



Climate Justice, Environmental Migration Intentions, and Vulnerability among Flood-Affected Households in Pakistan’s Indus Basin: A Mixed-Methods Study of Adaptive Capacity and Policy Gaps

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ABSTRACT

Background: Climate change has increased the frequency and severity of flooding, disproportionately affecting vulnerable populations in developing countries. Pakistan’s Indus Basin experiences recurrent floods that disrupt livelihoods, displace communities, and heighten social and economic vulnerability, emphasizing the need to understand factors influencing environmental migration.

Objective: To examine the relationship between climate justice, vulnerability, adaptive capacity, and environmental migration intentions among flood-affected households in Pakistan’s Indus Basin.

Methods: A mixed-methods cross-sectional study was conducted among 512 flood-affected households selected through stratified, purposive, and snowball sampling. Quantitative data were collected using structured household surveys, while qualitative data were obtained through semi-structured interviews with community leaders, NGO representatives, and affected households. Data were analyzed using descriptive statistics, reliability analysis, t-tests, ANOVA, multiple regression, logistic regression, and thematic analysis.

Results: Participants reported high levels of flood exposure, livelihood disruption, and limited adaptive capacity. More than half intended to migrate within Pakistan, while many also considered international migration. Frequent flood exposure significantly increased migration intentions, whereas greater adaptive capacity, access to early-warning systems, and stronger perceptions of climate justice reduced the likelihood of migration. Respondents expressed dissatisfaction with existing climate adaptation policies and identified substantial gaps between community needs and available institutional support.

Conclusion: Flood-affected households in Pakistan’s Indus Basin face considerable climate vulnerability that contributes to migration intentions. Strengthening adaptive capacity, improving climate governance, expanding early-warning systems, and promoting climate justice are essential for reducing vulnerability and supporting sustainable adaptation in flood-prone communities.

INTRODUCTION

Climate change has emerged as one of the most significant global challenges of the twenty-first century, affecting ecosystems, economies, and human societies across the world (Malhi et al., 2020; Abbass et al., 2022). Rising temperatures, changing precipitation patterns, sea-level rise, and the increasing frequency and intensity of extreme weather events have intensified environmental risks and threatened the livelihoods of millions of people (Hussain et al., 2020). Among the most severe consequences of climate change are floods, droughts, heatwaves, and storms, which disproportionately affect vulnerable populations in developing countries (Ngcamu, 2023). These climate-related hazards not only damage infrastructure and natural resources but also undermine food security, economic stability, public health, and social well-being (Safi et al., 2024; Assoua et al., 2024). As climate impacts continue to intensify, understanding how communities respond to environmental stressors has become a major focus of research and policy discussions worldwide.

Pakistan is recognized as one of the country’s most vulnerable to climate change despite contributing only a small fraction of global greenhouse gas emissions (Khoso et al., 2025). According to the Global Climate Risk Index, Pakistan consistently ranks among the nations most affected by climate-related disasters, particularly floods and extreme rainfall events. The Indus Basin, which supports the

livelihoods of millions of people through agriculture, livestock production, and related economic activities, is especially vulnerable to flooding due to its geographic characteristics and dependence on seasonal river systems. Recent catastrophic flood events, including the devastating 2022 floods, caused widespread destruction of homes, infrastructure, agricultural land, and livelihoods, affecting more than 33 million people and resulting in substantial economic losses (Bazai et al., 2025). These recurring disasters have exposed

HIGHLIGHTS	
Research insights	The study reveals that stronger informal social control, mutual trust, and cohesive neighborhood networks significantly reduce crime rates in low-income urban communities facing social disintegration.
Practical insights	Encouraging resident participation, rebuilding neighborhood trust, and addressing socio-economic barriers can strengthen informal social control mechanisms and effectively prevent crime in marginalized urban areas.
Industry insights	Urban planners and policymakers should integrate community-based safety programs emphasizing social cohesion to enhance sustainable crime prevention strategies in marginalized areas.

underlying social, economic, and institutional vulnerabilities within



flood-prone communities.

Climate vulnerability refers to the degree to which individuals or communities are susceptible to and unable to cope with the adverse impacts of climate change. Vulnerability is influenced by three key dimensions: exposure to environmental hazards, sensitivity to their impacts, and adaptive capacity (Zainab & Shah, 2024; Rahman & Hickey, 2020). Households with limited financial resources, weak infrastructure, low educational attainment, and restricted access to social services often experience higher levels of vulnerability than more affluent populations. In Pakistan, many rural communities depend heavily on climate-sensitive sectors such as agriculture and fisheries, making them particularly susceptible to flood-related disruptions. Repeated exposure to disasters can erode household assets, increase indebtedness, and reduce the capacity of communities to recover from future shocks (Islam et al., 2020; Ashraf et al., 2021).

One increasingly important consequence of climate vulnerability is environmental migration. Environmental migration refers to the movement of individuals or households in response to environmental changes that adversely affect living conditions and livelihoods (Daoust & Selby, 2024). Migration may occur temporarily or permanently and can involve movement within national borders or across international boundaries (Ofori et al., 2023). Scholars have increasingly recognized migration as both a consequence of climate change and a potential adaptation strategy that enables households to diversify income sources and reduce exposure to environmental risks (Kaczan & Orgill-Meyer, 2020; Maharjan et al., 2020; Hamza et al., 2024). However, migration decisions are complex and influenced by a combination of environmental, economic, social, political, and cultural factors. Consequently, not all climate-affected households possess the resources or opportunities necessary to relocate, creating unequal patterns of mobility and vulnerability (Hunter et al., 2021).

The concept of climate justice has gained considerable attention in recent years as researchers and policymakers have sought to address the unequal distribution of climate risks and adaptation resources. Climate justice emphasizes that the impacts of climate change are not experienced equally and that vulnerable populations often bear the greatest burdens despite contributing least to global greenhouse gas emissions. Climate justice encompasses distributive justice, which concerns the fair allocation of resources and burdens, and procedural justice, which focuses on meaningful participation in decision-making processes (Juhola et al., 2022; Walker et al., 2024). In many developing countries, affected communities frequently report exclusion from adaptation planning and dissatisfaction with disaster response efforts, raising concerns about fairness, accountability, and equity in climate governance (Nadiruzzaman & Scheffran, 2022; Bhanye, 2025).

The relationship between climate justice and migration has become increasingly important within contemporary climate policy debates. When adaptation policies fail to adequately protect vulnerable populations, migration may become a necessary coping mechanism rather than a voluntary choice. Research from Bangladesh, India, Sub-Saharan Africa, and other climate-sensitive regions has shown that perceptions of unfair resource distribution, inadequate disaster assistance, and limited institutional support can influence migration intentions and adaptation decisions (Nabong et al., 2023). Understanding these dynamics is particularly important in Pakistan, where flood-affected communities continue to face repeated environmental shocks while navigating socioeconomic challenges and institutional constraints.

Despite growing international interest in climate-induced migration and climate justice, empirical evidence from Pakistan remains limited (Kamal, 2023; Ullah et al., 2024; Harun et al., 2025). Existing studies have primarily focused on disaster impacts, vulnerability assessments, or migration patterns independently, with relatively little attention given to the interconnected relationships among

climate justice, adaptive capacity, vulnerability, and migration intentions. Furthermore, few studies have incorporated the perspectives of affected households, community leaders, and local organizations to examine how perceptions of fairness and institutional support shape adaptation responses. Addressing these knowledge gaps is essential for developing evidence-based climate policies that reflect the needs and priorities of vulnerable communities.

Therefore, the present study investigates climate justice, environmental migration intentions, and vulnerability among flood-affected households in Pakistan's Indus Basin. Specifically, the study examines the influence of demographic and socioeconomic factors, flood exposure, adaptive capacity, access to early-warning systems, and perceptions of climate adaptation policies on migration intentions and vulnerability outcomes. By integrating quantitative and qualitative data, the study provides a comprehensive understanding of how climate-related risks interact with social and institutional factors to shape adaptation decisions. The findings are expected to contribute to the growing literature on climate migration and climate justice while informing the development of equitable and effective adaptation policies for flood-prone regions of Pakistan.

METHODOLOGY

This study employed a mixed-methods cross-sectional research design to investigate climate justice, environmental migration intentions, and vulnerability among flood-affected households in Pakistan's Indus Basin. The research integrated quantitative household surveys with qualitative interviews to provide a comprehensive understanding of how climate-related disasters influenced migration decisions, perceptions of climate justice, adaptive capacity, and vulnerability. The study was conducted in selected flood-prone districts of the Indus Basin, including areas severely affected by recurrent flooding in Punjab, Sindh, and Khyber Pakhtunkhwa. Secondary data were obtained from the National Disaster Management Authority (NDMA), Provincial Disaster Management Authorities (PDMAs), Pakistan Meteorological Department records, and international climate databases to contextualize local experiences and assess regional vulnerability patterns.

The target population consisted of households residing in flood-affected communities within the Indus Basin. A total sample of 400–550 respondents was recruited using a stratified sampling approach based on district and rural–urban location to ensure representation across different levels of flood exposure and socio-economic conditions. Participants were selected through purposive and snowball sampling with the assistance of local non-governmental organizations (NGOs), village committees, community organizations, and local leaders working in disaster-prone regions. In addition, a qualitative subsample of 20–30 participants, including community leaders, NGO representatives, and affected household members, was selected using maximum variation sampling to capture diverse experiences and perspectives regarding climate impacts and migration decisions.

Primary data were collected through structured paper-based or tablet-assisted questionnaires administered face-to-face in Urdu at households, community centers, and local gathering places. The survey instrument included sections on demographic and socio-economic characteristics, including age, gender, household size, education, livelihood type, income level, asset ownership, housing tenure, and access to social support networks. Information on flood exposure history, severity of impacts, access to early-warning systems, perceptions of climate adaptation policies, and experiences of climate-related losses was also collected. Outcome variables included migration intentions (both internal and international), previous mobility history, perceived climate justice, vulnerability levels, preferred adaptation strategies, and actual support received

from governmental and non-governmental agencies. A composite vulnerability index was developed by combining indicators of exposure, sensitivity, and adaptive capacity. Semi-structured interviews were conducted with selected participants to explore perceptions of climate justice, barriers to adaptation, migration decision-making processes, and experiences with disaster management and recovery programs. Interviews were audio-recorded with participant consent and supplemented with detailed field notes. Secondary data from NDMA and PDMA reports, flood impact assessments, and climate vulnerability databases were used to triangulate findings and provide additional contextual information regarding disaster frequency, intensity, and policy responses.

Quantitative data were analyzed using SPSS version 24. Descriptive statistics, including frequencies, percentages, means, and standard deviations, were used to summarize participant characteristics and key study variables. Reliability analysis was performed to assess the internal consistency of multi-item scales. Independent-samples t-tests and one-way ANOVA were conducted to examine differences in vulnerability and migration intentions across demographic and socio-economic groups. Multiple linear regression analysis was conducted to identify factors associated with household vulnerability and perceptions of climate justice, while binary logistic regression was used to determine predictors of migration intentions. Qualitative interview data were transcribed verbatim and analyzed using thematic analysis to identify recurring themes related to vulnerability, adaptation, climate justice, and migration. Quantitative and qualitative findings were integrated through mixed-methods joint displays to provide a comprehensive interpretation of the results.

Ethical approval was obtained from the relevant Institutional Review Board prior to data collection. Informed consent was secured from all participants before participation. Confidentiality, anonymity, and voluntary participation were maintained throughout the study, and respondents had the right to withdraw from the research at any stage without penalty. The study adhered to established ethical guidelines for social science and disaster-related research.

RESULTS

A total of 512 flood-affected household representatives participated in the quantitative survey across selected districts of the Indus Basin, while 25 key informants participated in qualitative interviews. Respondents were drawn from both rural (68.4%) and urban (31.6%) communities with varying levels of exposure to recurrent flooding. The mean age of respondents was 39.7 ± 12.4 years, and the average household size was 6.8 ± 2.7 persons.

Table 1: Demographic and Socioeconomic Characteristics of Respondents (N = 512)

Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	329	64.3
	Female	183	35.7
Education	No Formal Education	156	30.5
	Primary	134	26.2
	Secondary	147	28.7
	Higher Education	75	14.6
Livelihood Type	Agriculture	234	45.7
	Informal Labour	168	32.8
	Small Business	67	13.1
	Other	43	8.4
Housing Tenure	Owned	356	69.5
	Rented	96	18.8
	Informal Settlement	60	11.7

The majority of respondents relied on agriculture (45.7%) or informal labour (32.8%) as their primary source of livelihood. Nearly one-third

had no formal education, reflecting socioeconomic vulnerabilities within flood-prone communities.

Table 2. Flood Exposure and Disaster Experiences

Variable	Category	Frequency (n)	Percentage (%)
Number of Major Flood Events Experienced	1–2	142	27.7
	3–4	228	44.5
	≥5	142	27.7
Severe Property Damage	Yes	371	72.5
	No	141	27.5
Livelihood Loss Due to Flooding	Yes	337	65.8
	No	175	34.2
Access to Early Warning Systems	Yes	223	43.6
	No	289	56.4

More than two-thirds of households experienced severe property damage (72.5%) and livelihood losses (65.8%) due to recurrent flooding. Only 43.6% reported access to formal early-warning systems.

Figure 1: Flood impacts and migration-related responses

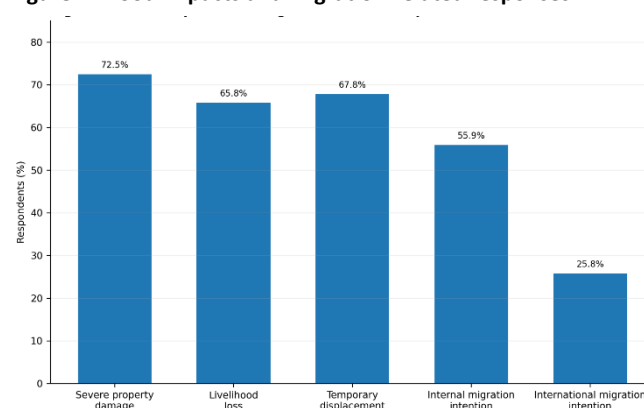


Table 3. Migration Intentions and Mobility History

Variable	Category	Frequency (n)	Percentage (%)
Intention to Migrate Within Pakistan	Yes	286	55.9
	No	226	44.1
Intention to Migrate Internationally	Yes	132	25.8
	No	380	74.2
Previous Displacement Temporary	Yes	347	67.8
	No	165	32.2
Previous Relocation Permanent	Yes	98	19.1
	No	414	80.9

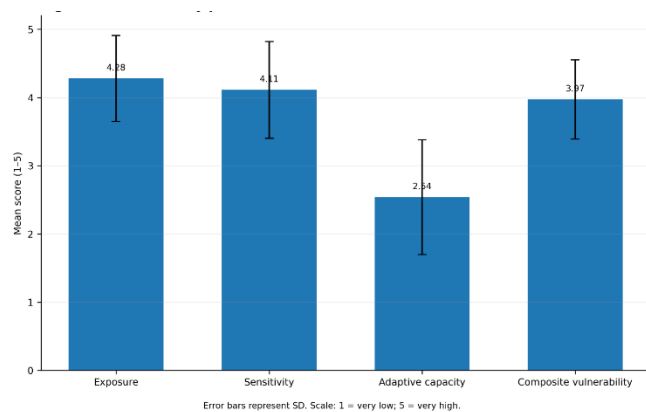
More than half of respondents (55.9%) expressed intentions to migrate internally due to increasing climate-related risks, while 25.8% reported interest in international migration. Temporary displacement following flood events was common, affecting 67.8% of households.

Table 4. Vulnerability Index Scores

Vulnerability Dimension	Mean $\pm$ SD
Exposure	4.28 $\pm$ 0.63
Sensitivity	4.11 $\pm$ 0.71
Adaptive Capacity	2.54 $\pm$ 0.84
Composite Vulnerability Index	3.97 $\pm$ 0.58

Scale: 1 = Very Low to 5 = Very High

Respondents demonstrated high levels of exposure and sensitivity to flooding, while adaptive capacity remained relatively low. The overall vulnerability index indicated substantial climate vulnerability among surveyed households.

Figure 2. vulnerability profile of flood-affected households**Table 5. Perceptions of Climate Justice and Policy Fairness**

Statement	Mean ± SD
Government assistance is distributed fairly	2.31 ± 1.04
Local communities participate in adaptation decisions	2.17 ± 0.98
Climate-vulnerable households receive adequate support	2.26 ± 1.01
Climate policies address local needs effectively	2.44 ± 0.95
Overall Climate Justice Score	2.30 ± 0.82

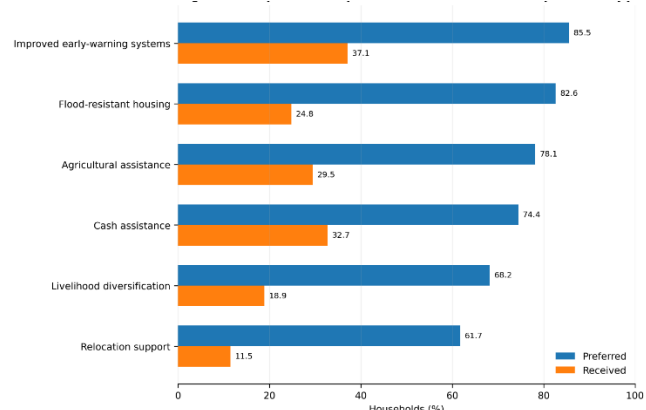
Scale: 1 = Strongly Disagree to 5 = Strongly Agree

Respondents generally perceived climate adaptation policies as inadequate and unfair. Low scores across all indicators reflected concerns regarding procedural justice, resource allocation, and inclusion in decision-making processes.

Table 6. Preferred Adaptation Strategies and Support Received

Adaptation Strategy	Preferred (%)	Received Support (%)
Flood-resistant housing	82.6	24.8
Agricultural assistance	78.1	29.5
Cash assistance	74.4	32.7
Relocation support	61.7	11.5
Livelihood diversification programs	68.2	18.9
Improved early-warning systems	85.5	37.1

Substantial gaps existed between the adaptation support desired by communities and the assistance actually received. Improved early-warning systems and flood-resistant housing were the most preferred interventions.

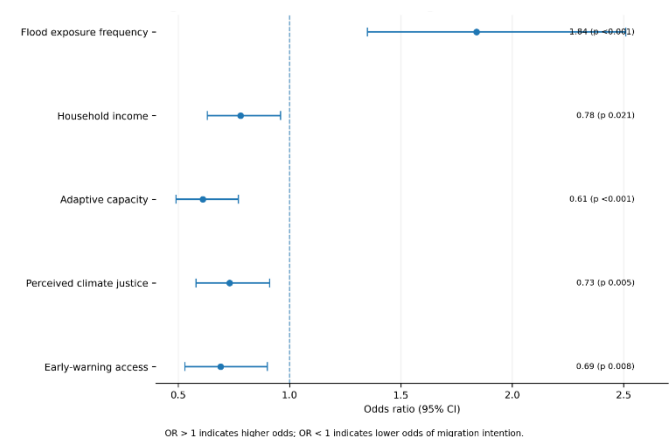
Figure 3: Gap between preferred and received adaptation support**Table 7. Logistic Regression Predicting Migration Intentions**

Predictor Variable	Odds Ratio (OR)	95% CI	p-value
Flood Exposure Frequency	1.84	1.35–2.51	<0.001
Household Income	0.78	0.63–0.96	0.021
Adaptive Capacity	0.61	0.49–0.77	<0.001
Perceived Climate Justice	0.73	0.58–0.91	0.005
Access to Early Warning Systems	0.69	0.53–0.90	0.008

The logistic regression model was statistically significant ($\chi^2 = 68.41$, $p < 0.001$). Households experiencing more frequent flooding were

significantly more likely to report migration intentions.

Conversely, greater adaptive capacity, higher perceptions of climate justice, and access to early-warning systems reduced the likelihood of migration intentions.

Figure 4: Predictors of Household migration Intention

OR > 1 Indicates higher odds; OR < 1 Indicates lower odds of migration intention.

Qualitative Findings

Thematic analysis identified four major themes: (1) recurring displacement and livelihood insecurity, (2) perceived inequities in disaster assistance, (3) migration as an adaptation strategy, and (4) community resilience despite limited institutional support. Participants frequently described feelings of abandonment and frustration with disaster response mechanisms. Many households viewed migration as a necessary survival strategy due to repeated flood-related losses, declining agricultural productivity, and insufficient governmental assistance. Community leaders emphasized the importance of locally informed adaptation planning, improved infrastructure, and equitable distribution of relief resources.

The results indicate that flood-affected households in Pakistan's Indus Basin experience high levels of climate vulnerability, limited adaptive capacity, and significant concerns regarding climate justice. Migration intentions were strongly associated with repeated flood exposure, economic insecurity, and perceptions of inadequate policy responses. The findings highlight critical gaps in adaptation support and underscore the need for more inclusive, equitable, and locally responsive climate adaptation policies.

DISCUSSION

The present study examined climate justice, environmental migration intentions, and vulnerability among flood-affected households in Pakistan's Indus Basin. The findings reveal high levels of climate vulnerability, widespread migration intentions, and substantial dissatisfaction with existing climate adaptation and disaster-management policies. These results highlight the complex interactions between environmental hazards, socioeconomic inequalities, adaptive capacity, and perceptions of climate justice in shaping household responses to recurrent flooding (Zainab & Shah, 2024; Rahman & Hickey, 2020).

One of the most significant findings of this study was the high level of exposure to recurrent flooding and its associated impacts on livelihoods and household well-being. More than two-thirds of respondents reported severe property damage and livelihood losses resulting from flood events. These findings are consistent with previous research demonstrating that repeated climate-related disasters disproportionately affect vulnerable populations in developing countries, particularly those dependent on agriculture and informal labor for income (Ngcamu, 2023). Pakistan has been identified as one of the country's most vulnerable to climate change despite contributing less than 1% of global greenhouse gas emissions, making climate vulnerability an important issue of environmental

justice. The severe floods experienced in recent years have intensified socioeconomic inequalities and placed significant pressure on already vulnerable households (Khosro et al., 2025; Bazai et al., 2025).

The study also found that more than half of respondents expressed intentions to migrate internally, while a substantial proportion considered international migration as a potential adaptation strategy. These findings support the growing body of literature suggesting that environmental migration is increasingly becoming a response to climate-related risks, livelihood insecurity, and repeated disaster exposure (Daoust & Selby, 2024). Migration decisions are rarely driven by environmental factors alone; rather, they emerge from a combination of economic, social, political, and environmental pressures (Ofori et al., 2023). The high prevalence of migration intentions observed in this study suggests that many households perceive relocation as a necessary strategy to cope with increasing climate risks and declining livelihood opportunities.

The logistic regression analysis revealed that flood exposure frequency was a significant predictor of migration intentions. Households experiencing repeated flooding were considerably more likely to consider migration than those with lower exposure levels. Similar findings have been reported in Bangladesh, India, and other South Asian countries, where recurrent environmental shocks contribute to population mobility and displacement (Kaczan & Orgill-Meyer, 2020). The results indicate that climate-induced migration in Pakistan may increase if adaptation measures remain inadequate and communities continue to experience recurring disaster-related losses (Maharjan et al., 2020).

A notable finding of the study was the low level of adaptive capacity among respondents. Despite facing high levels of exposure and sensitivity, households reported limited access to financial resources, infrastructure, early-warning systems, and institutional support. Adaptive capacity is widely recognized as a critical determinant of resilience to climate change impacts (Hunter et al., 2021). Households with stronger adaptive capacities are generally better positioned to recover from disasters, diversify livelihoods, and reduce vulnerability. In the present study, higher adaptive capacity significantly reduced migration intentions, suggesting that strengthening local resilience mechanisms may decrease the need for climate-related displacement (Ashraf et al., 2021).

The findings also revealed widespread concerns regarding climate justice and procedural fairness. Respondents expressed dissatisfaction with the distribution of disaster assistance, limited participation in adaptation planning, and perceived inadequacies in governmental support. These results are consistent with climate justice frameworks emphasizing that vulnerable communities often bear the greatest burden of climate impacts despite contributing minimally to global emissions. Climate justice extends beyond environmental outcomes and includes equitable access to resources, participation in decision-making processes, and fair distribution of adaptation benefits (Juhola et al., 2022). The low climate justice scores observed in this study suggest that affected communities perceive existing policies as insufficiently responsive to their needs and priorities.

An important finding was the substantial gap between preferred adaptation strategies and the support actually received. Most respondents prioritized flood-resistant housing, agricultural assistance, cash transfers, livelihood diversification, and improved early-warning systems; however, only a minority reported receiving such support. Similar adaptation deficits have been documented in other climate-vulnerable regions, where financial constraints, governance challenges, and institutional limitations hinder effective adaptation implementation (Nadiruzzaman & Scheffran, 2022). These gaps may contribute to increased vulnerability and encourage migration as an alternative coping mechanism (Bhanye, 2025).

The qualitative findings further enriched the quantitative results by illustrating how repeated displacement, economic insecurity, and

perceived neglect shape community experiences. Participants frequently described feelings of frustration, uncertainty, and abandonment following flood events. Many households perceived disaster assistance as unevenly distributed and insufficient to address long-term recovery needs. These perceptions reinforce existing evidence suggesting that trust in institutions and perceptions of fairness play critical roles in shaping adaptation behavior and resilience outcomes (Nabong et al., 2023; Ullah et al., 2024).

The study contributes to the growing literature on climate-induced migration and climate justice by providing empirical evidence from one of the world's most climate-vulnerable regions. The findings suggest that migration should not be viewed solely as a failure of adaptation but rather as one component of a broader spectrum of adaptive responses available to households facing environmental stress (Hamza et al., 2024). Nevertheless, reducing forced migration requires investments in local resilience, inclusive adaptation planning, and equitable distribution of climate resources (Harun et al., 2025).

Overall, the findings underscore the urgent need for climate policies that prioritize vulnerable populations within Pakistan's Indus Basin. Strengthening early-warning systems, improving flood-resilient infrastructure, expanding livelihood support programs, and enhancing community participation in adaptation planning may reduce vulnerability and improve resilience. Furthermore, integrating climate justice principles into national adaptation strategies can help ensure that climate-affected communities receive fair and adequate support (Walker et al., 2024). Such interventions are essential for addressing the growing challenges posed by climate change and for promoting sustainable and equitable development in flood-prone regions of Pakistan (Kamal, 2023).

CONCLUSION

This study found that recurrent flooding has increased vulnerability, disrupted livelihoods, and strengthened environmental migration intentions among households in Pakistan's Indus Basin. Limited adaptive capacity and inadequate institutional support were associated with greater perceived risk and a higher likelihood of migration. In contrast, access to early-warning systems, stronger adaptive capacity, and greater confidence in climate governance reduced migration intentions. The findings highlight significant gaps in climate adaptation support and concerns regarding climate justice and policy effectiveness. Strengthening community-centered adaptation, equitable resource distribution, disaster preparedness, and resilience-building initiatives is essential for reducing climate vulnerability, minimizing forced displacement, and promoting sustainable development in flood-prone regions.

Ethical Considerations

The study adhered to relevant ethical standards throughout the research process. Informed consent was obtained from all participants before their involvement in the study. Participation was voluntary, and participants were informed of their right to withdraw from the study at any stage without penalty. Confidentiality and anonymity were maintained throughout the research process, and all information collected was used exclusively for research purposes.

Data Availability

The data collected and analyzed during the current study are available from the corresponding author upon reasonable request, subject to appropriate ethical, privacy, and confidentiality considerations.

Author Contributions

Imran Jameel: Conceptualization, methodology, data curation, formal analysis, investigation, and writing—original draft preparation.

Muhammad Shoaib: Methodology, investigation, data curation, formal analysis, and writing—review and editing.

Fawad Hasan: Investigation, data analysis, interpretation of findings,

and writing—review and editing.

All authors contributed to the study, critically reviewed the manuscript, approved the final version, and agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the research were appropriately investigated and resolved.

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Conflict of Interest

None.

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Use of Artificial Intelligence

Grammarly was used to assist with language editing, grammar correction, and improvement of the clarity and readability of the manuscript. Gemini AI was used to assist with the preparation of images and visual materials. The authors reviewed and verified all AI-assisted content and remain fully responsible for the accuracy, originality, interpretation, and final content of the manuscript.

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