts, earthquakes, and severe storms. The impacts of these hazards depend not only on their physical intensity but also on population exposure, infrastructure vulnerability, warning lead time, communication effectiveness, and the capacity of institutions and communities to act. Artificial intelligence (AI) offers opportunities to enhance hazard monitoring, data integration, forecasting, risk assessment, and warning dissemination. However, the adoption of AI alone does not guarantee that early warnings will produce timely protective action.

This paper examines the potential role of AI in strengthening Pakistan's multi-hazard early warning systems, with particular attention to the National Disaster Management Authority (NDMA) and its existing disaster-risk management initiatives. It adopts a literature-based, conceptual research approach, drawing on NDMA's National Disaster Risk Reduction Strategy 2025–2030, international multi-hazard early warning guidance, a 2026 United Nations report on AI in early warning systems, and recent research evaluating Pakistan's flood forecasting and early warning system. The analysis indicates that a generic AI-enabled warning platform would overlap with existing policy directions and international frameworks. Accordingly, the paper proposes a complementary Risk-to-Action Integration Framework that connects hazard information, exposure and vulnerability assessment, uncertainty communication, authorized decision-making, localized warning dissemination, anticipatory action, and post-event learning. The framework is conceptual and has not been experimentally validated. Its proposed contribution is an operational structure for examining how AI-assisted information can support decisions across different hazards while preserving the responsibilities of relevant technical and disaster-management authorities. The paper recommends a phased, evidence-led approach to implementation and evaluation, subject to data availability, institutional feasibility, and further consultation.

Keywords: Artificial intelligence; multi-hazard early warning systems; disaster risk reduction; NDMA Pakistan; impact-based forecasting; anticipatory action; GLOF; risk communication.

1. Introduction

Disasters can cause extensive loss of life, damage infrastructure, disrupt livelihoods, and weaken economic and social development. Pakistan's geographical and climatic diversity exposes it to a range of hazards, including floods, droughts, earthquakes, heatwaves, forest fires, and GLOFs. The National Disaster Management Authority's National Disaster Risk Reduction Strategy 2025–2030 identifies multi-hazard risk understanding, technological innovation, improved preparedness, and coordinated disaster governance as national priorities (National Disaster Management Authority [NDMA], 2025).

Early warning systems are designed to provide information about potential hazards early enough for authorities and communities to prepare and reduce losses. Their effectiveness depends on more than the accuracy of a forecast. Risk information must be interpreted, communicated to the appropriate people, and connected to actions that can be taken before the hazard causes significant harm.

Artificial intelligence has the potential to improve several stages of this process. Machine-learning methods can identify patterns in historical observations, computer-vision systems can assist with satellite-image interpretation, and AI-based analytical tools can help combine information from different sources. Nevertheless, these applications have different technical requirements and limitations. A model developed for river-flow prediction cannot automatically be assumed suitable for earthquake prediction or GLOF monitoring.

International guidance increasingly treats AI as an enabling technology that must operate within effective institutions, reliable observation networks, and people-centred warning systems. The 2026 report Leveraging AI to Enhance Multi-Hazard Early Warning Systems, published by UNDRR and partner organizations, emphasizes infrastructure, human oversight, interoperability, inclusive communication, and feedback between the components of early warning systems (United Nations Office for Disaster Risk Reduction [UNDRR] et al., 2026).

This creates an important research question for Pakistan: how can AI-assisted hazard information be connected more consistently to impact assessment, authorized decisions, community warnings, and anticipatory action without duplicating existing systems or weakening institutional responsibilities?

This paper investigates that question through a literature-based review and proposes a conceptual framework intended to complement Pakistan's existing multi-hazard early warning arrangements.

1.1 Research problem

AI can improve the speed and scale of risk analysis, but its operational value depends on whether its outputs are relevant, reliable, understandable, and actionable. A technically sophisticated prediction may have limited practical value if it is not translated into a geographically specific warning, delivered through an accessible communication channel, or connected to an authorized protective action.

Pakistan already has policy commitments and publicly documented initiatives involving integrated risk information, impact-based forecasting, early warning, and technological innovation. Therefore, the central problem is not simply the absence of an AI-based early warning system. Instead, this paper examines how the different stages between AI-assisted risk identification and protective action can be organized and evaluated within the existing institutional context.

1.2 Research aim

To examine how AI can strengthen multi-hazard early warning systems in Pakistan and propose a conceptual framework connecting AI-assisted risk information with impact-based warnings, institutional decisions, and anticipatory action.

1.3 Research objectives

1. Review existing international guidance on AI and multi-hazard early warning systems.
2. Examine Pakistan's publicly documented disaster-risk reduction and early warning initiatives.
3. Identify operational considerations that influence the conversion of hazard information into protective action.
4. Propose a framework for integrating AI-assisted risk information with existing decision-making and warning processes.
5. Recommend practical measures for future implementation and evaluation by relevant disaster-management stakeholders.

1.4 Research questions

- What roles can AI reasonably perform across the stages of a multi-hazard early warning system?
- How do Pakistan's documented disaster-management initiatives align with established international approaches?
- What operational issues must be addressed when converting AI-assisted hazard information into impact-based warnings and protective action?
- How could a complementary framework be evaluated without assuming that it has already been implemented or validated?

2. Background and Literature Review

2.1 Multi-hazard early warning systems

A multi-hazard early warning system (MHEWS) supports preparedness for several hazards through connected risk assessment, monitoring, warning communication, and response arrangements.

The World Meteorological Organization (WMO) and its partners describe four essential elements of people-centred early warning systems:

1. Disaster risk knowledge.
2. Detection, observation, monitoring, analysis, and forecasting.
3. Warning dissemination and communication.
4. Preparedness and response capabilities.

These elements are interdependent. Better forecasting cannot compensate fully for inaccessible warning messages, and effective communication cannot compensate for a lack of feasible protective actions (WMO, 2018; WMO, 2023).

World Meteorological Organization

The multi-hazard approach does not require every hazard to use the same forecasting model. Instead, it requires appropriate hazard-specific information to connect with shared risk assessment, communication, institutional coordination, and preparedness processes. For example, flood forecasting may rely on rainfall, river discharge, soil moisture, and hydrological models. GLOF monitoring may require glacial-lake observations, temperature and precipitation information, remote sensing, and local monitoring. Heatwave warnings may depend on temperature, humidity, duration, and exposure of vulnerable populations. Earthquake early warning, where technically available, concerns

rapid detection and the delivery of alerts after an earthquake has begun; it should not be confused with reliably predicting the exact time and location of future earthquakes.

Consequently, an effective MHEWS needs both hazard-specific scientific methods and shared operational arrangements.

2.2 Applications of artificial intelligence

AI can potentially contribute to several early warning functions.

Hazard detection and monitoring. Machine learning and computer vision can assist in interpreting satellite imagery, identifying changes in land surfaces, monitoring water bodies, and detecting patterns in sensor observations. Their usefulness depends on data quality, spatial and temporal resolution, and validation against appropriate observations.

Forecasting and prediction support. Machine-learning models can identify relationships between historical observations and future conditions. Depending on the hazard, they may supplement physical models, provide additional estimates, or help identify unusual conditions. They should not automatically replace established scientific forecasting methods.

Risk and impact assessment. AI-assisted analysis may help combine hazard forecasts with information about population distribution, roads, buildings, hospitals, agricultural areas, and other exposed assets. This can help identify where a hazard could produce serious consequences, provided the underlying exposure and vulnerability data are sufficiently accurate and current.

Warning communication. Language technologies may help transform technical information into simpler, multilingual messages. However, messages concerning life safety require safeguards against incorrect translations, misleading summaries, or the omission of critical instructions.

Preparedness and resource planning. Analytical tools may support the identification of priority locations, planning of response resources, and comparison of possible actions under different risk scenarios. Final decisions must remain consistent with authorized responsibilities and established emergency procedures.

The UNDRR et al. (2026) report supports viewing AI as an enabling capability across all four early warning pillars, while emphasizing the need for sound observation infrastructure, human oversight, interoperability, and inclusive design.

UNDRR

2.3 Pakistan's documented early warning initiatives

NDMA's National Disaster Risk Reduction Strategy 2025–2030 identifies a broad range of hazards and emphasizes technological innovation, improved risk understanding, early warning, and institutional coordination. It also describes the National Common Operating Picture (NCOP), developed by NDMA's National Emergencies Operation Centre, as a centralized system for integrating hazard information and infrastructure data to support monitoring, warning dissemination, and disaster-management decisions (NDMA, 2025).

NDMA

The strategy also identifies the use of AI and machine learning, remote sensing, geographic information systems, and real-time monitoring among the technologies relevant to disaster risk reduction.

These documented commitments have an important implication for the present research. It would be inaccurate to claim that NDMA has no integrated risk-information infrastructure or has not considered AI for disaster management. Nor does a public strategy, by itself, prove that every planned capability is operational or independently validated.

The present paper therefore takes a complementary approach: it investigates how AI-assisted information can be connected to decisions and protective actions within existing arrangements, rather than proposing an entirely separate national warning platform.

2.4 Evidence from Pakistan's flood early warning system

Jamal and Rahman (2026) examined Pakistan's flood forecasting and early warning system in the Indus River Basin using a strengths, weaknesses, opportunities, and threats (SWOT) approach. Their study considered institutional coordination, technological adequacy, communication, and community-level response mechanisms. It reported progress in radar systems, satellite monitoring, and institutional collaboration while identifying challenges involving communication, community awareness, local infrastructure, and the integration of indigenous knowledge.

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This study provides relevant Pakistan-specific evidence that the effectiveness of an early warning system cannot be assessed through forecasting capability alone.

However, its scope is flood forecasting and early warning in the Indus River Basin. Its findings should not automatically be generalized to all hazards or interpreted as proof that the same weaknesses exist in every NDMA process.

The study also demonstrates why a new paper should avoid merely listing coordination problems. A useful contribution should specify how information, decisions, warnings, and feedback could be connected and how the proposed arrangements might subsequently be assessed.

2.5 International guidance and the remaining research question

Existing international guidance already covers multi-hazard system design, risk knowledge, communication, preparedness, and responsible AI integration. The WMO's Handbook on the Use of Risk Knowledge for Multi-Hazard Early Warning Systems provides guidance on the first pillar of the Early Warnings for All initiative (WMO, 2024).

World Meteorological Organization

Similarly, the UNDRR et al. (2026) report explicitly addresses AI integration across all four MHEWS pillars.

These publications mean that neither the general integration of AI into early warning systems nor the importance of connecting warnings to action can be claimed as new in themselves.

The more defensible direction for this paper is to develop a Pakistan-oriented operational synthesis: a conceptual structure for examining how hazard-specific AI outputs, risk and exposure information, uncertainty, decision authority, warning dissemination, and anticipatory action can be connected within existing arrangements.

This is a proposed contribution derived from the literature, not a claim that no comparable framework exists anywhere. A comprehensive systematic search and institutional consultation would be required before asserting that it is entirely novel.

3. Research Methodology

3.1 Research design

This paper uses a literature-based conceptual research design. It synthesizes official policy material, international guidance, and published academic research to identify relevant operational considerations and develop a proposed framework.

No AI model was trained. No computational experiments, primary surveys, interviews, or field trials were conducted. The proposed framework is therefore a conceptual output rather than an experimentally validated system.

3.2 Source selection

The review draws on four principal source categories:

- Pakistani government policy documentation, particularly NDMA's National Disaster Risk Reduction Strategy 2025–2030.
- International guidance on multi-hazard early warning systems and disaster-risk knowledge.
- The 2026 UNDRR-led report on AI applications in multi-hazard early warning systems.
- Pakistan-specific academic research on the effectiveness of flood forecasting and early warning.

Sources were selected for their relevance to the research questions, institutional or scholarly provenance, and ability to inform the proposed operational framework.

3.3 Analytical approach

The selected material was compared thematically across six areas:

1. Hazard detection and forecasting.
2. Exposure, vulnerability, and impact assessment.
3. Uncertainty and data quality.
4. Institutional decision-making.
5. Warning communication and protective action.
6. Monitoring, evaluation, and learning.

The framework was derived by identifying how these areas relate to one another and organizing them into a sequence of operational stages.

This is a focused conceptual synthesis, not a registered systematic review. The paper does not claim exhaustive coverage of every relevant publication or every internal NDMA capability. A broader database search and consultation with relevant technical agencies would strengthen the evidence base.

3.4 Methodological limitations

The analysis depends on accessible publications and publicly documented institutional plans. Internal procedures, system performance records, data-sharing arrangements, and implementation details may not be publicly available.

Furthermore, the selected sources differ in geographical coverage and methodological approach. International guidance establishes general principles, whereas Pakistan-specific flood research provides evidence for a particular hazard and region.

The proposed framework should therefore be treated as a basis for further examination, not as proof that a particular operational gap exists across all hazards in Pakistan.

4. Proposed Risk-to-Action Integration Framework

4.1 Framework overview

The proposed framework connects hazard information with risk assessment, decision-making, warning communication, and anticipatory action. Its objective is to make the relationship between AI-assisted analysis and operational decisions explicit.

It is intended to complement existing institutional arrangements, including NDMA's documented risk-information initiatives, rather than replace official forecasting agencies or create a separate national platform.

Stage 1 — Hazard information

Sensors, satellite observations, meteorological data, hydrological measurements and official forecasts

Stage 2 — AI-assisted analysis

Detection, forecasting support, anomaly identification and data-quality checks

Stage 3 — Risk and impact assessment

Hazard intensity, exposure, vulnerability, likely consequences, uncertainty and lead time

Stage 4 — Authorized decision

Technical review, applicable thresholds, responsible authority and documented decision

Stage 5 — Warning and protective action

Localized warnings, accessible communication, preparedness measures and anticipatory action

Stage 6 — Evaluation and learning

Forecast verification, warning reach, decision timing, response outcomes and corrective action

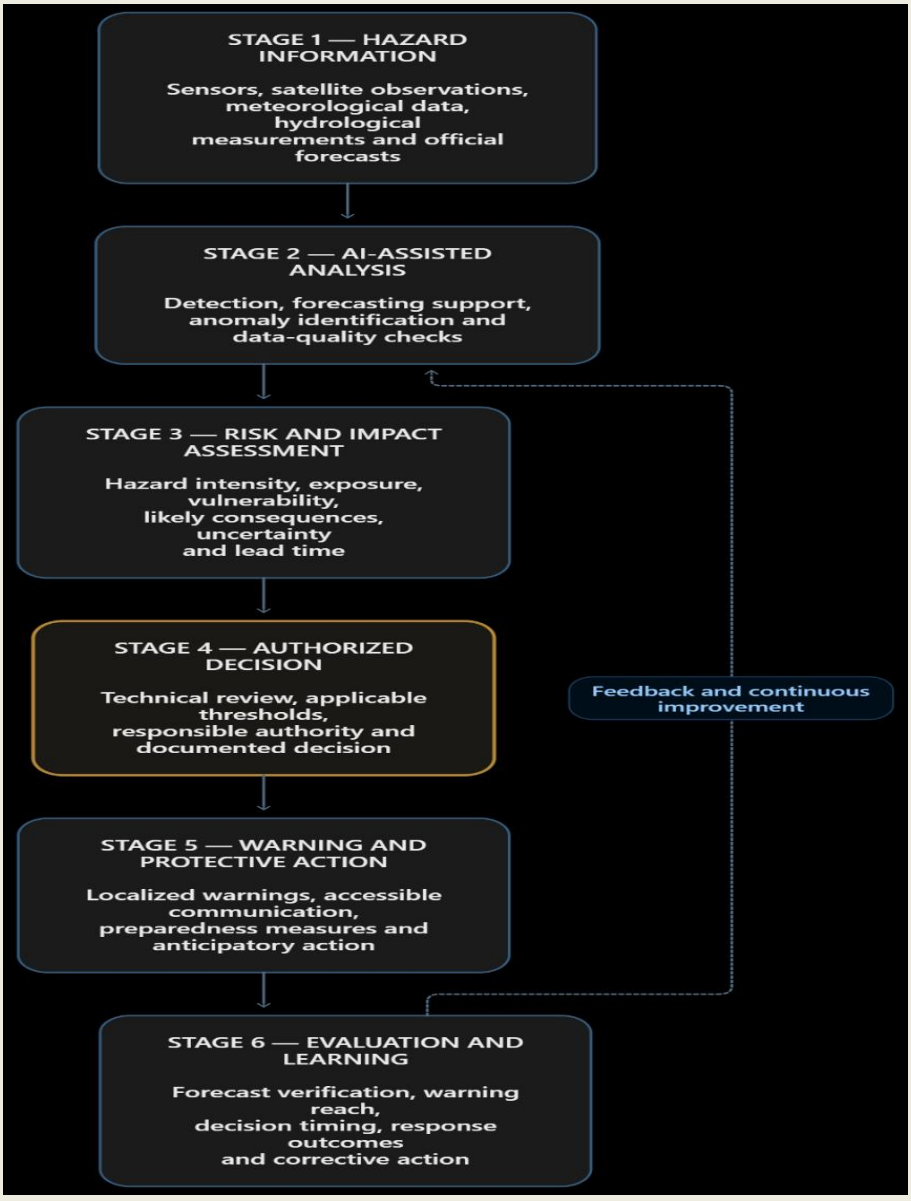


Figure 1. Author-proposed conceptual framework. This diagram represents a proposed process, not a verified description of NDMA's internal architecture.

4.2 Stage 1: Hazard information and data quality

The framework begins with information from appropriate observation and forecasting systems. Depending on the hazard, these may include weather stations, river gauges, satellite imagery, remote sensors, historical records, and official scientific forecasts.

Data quality is fundamental. Missing observations, outdated exposure maps, sensor failures, and inconsistent reporting periods can undermine AI outputs. Consequently, the

proposed framework includes checks for data freshness, completeness, consistency, and known limitations before model-generated information is used operationally.

Not every hazard requires the same data sources. The framework therefore allows separate hazard-specific pipelines while encouraging compatible data formats and clear metadata wherever feasible.

4.3 Stage 2: AI-assisted analysis

AI methods may support detection, forecasting, pattern recognition, anomaly identification, and data processing.

Their role should be defined according to the evidence available for each application. Where a validated physical forecasting model is the primary operational method, AI may supplement it rather than replace it. Where historical data are sparse or conditions differ substantially from the training data, AI predictions may be less reliable.

A proposed operational record should identify the model or analytical method used, the timestamp of the output, relevant input-data limitations, the applicable geographical area, and uncertainty information where available.

For life-safety decisions, an AI output should not automatically trigger a public warning without the safeguards required by the relevant hazard protocol and authorized institutions.

4.4 Stage 3: Risk and impact assessment

A hazard forecast estimates the potential occurrence or characteristics of a hazardous event. Impact assessment asks what that event could mean for people, infrastructure, services, livelihoods, and other exposed assets.

The proposed framework therefore combines hazard information with available exposure and vulnerability information.

For example, a forecast of rising river levels may have different implications for a densely populated settlement, a sparsely populated area, and a location containing critical infrastructure. The framework would examine whether the information available is sufficient to identify those differences.

Potential inputs include:

- Population distribution and settlement locations.
- Critical infrastructure and transport routes.

- Health facilities, schools, and essential services.
- Available vulnerability and socioeconomic indicators.
- Historical hazard footprints and relevant local knowledge.
- Forecast intensity, geographical extent, uncertainty, and lead time.

Such an assessment should not imply false precision. Where exposure information is incomplete or outdated, the limitations should be documented and considered in the decision process.

4.5 Stage 4: Authorized decision-making

Risk information must be connected to decisions made by the authorities responsible for the relevant hazard and jurisdiction.

The proposed framework would document:

- The applicable official forecast or risk threshold.
- The evidence available at the time of the decision.
- The authority responsible for reviewing and authorizing action.
- The action associated with the relevant threshold.
- Any override, disagreement, or delay and its recorded justification.

This is not a proposal to transfer statutory authority to AI. Rather, AI would provide analytical support to the responsible technical and disaster-management institutions.

The exact division of responsibilities would need to follow applicable laws, official mandates, approved operating procedures, and hazard-specific protocols.

4.6 Stage 5: Warning dissemination and protective action

An alert has limited value if affected people do not receive or understand it in time.

The framework therefore links authorized decisions to warning messages that identify the affected area, nature of the hazard, expected timing where known, level of uncertainty where relevant, and recommended protective action.

Different communication channels may be needed, including mobile alerts, broadcast media, official digital platforms, local authorities, and community-based warning arrangements. Channel selection must reflect actual coverage, accessibility, and the circumstances of affected populations.

AI-assisted translation or message simplification could support communication, but safety-critical instructions should be checked through appropriate review processes.

Preparedness measures should be defined in advance where possible. Depending on the hazard and authorized plans, these could include evacuation, temporary relocation, protection of essential equipment, movement of emergency resources, or public-health precautions.

4.7 Stage 6: Evaluation and learning

The final stage examines whether the system provided useful information and whether the warning process functioned as intended.

Evaluation should distinguish between forecasting performance and operational effectiveness.

Potential indicators include:

- Forecast lead time: Time available between a warning and the relevant event or impact.
- Forecast performance: Appropriate measures of accuracy and error for the specific hazard and forecasting task.
- False alarms: Warnings issued for which the predefined event criterion was not met.
- Missed events: Relevant events for which the expected warning was not issued.
- Warning reach: Whether intended recipients received the warning through available channels.
- Decision timeliness: Time between receiving relevant information and making an authorized decision.
- Protective-action completion: Whether planned actions were undertaken and documented.
- Equity and accessibility: Whether communication limitations affected particular locations or population groups.
- Data and system reliability: Availability, freshness, and integrity of the information used.

These indicators would need hazard-specific definitions. A single score should not be used to compare fundamentally different forecasting tasks without justification.

The evaluation process should also record whether a failure originated in observation, forecasting, risk assessment, authorization, communication, or response. This would help

institutions identify what needs improvement rather than attributing every unsuccessful outcome to the AI model.

5. Application Across Different Hazards

The framework is designed to share operational principles while preserving hazard-specific scientific methods.

Table 1. Illustrative applications based on general technical possibilities; it does not establish that any particular AI capability is deployed by NDMA.

Hazard	**Potential AI-supported function**	**Risk information and decision consideration**
Riverine and flash floods	Rainfall analysis, flow forecasting support, flood mapping	Settlement exposure, river levels, evacuation lead time
GLOFs	Satellite-image analysis, lake monitoring support, anomaly detection	Downstream settlements, infrastructure, short warning windows
Landslides	Terrain analysis, rainfall-pattern analysis, susceptibility mapping	Slope exposure, roads, settlements and site-specific conditions
Heatwaves	Temperature-pattern analysis and demand forecasting	Vulnerable populations, health facilities, water and cooling access
Droughts	Vegetation, rainfall and soil-moisture analysis	Water availability, agricultural dependence and food security
Earthquakes	Rapid event detection and shaking-impact estimation where systems exist	Population and infrastructure exposure, emergency response readiness

Severe storms and cyclones	Forecast interpretation and satellite-based monitoring	Coastal and inland exposure, shelter availability and evacuation needs
Wildfires	Satellite-based hotspot detection and spread-risk analysis	Communities, forests, air quality and evacuation routes

5.1 Floods and GLOFs

Floods and GLOFs are especially relevant to Pakistan's disaster-risk context because they involve different hydrological and mountainous environments. The proposed framework could connect available forecasts and observations with exposed settlements, infrastructure, warning lead time, and authorized protective actions.

However, the same forecasting model or trigger should not be assumed suitable for both hazards. GLOF risk assessment may require specialized monitoring and rapid local warning arrangements, while riverine flood forecasting may use hydrological observations and basin-scale forecasting.

5.2 Heatwaves and droughts

Heatwaves and droughts often require different warning horizons and response measures from sudden-onset hazards. Heatwave warnings may support public-health messaging and measures to protect vulnerable people. Drought information may inform water management, agricultural planning, and anticipatory support.

The framework would need to accommodate these different timescales and decision requirements rather than force all hazards into a single threshold system.

5.3 Earthquakes

Earthquake applications require particular care. AI may assist with seismic signal processing, rapid event characterization, damage estimation, or the operation of an earthquake early warning system where the required infrastructure exists. These functions do not establish the ability to predict the exact time and location of future earthquakes.

The framework must preserve this distinction to avoid misleading warnings or unrealistic expectations.

6. Discussion

6.1 Why a complementary framework is preferable to another AI platform

NDMA's National Disaster Risk Reduction Strategy 2025–2030 already documents centralized risk information, multi-hazard early warning, technological innovation, and impact-based forecasting. International guidance also addresses the integration of AI across the four pillars of early warning systems.

Consequently, proposing an entirely new AI platform would risk duplicating existing institutional and international directions.

The proposed Risk-to-Action Integration Framework instead focuses on the relationships between existing functions. Its purpose is to provide a structured way to examine how risk information moves from observation and analysis to decisions, warnings, action, and learning.

This distinction is important: the framework does not claim that these processes are absent in NDMA. It proposes a way to examine their interfaces and identify opportunities for improvement using evidence.

6.2 Potential benefits

If adapted successfully, the framework could support several benefits.

First, it could make the relationship between technical forecasts and operational decisions more explicit. Second, combining hazard information with exposure and vulnerability data could help authorities prioritize locations where consequences may be severe. Third, documenting uncertainty and decision authority could improve traceability. Fourth, linking warnings to evaluation and feedback could help identify weaknesses in the overall process.

These are anticipated benefits, not measured results. Their achievement would depend on the quality of available data, compatibility with existing systems, staff capacity, and the feasibility of the proposed procedures.

6.3 Technical and institutional challenges

Data limitations. AI methods require appropriate observations and representative historical information. Sparse monitoring networks, inconsistent records, and incomplete exposure data may reduce reliability.

Interoperability. Different agencies may use different formats, update schedules, spatial references, and access procedures. Integration requires agreed standards and clear responsibility for data quality.

Uncertainty. Model outputs may be unreliable under conditions that differ from those represented in historical data. Operational procedures must account for uncertainty and conflicting evidence.

Institutional responsibilities. Forecasting, warning authorization, communication, and response may involve multiple institutions. The framework must complement their mandates rather than create competing authority.

Communication and accessibility. A warning may fail to produce action if it is delayed, difficult to understand, unavailable in an appropriate language, or delivered through a channel that does not reach the affected population.

Financial and human capacity. Operational AI requires more than initial software development. Systems need maintenance, monitoring, technical staff, training, data infrastructure, and sustainable funding.

Trust and accountability. Communities and officials need clear explanations of what a warning means and what actions are recommended. Responsibility for decisions should not be obscured by the use of AI.

These considerations align with the international guidance that treats infrastructure, human oversight, inclusive design, interoperability, and institutional capacity as conditions for effective AI integration (UNDRR et al., 2026).

6.4 Research contribution and novelty limitations

The contribution of this paper is the synthesis of a proposed operational sequence linking hazard-specific AI-assisted analysis to impact assessment, authorized decisions, warning communication, anticipatory action, and feedback within Pakistan's multi-hazard disaster-management context.

However, the component ideas are not individually new. Multi-hazard early warning pillars, impact-based forecasting, risk assessment, and post-event evaluation are already established in international guidance and research.

The defensible claim is therefore that the paper proposes a Pakistan-oriented conceptual synthesis for further assessment, not that it presents the first integrated early warning framework or a proven new method.

Further research would need to compare the proposed framework with more operational documentation, identify any genuinely unaddressed requirement, and consult relevant agencies before a stronger novelty claim could be made.

7. Recommendations

7.1 Review existing processes before introducing new systems

NDMA and relevant stakeholders could examine how existing risk-information and early warning arrangements connect hazard forecasts to impact assessments, warning authorization, communication, and protective actions. The purpose would be to identify specific process gaps rather than duplicate existing infrastructure.

7.2 Establish hazard-specific requirements

The framework should be adapted separately for each hazard, with appropriate observations, forecasting methods, thresholds, uncertainty measures, lead times, and response protocols.

7.3 Strengthen data quality and interoperability

Where gaps are identified, agencies could prioritize data-quality procedures, consistent metadata, update schedules, access controls, and interoperable data formats. Integration should build on authorized systems and existing technical responsibilities.

7.4 Document decision authority and uncertainty

Operational procedures could specify how AI-generated information is reviewed, how uncertainty is communicated, who authorizes protective action, and how overrides or conflicting forecasts are recorded.

7.5 Evaluate the complete warning process

Evaluation should extend beyond forecast accuracy to include warning reach, decision timing, accessibility, protective-action completion, and learning after events. Existing international evaluation guidance should be reviewed before creating additional indicators.

7.6 Incorporate community needs

Warning messages should be understandable, actionable, accessible, and appropriate to local communication conditions. Community feedback can help determine whether people receive, understand, trust, and act upon warnings.

7.7 Adopt a phased implementation approach

Any future implementation should begin with a documented review of existing processes and data availability. A limited, hazard-specific pilot could then be considered by the responsible institutions, followed by evaluation before wider adoption.

Such a pilot would be a future recommendation, not an activity conducted as part of this paper.

8. Proposed Future Evaluation Plan

Although this paper does not conduct experiments, a future study could assess the feasibility and value of the framework through the following stages.

Stage 1: Institutional and document review. Identify existing workflows, responsibilities, data sources, and decision protocols for a selected hazard.

Stage 2: Gap assessment. Compare the documented workflow with the proposed framework and identify specific gaps supported by evidence.

Stage 3: Hazard-specific design. Define relevant indicators, decision points, uncertainty requirements, and warning procedures for the selected hazard.

Stage 4: Retrospective evaluation, where data permit. Use historical events and verified records to examine forecasting performance, warning lead time, decision timing, and communication outcomes. Any such analysis would require appropriate data and a defined methodology.

Stage 5: Operational assessment. If authorized and feasible, evaluate a limited pilot under institutional supervision before considering wider implementation.

Stage 6: Review and revision. Compare observed results with predefined objectives and revise the framework accordingly.

This future research plan would provide evidence on feasibility and performance. It should not be represented as completed validation.

9. Conclusion

Artificial intelligence offers important opportunities to strengthen multi-hazard early warning systems through improved observation analysis, forecasting support, risk

assessment, and communication. However, the effectiveness of an early warning system depends on the complete process through which information becomes protective action.

Pakistan's National Disaster Risk Reduction Strategy 2025–2030 already documents commitments to multi-hazard risk reduction, technological innovation, centralized risk information, and early warning. International guidance likewise provides established principles for integrating AI into warning systems. The research challenge is therefore not simply to propose another AI platform, but to determine how existing and emerging capabilities can work together effectively.

This paper proposes a Risk-to-Action Integration Framework that connects hazard information, AI-assisted analysis, impact assessment, authorized decisions, warning dissemination, anticipatory action, and evaluation. It is intended as a conceptual synthesis for further examination in Pakistan's institutional context.

The framework has not been implemented or validated, and this paper does not claim to have established an entirely novel approach. Its practical value will depend on further comparison with existing operational procedures, consultation with relevant authorities, availability of appropriate data, and future evaluation.

Ultimately, AI should be treated as a supporting capability within a people-centred disaster-management system. Its success should be judged not only by whether it improves predictions, but also by whether reliable and timely information helps responsible authorities and exposed communities take appropriate protective action.

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PARTICIPANT RESEARCH PAPER

Disaster Risk Reduction Strategies for GLOF Risk Management in Gilgit-Baltistan

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Abstract

Glacial Lake Outburst Floods (GLOFs) pose a growing threat to lives, livelihoods, infrastructure, and ecosystems in Gilgit-Baltistan (GB), Pakistan, due to glacier retreat, rising temperatures, and the formation of unstable glacial lakes. This study reviews disaster risk reduction (DRR) strategies for GLOF risk management in GB, focusing on hazard exposure, community vulnerability, existing interventions, and institutional challenges. A desk-based review of government documents, United Nations Development Programme (UNDP) project reports, scientific studies, and published sources from 2010 to 2026 was conducted. The findings highlight the importance of community-based early warning systems, structural protection measures, hazard mapping, and local preparedness. However, recurring GLOF events, including the Shishper Glacier outbursts and the 2025 floods in Ghizer, reveal persistent gaps in early warning communication, project implementation, geographical coverage, system maintenance, and coordination among institutions. The study recommends low-cost, community-centred measures, including mosque loudspeaker protocols, designated local observers, evacuation plans, safe gathering points, regular preparedness drills, and improved communication between communities and disaster management authorities. It also emphasizes sustained glacier monitoring, transparent project reporting, and dedicated provincial funding. These measures align with the Sendai Framework for Disaster Risk Reduction and can strengthen community resilience and reduce future GOLF-related losses in GB.

Keywords: Glacial Lake Outburst Floods (GLOFs); Disaster Risk Reduction; Gilgit-Baltistan; Early Warning Systems; Community Resilience

1. Introduction

A Glacial Lake Outburst Flood (GLOF) happens when the natural dam holding back a glacial lake suddenly gives way and a huge volume of water rushes out. These dams are usually made of loose rock, soil or ice, so they are not built to last forever. Climate change is doing more than making the weather extreme. It is slowly reshaping the mountains as well. As glaciers retreat, meltwater collects in new and growing lakes, and one breach can send a wall of water, sediment and debris into a quiet valley.

The Hindu Kush Himalaya is losing ice at a growing pace. ICIMOD (2023) reports that glacier mass loss in the region was about 65% faster in the 2010s than in the 2000s. Pakistan is reported to have over 13,000 glaciers (Global Voices, 2026), and the Ministry of Climate Change (n.d.) notes that 3,044 glacial lakes have formed in Gilgit-Baltistan (GB) and Khyber Pakhtunkhwa (KP), 33 of which are assessed as prone to hazardous outburst. The Green Climate Fund and UNDP (n.d.) estimate that about 7.1 million people are at risk.

Life in GB depends on the small amount of flat land in glacier valleys, where people farm and build their homes. A GLOF therefore threatens far more than lives. It puts homes, roads and livelihoods at risk too. One heatwave-triggered GLOF, for example, destroyed farmland, the Hassanabad bridge and houses (Green Climate Fund & UNDP, n.d.). Still, as WWF (2026) points out, a hazard does not have to turn into a disaster. What matters is how well people are prepared, warned and supported before it strikes.

GLOF risk management in GB, however, still leans heavily on projects and remains uneven. UNDP (2022) reports that GLOF-II directly benefits communities in 24 valleys, a small number next to the thousands of glacial lakes in the region, and Global Voices (2026) notes that the project has run since 2017 without preventing disasters across GB. Pulling existing strategies together can show what works and what is missing, in line with the Sendai Framework priorities of understanding risk, strengthening governance and building resilience (UNDRR, 2015).

This paper reviews disaster risk reduction (DRR) strategies for GLOF risk management in GB. It is a desk study based on government and UNDP project documents, ICIMOD

reports and published research from 2010 to 2026. The focus is GB, and KP and engineering design details are outside its scope. The objectives are to:

1. describe GLOF hazard and exposure in GB;
2. assess the factors that make communities vulnerable;
3. evaluate structural and non-structural DRR strategies;
4. identify scientific and institutional gaps; and
5. recommend policy measures aligned with the Sendai Framework.

2. Literature Review

2.1 Hazard and exposure

Around the world, glacial lakes are multiplying, and that has changed how GLOF risk is understood. Taylor et al. (2023) found that the number, area and volume of glacial lakes have risen by about 53%, 51% and 48% since 1990, and that roughly 15 million people are exposed to potential GLOFs. High Mountain Asia is the most exposed region, and India, Pakistan, Peru and China together hold more than half of the exposed population. What stands out in their study is that danger depends less on how many lakes there are and more on how many people live nearby and how well they can cope. Earlier work on the societal impacts of outburst floods points the same way (Carrivick & Tweed, 2016), and satellite records confirm how quickly glacial lakes have grown (Shugar et al., 2020).

In GB the picture is just as serious. The Karakoram has a long record of ice-dammed lakes and outburst floods (Hewitt & Liu, 2010). Mazhar et al. (2024) mapped lake changes in Ghizer between 2000 and 2023 and reported about 24 GLOFs in roughly 200 years, while Iqbal and Nisar (2023) used geospatial techniques to mark hazard zones and the people and assets at risk in Hunza-Nagar. Mapping has clearly improved, but it mostly covers single valleys and depends on satellite and secondary data.

2.2 Community vulnerability and perception

Vulnerability in GB is closely tied to scarce farmland and mountain livelihoods. In Hassanabad, Karim (2019) found that 74.1% of respondents had lost significant cultivable land to GLOFs, and that households coped by leaning more on social and human capital, with indigenous knowledge and religious practices also shaping their response. Awareness of the cause is high. Butt et al. (2025) found that 98.15% of

respondents in the Upper Indus Basin saw climate change as a major contributor to GLOFs, and 78.70% had faced frequent floods in the past ten years, yet the authors still call for hazard management guidelines aligned with international standards. Communication is another weak spot, since a study of Pakistani newspapers found little sustained attention to risk reduction compared with the scale of the threat (Dawn, 2026).

2.3 DRR strategies: early warning and protective works

Early warning is the main non-structural measure in GB. ICIMOD (2022) concluded that the Community Based Flood Early Warning System gives real-time warning and enough lead time, and that involving stakeholders from the start is key to its adoption and sustainability. The national response is led by the Ministry of Climate Change and UNDP through GLOF-I and GLOF-II. GLOF-II, funded by the Green Climate Fund, scales up GLOF-I (2011 to 2016) to 24 valleys by combining institutional strengthening, community-based early warning and long-term adaptation (UNDP, n.d.; UNDP, 2022). On the structural side, it plans at least 250 small works such as tree plantation, controlled drainage, mini dams, gabion walls and check dams (UNDP, 2022). Evidence on how well these systems perform is mixed, though. Reporting for Al Jazeera (n.d.) found that some villagers distrust the installed equipment, which suggests that trust and maintenance matter as much as technology.

3. GLOF Events and Responses from 2019 Onwards

In 2019, GLOF-II was still in its early phase, busy with needs assessments, a baseline study and knowledge, aptitude and practices (KAP) studies (UNDP, 2022). The glaciers did not wait for the paperwork to finish. That June, the Shishper Glacier lake in Hunza grew to 0.32 km² and breached, and it breached again on 29 May 2020 (Ali et al., 2024). The lake existed because the glacier had begun to surge in 2018 and blocked the river (Muhammad et al., 2025). By 2021, the project had completed the purchase of early warning equipment for the 24 target valleys and trained more than 150 district officials, but the equipment had not yet reached Pakistan (UNDP, 2022).

The year 2022 was the most damaging of the period. On 7 May, the Shishper GLOF destroyed the Hassanabad Bridge on the Karakoram Highway and damaged homes, buildings and hydropower facilities (Muhammad et al., 2025), just after Pakistan’s hottest

April since 1961 (EcoWatch, 2022). Ali et al. (2024) linked a 2.73 °C temperature rise that year to the lake expansion before the outburst. In July, a prolonged heatwave damaged link roads across several districts and washed away the only bridge serving eight villages in Badswat, Ishkoman (Dawn, 2022). The project brief of December 2022 shows that the full equipment was only delivered that year, while risk assessments, GIS hazard mapping and structures such as check dams were still planned (UNDP, 2022). No major GB flood was documented in the sources reviewed for 2023, and research that period focused on mapping and monitoring. Muhammad et al. (2025) showed that Shishper filled and drained in six phases, with a lake of up to 33.7 million m³ forming in four consecutive years, so the hazard can outlast the surge itself.

Then came August 2025. A GLOF in Gupis Valley, Ghizer, destroyed over 330 houses across at least six villages on 22 August (The Watchers, 2025), and at least 200 people were rescued as heavy rain was followed by outbursts that created two large lakes (Dawn, 2025a). The disaster was made worse by pre-monsoon rain and upstream water releases (Global Voices, 2025). Reports say a local shepherd's warning saved lives, while formal alert systems failed to give warnings people could act on (The Watchers, 2025). The 2026 season has followed a similar pattern with one encouraging difference. The Pakistan Meteorological Department (PMD) warned of rising GLOF threats during an extended heatwave (Daily Pakistan, 2026), and its system picked up a surge from the Hisper catchment, which let authorities alert downstream villages in time (ProPakistani, 2026a). Even so, a GLOF on 8 July caused flash floods and riverbank erosion in Ishkoman, in a district that had already suffered severe floods in 2022 and 2025 (Community World Service Asia, 2026).

4. Why These Events Happen

Three explanations come up again and again. Surging glaciers block valleys and form unstable ice-dammed lakes that fill and drain repeatedly (Muhammad et al., 2025). Heat is usually the trigger, as in the heatwaves of 2022 and 2026 (Ali et al., 2024; Community World Service Asia, 2026). And rainfall and exposed infrastructure turn a hazard into a disaster, because roads, bridges, farmland and homes sit in narrow valleys right in the

flood's path (Global Voices, 2025). This agrees with Taylor et al. (2023), who found that exposure and the ability to cope matter as much as the hazard.

5. Gaps Identified

The reviewed sources point to several gaps. These are an interpretation of the evidence, not statements made by the original authors.

Delivery delays. GLOF-II was approved in October 2016, but by 2017 the first tranche had not arrived (Green Climate Fund [GCF], 2017). The project became operational in July 2018 and the equipment arrived in 2022, after several damaging events, with risk assessments and protective works still pending (UNDP, 2022).

Limited coverage. GLOF-II covers 24 valleys (UNDP, n.d.), while more than 3,000 glacial lakes exist and 33 are considered hazardous (UNDP, 2022).

Weak link between warning and action. Systems exist, but trust, maintenance and last-mile response remain problems (Al Jazeera, n.d.; The Watchers, 2025).

Short projects, long hazards. Surge-dammed lakes can stay dangerous for years (Muhammad et al., 2025), yet projects run on fixed cycles.

Governance and finance. Pakistan has limited direct access to Green Climate Fund resources, relies on international intermediaries and faces overlapping ministry mandates that slow implementation (Climate Finance in Pakistan, 2025).

6. Practical Strategies and Policy Measures

The strategies below are meant to be low in cost and easy to start in GB. Most build on what communities and authorities already do. They are recommendations drawn from the evidence above, not measures tested in the cited studies.

6.1 Mosque loudspeaker protocol. Villagers used the mosque loudspeaker to warn each other in Ghizer in 2025 (The Friday Times, 2025), and authorities used mosque and Imambargah announcements in the Hisper-Hoper area in 2026 (ProPakistani, 2026a). Each vulnerable village could write down who triggers the announcement, who is the backup, and what the standard message is.

6.2 A direct line for local watchers. A shepherd's phone call helped save lives in Roshan (Dawn, 2025b), yet no real-time link connects village "human sensors" to rescue

teams (Al Jazeera, n.d.). A recognised list of shepherds and guides, with district disaster authority and Rescue 1122 numbers and a WhatsApp group, would help. Since signals can fail (The Friday Times, 2025), a handheld radio or whistle code is a sensible backup.

6.3 Starter kits for valleys outside the big projects. Roshan was reported to be outside the government and UNDP GLOF projects (Pamir Times, n.d.). A hand siren, painted river-level markers, an evacuation map and a contact list are cheap first steps, and LUMS researchers are exploring low-cost, off-grid IoT warning systems for the next stage (APNIC Foundation, n.d.).

6.4 Watchers at bridges and crossings. Monitoring teams were placed at key bridges and river crossings in June 2026 (ProPakistani, 2026a). Doing this routinely from May to August, when the Shishper lake peaked and drained (Muhammad et al., 2025), would also protect the Karakoram Highway.

6.5 Alert-triggered village checklists. The PMD and NDMA already issue heatwave and GLOF alerts, and Rescue 1122 advises people to avoid rivers and glacier areas (ProPakistani, 2026b). Each alert could trigger a short checklist: move livestock and campers away from rivers, test the siren and phone tree, and keep vehicles fuelled.

6.6 Alerts for travellers and tourists. Hotels, check posts and petrol stations along the Karakoram Highway could show a simple alert board and receive WhatsApp broadcasts from the district administration, building on the tourist advisories already issued (ProPakistani, 2026b).

6.7 Safe gathering points outside the flood path. In Ghizer in 2025, a mosque, a school, a Jamat Khana and a bridge were submerged (Dawn, 2025b). Using existing hazard maps (Mazhar et al., 2024; Iqbal & Nisar, 2023), each village can mark higher ground for gathering and store basic supplies there, and GLOF-II's community disaster management centres should be checked against flood paths (UNDP, 2022).

6.8 Local knowledge, women and youth. A village "hazard book" recording past floods, early signs and safe routes would cost almost nothing, and a GB researcher argues that community expertise belongs in warning-system planning (Pamir Times, n.d.). Women have already joined mock drills (UNDP, n.d.), and schools and youth groups could run short yearly drills. Practices such as glacier grafting, documented under GLOF-II (UNDP,

2022), should be recorded rather than promoted, since their protective effect is not established in the sources reviewed.

At the policy level, four measures follow from the gaps above: fixed delivery milestones with public yearly reporting; long-term glacier and lake monitoring held by a permanent agency such as the PMD, not only by projects; a coordinating body and provincial budget line so monitoring survives after donor funding ends (Climate Finance in Pakistan, 2025); and formal inclusion of community warning systems in official plans (Pamir Times, n.d.). Table 1 shows how these actions fit the Sendai Framework (UNDRR, 2015).

Table 1. Fit of the proposed actions with the Sendai Framework priorities

Sendai priority	**Actions in this paper**
1. Understanding disaster risk	Bridge and crossing watchers (6.4); local hazard book (6.8); long-term glacier monitoring
2. Strengthening risk governance	Direct line for watchers (6.2); alert-triggered checklists (6.5); delivery milestones; coordination body
3. Investing in resilience	Starter kits (6.3); safe gathering points (6.7); provincial budget line
4. Enhancing preparedness	Loudspeaker protocol (6.1); traveller alerts (6.6); yearly drills (6.8)

7. Conclusion

GLOFs in GB are not a distant threat. Since 2019 the Shishper lake has breached repeatedly, Ghizer has flooded three times, and the damage keeps reaching bridges, roads, farmland and homes. The evidence suggests that people are saved less by expensive equipment than by systems that communities trust and that connect villages to the authorities. Delivery delays, thin coverage and short project cycles remain the main

weaknesses. The practical steps proposed here are modest in cost, build on existing practice and fit the Sendai Framework, which makes them realistic starting points for stronger GLOF risk management in GB.

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PARTICIPANT RESEARCH PAPER

Hill Torrent and Flash Flood Risk in Dera Ismail Khan District: Hazard Mapping, Early Warning, and Anticipatory Action

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Abstract

Hill torrents, known locally as Zams, are seasonal channels that carry intense monsoon runoff from the mountains onto the plains of Khyber Pakhtunkhwa. In Dera Ismail Khan (D.I. Khan) district, steep catchments, heavy rainfall, and dense settlement near torrent outlets combine to produce rapid flash floods that leave communities little time to respond. This paper reviews regional evidence on the hazard and examines how hazard mapping, impact-based early warning, and anticipatory action can reduce its consequences. Reported figures indicate that approximately 68,400 hectares were inundated in July 2026 and that about one quarter of the district falls within the high-risk class. The analysis finds that warnings often describe river conditions rather than local impacts, that community resilience is more assumed than measured, and that the research base for torrent management is thin. The paper argues that hill torrents should be managed as a water resource as well as a hazard, through integrated watershed planning, retention structures, and people-centred warning. Recommendations address governance, data, and community participation.

Keywords: hill torrents; flash floods; early warning; anticipatory action; hazard mapping

1. Introduction

Pakistan experiences recurrent flooding, and a significant share of it originates in the mountains rather than in its major rivers. Hill torrents collect runoff from steep, sparsely vegetated catchments and deliver it to the plains within hours (Figure 1). Because many channels are unmonitored, communities below them often receive little warning (Hill torrent flooding explainer, n.d.).



Figure 1. Hill torrent in flood in the study area

Water scarcity compounds the problem. Pakistan ranks among the countries with the most severe water shortages, and per-person water availability is projected to fall to about 809 cubic metres a year by 2025 (Bakhsh et al., 2014, as cited in Mubeen, Year). Water that leaves the hills during floods is therefore lost at the moment the country most needs it.

D.I. Khan is a suitable case because it combines both conditions. The district lies where the Gomal and Indus rivers meet, receives runoff from several major torrents, and was among the most severely affected areas in the 2022 floods (Regional reporting on the 2022 floods, n.d.). This paper pursues four objectives: to describe the hazard and its regional context; to assess risk and vulnerability; to examine early warning and anticipatory action; and to recommend integrated, evidence-based policy measures.

Four findings emerge. The hazard is severe and concentrated in identifiable zones. Current warnings describe river conditions rather than local impacts. Community resilience is assumed more than documented. Fragmented institutions slow the path from forecast to action. The study relies on secondary sources and includes no new field data; recent mapping figures are used as published, with their limitations noted.

2. Regional Context and Hazard Profile

Around 55 percent of Pakistan's land area is drained by hill torrents, which carry an average annual runoff of about 12.15 million acre-feet (NESPAK, 1995, as cited in Mubeen, Year). Studies of fourteen major torrents estimate a potential yield of around 23 billion cubic metres per year (Sufi et al., 2011, as cited in Mubeen, Year). Figure 2 shows how a torrent system works: the catchment feeds the Zam, which carries flood water to riverine channels and fields, while check dams (ghabr) can slow and spread it.



Figure 2. Anatomy of a hill torrent (Zam) system

Three terms structure the analysis. A hazard is a potentially damaging physical event, here intense torrent flow. Exposure refers to people, livelihoods, and assets where that hazard can reach them. Vulnerability describes characteristics that make exposed elements susceptible to harm, such as poverty, dependence on rain-fed farming, or weak housing (United Nations Office for Disaster Risk Reduction [UNDRR], 2017). Risk results from the combination of the three, so lowering any one of them reduces risk (Intergovernmental Panel on Climate Change [IPCC], 2012).

Storage is the second constraint. Figure 3 compares per-person storage capacity, which is far lower in Pakistan than in comparable countries. Regional observations also indicate that South Asian rainfall is becoming shorter, sharper, and more intense (World Meteorological Organization [WMO], n.d.), which makes torrent floods harder to predict.

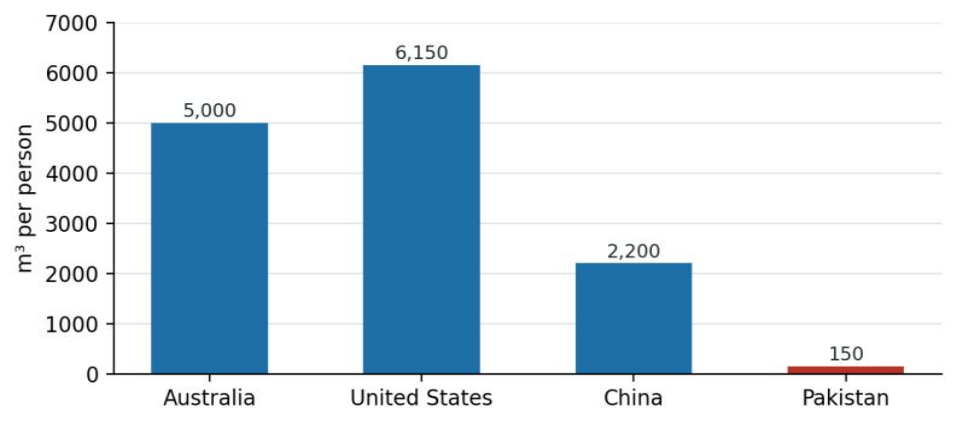
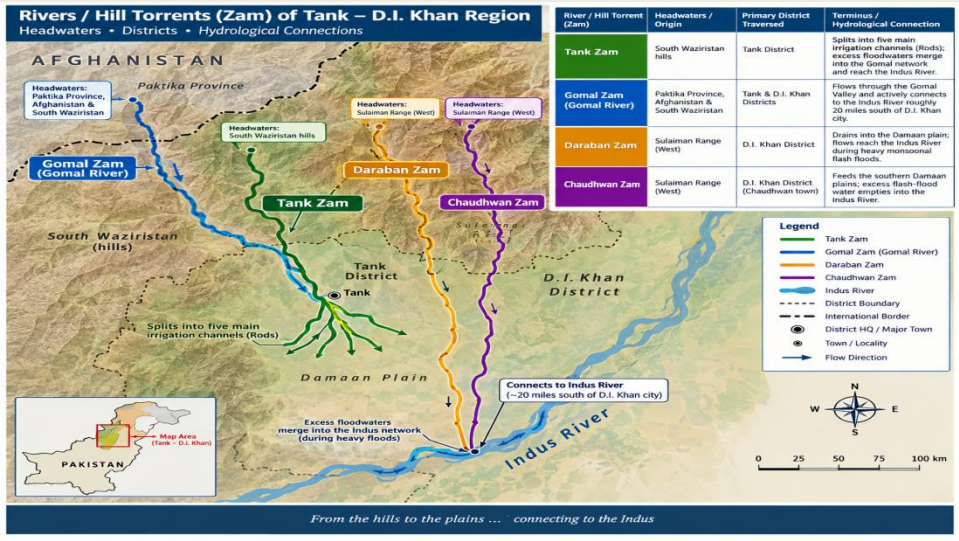


Figure 3. Per-person water storage capacity (m³)

Note. Data from Amin and Han (2009) and Qureshi (2011), as cited in Mubeen, Year.

3. Study Area, Risk and Vulnerability

D.I. Khan is fed by several Zams, including the Gomal, Tank, Sheikh Haider, Daraban, and Chaudhwan torrents, which drain the western mountains onto the plains (Figure 4). The Gomal Zam is the largest and now has a major dam. Neighbouring areas such as Tank, Dadu, and Jhal Magsi are also affected by hill torrent floods.



River / Hill Torrent (Zam)	Headwaters / Origin	Primary District Traversed	Terminus / Hydrological Connection
Tank Zam	South Waziristan hills	Tank District	Splits into five main irrigation channels (Rods); excess floodwaters merge into the Gomal network and reach the Indus River.
Gomal Zam (Gomal River)	Paktika Province, Afghanistan & South Waziristan	Tank & D.I. Khan Districts	Flows through the Gomal Valley and actively connects to the Indus River roughly 20 miles south of D.I. Khan city.
Daraban Zam	Sulaiman Range (West)	D.I. Khan District	Drains into the Damaan plain; flows reach the Indus River during heavy monsoonal flash floods.
Chaudhwan Zam	Sulaiman Range (West)	D.I. Khan District (Chaudhwan town)	Feeds the southern Damaan plains; excess flash-flood water empties into the Indus River.

Figure 4. Rivers and hill torrents (Zams) of the Tank–D.I. Khan region

WWF-Pakistan's flood mapping shows the scale of the July 2026 event. Figure 5 compares the March and July 2026 maps. The mapping estimates that approximately 68,400 hectares were inundated, affecting 29,761 hectares of cropland and exposing

85,961 people (WWF-Pakistan, 2026). These figures describe one event and are not an annual average.

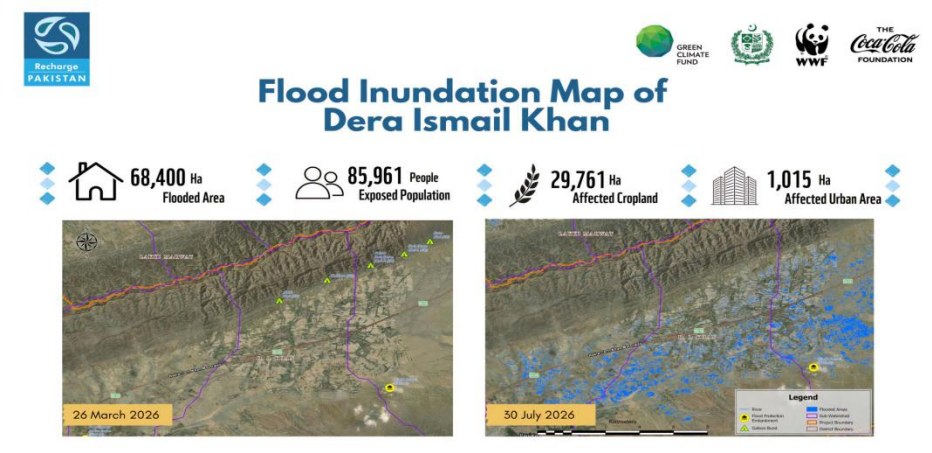


Figure 5. Flood inundation maps for D.I. Khan, March and July 2026 WWF-Pakistan (2026)

A 2026 spatial study combining remote sensing, GIS, and the Analytic Hierarchy Process classifies the district into three risk zones: about 24.68 percent of the area (1,808.87 km²) is high risk, 59.58 percent moderate, and 15.74 percent low ([Author(s)], 2026). Hotspots lie where steep slopes, heavy rain, and torrent proximity overlap with dense union councils. Figure 6A shows the zones. Figure 6B shows a canal breach in September 2026, which spilled water into nearby settlements in Paharpur Tehsil (Author, 2026), adding an infrastructure risk to natural flooding.

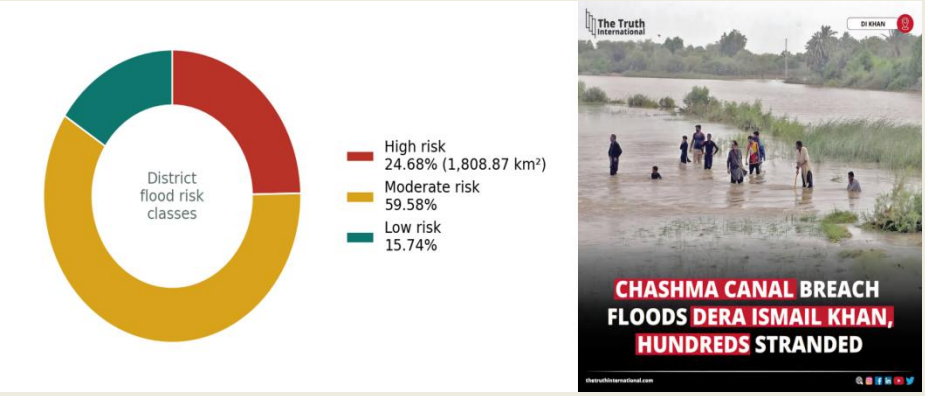


Figure 6 *Flood risk zones (A) and canal breach reporting (B)*

Impacts extend beyond the flood itself. Inundated cropland reduces household food supply and income, and damaged canals disrupt the next irrigation season. Livestock losses remove a household's most liquid asset, which can push poor families into debt. The sources reviewed give little analysis of gender. Women's mobility, access to warnings, and roles in livestock care and water collection are likely to shape who can evacuate and who recovers slowly. This is identified as a priority for further research.

4. Community Resilience Factors

Communities here have long adapted to torrent flow. Spate irrigation, known locally as rod-kohi, uses torrent water to cultivate land and reflects detailed local knowledge of flow patterns (Mubeen, Year). Mubeen argues that spate systems hold substantial untapped potential, yet farm productivity in them remains low. Kinship ties and informal knowledge of safe routes can also speed response, although the sources describe these networks only in general terms.

A critical reading suggests that resilience is more assumed than measured. Strengthening it would require recording local knowledge, identifying community institutions that already perform warning and response roles, and linking them to formal systems.

5. Scientific and Institutional Gaps

Research on hill torrent management is limited. Mubeen notes that Pakistan has no established research system on hill torrent water management or spate irrigation (Mubeen, Year). Data availability is the central constraint. Widely cited runoff estimates date from 1995 and 2011 (NESPAK, 1995; Sufi et al., 2011, as cited in Mubeen, Year), and the sources do not show how often they are updated. Flood maps built from remote sensing also need ground validation before they can guide design.

Technical tools exist but are not documented locally. Hydraulic models such as HEC-RAS 2D can trace where torrent water will move across the plains (Regional technical summary, n.d.). The sources do not report their use in D.I. Khan, nor do they discuss artificial intelligence or machine learning for flood prediction. Institutional roles are also fragmented across the National Disaster Management Authority, the Pakistan Meteorological Department, provincial irrigation departments, and local government. The

chain from forecast to community action slows when no single body is accountable for linking them.

6. Mitigation Strategies and Best Practices

Retention areas capture fast-moving torrent flow, reduce its force downstream, and allow water to recharge groundwater for dry-season use (Recharge Pakistan, n.d.). The Recharge Pakistan project plans nine large and 42 small retention areas across Khyber Pakhtunkhwa, Sindh, and Balochistan, a figure to confirm against official documentation. Mubeen proposes channelling torrent water into spate basin irrigation systems designed for local geography (Mubeen, Year). Non-structural measures address the human side of risk: watershed management reduces runoff at source, floodplain management limits construction in exposed zones, and shelters and pre-positioned supplies shorten response time.

These measures are most effective in combination. A retention area without warning, or a warning without a plan to act, delivers only part of the benefit.

7. Risk Communication and Early Warning

Traditional alerts describe the hydrological state of a river, such as its discharge, without explaining whether a particular village or field will flood. Impact-based early warning fills this gap by turning forecasts into local advice. An example message reads: “The bridge connecting your village will likely submerge. Relocate livestock and families to the nearest designated shelter immediately” (Pakistan Meteorological Department [PMD], n.d.).

Figure 7 shows the warning chain, from forecast to hydraulic model, impact map, local message, and community action. Each link adds value only if the next link acts on it. Messages must reach households through trusted channels and in local languages, including Pashto and Urdu, and must reach women and older people who may have less access to phones or public meetings. These recommendations follow from people-centred warning principles and should be tested locally.

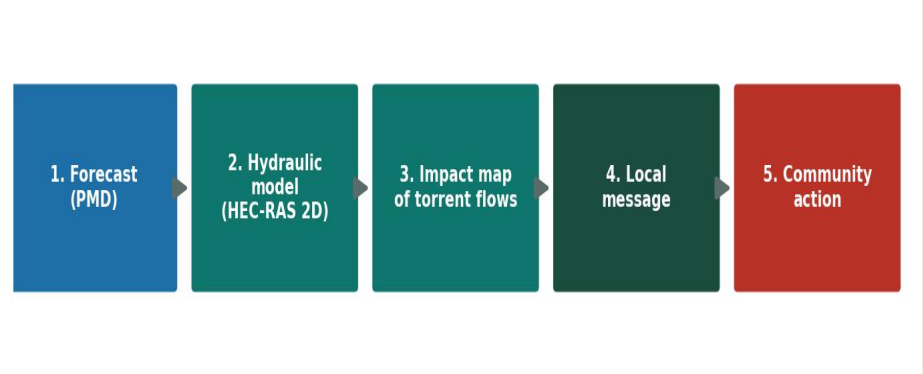


Figure 7. The impact-based warning chain

Note. Adapted from PMD impact-based warning practice and hydraulic modelling as described in regional sources (PMD, n.d.).

8. Policy Recommendations

The recommendations below follow from the analysis in Sections 2 to 7. The suggested leads are proposals for discussion, not assigned responsibilities.

Table 1. Policy recommendations and suggested leads

No.	Recommendation	Addresses	Suggested lead
1	Create a single coordinating mechanism for each torrent catchment, spanning mountain and plain areas	Fragmented institutions	Provincial disaster authority
2	Make impact-based warnings the standard for torrent areas, developed with communities	Warnings that describe rivers	PMD with local authorities
3	Set forecast triggers and pre-committed funds, and review performance after each event	Slow response	NDMA with provincial partners
4	Pilot spate basin and retention systems in selected union	Water loss and	Irrigation departments with

No.	Recommendation	Addresses	Suggested lead
	councils, with groundwater and crop monitoring	scarcity	research institutes
5	Fund updated flow measurements, ground validation, and gender-disaggregated vulnerability studies	Data gaps and social blind spots	Universities and government research bodies

Note. Recommendations derive from Sections 2 to 7. Suggested leads are proposals for discussion.

9. Conclusion

Hill torrents in Dera Ismail Khan combine a severe physical hazard with high exposure and uneven vulnerability. Mapping shows where risk is concentrated, and reported inundation shows what is at stake. The current response, however, relies on warnings that describe rivers rather than consequences, on resilience that is assumed rather than measured, and on a research base too thin for confident planning. Science-based planning, documented local knowledge, technology that turns forecasts into action, and integrated watershed management can together reduce this risk. Hill torrents can be managed as a water resource as well as a hazard, provided institutions act on the evidence before the water arrives.

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PARTICIPANT RESEARCH PAPER

Climate Change as a Key Driver of Increasing Disaster Risk: Lessons from Pakistan's 2022 Floods

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Abstract

Climate change is influencing the intensity of some weather-related hazards, while social and institutional conditions determine whether these hazards become disasters. Pakistan's 2022 monsoon floods illustrate this interaction. The floods affected approximately 33 million people and caused estimated damage exceeding US$14.9 billion, economic losses of about US$15.2 billion, and recovery and reconstruction needs of at least US$16.3 billion. Attribution research found evidence that human-caused warming intensified extreme five-day rainfall in Sindh and Balochistan, although uncertainty remained substantial in quantifying the climate-change contribution to the wider 60-day monsoon rainfall across the Indus basin. This paper examines the hazard profile, socioeconomic vulnerability, community resilience, and scientific and institutional gaps shaping disaster risk in Pakistan. It argues that disaster losses cannot be explained by climate hazards alone: settlement patterns, poverty, fragile livelihoods, infrastructure deficits, land and water management, and unequal access to warnings and resources also influence outcomes. The paper recommends people-centred early-warning systems, risk-informed land-use planning, resilient infrastructure, climate-smart livelihoods, stronger local disaster institutions, and sustained adaptation finance. A Global South approach should combine scientific forecasting with community knowledge and locally led implementation.

Keywords: adaptation, climate change, disaster risk reduction, early warning, Pakistan

1. Introduction

Climate change is reshaping disaster risk by influencing the frequency, intensity, duration, and location of some extreme events. Yet a hazard does not automatically become a disaster. Disaster risk emerges through the interaction of hazard, exposure, vulnerability, and capacity: intense rainfall becomes more destructive where people and assets occupy flood-prone areas, housing and infrastructure are weak, livelihoods are insecure, and institutions cannot deliver timely protection. This distinction is central to climate change adaptation and disaster risk reduction (DRR).

Pakistan is exposed to multiple climate-related hazards, including intense monsoon rainfall, riverine and flash floods, heatwaves, drought, glacial hazards, and water stress. The 2022 floods revealed how an extreme event can compound existing development challenges. The Post-Disaster Needs Assessment (PDNA) estimated damages above US$14.9 billion, economic losses of approximately US$15.2 billion, and at least US$16.3 billion in resilient recovery and reconstruction needs (Government of Pakistan et al., 2022).

This paper assesses how climate change interacts with vulnerability to increase disaster risk in Pakistan, using the 2022 floods as its central case study. It identifies exposure and vulnerability factors, considers community resilience and institutional gaps, and recommends practical adaptation and DRR measures relevant to Pakistan and other Global South contexts. The analysis draws on event-attribution research, official post-disaster assessment, and international climate-risk literature.

2. Regional Context and Hazard Profile

Pakistan’s geography creates a diverse hazard profile. The Indus River system supports major population centres, agriculture, and economic activity, while monsoon rainfall can generate riverine flooding, urban inundation, and flash floods. In northern mountain regions, glacier melt, glacial lake outburst floods, landslides, and changing snow and ice conditions create additional risks. Heatwaves and drought affect health, water availability, energy demand, and agricultural productivity. These hazards can interact rather than occurring in isolation.

The Intergovernmental Panel on Climate Change (IPCC) concludes that climate risks in Asia are increasing and that adaptation must account for physical hazards and underlying

socioeconomic vulnerability (IPCC, 2022). In 2022, exceptional monsoon rainfall caused severe impacts, especially in Sindh and Balochistan. Attribution must nevertheless be expressed carefully. Otto et al. (2023) found that most models and observations they assessed indicated that extreme five-day rainfall over Sindh and Balochistan had become heavier as the climate warmed. The study also highlighted substantial uncertainty in quantifying the influence of human-caused climate change on the broader 60-day rainfall across the Indus basin. The floods should not be described as being caused by climate change alone.

The disaster-risk framework distinguishes four connected concepts. A hazard is a potentially damaging event, such as extreme rainfall or flooding. Exposure refers to people, homes, infrastructure, and livelihoods located in areas that may be affected. Vulnerability describes conditions that make exposed people or assets more susceptible to harm. Capacity includes the skills, resources, institutions, infrastructure, and networks available to anticipate, respond to, and recover from impacts. Risk increases when severe hazards intersect with high exposure and vulnerability and limited capacity.

3. Risk and Vulnerability Assessment

The 2022 floods affected around 33 million people and caused more than 1,730 deaths, according to the joint PDNA and associated World Bank reporting (Government of Pakistan et al., 2022; World Bank, 2022). Housing, agriculture and livestock, and transport and communications were among the hardest-hit sectors. Disaster losses extend beyond immediate deaths and physical damage: they interrupt schooling, health services, markets, employment, transport, and access to clean water and sanitation.

Rural households dependent on crops, livestock, daily wages, or informal work can lose both immediate income and the assets needed to recover. Crop losses can reduce household food availability while affecting food supply and prices. Damaged roads and bridges make it harder to reach markets, clinics, and evacuation points. When homes are destroyed, families may face prolonged displacement, debt, insecure shelter, and heightened exposure to disease. Recovery can be especially difficult for households with limited savings, insurance, formal employment, or access to credit.

Vulnerability is unevenly distributed. Poverty limits the ability to build safer housing, relocate, store food, or recover without borrowing. Women and girls may face additional

barriers to receiving warnings, evacuating safely, accessing health care, and using sanitation facilities in temporary shelters. Older people, people with disabilities, children, landless labourers, and socially marginalised groups may have fewer options for evacuation or recovery. These are not inherent weaknesses in these groups; they reflect unequal access to resources, decision-making, information, and services.

Exposure also reflects planning and governance choices. Settlements and infrastructure located in floodplains, drainage corridors, or poorly protected areas can experience repeated losses. Inadequate drainage, weak construction, environmental degradation, and fragmented water and land management may magnify heavy rainfall impacts. Otto et al. (2023) identify settlement and infrastructure proximity to floodplains, inadequate infrastructure, limited prior risk-reduction capacity, poverty, and socioeconomic inequalities among factors contributing to the severity of impacts. Reducing disaster risk therefore requires development planning as well as climate adaptation.

A critical implication is that rebuilding damaged assets to their previous standard can reproduce risk. Recovery should instead apply risk-informed siting, stronger building standards, safe access routes, reliable water and sanitation, and livelihood protection. Relocation or land-use restrictions must be developed with affected communities, provide fair alternatives, and avoid transferring risk or costs to poorer households.

4. Community Resilience Factors

Community resilience depends on the ability of people to organise, share information, mobilise resources, and maintain essential functions during and after a shock. Local knowledge can help identify flood pathways, seasonal changes, safe routes, elevated ground, and households requiring assistance. Neighbourhood networks, local organisations, volunteers, and trusted community leaders can support evacuation, temporary shelter, food distribution, and recovery.

However, community resilience should not substitute for public responsibility. Informal networks may be under-resourced or unable to protect people against large-scale floods. Participation is most effective when it informs official planning, receives practical support, and includes women, people with disabilities, tenants, landless workers, and other groups whose needs may be overlooked. Participatory hazard mapping, community drills, locally

understandable warnings, and small grants for risk-reduction activities can connect local knowledge with scientific and institutional capacity.

5. Scientific and Institutional Gaps

Effective adaptation depends on reliable data and the ability to convert forecasts into action. Challenges can include uneven observation coverage, limited local-scale forecasting, incomplete exposure and vulnerability data, fragmented information sharing, and gaps between national warnings and community-level response. Flood risk also changes as settlements, infrastructure, and land use change; hazard maps and contingency plans therefore require regular updating.

Artificial intelligence and machine-learning tools may help analyse satellite imagery, rainfall patterns, river levels, and damage reports. However, they cannot replace dependable observations, transparent validation, local expertise, and clear accountability. Models trained on incomplete or biased data can misrepresent risk in poorly monitored districts. Technology should be used where it demonstrably improves decisions, with human oversight and non-digital warning channels for people without reliable internet or smartphones.

Institutional coordination is equally important. Forecasting agencies, disaster management authorities, local government, water and irrigation departments, health services, and community organisations need agreed roles and interoperable information. The challenge is not simply the absence of technology; it is often the difficulty of linking risk information to land-use decisions, evacuation resources, public investment, and accountable local action.

6. Adaptation Strategies and Relevant Practices

Pakistan’s adaptation strategy should combine structural measures with non-structural and nature-based approaches. Structural measures include climate-resilient bridges and roads, safer schools and health facilities, improved urban drainage, flood-resistant housing, and protection of critical water and energy systems. These investments should be based on updated hazard assessments and designed for future conditions rather than historical averages alone. Engineering works must also be assessed for downstream effects, maintenance needs, and the possibility of shifting flood risk to other communities.

Non-structural measures include risk-sensitive land-use planning, enforcing building standards, protecting floodplains and drainage routes, maintaining evacuation routes, and integrating climate risk into public investment decisions. In rural areas, climate-smart agriculture can include locally appropriate crop varieties, adjusted planting calendars, soil and water conservation, diversified livelihoods, and improved access to climate information. Watershed restoration, wetlands, floodplain management, and other nature-based solutions can complement engineered defences, provided they are locally suitable and do not displace communities or restrict essential livelihoods without fair consultation.

A Global South approach should be locally led, affordable, inclusive, and attentive to unequal historical responsibility for global emissions. Pakistan can learn from other developing countries, but interventions should not be copied without considering local hydrology, settlement patterns, institutions, and community priorities. International partnerships should support local technical capacity, open data, maintenance budgets, and long-term implementation—not only short-term emergency projects. The PDNA's call for resilient recovery provides a basis for applying 'build back better' principles to housing, agriculture, transport, and essential services (Government of Pakistan et al., 2022).

7. Risk Communication and Early Warning

An early-warning system reduces risk only when people receive, understand, trust, and can act on a warning. Pakistan should strengthen the chain from monitoring and forecasting to communication, evacuation, and post-warning support. Messages should explain the expected hazard, likely timing and location, level of urgency, safe actions, and where assistance is available. They should be issued in locally understood languages and through multiple channels, including mobile alerts, radio, local volunteers, and door-to-door communication.

Warnings should be people-centred and gender-sensitive. Plans must consider people who lack phones, electricity, transport, mobility, or literacy, as well as those who need assistance to evacuate. Local authorities should identify safe shelters, accessible routes, transport arrangements, and support for essential household assets where feasible. Community drills and post-event reviews can reveal whether warnings arrived in time and whether recommended actions were practical. Forecasts must be linked to pre-agreed

responsibilities and resources so warnings trigger action rather than merely communicate danger.

8. Policy Recommendations

First, integrate climate-risk information into district development plans, land-use decisions, infrastructure approvals, and public budgets. Floodplain development and drainage obstruction should be addressed through risk-based planning, fair enforcement, and viable alternatives for affected households. Second, strengthen multi-hazard early-warning systems and connect forecasts to locally resourced evacuation plans, accessible shelters, and community drills.

Third, direct adaptation funding toward vulnerable districts and communities, with transparent criteria and meaningful participation by women and marginalised groups. Fourth, invest in resilient housing, schools, health facilities, roads, drainage, water systems, and livelihood recovery, using future climate scenarios and maintenance plans. Fifth, improve the sharing of meteorological, hydrological, satellite, and local vulnerability data, while independently validating AI-supported tools and preserving non-digital communication options.

Sixth, strengthen coordination among national and provincial agencies, local government, research institutions, civil society, and communities through clear roles, shared protocols, and regular exercises. Finally, international climate finance and technology partnerships should be predictable, accessible, and aligned with locally identified priorities. Adaptation finance should help close the gap between the cost of resilience and the fiscal capacity of a highly exposed developing country, while ensuring transparent spending and measurable outcomes.

9. Conclusion

Pakistan’s 2022 floods demonstrate that climate change can intensify extreme weather risks, but the scale of disaster is also shaped by exposure, poverty, infrastructure, land and water management, and institutional capacity. Scientific attribution supports a climate-change influence on extreme five-day rainfall in the worst-affected provinces, while important uncertainty remains regarding the broader monsoon rainfall signal. Accurate communication of this evidence is essential for credible policy.

Reducing future losses requires a shift from reactive relief toward prevention, preparedness, and resilient recovery. Risk-informed planning, community-centred early warnings, resilient infrastructure, livelihood protection, and inclusive local governance should form the core of Pakistan's adaptation agenda. For Pakistan and other Global South countries, international finance and technology can contribute meaningfully when they strengthen local capacity and respond to locally defined needs. Climate resilience is not only a technical challenge; it is also a question of equitable development, public accountability, and whose safety is prioritised.

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PARTICIPANT RESEARCH PAPER

Integrating the Sustainable Development Goals and Disaster Resilience in Pakistan

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Abstract

Pakistan has long treated development and disaster management as separate files on separate desks. The 2022 floods showed what that division costs. This paper argues that the Sustainable Development Goals (SDGs) and disaster resilience must be planned, financed and measured as a single agenda. Drawing on the Sendai Framework, recent UN assessments and the 2022 Post-Disaster Needs Assessment, it examines how floods reverse progress on poverty, hunger, health, education and gender equality, and how Pakistan's institutions and communities handle that risk. The analysis finds that integration exists mostly on paper: budgets, early warning and local planning still run in parallel. Gaps in disaster-loss data, local capacity and last-mile communication keep the most exposed households, particularly women, at the back of the line. The paper recommends risk-informed development planning, protected resilience finance, women-led and community-based early warning, and shared SDG-Sendai indicators. Resilience, it concludes, is not a side project of the SDGs. It is the condition under which the Goals survive.

Keywords: Sustainable Development Goals; disaster resilience; Sendai Framework; early warning; Pakistan

1. Introduction

Every few years, Pakistan rebuilds what a flood has taken, and every few years the bill gets larger. The 2022 monsoon floods submerged about a third of the country and affected 33 million people. The post-disaster assessment put damages at over USD 14.9 billion and economic losses at about USD 15.2 billion, and it estimated that at least USD 16.3 billion would be needed to rebuild in a resilient way (Government of Pakistan, 2022). In 2025, the monsoon affected nearly seven million people and killed more than a thousand (Arab News, 2026). Behind each number is a school, a clinic, a harvest or a household pushed back down the ladder it had spent years climbing.

That is the problem this paper takes up. The 2030 Agenda for Sustainable Development and the Sendai Framework for Disaster Risk Reduction were agreed within months of each other and both expire in 2030, yet they are often run through separate ministries, budgets and reports (Willetts et al., 2023). Only about a third of SDG targets are making adequate progress, and nearly one in five has slipped below its 2015 baseline (Agence Française de Développement [AFD], 2025). Disasters are not the only reason, but they are one the world already knows how to reduce.

The purpose of this research is to argue that integration is a practical necessity, not a diplomatic nicety. Its objectives are to show how disaster risk undermines specific SDGs, to assess vulnerability and community resilience in Pakistan, to identify the gaps that hold integration back, and to propose workable policy measures. The scope is national, with the 2022 and 2025 floods as the main cases.

2. Regional Context and Hazard Profile

A few terms first. A hazard is a potentially damaging event, such as a flood. Exposure describes the people, homes and assets in its path. Vulnerability is the set of conditions, such as poverty or poor housing, that make exposure more harmful. Risk is what emerges when the three meet. Governments can rarely change a hazard, but they can change exposure and vulnerability, and that is exactly where the SDGs do their work.

Pakistan sits where monsoon systems, glaciers and active fault lines meet, and its own national authority describes the country as highly disaster prone (National Disaster Management Authority [NDMA], 2022). The 2005 earthquake pushed policy away from pure response and towards prevention, which led to the National Disaster Management

Act of 2010 and the National DRR Policy (NDMA, 2012). The hazard itself is changing. The 2022 floods followed heavy rain and melting glaciers (Arab News, 2022), and the 2025 monsoon arrived after a record spring heatwave. By mid-September 2025, about 972 people had died and more than 8,000 houses had been damaged or destroyed (Shelter Cluster, 2025).

The global picture points the same way. The 2025 Global Assessment Report puts direct disaster losses at roughly USD 200 billion a year, and above USD 2.3 trillion once cascading and ecosystem costs are counted (United Nations Office for Disaster Risk Reduction [UNDRR], 2025). The Sendai midterm review found progress on only two of its seven global targets (International Institute for Sustainable Development [IISD], 2023), and Pakistan's 2019 status report listed the difficulty of creating coherence between the global frameworks among its main challenges (UNDRR, 2019).

3. Risk and Vulnerability Assessment

Disasters do not strike evenly, and they do not stay inside one sector. Take livelihoods first. The 2022 assessment found that damage to agriculture spilled over into industry, trade and services, and that women lost livelihoods in agriculture and livestock to a notable degree (United Nations Development Programme [UNDP], 2022). In 2025, more than a million acres of farmland were inundated (Shelter Cluster, 2025). For a household that depends on one harvest, that is a year of food and income gone at once, which puts SDG 1 (No Poverty) and SDG 2 (Zero Hunger) at risk together. Both SDG 2 and SDG 11 already show little or no progress since 2015 (Earth.org, 2025).

The effects then travel. Flooded roads cut off clinics, standing water brings disease, and schools are damaged or turned into shelters. In 2025 alone, 239 bridges and nearly 675 kilometres of road were damaged (Shelter Cluster, 2025). These losses land on SDG 3, 4, 6 and 9, goals the latest UN review already finds behind schedule (AFD, 2025).

Vulnerability is not distributed by chance. The International Federation of Red Cross and Red Crescent Societies, reporting on the 2025 floods, stressed that women, children and other vulnerable groups were disproportionately affected (Arab News, 2026). The World Meteorological Organization (WMO) makes the underlying point plainly: the climate crisis is not gender neutral, because women and men experience hazards differently (WMO, 2024). Add settlement on floodplains, weak housing materials and households with thin

savings and little insurance, and a pattern emerges. The people development left behind are the first in the path of the water.

This is why integration is more than a slogan. Target 1.5 of the SDGs explicitly asks countries to build the resilience of the poor and reduce their exposure to disasters (United Nations, 2015). Every gap in poverty, housing, health or education is also a gap in disaster protection, and every disaster widens those gaps again.

4. Community Resilience Factors

Official systems rarely reach a flooded village first. Neighbours do. Experience from disasters in Pakistan and elsewhere suggests that kinship ties, local mosques, village elders and young volunteers move people and share food long before an agency arrives. This social capital is hard to measure and easy to overlook, yet it often separates a bad week from a lost year.

Communities also carry knowledge that no weather model holds. People who have lived beside a river for generations know which channels flood first and how high a floor or grain store must be raised. The Sendai Framework asks governments to combine traditional, indigenous and local knowledge with scientific knowledge when assessing risk (UNDRR, 2015). Treating that knowledge as data, not as a curiosity, would improve both hazard maps and public trust.

Participation is the third ingredient. Pakistan's National DRR Policy already provides for community-based disaster risk management (NDMA, 2012). What it needs is steady funding and real local authority, so that village committees are partners in planning and not only recipients of relief. Women need a seat in those committees, a point the Sendai Framework makes by calling for women's participation and leadership (UNDRR, 2015). Resilience, in the end, is the ability to absorb a shock, adapt before the next one and change the conditions that created the risk. Communities already do the first two surprisingly well. The third is the part that requires government.

5. Scientific and Institutional Gaps

Integration stalls mostly for institutional reasons, and for a few technical ones. Data comes first. The International Science Council (ISC, n.d.) has produced policy briefs on disaster-loss data and on the synergies among the Sendai Framework, the Paris Agreement and the SDGs. Where loss records are held by different agencies using

different methods, they cannot be compared with SDG indicators, and nobody can show a finance ministry that a flood-proofed school protected an education target.

Technology is often offered as the answer. Artificial intelligence and machine learning hold real promise for flood forecasting and satellite damage mapping, but these tools learn from records. Where rainfall, river-flow and loss data are patchy, a model inherits the patches. Adoption also depends on trained staff, who tend to be thinnest at the provincial and district level where decisions are made.

The WMO notes that major gaps in early warning remain in developing countries, along with a global inability to turn warnings into early action (WMO, 2022). Money is the other constraint. The 2025 Sustainable Development Report names a lack of fiscal space as a major obstacle for many developing countries (Inter Press Service [IPS], 2025). Without a protected budget line, resilience competes with every other urgent claim and tends to lose, until the next flood.

6. Mitigation Strategies and Best Practices

Structural measures still matter. Embankments, drainage, flood-resistant roads and bridges, and better-built houses all reduce the damage a given flood can do. But structures are costly, they can fail, and they can create a false sense of safety. The stronger approach pairs them with non-structural measures: land-use zoning that keeps new settlement off floodplains, enforced building codes, watershed and wetland restoration, insurance, and social protection that reaches households before the water does.

The 2022 recovery assessment offers a useful test for any of these measures. It called for reconstruction guided by four principles: the poor first, transparency, inclusion and climate resilience (UNDP, 2022). Applied consistently, those principles turn rebuilding from restoration into development.

Capacity building deserves the same attention. The National DRR Policy names the National Institute of Disaster Management as the nodal body for training, research and education (NDMA, 2012), and its reach can be extended to district officials, teachers and health staff. A practical example of cross-sector integration is the 2017 national action plan that applied the Bangkok Principles to bring the health sector and disaster managers into shared planning (Malteser International, 2017). The same model could tie education,

water and housing to risk reduction. On finance, UNDRR (2025) argues that investing in risk reduction saves both money and lives, which is the strongest argument a planning ministry can be given.

7. Risk Communication and Early Warning

A warning that does not reach someone, or reaches them in a form they cannot use, is not a warning. The UN's Early Warnings for All initiative, whose executive action plan was launched at COP27, grew out of this recognition and tracks country progress through a monitoring framework and a global dashboard (WMO, 2022). The weak link is usually the last mile, the stretch between a forecast in Islamabad and a family in a riverside village in southern Punjab or Sindh.

Closing it takes practical choices. Messages should go out in Urdu and regional languages, through the channels people actually use: mosque loudspeakers, community radio, SMS and trusted local volunteers. Warnings should say what to do, not only what is coming. Evacuation drills and agreed safe routes before the monsoon give the message meaning on the day it arrives.

Gender needs deliberate design. WMO members have agreed on steps to mainstream gender-responsive early warning (WMO, 2024), and the Latin American and Caribbean Women's Network for DRR (n.d.) has built a Gender Observatory that assesses warning systems through rights, inclusion and justice. Pakistan could adopt a similar test. Do women hear the warning? Can they leave on their own? Is a woman on the committee that decides when to go?

8. Policy Recommendations

Five measures follow from the analysis above.

I. **Merge the planning, not just the language.** Create a joint SDG-Sendai reporting framework under the planning ministry, with the NDMA and provincial authorities at the table, so that one set of indicators serves both agendas. The 2030 Agenda already names disaster risk in targets 1.5, 11.5, 11.b and 13.1 (United Nations, 2015).

II. **Risk-screen public investment.** Require every major public project to carry a disaster and climate risk assessment before approval.

III. **Protect resilience finance.** Ring-fence a share of development spending for risk reduction and fund the National Disaster Risk Management Fund, the existing dedicated vehicle for DRR investment (NDMA, 2022), predictably, in line with the finding that resilience pays (UNDRR, 2025).

IV. **Put communities and women in charge of local plans.** Resource union-council committees, place women in leadership roles and write local knowledge into risk mapping.

V. **Build the evidence base.** Establish a single open disaster-loss database, test AI-based forecasting alongside community observation, and strengthen provincial and district staff so that national policy does not stop at the provincial capital.

9. Conclusion

The evidence points one way. Disasters erase development faster than development can build it, and the people who lose the most are the ones the SDGs promise to put first. Yet nothing here is inevitable. Pakistan already has a national policy, a disaster authority, a dedicated risk fund and strong community traditions. What is missing is a single line of sight from the national plan to the riverside village.

Science-based planning gives that line its direction, social capital and local knowledge give it reach, technology gives it speed, and integrated governance keeps it funded. Treating the SDGs and disaster resilience as one agenda is not an extra burden on a stretched system. It is the cheaper and the fairer option. With 2030 little more than three years away, the choice is between investing in resilience now and paying far more for it in the next flood.

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Annex A: Links between selected SDGs and disaster impacts

SDG / target	**How disasters undermine it**	**Evidence used in this paper**
SDG 1, Target 1.5 (resilience of the poor)	Floods strip assets from households with no savings or insurance.	33 million people affected in 2022; women lost agricultural and livestock livelihoods (UNDP, 2022).
SDG 2 (Zero Hunger)	Crop and livestock losses cut food supply and income together.	Over 1 million acres of farmland inundated in 2025 (Shelter Cluster, 2025).
SDG 9 and SDG 11, Targets 11.5 and 11.b	Roads, bridges and homes are destroyed; local risk planning is weak.	239 bridges and about 675 km of road damaged in 2025 (Shelter Cluster, 2025).
SDG 13, Target 13.1	Hazards intensify faster than adaptation.	Heatwave, glacial melt and monsoon combined in 2025 (Shelter Cluster, 2025).
SDG 5 (Gender Equality)	Women and children bear a heavier burden and need gender-sensitive warnings.	Disproportionate impact reported by IFRC (Arab News, 2026); WMO (2024).

PARTICIPANT RESEARCH PAPER

A Study of El Nino and Climate-Related Disaster Risk in Pakistan: Evidence Synthesis, Vulnerability Assessment, and Adaptation Pathways

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Abstract

The El Nino influences rainfall, temperature, and drought in Pakistan, though its effects are modified by the Indian Ocean Dipole (IOD), Pacific Decadal Oscillation (PDO), Tropical Southern Atlantic (TSA) pattern, and regional circulation. This study synthesizes research on monsoon rainfall, satellite drought monitoring, early-summer temperature, drought precursors, and the Upper Indus Basin during different time zones. In recent years' floods estimated that declining El Niño conditions roughly doubled the event's likelihood and increased intensity by about 8% versus neutral ENSO. El Niño is an important influence but cannot independently explain every drought, heatwave, or flood. It was identified that severe droughts in 2001, 2002, and 2006, with the 2000–2002 episode affecting over 60% of Pakistan. In Balochistan, it was found a declining January rainfall and increasing June rainfall, while satellite products diverge from ground observations. The paper recommends multi-source climate monitoring, seasonal and impact-based early warning, drought and heat action plans, water conservation, climate-smart agriculture, community participation and targeted risk finance. Since the reviewed studies do not establish the impacts of the specific 2026 event in real time, current-season claims should be verified against official Pakistan Meteorological Department (PMD) and National Disaster Management Authority (NDMA) updates.

***Keywords*:** El Nino; Pakistan; Drought risk; Monsoon variability; Climate adaptation, Climate Risk, Policy

1. Introduction

El Niño is a natural climate pattern associated with tropical Pacific sea-surface temperature and atmospheric circulation changes. It can influence Pakistan's monsoon rainfall, temperature, and drought risk, though effects vary by region and season. Historical analyses associate many El Nino events with below-normal monsoon rainfall, but exceptions and IOD influence show ENSO is not a deterministic predictor (Adnan et al., 2016; Aamir & Hassan, 2020). Relationships between ENSO indices, drought, and temperature can also change over time (Latif et al., 2024; Rashid et al., 2022).

Pakistan is exposed because agriculture, seasonal rainfall, irrigation, and livestock support many livelihoods. Agriculture contributes 23.4% of GDP and 33.1% of employment (Express Tribune, 2026a). Reported 2026 monsoon rainfall was 50.8% below normal in Sindh, 92% below normal in Karachi, and 33.7% below normal in Balochistan, while Gilgit-Baltistan was 4.6% above normal (Express Tribune, 2026b); these secondary figures should be verified against PMD records. The PMD drought bulletin identifies drought-prone areas including Sindh and Balochistan. PMD (2021), and FEWS NET (2026) projected increased food-assistance needs for December 2026–January 2027.

This paper report data from the recent literature alongside selected government, humanitarian, and community-resilience sources. It examines regional hazards, vulnerability, research gaps, and adaptation options. It is a literature review, not a new statistical attribution study; current-season claims should be checked against dated official observations and forecasts. The review does not independently attribute the 2026 rainfall deficit to El Niño.

Objectives of the Study:

1. To synthesize existing research evidence on El Niño and climate-related disaster risk in Pakistan
2. To assess climate-related vulnerability in Pakistan
3. To identify adaptation pathways and recommend risk-reduction measures

2. Regional Context & Hazard Profile

Adnan et al. (2016) found 8-11 El Niño events brought below-normal monsoon rainfall and nine La Niña events above-normal rainfall, though some El Niño years had positive departures when the IOD modified the signal. Aamir and Hassan (2020), using 13 Balochistan stations (1977–2017), found monsoon influence in the east and western disturbances in the west, with January rainfall declining 0.615 mm/year and June rainfall increasing 0.832 mm/year.

Ali et al. (2023) identified severe drought in 2001, 2002, and 2006 using MODIS and TRMM data (2001–2017), with 2001–2002 the most intense episode, supporting NDVI, VHI, CWSI, and TVDI indicators where ground data are limited. Latif et al. (2024) identified drought years in 1971, 2000, 2001, 2002, 2015, and 2018; the 2000–2002 episode affected over 60% of Pakistan (Figure 01), with links to PDO and TSA and changing climate-index relationships. Hina et al. (2021) identified 1987, 1991, 2000, 2001, 2002, and 2005 as severe or extreme drought years and proposed atmospheric precursors requiring validation.

Rashid et al. (2022) reported a negative association between Niño 3.4 and May–June temperature anomalies ($r = -0.43$, significant at 95%), linked to cloud cover and subsidence changes, though not a rule for every year. Latif and Yaseen (2026) found ENSO drought signals differed across the Upper Indus, Jhelum, and Kabul basins, with consecutive dry days increasing at some stations and decreasing at others. Abro et al. (2025) documented divergence between gridded products and rain gauges in Balochistan, supporting multi-index, multi-source, location-specific monitoring rather than reliance on ENSO alone. Adnan et al. (2016) found the IOD can modify rainfall response, while Latif et al. (2024) cautioned against attributing every drought or flood directly to El Niño. Abro et al. (2025), examining 1980–2016 Balochistan rainfall, identified droughts in 1988–1989, 1998–2002, 2003–2004, and 2005–2006; APHRODITE slightly underestimated rainfall, CPC substantially underestimated it, and MSWEP overestimated it relative to gauges. Hazard monitoring should combine climate indices, local observations, and multiple data sources.

3. Risk & Vulnerability Assessment

Main Climate-Related Risks: El Nino-influenced seasons can bring rainfall deficits, heat stress, agricultural drought, water pressure, and food-price impacts. Pakistan's record includes the 1999–2002 drought, 2010 floods, 2015 Karachi heatwave (1,233 reported deaths; (Associated Press, 2015), and 2022 floods (about 33 million people affected; over US$30 billion in losses; (World Bank, 2022), events with different drivers that should not all be attributed to ENSO. The April–May 2024 floods in Afghanistan, Pakistan, and Iran occurred amid declining El Niño conditions, which an attribution study estimated roughly doubled the event's likelihood and raised intensity by about 8% versus neutral ENSO (Zachariah et al., 2024), (Figure 3). Risk depends on exposure, infrastructure, preparedness, and recovery capacity, not hazard alone.

Agriculture and Water Security: Rainfall deficits can delay sowing, raise irrigation demand, lower yields, and reduce fodder; rain-fed crop losses of 60–100% were reported in parts of Balochistan and Sindh during 1999–2002 (Food and Agriculture Organization of the United Nations (FAO, 2003). Preparation must address agricultural and hydrological impacts, not rainfall deficits alone (PMD, 2021; Latif et al., 2024), and substantial agricultural and livestock losses were also reported in the 2022 floods (World Bank, 2022).

Unequal Vulnerability: Heat exposure is especially serious for outdoor workers, older adults, children, people with chronic vulnerabilities, and households without reliable electricity or cool spaces; Rashid et al. (2022) emphasise early-summer temperature variability for water, energy, agriculture, and health. Smallholders, tenant farmers, landless labourers, pastoralists, and single-income households often have fewer recovery resources. Rural women and girls often collect water, and lack of identity documents can restrict access to services; pregnant and breastfeeding women face specific needs (Zahidi, 2023).

Exposure, Vulnerability, and Cascading Risk: A rainfall deficit is a hazard; a farm in a drought-prone area is exposed; limited irrigation, debt, poor forecast access, or lack of savings increase vulnerability. Risk emerges from their interaction. Assessment should map hazard probability, exposed populations and assets, livelihood sensitivity, and coping capacity, and should account for compound risks—heat with low reservoirs, crop

losses followed by food-price increases, or drought followed by intense rainfall on degraded land.

4. Community Resilience Factors

Research on rural Pakistani communities found social capital can support disaster-risk understanding and dissemination, though benefits are not equally distributed. Community-based preparedness can include village risk committees, participatory hazard mapping, local volunteers, water-use plans, and seed or fodder banks, connecting local knowledge with official forecasts and ensuring women, tenants, remote households, older people, and people with disabilities can participate and receive assistance.

The present study shows, why locally tailored information matters: rainfall patterns and drought signals vary across regions, and precipitation products can contain substantial biases (Abro et al., 2025). Resilience can be strengthened through village-level risk committees, participatory hazard mapping, locally agreed drought triggers, community water-use plans, seed and fodder banks, and volunteer training. Women and vulnerable groups should participate in designing alert messages and delivery mechanisms, and community feedback should be collected after each season to determine whether warnings were received, understood, and acted upon.

5. Scientific & Institutional Gaps

There are four important gaps found by the present study.

1. First, El Niño rainfall relationships are variable rather than uniform: Adnan et al. (2016) found exceptions among El Niño years, while Latif et al. (2024) identified a shift in the drought–Niño 3.4 relationship around 2006. Forecasts should therefore combine El Niño with the IOD, longer-term Pacific variability, regional circulation, and local observations.
2. Second, observation and data quality matter. Abro et al. (2025) found gridded precipitation products can over- or underestimate rainfall compared with gauges. Satellite products and drought indices help fill spatial gaps but should be validated against quality-controlled ground observations, particularly in remote and mountainous areas (Ali et al., 2023; PMD, 2021).
3. Third, seasonal outlooks do not always translate into impact-based decisions. Agencies and communities need information on what is likely to happen, where,

when, who is exposed, and what action is recommended. Forecast communication should link to agriculture, irrigation, health, livestock, and disaster-management decisions.

4. Fourth, risk assessment and planning can be fragmented across sectors. Drought, heat, agriculture, public health, and water management are often handled through different plans and budgets. Consistent loss accounting is needed so drought and heat impacts can be compared with flood losses. Future research should examine sub-provincial exposure, forecast skill, early-warning effectiveness, gender-disaggregated impacts, and adaptation costs and benefits.

6. Mitigation Strategies & Best Practices

Water Management and Nature-Based Solutions: Structural and nature-based measures should reduce water scarcity and damage from rainfall extremes. Options include rainwater harvesting, farm ponds, efficient irrigation, sustainable groundwater recharge, and protection of wetlands and floodplains. Pakistan's National Adaptation Plan provides a relevant framework for integrating climate adaptation into development planning (MCCEC, 2023).

Climate-Smart Agriculture: Agricultural adaptation should include locally suitable drought- and heat-tolerant varieties, sowing dates adjusted to seasonal forecasts, crop diversification, soil-moisture conservation, mulching, improved farm-water scheduling, and extension advice. Livestock measures include fodder reserves, veterinary preparedness, shade, reliable drinking-water points, and contingency plans for feed shortages. Advice must be tailored to local rainfall regimes rather than applied uniformly.

Heat Preparedness and Risk Financing: Heat preparedness requires public communication, access to drinking water and shade, occupational safety measures, health-facility readiness, and heat-action plans with clear thresholds and responsibilities. Schools, workplaces, and outdoor labour arrangements should be adjusted during dangerous heat where feasible. Urban greening and reflective or well-ventilated buildings can contribute to longer-term heat risk reduction.

7. Risk Communication & Early Warning

Forecasts Linked to Action: Effective early-warning systems must connect forecasts with clear messages and practical action. Pakistan's evolving disaster-management

approach reportedly uses satellite information, drones, artificial intelligence, and regional-language alerts; specific claims should be confirmed with official NDMA and PMD documentation.

Coordinated Warning Channels: Alerts should be available in relevant local languages and through multiple channels, including SMS, radio, television, social media, mosque announcements, and community focal persons. Redundancy is important where mobile coverage, electricity, or internet access is unreliable.

Inclusive and Impact-Based Messages: Warnings should be impact-based and action-oriented. Farmers need advice on sowing, irrigation, and crop protection; livestock keepers need water and fodder information; health services need heat-related readiness triggers; and local administrations need protocols for water distribution and targeted assistance. Messages should specify the expected hazard, affected area, confidence level, recommended action, and where support can be obtained. Gender-sensitive and inclusive communication requires consultation with women, people with disabilities, older people, linguistic minorities, and remote communities.

8. Policy Recommendations

The following measures are recommended as a practical, phased programme:

- **Integrated coordination:** Establish a standing seasonal climate-risk coordination mechanism involving PMD, NDMA, provincial disaster authorities, agriculture, irrigation, health, and social-protection agencies. Link flood, drought, and heat warning chains, agree on shared triggers.
- **Improve climate observations:** Maintain and expand quality-controlled weather stations and rain gauges, validate satellite products against ground observations, and make data accessible to researchers and decision-makers.
- **Adopt trigger-based drought and heat plans:** Define measurable triggers for water conservation, heat alerts, livestock support, health-facility readiness, and temporary social assistance. Review thresholds after each season.
- **Strengthen household resilience and risk finance:** Expand appropriately designed social protection and explore affordable crop and livestock insurance based on reliable data and transparent claims processes.

- **Evaluate adaptation:** Track indicators such as warning reach, response time, crop and livestock losses, water availability, health impacts, and support reaching vulnerable households. Publish a post-monsoon review and update plans accordingly.

9. Conclusion

The literature shows that El Niño influences Pakistan's climate but does not independently explain every rainfall deficit, heatwave, drought, or flood. Many historical El Niño years were associated with weaker monsoon rainfall, but exceptions and the IOD require cautious interpretation. Temperature relationships vary by season, while drought studies show spatial variability, changing teleconnections, and data limitations. The 2026 rainfall deficits and food-security and gender concerns should be verified against official records; they do not prove El Niño alone caused the deficits.

Adaptation must therefore combine scientific monitoring with community participation, climate-smart agriculture, water conservation, heat and drought preparedness, inclusive communication, and risk finance. The current-season status and reported impacts of the 2026 El Niño should be verified against official updates before being stated as established fact. A flexible, evidence-led approach can help Pakistan prepare for both rainfall deficits and the possibility of intense rainfall, while protecting the people and sectors least able to absorb climate shocks.

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Appendices

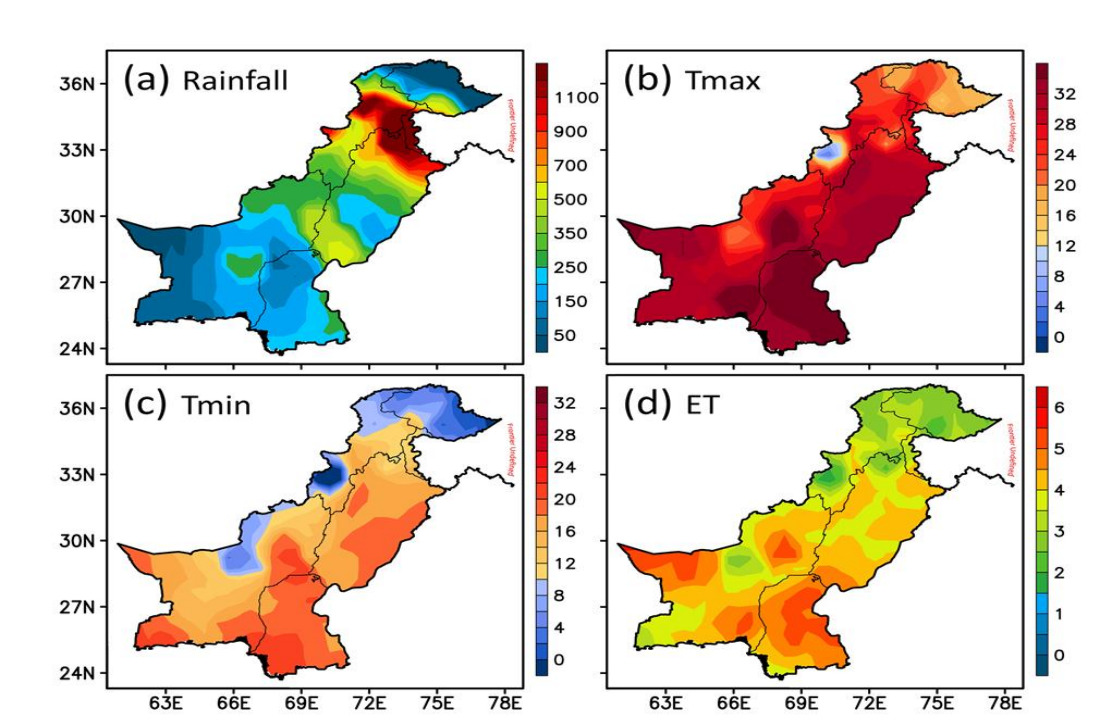


Figure. 1. Spatial distribution of (a) mean annual total precipitation (mm) across Pakistan from 1971 to 2020, and climatological patterns of (b) maximum temperature (Tmax, °C), (c) minimum temperature (Tmin, °C), and (d) evapotranspiration (ET, mm/day) (Aquired from Latif et al. 2024).

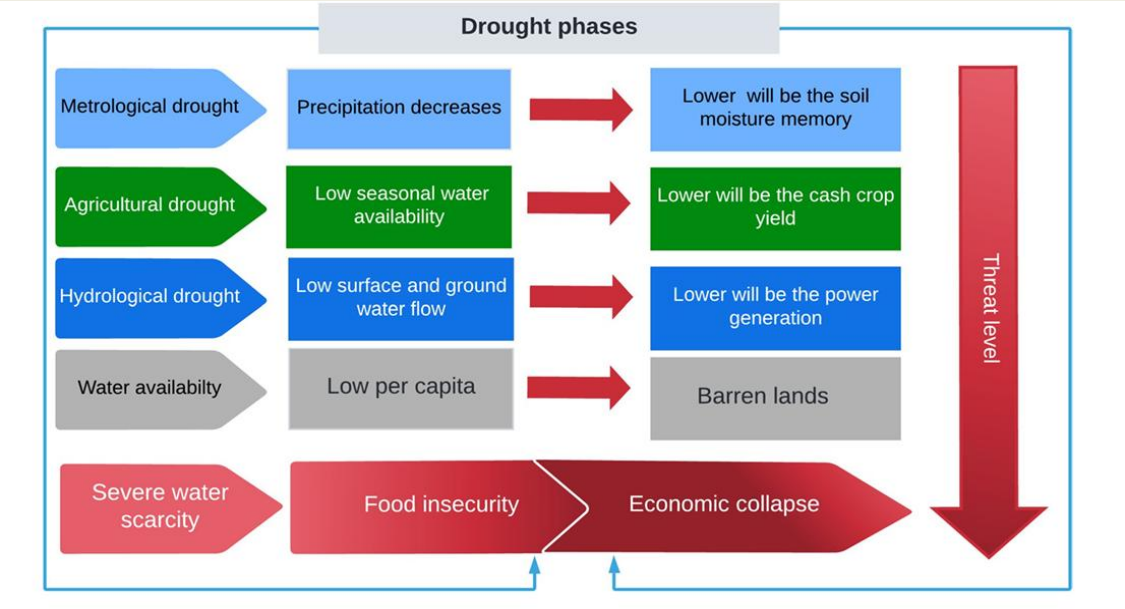


Figure 2. Drought types, phases and their resulting threats

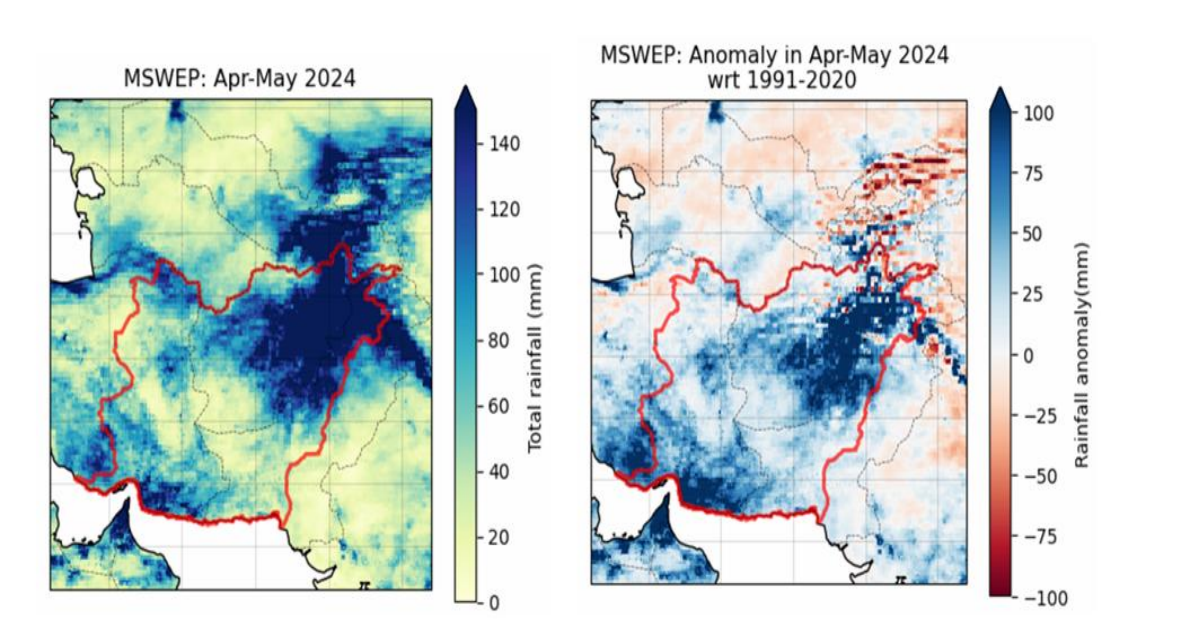


Figure 3. (a) Total accumulated precipitation across the study region during April–May 2024, with the most severely affected areas highlighted in red. (b) Precipitation anomalies for the same period relative to the 1991–2020 climatological baseline. Data source: Multi-Source Weighted-Ensemble Precipitation (MSWEP). (Acquired from Zachariah et al., 2024)

PARTICIPANT RESEARCH PAPER

Satellite-Based Earth Observation for Disaster Monitoring and Damage Assessment

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Abstract

Natural hazards are intensifying under climate change, and timely, objective information is essential for response and risk reduction. This paper examines how satellite-based Earth observation (EO) supports disaster monitoring and damage assessment, with emphasis on South Asia and Pakistan. Drawing on peer-reviewed literature, institutional reports and the 2022 Pakistan floods, it reviews optical, synthetic aperture radar (SAR) and thermal sensors, analyses vulnerability and community resilience, and identifies scientific and institutional gaps. The findings show that EO provides rapid, wide-area and repeatable information that complements ground surveys, particularly in inaccessible areas. However, its value is limited by cloud cover, restricted access to very high-resolution imagery, scarce validation data, weak local capacity and poor last-mile communication. Artificial intelligence (AI) improves speed and scale but depends on representative training data. The paper recommends embedding EO products in national disaster management systems, investing in open data pipelines and local skills, combining satellite outputs with community knowledge, and building people-centred, gender-sensitive early warning, in line with the Sendai Framework.

Keywords: Earth observation; disaster monitoring; damage assessment; SAR; disaster risk reduction

1. Introduction

Disasters triggered by natural hazards cause large human and economic losses, and climate change is increasing the frequency and intensity of many hydro-meteorological events (IPCC, 2022). Effective response depends on knowing quickly what has happened, where, and how severely. After a major event, roads, communication networks and survey teams are often disrupted, so ground-based assessment is slow and incomplete. Satellite-based Earth observation (EO) addresses this problem by providing synoptic, repeatable and independent information over large areas (Joyce et al., 2009; Voigt et al., 2016).

Problem statement and rationale: Despite the growing availability of free satellite data, many disaster management authorities in developing countries still depend on manual assessments and have limited operational use of EO. This delays relief, weakens damage estimates for recovery planning, and reduces the evidence available for risk reduction. The Sendai Framework calls for improved access to science, technology and risk information (United Nations Office for Disaster Risk Reduction [UNDRR], 2015).

Purpose, objectives and scope: This paper aims to assess how satellite EO supports disaster monitoring and damage assessment. Its objectives are to (a) review the main EO technologies and their applications, (b) examine vulnerability and community resilience dimensions, (c) identify scientific and institutional gaps, and (d) propose practical recommendations. The scope covers floods, earthquakes, landslides and drought, focusing on South Asia and the 2022 Pakistan floods.

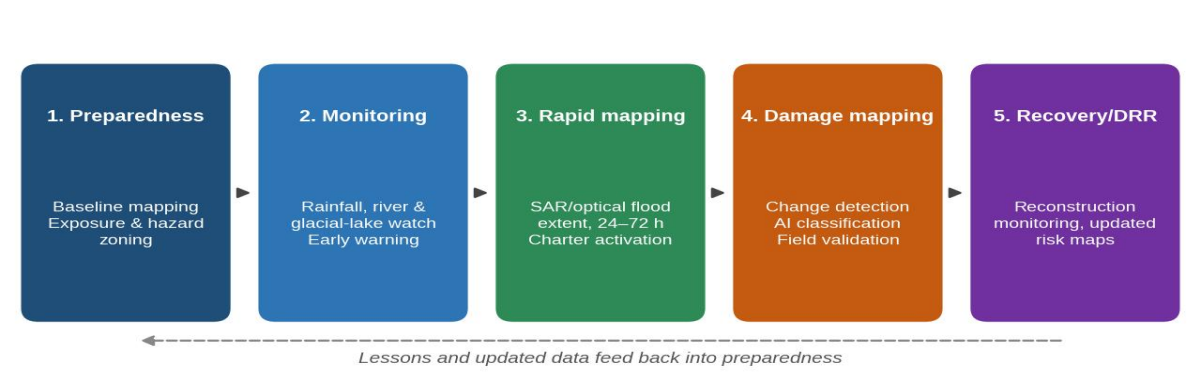


Figure 1. Role of satellite EO across the disaster management cycle

Source: Author's synthesis based on Joyce et al. (2009) and Voigt et al. (2016).

2. Regional Context and Hazard Profile

Key Definitions: Following UNDRR (2015), a hazard is a process or phenomenon that may cause loss of life, injury or damage; exposure refers to people and assets located in hazard-prone areas; vulnerability is the set of conditions that increases susceptibility to harm; and risk is the likelihood of losses resulting from the interaction of these three elements.

Regional context: South Asia is among the world's most disaster-prone regions because of its dense population, monsoon climate, tectonic setting and glaciated mountains. Pakistan faces riverine and flash floods, earthquakes, landslides, glacial lake outburst floods, cyclones and drought. The 2005 Kashmir earthquake and the floods of 2010 and 2022 demonstrate this exposure. The 2022 floods affected about 33 million people, killed more than 1,700 and caused estimated damage of US$14.9 billion and losses of US$15.2 billion (Government of Pakistan, 2022).

EO technologies and trends: Optical sensors such as Sentinel-2 and Landsat capture land cover, burn scars and building condition, but cannot see through cloud (Drusch et al., 2012). SAR sensors such as Sentinel-1 operate day and night and penetrate cloud, which makes them the principal tool for flood mapping during monsoon conditions (Torres et al., 2012; Schumann et al., 2018). Very high-resolution commercial satellites support building-level damage assessment (Dell'Acqua & Gamba, 2012). Cloud platforms such as Google Earth Engine now allow rapid processing of large archives (Gorelick et al., 2017), and international mechanisms such as the International Charter Space and Major Disasters speed up access to imagery after major events (Voigt et al., 2016).

Table 1. Main satellite sensors used for disaster monitoring

Sensor	Type	Resolution / revisit	Typical disaster use
Sentinel-1	SAR	10 m / 6–12 days	Flood extent, landslides, ground deformation

Sensor	Type	Resolution / revisit	Typical disaster use
Sentinel-2	Optical	10 m / 5 days	Land cover change, damage, drought vegetation stress
Landsat 8/9	Optical, thermal	30 m / 8 days	Long-term change, burn scars, drought
MODIS	Optical, thermal	250–500 m / daily	Regional flood and drought monitoring
Commercial VHR (e.g., WorldView-3, PlanetScope)	Optical	0.3–3 m / daily to near-daily	Building and infrastructure damage

Note: Values are approximate nominal specifications. VHR = very high resolution.

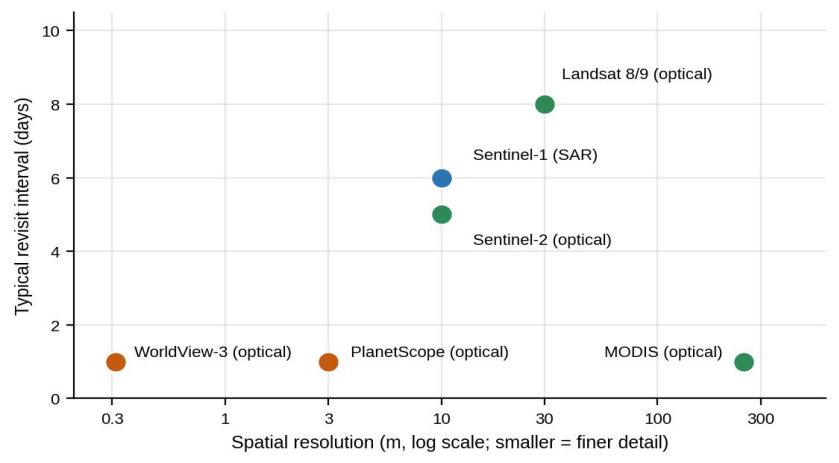


Figure 2. Trade-off between spatial resolution and revisit interval

Source: Author's compilation from agency specifications (approximate nominal values).

3. Risk and Vulnerability Assessment

Disasters affect livelihoods unevenly. In 2022, floods in Sindh and Balochistan submerged farmland, destroyed standing crops and killed livestock, threatening food security for rural households that depend on agriculture (Government of Pakistan, 2022). Women, children, older persons, people with disabilities, landless tenants and the rural poor face higher risk because of lower mobility, limited assets, restricted access to information and, for women, social norms that constrain evacuation and decision-making.

EO contributes to risk assessment by mapping exposure (settlements, cropland, infrastructure), susceptibility (slope, soil moisture, elevation) and change over time. Remote sensing proxies, such as building density, road access and vegetation condition, can approximate social vulnerability where census data are outdated (Ghaffarian et al., 2018). However, satellites show physical exposure better than social vulnerability, so they must be combined with household and gender-disaggregated data.

Table 2. Impacts of the 2022 Pakistan floods

Indicator	Estimate
People affected	About 33 million
Deaths	More than 1,700
Damage to assets	US$14.9 billion
Economic losses	US$15.2 billion
Reconstruction and recovery needs	US$16.3 billion

Source: Government of Pakistan (2022).

4. Community Resilience Factors

Resilience depends on social capital, trust, local networks and prior experience. Community members often know safe routes, historical flood levels and local warning signs that satellite data cannot capture. Village committees, mosques, local organisations and volunteers can validate satellite maps, share warnings and organise evacuation.

Community participation also improves acceptance of EO products, for example through participatory mapping that overlays local observations on flood extent maps. Indigenous knowledge and traditional coping practices, such as raised plinths, seasonal migration and grain storage, should complement, rather than be replaced by, technical information.

5. Scientific and Institutional Gaps

- **Technical limits:** Cloud, vegetation and urban shadows reduce accuracy, and SAR flood mapping often underestimates flooding in dense urban areas (Schumann et al., 2018).
- **AI/ML adoption:** Deep learning can classify building damage rapidly, but models trained on one region transfer poorly to others, and labelled datasets such as xBD are mostly drawn from other regions (Gupta et al., 2019).
- **Data quality and access:** Very high-resolution imagery is costly, and in-situ validation data, such as gauge records and post-event surveys, are limited (Rahman & Di, 2017).
- **Institutional weaknesses:** Agencies often lack trained analysts, standard operating procedures for EO use, and data-sharing arrangements. Products arrive in formats that decision-makers cannot readily use.

6. Mitigation Strategies and Best Practices

Structural measures include embankments, drainage and retrofitting of buildings in areas identified by EO-based hazard maps. *Non-structural measures* include land-use zoning, building codes, insurance and regular monitoring of changing river courses and glacial lakes. Capacity building should train provincial and district officers in satellite data interpretation and field verification.

Good practice already exists. The International Charter provides free emergency imagery to affected countries, and Copernicus Emergency Management Service delivers rapid mapping products within days (Voigt et al., 2016). Open Sentinel data and Google Earth Engine have enabled near-real-time flood mapping in many countries (Gorelick et al., 2017). Pakistan can adapt these models by strengthening links between NDMA, provincial authorities and national space and survey agencies.

7. Risk Communication and Early Warning

Satellite information reduces risk only when it reaches people in time and in usable form. Rainfall estimates, river monitoring and flood forecasts should feed people-centred early warning systems that are tailored to local languages, literacy levels and gender roles. Last-mile channels include mosque loudspeakers, mobile messages, radio and community volunteers. Simple flood-extent maps, colour-coded risk levels and clear action messages are more effective than technical products. Two-way feedback allows communities to report conditions on the ground and to correct satellite-derived maps.

8. Policy Recommendations

- Integrated governance: Establish a national EO coordination mechanism linking NDMA, provincial authorities, SUPARCO, the Survey of Pakistan and the meteorological service.
- Technology integration: Adopt standard protocols for rapid flood and damage mapping, including pre-agreed activation of the International Charter.
- Institutional strengthening: Invest in trained analysts, cloud-based processing and open data portals, and in field validation networks.
- Climate adaptation: Use EO time series to update hazard maps and climate risk projections for land-use and infrastructure planning (IPCC, 2022).
- Community participation: Combine satellite products with participatory mapping, and ensure gender-sensitive communication.
- Evidence-based policy: Fund research on locally trained AI models and publish accuracy assessments to build trust in EO outputs.

9. Conclusion

Satellite EO has become an essential tool for monitoring hazards and assessing damage quickly and objectively, especially where access is limited. SAR and optical data, supported by cloud computing and AI, can reduce the time between disaster and informed action from weeks to days. Yet technology alone does not build resilience. Its benefits depend on science-based planning, validation with ground data, institutional capacity, social capital, indigenous knowledge and effective last-mile communication. An

integrated approach that links satellite evidence with community engagement and clear policy mandates will best support the Sendai Framework goal of reducing disaster losses.

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Annex A: Hazard–EO Application Matrix

Table A1. Satellite EO applications by hazard

Hazard	Primary data	Key products	Main limitation
Flood	SAR (Sentinel-1), optical	Flood extent, inundation duration, cropland affected	Urban areas, vegetation, revisit gaps
Earthquake	VHR optical, InSAR	Building damage, ground deformation	Needs pre-event imagery and validation

Hazard	Primary data	Key products	Main limitation
Landslide	Optical, SAR, DEM	Inventory maps, susceptibility, slope movement	Small features, shadows, cloud
Drought	MODIS, Landsat, rainfall estimates	Vegetation and soil moisture indices	Coarse resolution, slow onset
Cyclone / storm surge	Optical, SAR, scatterometer	Track, coastal inundation, damage	Cloud, rapid change

Source: Author's synthesis based on Joyce et al. (2009) and Rahman & Di (2017).

PARTICIPANT RESEARCH PAPER

Smart Cities and Urban Disaster Risk Management Strategies

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Abstract

Smart-city technologies can strengthen urban disaster risk management, but their value depends on the institutions and actions they support. This critical narrative review examines 18 academic and institutional sources on spatial analysis, flood forecasting, monitoring, urban heat, and disaster governance, with particular attention to Pakistan. The evidence supports improved risk identification and selected forecasting capabilities; evidence that digital systems independently reduce disaster losses is more limited. Effective strategies connect information to land-use planning, maintained infrastructure, accessible warnings, community participation, and accountable financing. Pakistan's adaptation policies provide a foundation, although implementation capacity remains uneven. The paper proposes a staged approach that begins with local risk baselines and focused pilots, then expands interventions supported by measurable improvements in protection, service continuity, and equity.

Keywords: smart cities; urban resilience; disaster risk management; early warning; Pakistan.

1. Introduction and Conceptual Framework

Cities concentrate people, infrastructure, and economic activity, creating interconnected risks from flooding, extreme heat, and service disruption. Climate change interacts with urban expansion, inadequate infrastructure, and social vulnerability, making disaster management a planning and governance challenge (Intergovernmental Panel on Climate Change [IPCC], 2022). Smart-city systems can contribute through geographic information systems (GIS), sensors, forecasting, and communication networks, provided that information leads to protective action.

Disaster risk reflects interactions among hazards, exposure, vulnerability, and capacity (United Nations Office for Disaster Risk Reduction [UNDRR], 2017). Consequently, a more accurate hazard map cannot compensate for unsafe housing, inaccessible shelters, or ineffective drainage maintenance. The Sendai Framework places risk understanding alongside governance, investment, preparedness, and recovery, supporting an integrated approach to urban resilience (UNDRR, 2015).

A people-centred smart city uses technology to advance public needs, inclusion, and responsive government (United Nations Human Settlements Programme [UN-Habitat], 2021). This paper therefore asks how digital capabilities can support practical disaster risk reduction, what the evidence demonstrates, and which strategies are relevant to Pakistan. Its central proposition is that each information service should connect to a responsible institution, a funded action, and an observable public benefit. Resilience should be assessed through protection and service continuity, rather than the number of installed devices.

2. Review Methodology

This critical narrative review draws on 18 academic studies and institutional publications dated 2014–2024. Sources were selected purposively for their relevance to urban hazards, digital technologies, governance, or Pakistan. Searches were completed on 21 October 2026, but the selection does not provide comprehensive coverage of research published in 2025–2026. Where full text was unavailable, interpretation was restricted to the verified abstract or accessible institutional record. Studies were compared by setting, methods, outcomes, and transferability, distinguishing technical performance from demonstrated reductions in human or economic harm. The review is neither systematic

nor a meta-analysis and contains no original surveys, interviews, GIS classifications, or disaster-loss measurements. Its management framework and implementation sequence are proposals derived from the selected literature.

3. Evidence and Findings

Spatial Information and Urban Heat

Spatial data help identify where hazards overlap with exposed populations and infrastructure. In Lahore, Farid et al. (2022) examined urbanization and land surface temperature using four March Landsat images from 1990, 2000, 2010, and 2020. These observations support analysis of landcover associations but do not establish summer heatwave trends. Massaro et al. (2023) analysed 200 cities and modelled how spatially targeted greening could reduce exposure to extreme surface temperatures. Their results represent scenarios, not measured intervention effects. Satellite land surface temperature also differs from air temperature and personal heat exposure, which depend on additional environmental and social conditions.

Monitoring, Forecasting, and Digital Twins

Jang and Jung (2023) demonstrated radar-based water-level monitoring through indoor and river experiments, providing evidence of measurement capability without establishing citywide reliability or avoided losses. Nearing et al. (2024) showed that artificial intelligence could improve extreme river-flood forecasting in ungauged watersheds. River forecasts, however, do not automatically predict street-level flooding from blocked drains or establish successful evacuation. Ghaith et al. (2022) developed a synchronization-enhanced flood-prediction approach as a core component of a proposed city digital twin. Its predictive results do not demonstrate the operational impact of a complete municipal system. Such tools require local validation, maintenance, and clearly assigned responses.

Environmental and Human Outcomes

Evidence from physical and public-health interventions offers a broader perspective. Ziter et al. (2019) found relationships between tree canopy, impervious surfaces, and summer air temperature in a temperate city; transfer to Pakistan requires attention to climate, water availability, and maintenance. Hess et al. (2018) reported an association between Ahmedabad’s heat action plan and lower mortality. This observational evaluation

supports coordinated heat management, although it cannot isolate the contribution of digital tools. Across these studies, improved measurement or prediction should be distinguished from demonstrated protection of people and assets.

4. Urban Disaster Risk Management Strategies

Connect Risk Information to Planning

Cities should combine hazard maps with housing conditions, critical facilities, transport access, and indicators of social vulnerability. Municipalities can use these assessments to guide drainage maintenance, development controls, settlement upgrading, and infrastructure investment. Community validation is necessary where official records omit informal settlements or local drainage obstructions. Maps should present uncertainty and be updated after major land-use changes. Planning decisions should reduce exposure while protecting housing security and livelihoods, consistent with Sendai's emphasis on preventing new risk (UNDRR, 2015). Purchasing a mapping platform is useful only when agencies have the authority and resources to act on its findings.

Make Warnings Actionable

The World Meteorological Organization (WMO, 2023) identifies four connected components of early warning: risk knowledge, observation and forecasting, communication, and preparedness to respond. Cities should assign an institution to each alert threshold and specify actions such as opening cooling centres, arranging evacuation transport, or protecting essential equipment. Communication should combine mobile alerts with radio, public announcements, and trusted community networks, using accessible language and formats. Drills can identify whether residents understand warnings and can act safely. Backup power and communication channels are necessary because the systems delivering warnings may themselves fail during a disaster.

Strengthen Infrastructure and Environmental Protection

Digital monitoring should complement drainage clearance, building retrofits, reliable water supplies, and continuity planning for hospitals and utilities. Investment appraisal should include maintenance, replacement, training, and emergency operation costs. Green spaces, shade, permeable surfaces, and restored waterways may support heat and flood management, but design must reflect local hazards, land availability, and maintenance capacity (IPCC, 2022). Tree planting should be assessed through survival, shade

distribution, and thermal conditions over time. Advanced analytics should receive priority when they resolve a defined operational problem and can be sustained within municipal resources.

Embed Inclusion, Accountability, and Recovery

Vulnerability assessments should include outdoor workers, older residents, people with disabilities, and households facing insecure housing or limited services. In Karachi, Ghumman and Horney (2016) associated socioeconomic disadvantage with recorded mortality during the June 2015 heatwave. This supports attention to unequal protection, while the study's observational design and possible undercounting limit causal conclusions. Participation and nondigital access should accompany technical investment.

Data governance should define collection purposes, access rights, retention periods, security responsibilities, and routes for correction or appeal. Kitchin (2014) identifies concerns about surveillance, technocratic decision-making, and dependence on technology providers. Procurement should therefore provide for data portability, staff capacity, and system continuity.

Recovery systems should accept claims through accessible channels and connect reconstruction to safer housing and infrastructure, consistent with Sendai's recovery priorities (UNDRR, 2015). Each programme needs a named owner, a funded maintenance plan, and public reporting of service outcomes.

Implications for Pakistan

Pakistan's 2022 floods caused an estimated US$14.9 billion in physical damage and US$15.2 billion in economic losses. These are national totals covering urban and rural areas, rather than measures of urban losses alone (Government of Pakistan et al., 2022). They underline the importance of connecting disaster preparedness with development planning and resilient services.

The National Adaptation Plan identifies priorities including detailed risk information, urban master planning, land management, informal-settlement upgrading, drainage, and nature-based measures (Government of Pakistan, 2023). These are policy commitments, not evidence of completed implementation. Lahore's historical Heatwave Management Plan for 2022–2025 provides a local example of linking vulnerability assessment, warnings,

institutional responsibilities, and services (The Urban Unit, 2022); the document alone cannot establish mortality benefits.

Implementation requires attention to fragmented responsibilities and limited municipal capacity. Masud and Khan (2024), drawing on stakeholder interviews and document analysis, identify barriers involving consultation, policy specificity, and coordination across levels of government. Their qualitative findings offer context rather than a representative assessment of every municipality.

A practical starting point is a small number of locally selected flood and heat pilots, integrating municipal records, community knowledge, and existing warning services. Each pilot should address a documented service gap, specify agency responsibilities, and budget for maintenance. Lahore and Karachi's published heat evidence can inform local assessment, but intervention design should follow current neighbourhood conditions. Expansion should depend on performance and inclusion, not uniform adoption of a preferred technology.

Implementation and Evaluation

Implementation can proceed through three stages: establish a baseline, test focused pilots, and expand effective interventions. The baseline should document hazards, vulnerable groups, critical services, existing warning channels, and institutional responsibilities. Pilot design should set alert thresholds, response procedures, maintenance arrangements, and accessible feedback channels before procurement. Expansion should follow demonstrated usability, reliability, and affordability. This sequence is a proposed planning approach, not an existing government timetable.

Evaluation should distinguish outputs, outcomes, and impacts. Outputs include validated maps and trained personnel; outcomes include warning comprehension, response times, and service continuity; impacts include changes in mortality, injury, displacement, and economic loss.

Results should be examined across neighbourhoods and vulnerable groups to identify unequal benefits. Comparisons must account for hazard severity, exposure, reporting practices, and other interventions: lower losses in a mild year do not establish programme effectiveness. Credible estimates of avoided losses require a defensible comparison and explicit uncertainty. Reporting these measures can guide revisions and

funding decisions more usefully than counts of sensors, applications, or dashboards alone.

5. Discussion and Limitations

The review indicates that digital systems are most useful when embedded in functioning institutions and practical services. However, purposive selection may omit conflicting evidence, and the literature emphasizes heat and flooding more than other urban hazards. Technical studies, policy documents, and observational evaluations provide different forms of evidence and cannot be treated as equally strong demonstrations of impact. Findings from other cities require local validation, while limited causal evidence restricts claims about the independent benefits of smart-city technologies. The proposed framework needs testing through municipal pilots with transparent reporting of costs, failures, distributional effects, and disaster outcomes.

6. Conclusion

Smart city approaches can support urban disaster management by improving risk information and operational coordination. Their effectiveness depends on sound planning, maintained infrastructure, accessible warnings, community participation, and accountable institutions. For Pakistan, focused local pilots offer a practical route from adaptation policy to implementation. Progress should be judged by safer lives, reduced exposure, and reliable essential services, with technology selected according to the public problem it helps solve.

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PARTICIPANT RESEARCH PAPER

Supply Chain Resilience During Climate-Related and Natural Disasters: A Qualitative Study of Humanitarian Logistics in Pakistan

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Abstract

Climate-related and natural disasters disrupt humanitarian supply chains by damaging infrastructure, interrupting transportation, limiting storage capacity, and increasing demand for essential relief supplies. These challenges are particularly significant in Pakistan, where floods, earthquakes, droughts, heatwaves, and landslides threaten vulnerable communities. This study examines how disasters affect humanitarian supply chains and identifies measures that can strengthen their resilience. A qualitative documentary research design is adopted using secondary sources, including academic literature, government publications, disaster assessments, and reports from humanitarian organizations. The study does not involve interviews, questionnaires, or other primary data collection. The literature is examined thematically, focusing on transportation disruptions, inventory management, anticipatory logistics, flexible sourcing, information sharing, and organizational coordination. The analysis suggests that effective humanitarian logistics requires proactive preparedness, strategically positioned supplies, alternative transport arrangements, reliable information, and coordinated decision-making. Pakistan's 2022 floods illustrate the importance of integrating disaster preparedness with resilient infrastructure and logistics planning. The study proposes a conceptual framework linking disaster-related disruptions, resilience capabilities, and humanitarian response performance. Its recommendations aim to support more timely, coordinated, and reliable humanitarian assistance in Pakistan.

Keywords: supply chain resilience, humanitarian logistics, natural disasters, climate-related disasters, anticipatory logistics, Pakistan, disaster preparedness.

1. Introduction

Humanitarian supply chains facilitate the delivery of essential goods, including food, drinking water, medicines, and shelter materials, to communities affected by disasters. They connect suppliers, warehouses, transport providers, government agencies, humanitarian organizations, and affected populations. Unlike commercial supply chains, their primary objective is to meet urgent humanitarian needs under conditions of uncertainty, limited resources, and time pressure (Van Wassenhove, 2006).

Climate-related and natural disasters can disrupt these supply chains at multiple stages. Floods may damage roads and bridges, earthquakes may affect warehouses and transport infrastructure, and extreme weather may prevent vehicles from reaching affected communities. Simultaneously, demand for relief supplies increases, while the capacity to deliver them may decline. These conditions can delay assistance, increase operating costs, and create inequalities in the distribution of essential resources.

Supply chain resilience is therefore an important component of humanitarian preparedness. It refers to the capacity to anticipate, withstand, respond to, and recover from disruptions. Christopher and Peck (2004) emphasize risk management and collaboration as important foundations of resilience, while Pettit et al. (2010) highlight the relationship between supply chain vulnerabilities and the capabilities needed to manage them.

Pakistan provides a relevant context for examining these issues because of its exposure to floods, earthquakes, droughts, heatwaves, and landslides. This study examines disaster-related humanitarian supply chain disruptions and identifies practical measures to improve resilience through secondary research.

2. Problem Statement

Disasters can simultaneously affect transportation networks, storage facilities, suppliers, communication systems, and distribution arrangements. Humanitarian organizations may struggle to identify available stocks, establish accessible delivery routes, and determine which communities require immediate assistance. Inadequate preparedness and coordination can consequently delay relief and result in inefficient resource allocation.

Although supply chain resilience is widely discussed in academic literature, practical implementation requires context-specific planning. Pakistan needs logistics arrangements

that account for differences in geography, infrastructure, disaster exposure, and institutional capacity. This study addresses the need to synthesize existing knowledge into practical recommendations for strengthening humanitarian supply chain resilience in the country.

3. Research Objectives and Questions

3.1 Research Objectives

1. To examine how climate-related and natural disasters affect humanitarian supply chains.
2. To identify measures that can improve supply chain resilience and humanitarian disaster response.

3.2 Research Questions

1. How do climate-related and natural disasters affect humanitarian supply chains?
2. What measures can improve supply chain resilience and disaster response?

4. Literature Review

4.1 Humanitarian Logistics and Supply Chains

Humanitarian logistics involves planning, implementing, and controlling the movement and storage of relief goods and related information. Its effectiveness depends on timely deliveries, accurate information, and coordination among multiple stakeholders. Van Wassenhove (2006) explains that logistics is central to humanitarian operations because the availability of appropriate supplies at the required location directly affects the effectiveness of disaster response.

Kovács and Spens (2007) also highlight the distinctive challenges of humanitarian logistics, including uncertainty, emergency procurement, and coordination among diverse organizations. These characteristics make humanitarian supply chains particularly vulnerable to disruptions and increase the importance of flexible operational planning.

4.2 Supply Chain Resilience and Disaster Preparedness

Supply chain resilience involves preparing for disruptions, responding to unexpected events, adapting operations, and restoring essential functions. Christopher and Peck (2004) identify risk management and collaboration as important elements of resilient supply chains. Pettit et al. (2010) further suggest that resilience depends on balancing vulnerabilities with capabilities that help organizations manage risk.

In humanitarian settings, these capabilities include emergency inventory, alternative transport routes, multiple sourcing options, reliable information systems, and established coordination arrangements. Resilience should therefore be integrated into preparedness planning rather than treated exclusively as an emergency response activity.

4.3 Research Gap

Existing research provides important insights into humanitarian logistics and supply chain resilience. However, practical application requires an integrated understanding of transportation, inventory, anticipatory action, information sharing, and coordination within Pakistan's disaster-management context. This study addresses this need by synthesizing established literature and documentary evidence into a context-specific conceptual framework. It does not claim to generate new empirical findings from interviews or surveys.

5. Research Methodology

5.1 Research Design and Data Sources

This study adopts a qualitative documentary research design based entirely on secondary data. Sources include peer-reviewed journal articles, scholarly books, official disaster assessments, government publications, and reports from humanitarian organizations. Particular attention is given to material published by Pakistan's National Disaster Management Authority, relevant Provincial Disaster Management Authorities, the United Nations, and the World Bank.

Documents are selected according to their credibility, relevance to the research questions, and applicability to humanitarian logistics and disaster preparedness. Pakistan-specific reports provide contextual evidence, while academic publications establish the theoretical foundation.

5.2 Data Analysis

The study uses thematic analysis to identify recurring concepts across the selected literature. The analytical process involves reviewing documents, identifying relevant information, grouping related concepts, and interpreting their implications for humanitarian supply chain resilience. Six themes guide the analysis: transportation disruption, inventory management, anticipatory logistics, sourcing flexibility, information sharing, and inter-organizational coordination.

Because the research relies on secondary sources, its conclusions represent a literature-based synthesis rather than findings from primary fieldwork. All sources are acknowledged, and documentary evidence is interpreted within its stated limitations.

6. Analysis and Discussion

6.1 Transportation and Infrastructure Disruption

Transportation is essential for moving relief supplies from suppliers and warehouses to distribution points and affected communities. Flooding, landslides, earthquakes, and severe weather can damage roads, block bridges, and restrict access to remote locations. These disruptions increase delivery times and may prevent assistance from reaching vulnerable populations.

Resilience can be strengthened by mapping critical transport links, identifying alternative routes, establishing emergency agreements with transport providers, and coordinating with relevant authorities. Contingency plans should also consider the possibility that several routes may become inaccessible simultaneously. Where road transport is unavailable, organizations may need to assess other feasible delivery options according to local conditions and available resources.

6.2 Warehouse and Inventory Management

Warehouses provide essential storage capacity before and during emergencies. However, facilities located in hazard-prone areas may be damaged or become inaccessible. Poor inventory control can also cause shortages, expiry, waste, and delays in distributing essential goods.

Humanitarian organizations should identify priority relief items, maintain accurate stock records, monitor expiry dates, and establish appropriate minimum inventory levels. Pre-positioning essential supplies closer to high-risk communities can reduce delivery times after a disaster. Nevertheless, stock locations and quantities should reflect hazard exposure, expected demand, storage capacity, and replenishment options. Distributing stocks across several suitable locations may reduce dependence on a single vulnerable warehouse.

6.3 Early Warning and Anticipatory Logistics

Early warning systems provide information about potential hazards and their likely impacts. Anticipatory logistics translates this information into practical actions before a

disaster occurs. These actions may include relocating vulnerable stocks, preparing vehicles, checking alternative routes, and alerting emergency teams.

However, warnings are useful only when organizations have clear operational responsibilities, decision-making procedures, and resources available for action. Forecast uncertainty and limited warning periods also mean that anticipatory measures cannot eliminate every disruption. Humanitarian supply chains must therefore combine early action with contingency arrangements for unexpected events.

6.4 Flexible Sourcing and Logistics Arrangements

Dependence on a single supplier, transport provider, or delivery route increases vulnerability when that resource becomes unavailable. Flexible sourcing can reduce this risk through alternative suppliers, emergency procurement agreements, multiple transport options, and contingency routing.

Maintaining backup capacity may increase costs, making risk-based prioritization necessary. Organizations should give particular attention to essential supplies, isolated communities, and disruptions likely to produce severe humanitarian consequences. The objective is not to eliminate all operational costs but to balance efficiency with the ability to maintain critical services during emergencies.

6.5 Information Sharing and Organizational Coordination

Reliable information helps organizations identify available supplies, monitor deliveries, assess road accessibility, and determine where assistance is most urgently needed. Weak information systems can produce duplicated deliveries, shortages, and unequal distribution.

Digital inventory systems, shared logistics dashboards, and regular situation reports can improve visibility. Nevertheless, their effectiveness depends on accurate data, compatible systems, staff capacity, and reliable communications. Backup procedures are also necessary because disasters may disrupt electricity and telecommunications.

Coordination among disaster-management authorities, humanitarian organizations, local administrations, suppliers, and transport providers is equally important. Clearly defined responsibilities, common reporting procedures, and joint contingency planning can reduce duplication and improve resource allocation. Information sharing and coordination should therefore operate together rather than as separate preparedness activities.

7. Pakistan Context and Proposed Conceptual Framework

Pakistan's disaster exposure makes resilient humanitarian logistics an important national priority. The 2022 floods demonstrate the scale of potential disruption. The joint post-disaster assessment estimated damages exceeding US$14.9 billion, economic losses of approximately US$15.2 billion, and resilient rehabilitation and reconstruction needs of at least US$16.3 billion (Government of Pakistan et al., 2022). These figures illustrate the broader consequences of disaster-related damage to infrastructure, livelihoods, and essential services.

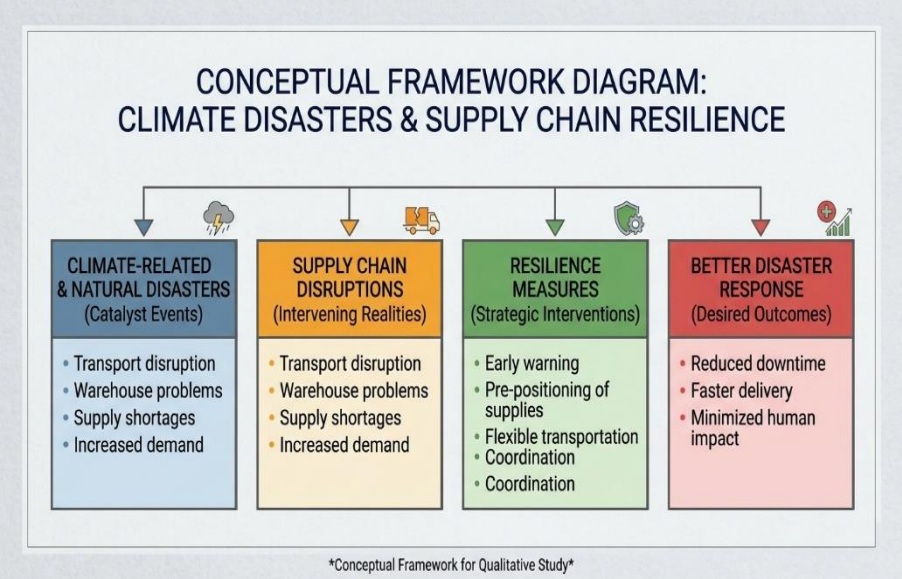
For humanitarian logistics, the implications include the need to protect storage facilities, identify alternative transport routes, position emergency supplies, and coordinate relief operations across national, provincial, and district levels. Strategies must also reflect geographical differences between urban centres, flood-prone plains, and remote mountainous communities.

The study proposes the following conceptual relationship:

Disaster-related disruptions → Resilience capabilities → Humanitarian response performance

Disaster-related disruptions include infrastructure damage, transportation interruptions, storage problems, supplier shortages, and sudden increases in demand. Resilience capabilities include anticipatory logistics, strategic inventory, flexible transportation, information sharing, and organizational coordination. These capabilities are expected to support faster deliveries, improved resource allocation, and more reliable access to relief supplies.

The framework is conceptual rather than empirically tested. Actual outcomes depend on implementation quality, available resources, disaster severity, and accessibility. It provides a basis for organizing preparedness priorities rather than claiming that particular interventions have demonstrated causal effects in Pakistan.



The framework proposes that resilience measures can help reduce the effects of disaster-related disruptions and support more effective humanitarian response. Actual effects will depend on the quality of implementation, available resources, the severity of the disaster, and the accessibility of affected communities.

8. Recommendations

I. **Strengthen risk-based preparedness.** Identify vulnerable infrastructure, high-risk communities, critical supplies, and likely logistical bottlenecks before disasters occur.

II. **Improve inventory and warehouse management.** Maintain accurate stock records, establish appropriate emergency reserves, monitor expiry dates, and protect storage facilities against relevant hazards.

III. **Expand anticipatory logistics.** Link early warnings to clear operational triggers, assigned responsibilities, and feasible pre-disaster actions.

IV. **Develop alternative transport and sourcing arrangements.** Identify backup routes, suppliers, and transport providers to reduce dependence on individual resources.

V. **Improve information sharing.** Use reliable inventory records, regular situation updates, and compatible reporting systems to strengthen supply visibility and decision-making.

VI. **Strengthen inter-organizational coordination.** Establish clear responsibilities and joint contingency plans among disaster-management authorities, humanitarian organizations, and logistics partners.

VII. **Review preparedness plans regularly.** Incorporate lessons from previous disasters, changing hazard exposure, infrastructure conditions, and available operational capacity.

9. Limitations of the Study

This study relies on existing literature and documentary sources and does not include interviews, questionnaires, direct observation, or newly collected operational data. Consequently, it cannot independently quantify the frequency of specific disruptions, compare the measured effectiveness of individual interventions, or establish causal relationships between resilience measures and humanitarian outcomes.

The analysis is also dependent on the availability, quality, and coverage of published information. Differences in reporting practices may limit comparisons across disasters and organizations. Future research could examine documented disaster cases systematically or use primary data collection to investigate implementation challenges. Such research would extend, rather than replace, the present secondary-data-based study.

10. Conclusion

Climate-related and natural disasters can disrupt humanitarian supply chains through infrastructure damage, transportation interruptions, warehouse vulnerability, supplier shortages, and increased demand for relief supplies. This study examined these challenges through qualitative analysis of existing literature and documentary evidence.

The analysis identifies anticipatory logistics, strategic inventory management, flexible transport and sourcing, reliable information sharing, and inter-organizational coordination as important resilience capabilities. Pakistan's experience, particularly the 2022 floods, highlights the importance of integrating preparedness with infrastructure protection and coordinated logistics planning.

Resilient humanitarian supply chains require action before, during, and after disasters. By incorporating risk-informed planning, appropriate stock positioning, alternative delivery arrangements, and clear coordination procedures, relevant organizations can strengthen their capacity to maintain essential relief operations. The proposed conceptual framework offers a practical basis for preparedness planning while recognizing that its relationships require further empirical evaluation.

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PARTICIPANT RESEARCH PAPER

Drought Management in Tharpakar, Sindh

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Abstract

Tharparkar, the largest district of Sindh, lies almost entirely within the Thar Desert and is among the most drought-prone parts of Pakistan. Most of its 1.78 million people live in scattered rural settlements and rely on rain-fed crops and livestock. Groundwater is the only year-round source of water, and much of it is brackish, with fluoride and arsenic above safe limits in many locations [1, 2, 3]. This paper reviews drought in Tharparkar using government plans and notifications, United Nations and humanitarian assessments, published research and press reports. Rainfall records do not show a simple drying trend. Annual totals appear to have risen slightly since the 1970s, but rain has become more erratic, and poorly timed rain is now as damaging as low rain [4, 5]. Whether a dry year becomes a crisis depends largely on conditions that exist before the rains fail: widespread poverty, very high child undernutrition, weak health services, unsafe water and a livestock market that collapses when many households sell at once. Public response has relied mainly on calamity declarations and free wheat, usually after losses are already visible. Reverse osmosis (RO) plants, the largest single investment in drinking water, have had high failure rates because their running costs were never secured. The paper proposes a drought management framework for the district covering early warning tied to pre-arranged action and finance, a mix of water sources that communities can maintain, protection of livestock, permanent nutrition and social protection services, and stronger local governance, including over the water used by Thar coal projects. A phased action matrix with suggested lead agencies and progress indicators is included.

Keywords: drought management; Tharparkar; Thar Desert; Sindh; malnutrition; water security; reverse osmosis; anticipatory action; disaster risk reduction; climate adaptation

1. Introduction

Background

Drought develops slowly. It can build over months or years, it covers large areas and it leaves little physical damage, so its start, end and severity are hard to pin down and its effects are often noticed late [6]. In Sindh, the arid zone made up of the Kohistan hills and the eastern Thar Desert, including the Nara region, covers about 68,000 square kilometres, roughly 48 percent of the province. It lies above the reach of the Indus barrages and depends entirely on rain [6]. The Provincial Disaster Management Authority (PDMA) Sindh describes the Thar Desert as the most drought-prone part of the province [6].

Tharparkar district covers most of the Sindh portion of the desert. It is the largest district in the province by area, with 1,778,407 people recorded over 19,637 square kilometres in the 2023 census [1]. In 2014, only nine of its 166 revenue dehs were reported to lie within a barrage command area; the rest are desert settlements that grow food and fodder only when the monsoon allows [7]. The drought of 20132016, during which child deaths in district hospitals led the Supreme Court of Pakistan to take suo motu notice, made Tharparkar a national reference point for the human cost of drought [8, 9, 10].

Problem Statement

Tharparkar has been through repeated droughts, relief operations and large public investments, yet each dry spell still brings malnutrition, child deaths, distress migration and heavy livestock losses. Government action has usually started after impacts were visible and has focused on food distribution. Longer-term investments, especially RO water treatment, have often stopped working within a few years [11, 12]. The evidence on these problems is spread across official reports, humanitarian assessments, academic studies and news coverage. This paper brings it together to explain why drought management in the district has underperformed and what could be done differently.

Objectives

The study has five objectives: to describe the drought hazard in Tharparkar, including its frequency, changes in rainfall and recent episodes; to analyse its effects on health and nutrition, water, livestock and agriculture, migration, women and the local economy; to identify the institutional, technical, financial and social constraints on drought

management; to review the main interventions to date and what can be learned from them; and to set out a phased set of solutions and recommendations.

Research Questions

- How has drought in Tharparkar changed over recent decades, and what does that change mean for how it is managed?
- How does a rainfall deficit turn into a humanitarian emergency in the district?
- Why have RO plants and calamity relief done little to build lasting resilience?
- What combination of measures could move the district from reactive relief to planned drought risk management?

Scope

The study covers Tharparkar district within its present boundaries and refers to provincial and national arrangements where they affect outcomes in the district. It considers the period from the late 1990s to 2025, with most attention on the 2013-2016 and 2018-2019 droughts, which are the best documented.

2. Methodology

The paper is a qualitative desk review supported by secondary data. Four types of sources were used. The first were official statistics and government documents, including Pakistan Bureau of Statistics census tables, PDMA Sindh contingency plans, Government of Sindh drought reports and releases of the National Disaster Management Authority (NDMA). The second were United Nations and humanitarian assessments, among them Integrated Food Security Phase Classification (IPC) analyses, OCHA and ReliefWeb compilations and the 2019 Sindh Drought Needs Assessment [13]. The third was published research on rainfall, groundwater, nutrition, poverty and resilience in Tharparkar. The fourth was national and international press reporting, used mainly for events, official statements and figures that were not published elsewhere.

Figures were taken directly from the cited sources and compared where more than one source reported the same indicator. Where sources disagree, as they do on migration and on the number of working RO plants, the range is given and the differences are discussed. A few indicators, such as the rural and literate shares of the population, were calculated from census counts.

No primary fieldwork was carried out. Some important figures, particularly hospital child death counts, come from official statements reported in the press. They show the scale of distress but are not population-based mortality rates and should not be compared directly across years. District data on livestock numbers, groundwater levels and drought losses are limited and often old.

Study Area Profile

Geography and Administration

Tharparkar is in south-eastern Sindh on the border with India. The landscape is made up of moving and partly fixed sand dunes, sandy plains and low rocky hills, with scattered saline depressions known locally as dhands. Soils are coarse, calcareous and low in fertility, and natural grasses are the main resource for herding [6]. The district has seven talukas (Chachro, Dahli, Diplo, Islamkot, Kaloi, Mithi and Nagarparkar), and Mithi is the headquarters [2]. Most of the small rainwater dams built in recent years are in the Nagarparkar area in the south-east [14].

Demography

Between the 1998 and 2023 censuses the population nearly doubled, from 914,291 to 1,778,407, although growth slowed to 1.29 percent a year between 2017 and 2023 [2, 1]. In 2023, 91.9 percent of residents lived in rural areas and 51.9 percent were under 15 [2]. About 36 percent of people aged ten and above were literate [2]. Table 1 gives the main figures.

Table 1. Demographic profile of Tharparkar district (Census 2023)

Indicator	Value	Source
Area	19,637 km2	PBS [1]
Population (2023)	1,778,407	PBS [1]
Population (1998 / 2017)	914,291 / 1,647,036	PBS via City Population [2]
Annual growth rate, 2017-2023	1.29 percent	PBS [1]

Population density	90.6 persons per km2	PBS [1]
Urban share	8.1 percent	PBS [1]
Average household size	5.4 persons	PBS [1]
Population aged 0-14	922,411 (51.9 percent)	Calculated from [2]
Literacy, population aged 10+	396,323 of 1,088,975 (36.4 percent)	Calculated from [2]
Largest talukas by population	Chachro 371,769; Dahli 326,034; Nagarparkar 283,074	PBS via City Population [2]

Climate and Rainfall

The climate is hot and arid, and rainfall varies greatly from year to year. Mithi, for long the only continuously recording rain gauge in the district, averages about 277 mm a year [5]. Across the desert belt, annual totals of between about 100 mm and 700 mm have been reported [15]. According to the Pakistan Meteorological Department (PMD), about 87 percent of the district's rain falls between June and September [16]. Rain-fed farmers in Thar and neighbouring Umerkot need three or four spells of rain, 15 to 20 days apart, between June and August to bring a crop to harvest, and the same rains renew the pastures [17].

Rainfall monitoring is limited. Climatic stations in Sindh are 100 to 150 km apart, which is why researchers have tested satellite rainfall estimates for the district [5]. PMD's analysis of the Tharparkar record found that moderate to severe drought is common and that, on average, four years in ten are drought years [18].

Livelihoods

For about 80 percent of households, rain-fed farming and livestock have been the main source of income [19]. Millet and other short-season crops are sown after the first monsoon rains, and cattle, sheep, goats and camels are raised on open rangeland [6]. The 1998 livestock census counted 3,656,933 animals in the district. Later estimates range from five to 6.5 million head [20, 21, 22]. The local Tharparkar cattle breed is among the best milk producers in the region [6]. For most families, animals are the main

asset and also their savings and insurance, so losing them in a drought sets a household back for years.

3. The Drought Hazard in Tharparkar

Frequency and History

Sindh has a long history of drought and famine. PDMA Sindh lists 1871, 1881, 1899, 1931, 1942, 1999, 2003 and 2020-2022 among the province's worst drought years, and notes that the 1999 drought lasted until 2002 [23]. Officials and the press commonly describe Tharparkar as being hit by drought every two or three years [7, 20], which matches PMD's estimate of four drought years in ten [18]. Provincial response is based on the Sindh Natural Calamities (Prevention and Relief) Act, 1958, under which the Relief Commissioner notifies affected dehs [17], together with the institutional set-up created under the National Disaster Management Act, 2010 [6].

The Changing Nature of Drought

It is often assumed that Tharparkar is getting steadily drier. The rainfall record is more complicated than that. A study in The Pakistan Development Review compared 1975-1994 with 1995-2014 and found a small increase in average annual rainfall, but with much more irregular patterns. Its authors argue that drought in the district has shifted from years with little or no rain to years with more rain that arrives at the wrong times, and that this is harder on livelihoods [4]. A remote sensing study reported a similar result, an increase of about 6.35 mm per year alongside falling crop yields, and found that low yields often occurred where heavy rain damaged ripening crops. A steady supply of moisture through the season mattered more than the seasonal total [5].

This has practical consequences. Seasonal rainfall totals are a weak basis for deciding when to act; the timing and spacing of rain, and how crops and pastures respond, need to be tracked as well. The district also faces heavy rain events as well as dry spells, so storage should be designed to capture intense rain when it comes. Temperatures appear to be rising too. One study found that average temperature in Thar rose by almost 1 degree Celsius over a decade [24], and PMD has projected a hotter and drier region by 2030 [25]. Higher temperatures mean more evaporation from ponds and soil and greater water needs for people and animals.

Recent Drought Episodes

The main documented droughts since the late 1990s are listed in Table 2.

Table 2. Major documented drought episodes affecting Tharparkar

Period	Hazard characteristics	Documented impacts and response
1999-2002	Multi-year drought across Sindh's arid zone [23].	District officials reported about 40 percent out-migration to adjoining districts; many peasants were left in debt after the 1997-2000 dry years [20].
2013-2016	Below-average rainfall in Chachro, Diplo, Khinser, Islamkot and Mithi; sheep pox outbreak killing thousands of small animals [10].	Acute malnutrition reported as high as 20 percent; reported under-five deaths rose from 188 (2012) to 234 (2013), 326 (2014) and 398 (2015); Supreme Court suo motu notice; federal relief package of Rs 1 billion [10, 8, 26].
2018-2019	June-August 2018 rainfall of 10-120 mm across talukas (Mithi 58 mm, Islamkot 24 mm, Kaloi 10 mm) [27].	167 of 172 revenue dehs notified as drought-hit; 323,435 families affected; free wheat of 50 kg per family per month; 71 percent of surveyed households in eight districts food insecure [17, 27, 28].
2020-2022	Rainfall 77.3 percent below normal in Sindh's drought-prone areas between October 2020 and March 2021, linked to La Nina [23].	Moderate drought intensified into severe drought, especially in southeastern Sindh [23].
2024-2025	Rainfall in Sindh 52 percent below normal from 1 September 2024 to 15 January 2025; mild meteorological drought declared [6].	Tharparkar listed among 13 vulnerable districts; PDMA issued Provincial Drought Contingency Plan 2025 [6]; IPC analysis cited drought among drivers of acute food insecurity [29].

4. Impacts of Drought

Health and Nutrition

Young children and mothers have suffered most. In March 2014, OCHA reported, based on information from district authorities, that 99 children and 67 adults had died since the start of the year. It attributed the deaths to a combination of chronic malnutrition, poor access to health care, below-average rain and livestock disease, and reported acute malnutrition among children of up to 20 percent, above the 15 percent emergency threshold [10]. By the end of 2014, press reports put the death toll at about 650, most of them children [30]. In 2016, more than 190 child deaths and 22,000 hospital admissions for waterborne and viral illness were reported [10], and by October 2018 child deaths in hospitals had reached 531 for the year [31].

These are hospital counts, and their causes have been disputed. Officials have blamed premature birth, low birth weight and poor maternal health rather than hunger [30, 32]. The two explanations overlap. Doctors in the district linked newborn deaths to anaemia among pregnant women who could not get an adequate diet [33], and the Sindh government's relief coordinator acknowledged in 2014 that severely malnourished children fall ill more quickly and recover less often [32]. Drought makes an already weak nutritional situation worse.

Child nutrition in the district is poor even in normal years. A survey of 597 children under five in four talukas, carried out between October 2017 and March 2018, found 81.1 percent stunted, 57.3 percent underweight and 18.2 percent wasted. The corresponding national figures from the Pakistan Demographic and Health Survey 2017-18 were 37, 23 and 7 percent [34]. At national level, the National Nutrition Survey 2018 found four in ten children under five stunted and the highest wasting rate the survey had ever recorded [35]. The IPC acute malnutrition analysis for March 2023 to January 2024 placed Tharparkar in Phase 4 (Critical), along with ten other districts of Sindh [36].

Water Security and Water Quality

There are no rivers or perennial streams in Tharparkar. People use rainwater stored in ponds and tanks first, and then turn to dug wells and tube wells, which mostly tap deep, saline groundwater [6]. A dry year therefore hurts twice. Less rainwater is stored, and

less water recharges the thin layers of fresher water that sit above the saline aquifer, so people are pushed towards worse sources.

Studies of groundwater quality have found serious and widespread problems (Table 3). A European Commission summary of research by Dow University of Health Sciences and PCSIR reported that 80 percent of water sources in the district were unfit to drink, with fluoride above 13 mg per litre at some sites [37]. The WHO guideline is 1.5 mg per litre [3]. Excess fluoride causes dental and skeletal fluorosis, and residents report diarrhoea, joint deformities and thyroid and kidney problems that they link to polluted water [38].

Table 3. Selected groundwater quality findings in Tharparkar

Study	**Coverage**	**Key findings**
Khalique Alvi et al. (2008) [3]	33 samples, district-wide	Fluoride 0.93-11.8 mg/L; 27 of 33 samples above the WHO guideline of 1.5 mg/L; water moderately to highly saline and hard to very hard.
Diplo and Chachro study (2012) [39]	Groundwater of two talukas	Arsenic and fluoride above WHO and US EPA limits; high salinity and alkalinity associated with both contaminants.
Islamkot WQI study (2020) [40]	Islamkot taluka	28 samples had TDS above 3,000 mg/L and 12 between 1,500 and 3,000 mg/L; water quality ranged from very poor to unsuitable for drinking.
Kumar et al. (2022) [41]	25 open dug wells across talukas	TDS mostly 800-11,000 mg/L; fluoride 0.1-5.1 mg/L; arsenic up to 80 micrograms per litre; fluoride above limits in Mithi, Dharar, Harmar and Satar.

Fetching water takes a great deal of time, mostly that of women and girls, who traditionally manage household water and whose workload grows during drought [4]. When RO plants have shut down, villagers have had to go back to brackish and often dirty water from ponds and wells [42].

Livestock and Agriculture

Because all cropping depends on rain, a failed or badly spread monsoon means most households lose their harvest, and animals lose the seasonal grass they depend on [17]. Livestock are lost to hunger, disease and forced sales. In 2014 a sheep pox outbreak killed thousands of small animals [10], and one herder in Diplo said that 12 of his 40 cattle had died in the previous two months [32]. During the 2002 drought, livestock sales were reported to have risen by 65 percent while their market value fell by more than 53 percent on average [19]. In 2014, a goat that would normally sell for Rs 5,000 was expected to fetch only Rs 1,500 once weakened, and analysts called for fodder supplies, vaccination and livestock sanctuaries to keep animals alive and in the district [21].

When many families sell at the same time, prices fall exactly when they need cash most, and herds built over years are sold cheaply. Rebuilding them after the drought is slow and costly, so each drought can leave a household poorer for a long time afterwards.

Migration

Moving to the canal-irrigated barrage areas of Sindh, with or without animals, is an old way of coping with drought. How many people move is disputed. Some commentators have put the figure at 25 to 35 percent of the population during severe droughts [21]. In 2015, local residents suggested that nearly half the population might leave along with 40 percent of livestock, while the Deputy Commissioner at the time said no more than 10 percent moved, mostly from Kolhi, Bheel and Menghwar communities with a tradition of seasonal migration [43]. In 2018 the provincial livestock department said that about half of large cattle and 15 percent of sheep and goats are usually taken to irrigated areas in a drought year, and that more were being moved that year [44]. The 2019 Sindh Drought Needs Assessment, which covered eight districts, found that about five percent of households had a member who had migrated because of drought in the previous six months [28]. The estimates use different definitions, periods and populations, and no system exists to track migration consistently.

Migration helps some families get through a drought. Research in the district lists temporary migration, handicrafts, daily wage work and selective sale of animals among the main ways households adapt [22]. Migrants are not always welcome in host areas,

however [32], and many Thari workers end up as haris (tenant farmers) for landlords elsewhere after taking loans, which can trap them in debt [20].

Gender Dimensions

Women carry most of the burden of collecting and managing water, and it gets heavier during drought [4]. When men leave to find work, women look after the animals, walk further for water, care for older relatives and keep the household farming [25]. Pregnant and breastfeeding women face particular nutritional stress, which shows up in low birth weight among newborns [33]. The 2018 provincial response included nutritional support for 49,910 pregnant and breastfeeding women in Tharparkar and Umerkot [45].

Poverty and the Local Economy

Poverty makes drought more dangerous, and drought in turn makes people poorer. Tharparkar has had the lowest Human Development Index of any district in Sindh [30]. A household survey found that about three-quarters of the population lived below the poverty line, with higher risk among households whose heads had little education, larger households and households headed by women [46]. Drought uses up savings, forces sales and leads to borrowing. After the 1997-2000 drought, farmers were reported to have taken loans of Rs 20,000 to 25,000 each just to sow their fields again [20]. A community resilience assessment in the district gave an overall score of 51 percent, with process indicators at 56 percent and outcome indicators at only 45 percent, which suggests that project activities had not yet produced matching gains in resilience [47].

Environmental Impacts

Long droughts reduce vegetation and soil moisture, increase wind erosion and speed up desertification [6]. Satellite analysis shows that vegetation in Thar improved from 2002 to 2011 and then declined again up to 2014 [24]. Reduced recharge also concentrates contaminants in groundwater [6], so land degradation feeds directly into health problems.

5. Challenges in Drought Management

Late, Declaration-Based Response

Drought response in Tharparkar has usually waited for a formal calamity declaration. In 2003 the district council noted that the district had faced nine drought years in thirteen. In each case, it said, the recommendation to declare a calamity came three to four months late and the provincial government took about three more months to act, so subsidised

food and fodder reached people for only around two months [11]. The same pattern was seen in 2014. The district had been declared calamity-hit, but the promised 60,000 bags of wheat had not arrived when child deaths were being reported, and the district administration warned that this amount would not cover the roughly 175,000 affected families [7]. Large-scale action, including the federal relief package and proceedings in the Supreme Court, followed media coverage of the deaths [8, 26].

The 2018 response was quicker. Free wheat distribution began on 24 September 2018 and had reached 227,661 families by 30 October, using family lists provided through NADRA and NDMA [45, 48]. The main tool, however, was still a wheat ration delivered after the crop had failed. Wheat does nothing for micronutrient deficiencies, unsafe water, livestock or access to health care.

Divided Responsibilities and Uncertain Funding

Many agencies share responsibility for drought: PMD, NDMA, PDMA, the District Disaster Management Authority (DDMA), the Relief (Revenue) Department and the departments of health, agriculture, livestock, public health engineering, food and social welfare [6]. Coordinating them is difficult, and long-term investment in water and livelihoods is not linked to drought warnings. Funding has been disputed as well. In 2019 the federal cabinet approved a USD 96.3 million drought response plan for Sindh and Balochistan but decided, with reference to the 18th Amendment and provincial resource shares, not to provide federal money for it [49]. PDMA's own plan says that the number of people affected by a drought cannot be estimated in advance because it depends on how quickly mitigation happens and how resilient communities are [6]. Without pre-arranged funding, this makes budgeting very difficult.

RO Plants and the Problem of Maintenance

The RO programme shows most clearly what goes wrong when infrastructure is built without a plan to run it. In 2015 the Sindh government began installing 750 solar-powered RO plants in Tharparkar, at a reported cost of more than EUR 46 million [37, 50]. Several reviews since then have found many of the plants out of service (Table 4). In 2018, operators shut more than 450 plants after going four months without pay [42]. Other causes include tube well and membrane failures and the lack of a budget for operation and maintenance [50, 12]. Some experts argued from the start that RO was unsuitable

for Thar, and the NGO AWARE asked who would be responsible for keeping the plants running once the 18th Amendment had moved the subject to the province [50, 51].

Table 4. Reported functionality of RO plants in Tharparkar

Source	Scope	Reported status
Sindh government inspection team (2015) [52]	Plants across seven talukas	More than 50 percent out of order; 88 of 102 plants in one group found not working.
Supreme Court-mandated water commission (reported) [53]	Sindh-wide inventory	Tharparkar had the most plants in Sindh, 589, of which 454 were working and 128 out of order; PKR 336.7 million released to revive 110 plants.
Nagarparkar case before judicial magistrate (2022) [50]	86 plants in Nagarparkar	By 2020 only half of the planned 750 had been built and at least 70 percent of those were not working; only 6 of 86 Nagarparkar plants in operation.
Journal of Development and Social Sciences (2023) [12]	Plants in 148 villages across all talukas	53 percent not functional; 35 percent of these temporarily and 65 percent permanently closed.

The figures cover different years and samples, so they are not directly comparable, but all of them point the same way. The plants were installed faster than the budgets, staff and local skills needed to keep them running were put in place. Water infrastructure without funded and accountable operation and maintenance will not make the district more resilient.

Gaps in the Health System

District health facilities have struggled when drought cases rise. During the 2014 crisis, the medical superintendent and district health officer at Mithi Civil Hospital told a visiting judge that no special drought budget had been released, that the hospital was

overcrowded and that posts for surgeons, specialists and gynaecologists were vacant [33]. A judicial inquiry found that more than 20 percent of provincial health staff and officers who came from Tharparkar were not posted in the district [30]. Its large area and scattered villages make outreach difficult, and children are often brought to hospital late. As long as malnutrition and maternal nutrition are dealt with mainly in hospitals rather than through routine community services, deaths that could be prevented earlier will continue.

Weak Monitoring and Early Warning

PMD's National Drought Monitoring Centre issues drought advisories using measures such as the Standardised Precipitation Index and departures from normal rainfall [18, 6]. However, the station network in Sindh is thin [5], and research shows that crop and pasture outcomes are hard to predict early in the season in a climate this variable [5]. Warnings have also rarely been tied to agreed actions or funds. The 2025 provincial plan asks departments to set thresholds and issue watch, warning and emergency alerts based on PMD data [6], but no district thresholds or linked actions have yet been published. Nor is there regular monitoring of livestock prices, fodder, migration or child nutrition that could show when impacts are beginning.

Saline Groundwater and Few Safe Alternatives

About two-thirds of the groundwater in Sindh is brackish [6], and in Tharparkar much of it also contains fluoride and arsenic (Table 3). Small dams in Nagarparkar have helped farmers, but specialists point out that recharging groundwater through such dams only works in freshwater zones, and that the stored water is not safe to drink without treatment [14, 54]. The safe options are therefore limited to well-managed rainwater harvesting, carefully located fresh-water aquifers, treated supplies and, where the cost can be justified, piped water from the canal system.

Water and Thar Coal Development

The Thar coalfield covers about 9,000 square kilometres and is divided into 12 blocks [55]. It has brought roads, power plants and investment, and also new pressure on land and water. The coal lies between aquifers, so mines have to pump out large volumes of groundwater. Plans to store the saline mine water in a reservoir at Gorano led to months of protest by residents worried about their farmland and health [56, 57]. About 1,200

families were displaced by Block-II, and the provincial government approved a Rs 950 million grant to pay them monthly stipends [55]. In a 2022 survey of 190 families near the coalfield, 75 percent said mining had reduced the quality and quantity of their water [58], and the same research group reported toxic metals in mine effluent [59]. To supply power plants, the province is building the NabisarVajihar water scheme, including a 61 km pipeline carrying 45 cusecs at a reported cost of USD 190 million [60]. The feeder canal is designed for 200 cusecs, of which 155 cusecs were announced for agriculture at Nabisar [61]. Whether any of this water reaches Thari villages, and not just industry, will matter a great deal for drought resilience.

Underlying Social and Economic Vulnerability

Drought turns into disaster in Tharparkar because it hits people who already have low literacy, high poverty, very high child undernutrition, few assets and limited access to services [2, 46, 34]. Drought measures, however well designed, will have limited effect unless these conditions also improve.

5. Existing Responses and Lessons Learned

Relief Distribution

The provincial response has relied mainly on free and subsidised wheat, fodder support, medical camps and compensation for deaths. In

2018 the Sindh cabinet approved 50 kg of wheat per family per month for affected families [17], and later phases reached about 247,000 and 252,000 families [62]. These measures prevent the worst outcomes, but they are costly, have to be repeated in every drought, usually arrive late and leave communities no better prepared for the next one.

Water Infrastructure

Alongside the RO plants, the government built about 60 small rainwater dams in Nagarparkar and Kohistan, each holding about 100,000 gallons on average, and credited them with a record onion harvest worth Rs 600 million in Nagarparkar [14]. Community ponds built with NGO support since around 1995 can supply villages for about six months after the monsoon [38]. They draw on the traditional tarai system of collecting rainwater in natural hollows [63]. Cheap storage close to settlements, maintained by the people who use it, has worked well where it was properly sited and protected from contamination.

Contingency Planning

PDMA Sindh's Provincial Drought Contingency Plan 2025 sets out standard operating procedures and assigns roles to 19 groups of stakeholders, including the Sindh Emergency Service Rescue 1122. It makes the Agriculture Department the lead agency, supported by Livestock, and lists mitigation measures such as rainwater harvesting and artificial recharge, repair of tanks and tarais, more automatic weather stations and a real-time water resource information system [6]. It also proposes a desk for bio-saline agriculture using Thar's saline water, and community seed banks [6]. Many of the measures are general, however, and the plan does not give district thresholds, budgets or timelines.

Anticipatory Action

Anticipatory action means releasing support that has been agreed in advance once a forecast shows that impacts are likely, rather than waiting for them to happen. With funding from ECHO, FAO has worked in Tharparkar and Umerkot on building drought anticipatory action into social protection systems [64]. It also ran a drought simulation exercise with PDMA, PMD and the Tharparkar district administration, reported as the first of its kind in the province [65]. A drought risk financing model developed for Punjab, Sindh and Balochistan has shown useful forecast skill up to two months before the end of the season, early enough to release funds [66]. FAO analyses suggest that each US dollar spent on anticipatory action can return up to USD 7.1 in avoided losses and other benefits [67]. In May 2025 a three-year, EUR 4 million project called RAFAA was launched in Sindh to strengthen early warning, water monitoring and anticipatory action protocols [68].

Bio-Saline Agriculture and Tree Planting

Pilot projects have shown that saline water, including water pumped from the coal mines, can grow salt-tolerant fruit and fodder. A 40-acre fruit and fodder farm set up in 2017 by the Sindh Engro Coal Mining Company and the Pakistan Agricultural Research Council grows jujube and Rhodes grass among other crops, and a company tree-planting drive reached one million trees in 2021 [69]. A provincial bio-saline agriculture project approved in 2022 and started in Tharparkar, Khairpur and Umerkot has reported reclaiming 460 acres [70]. Some local species, such as Salvadora oleoides (jar), tolerate

both salt and drought [71]. These approaches could increase fodder supply, but it is not yet clear whether ordinary farmers can adopt them without the backing of a coal company.

6. Proposed Solutions

Tharparkar's droughts recur and can be anticipated, and they should be planned for in the same way as any other recurring risk. The proposals below are grouped into five areas that depend on one another. Early warning is of little use without funds to act on it, and water and livestock measures will not save lives if child malnutrition goes untreated.

Early Warning Linked to Action and Finance

Monitoring should be extended to every taluka with automatic weather stations and rain gauges, as the 2025 plan already proposes [6], and combined with satellite rainfall and vegetation data calibrated for local conditions [5]. Rainfall alone is not enough. Lady Health Workers and DDMA staff could report monthly on livestock and grain prices, fodder supply, the state of water sources, migration and child nutrition (using MUAC screening). The district should publish drought thresholds with actions attached to each stage (watch, warning and emergency), so that support starts when indicators are crossed and not only after a calamity has been declared. The money for these actions should be set aside in advance through a provincial drought risk financing window or a contingency budget line, building on the forecast model already tested for Sindh [66] and the anticipatory action protocols under development with FAO [64, 68].

A Water Supply Communities Can Maintain

For scattered villages, rainwater should be the first source of drinking water: rooftop and courtyard tanks, lined community ponds and restored tarais, fenced and fitted with silt traps to keep the water clean [38, 63]. Small dams should continue where the ground and catchments are suitable, mainly around Nagarparkar, on the understanding that they serve farming and recharge more than drinking water [14, 54]. No new RO plants should be built until the existing ones have been audited. Plants worth saving should be revived under performance-based maintenance contracts with a guaranteed annual budget, a village water committee, a clear tariff or subsidy and remote monitoring of output [12]. Fresh-water aquifers and fluoride hotspots should be mapped and a public network for testing groundwater quality set up, so that villages where fluoride exceeds 1.5 mg per litre can be given other sources first [3, 41]. A fixed share of the canal water being

brought to Thar for the power plants should also be reserved for treated domestic supply to nearby villages [61].

Protecting Livestock and Livelihoods

Fodder banks and reserves, including fodder grown with saline water, would allow feed to be supplied at stable prices once a warning is issued [69, 70]. Voluntary destocking schemes that buy animals at fair prices early in a drought, before forced sales drive prices down, should be paired with help to restock afterwards. Routine vaccination and mobile veterinary services need to be expanded, given the disease outbreaks seen in past droughts [10, 6]. Community seed banks can supply drought-tolerant and short-season varieties, and index-based crop and livestock insurance is worth piloting [6, 68]. Other sources of income, such as handicrafts, guggal tree planting by women's groups and skills for jobs in the coal economy, would reduce dependence on rain [25, 22].

Health, Nutrition and Social Protection

Community-based treatment of acute malnutrition should be a permanent service with routine screening, outpatient therapeutic feeding and referral, rather than something started in an emergency. Pregnant and breastfeeding women need regular nutrition support, iron and folic acid and antenatal care, building on the package provided in 2018 [45]. Specialist and gynaecology posts should be filled, mobile health teams sent to remote villages, and incentives offered to health staff from the district to serve there [33, 30]. Using existing social protection registries and NADRA data, cash or mixed cash and food transfers could be scaled up automatically when drought thresholds are reached, instead of depending on wheat alone [48, 64].

Governance and Community Participation

DDMA should prepare a Tharparkar District Drought Management Plan, based on the provincial plan, with taluka and union council annexes, budgets, timelines and named focal persons [6]. A standing district drought cell should meet every month, not only during emergencies, and publish the indicators it tracks and the action taken. Village disaster management committees, with women members, could manage water points, report warning signs and help decide who receives assistance. In the coalfield, independent monitoring of groundwater and effluent, fair compensation and livelihood support for displaced families, and open reporting on how coal royalties are spent on

water, health and education are all needed [55, 59]. Major drought programmes, including RO and relief distribution, should be independently evaluated and the results published.

Phased Action Matrix

Table 5 sets out these proposals by timeframe. The timeframes are indicative: short term means within 12 months, medium term one to three years and long term more than three years.

Table 5. Phased action matrix for drought management in Tharparkar

Action	Timeframe	Suggested lead	Indicator of progress
Publish district drought thresholds and anticipatory action protocol	Short	PDMA, DDMA, PMD	Protocol notified; thresholds applied in next season
Audit all RO plants; revive viable plants under maintenance contracts	Short	PHED, Special Initiatives Dept.	Share of plants working, checked quarterly
Monthly monitoring of prices, fodder, water, migration and MUAC	Short	DDMA, Livestock, Health	Monthly bulletin issued
Permanent CMAM and maternal nutrition services	Short-medium	Health Department	Coverage and cure rates; low birth weight trend
Drought risk financing window and pre-agreed cash transfers	Medium	Finance, PDMA, Social Protection	Funds released before peak impacts
Rainwater harvesting and pond rehabilitation in every union council	Medium	PHED, Local Government, NGOs	Storage capacity per person

Fodder banks and bio-saline fodder production	Medium	Livestock, Agriculture	Tonnes stored; fodder price stability
Groundwater quality and aquifer mapping	Medium	PCRWR, Irrigation, Universities	Village-level water quality map published
Domestic water allocation from Nabisar-Vajihar system	Medium-long	Irrigation, Energy Department	Villages served with treated water
Investment in literacy, health and livelihoods	Long	Government of Sindh, partners	HDI, stunting and poverty trends

7. Recommendations

The following recommendations are made to the Government of Sindh, the district administration and development partners:

I. Publish impact-based district drought thresholds so that assistance begins at the warning stage, well before a calamity is notified.

II. Require a costed, multi-year operation and maintenance plan before any new water infrastructure is approved, and repair or formally close failed RO plants.

III. Make rainwater harvesting and pond rehabilitation the main drinking water strategy for scattered villages, backed by regular water quality testing.

IV. Protect livestock through fodder reserves, vaccination and early destocking at fair prices.

V. Make screening and treatment of malnutrition and maternal nutrition a routine part of primary health care.

VI. Replace wheat-only relief with timely cash or mixed transfers through existing registries, giving priority to women, children and older people.

VII. Expand the weather station network, set up groundwater and nutrition surveillance and publish the data regularly.

VIII. Reserve part of the new canal water and coal royalties for domestic water, health and livelihoods in Thari communities, with independent environmental monitoring.

IX. Strengthen village committees, including women members, to manage water points, report warning signs and oversee targeting.

X. Evaluate major programmes independently and update the district drought plan after every season.

8. Conclusion

Drought in Tharparkar recurs often enough to be planned for, and erratic rainfall and rising temperatures are changing its character. The district's experience shows that rainfall failure on its own does not explain the crises of recent decades. Deaths and losses have been greatest where poor rains met poverty, child undernutrition, unsafe water and weak health services, and where the government acted late and relied on short-term relief. Large investments, RO plants in particular, failed when nobody was made responsible and paid for keeping them running.

No single project will solve these problems. What the district needs is a combination of measures: monitoring that tracks impacts as well as rain, thresholds linked to money set aside in advance, water sources that villages can look after themselves, protection for livestock, nutrition and social protection services that run all year, and local institutions that answer to Thari communities, including on the use of water by the coal industry. The 2025 Provincial Drought Contingency Plan and the anticipatory action work now under way are a starting point. Turning them into a costed district programme, with clear responsibilities and regular monitoring, would allow Tharparkar to prepare for drought instead of reacting to it each time.

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