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ICTs for Climate Resilience and Rural Development in Pakistan: Bridging Digital Divides for Inclusive Innovation

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Abstract

Escalating climate risks in Pakistan's high-altitude glacier regions increasingly test the adaptive capacities of rural communities. Yet the contribution of Information and Communication Technologies (ICTs) to these efforts seems to remain uneven and contingent. On the other hand, ICTs in the valleys of Chitral and Gilgit-Baltistan (GB) bring forth far from straightforward solutions. Rather, their value seems to depend on how residents are likely to negotiate infrastructural fragility, gendered digital inequalities, and fragmented institutional support. This qualitative case study draws on 26 semi-structured interviews and 04 gender-segregated focus group discussions. It is further complemented by field observations conducted over a six-month period. Participants were recruited through purposive and community-mediated sampling to ensure the inclusion of elderly, women, youth, and locally embedded knowledge holders. Thematic analysis, informed by Diffusion of Innovations (DOI) and Technology Acceptance Model (TAM3), guided the interpretation of how ICTs are adopted, questioned, or resisted. Findings seem to indicate that media technology tools such as satellite-based telemetry, Short Message Service (SMS) alerts, and Community-Based Flood Early Warning Systems (CBFEWS) may enhance anticipatory governance. Yet their uptake appears to remain constrained by low digital literacy, unstable connectivity, and socio-cultural norms that limit, particularly elderly women's, access to technology. Respondents seem to repeatedly emphasized the decisive influence of Community Trust Networks, local religious leaders, teachers, and youth volunteers on whether ICTs are perceived as credible or usable. Comparative accounts further seem to suggest that ICTs gain legitimacy when co-designed with local actors when they are translated into vernacular forms, and supported through inclusive community-based training architectures. Whereas, top-down technology deployment, by contrast, tends to widen digital divides rather than bridge them. The study therefore, likely reframes ICTs as socially embedded infrastructures whose climate-

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resilience potential depends on relational trust, and gender-sensitive design. Moreover, sustained local capacity-building insights that may hold relevance across the wider Global South appear as a pivot point in this study.

***Keywords*:** ICTs, climate resilience, digital exclusion, glacial melt, participatory adaptation, Chitral, Gilgit-Baltistan, diffusion of innovations, technology acceptance model, inclusive innovation, climate communication

Introduction

Rural Pakistan is a big concern of climate change. The melt of glaciers, erratic precipitation, and protracted heat waves have become very real instead of being far-off forecasts (Allan et al., 2023). In Gilgit and Chitral, farming families complain that they have lost crops overnight or they've had their animals carried away by the overflow of the rivers. These environmental shocks very seldom happen in a vacuum. They overlap with poverty, poor infrastructure and gender inequality, resulting in spirals of vulnerability that are hard to shatter (Adger, 2006; Adger et al., 2008).

ICTs have come into this scene in an unequal manner. ICTs may be used as pragmatic instruments of adaptation to provide weather information, water management, and link farmers with outside-valley advice. The authors have determined that the main reasons for the issue are the uneven economic status of the general public and the expansion of capitalist industries (Ajani & van der Geest, 2021; Rahman et al., 2021). A simple SMS alert about heavy rain can change the timing of planting, or allow livestock to be moved to safer ground, if disseminated and received on required time in a well-crafted form by suitable ICT tools. In practice, such tools have saved crops and reduced losses during recent flood seasons (Cheong et al., 2023; Drechsel et al., 2022). Yet their reach remains patchy.

Rural Pakistan continues to face structural barriers to digital adoption. Electricity outages, low network coverage, and cultural norms restricting women's access to devices all limit the promise of ICTs (GSMA, 2023; International Telecommunication Union [ITU], 2020). In many valleys, persons with disabilities are excluded altogether because training programs rarely reach them and mobility is restricted (GSMA, 2023).

This paper aims at Chitral (Khyber Pakhtunkhwa) and the Gilgit District (Gilgit-Baltistan), the two regions which integrate natural beauty with

delicate ecology. They both constitute essential locations to the Glacial Lake Outburst Flood Risk Reduction Project Phase II (GLOF-II), which was managed by the Ministry of Climate Change and UNDP. This program has introduced satellite surveillance of glaciers, warnings (via SMS), and flood sirens led by the community. The given measures serve as a benchmark of how digital tools can be recognized in challenging topographies (Rasul et al., 2020; UNDP, 2023).

The primary goal is to examine how rural populations in Chitral and Gilgit-Baltistan utilize and value information and communication technologies (ICTs) as the tools of climate resilience by placing them within the contexts of poor infrastructure and a range of digital mindsets enforced along the gendered lines of accessibility.

The second objective aims at assessing the impact of community trust networks, participatory design practices, and gender-sensitive capacity building efforts towards the equitable and effective adoption of ICT based early-warning and climate information systems.

The analysis has taken two theoretical frameworks. To begin with, the first theory is known as the Diffusion of Innovations theory, which focuses on the systemic conditions of compatibility and peer influence (Rogers, 2003). Second, the Technology Acceptance Model 3 is based on the level of perception of usefulness, an easy-use, and a facilitating condition to use ICT (Venkatesh & Bala, 2008). Collectively they lead to a stratified analysis of the integration of ICTs in rural social worlds.

The study uses a qualitative design methodologically. Primary sources such as interviews with policymakers, NGO staff and local government actors, focus group discussions with local women, and the rural elders and youth were incorporated. There is a combination of document analysis of climate policy documents and ICT deployment reports. The practical dimensions of the reality are revealed through profound insights of district-level officials, women and project associates. Once these various views are looked at in combination, a more detailed view of digital climate resilience is provided.

It provides an empirical richness to debates about ICT use in glacial hazard areas, that is a frontier mostly overlooked in climate communication and adaptation literature. Second, it is interested in integrating a gendered and intersectional perspective, through which women and digitally

marginalized subjects interact (or are excluded) with new digital systems. Third, it facilitates practice-oriented debates because it provides scalable and context sensitive models of inclusive ICT intervention in the Global South.

The study contributes theoretically by reframing Information and Communication Technologies (ICTs) as socially embedded infrastructures, where climate-resilience potential seems to emerge from relational trust, gendered access conditions, and situated acceptance processes rather than from linear models of technological diffusion.

Finally, the paper provides an argument that ICTs are not self-sufficient but rather a part of larger socio-technical systems. Their effectiveness is not just limited to technological infrastructure but also on trust network, participatory governance and specific capacity building. Thoughtful embedding of ICTs in local ecosystems, can help bridge the digital divide and advance both climate resilience and sustainable development in Pakistan's most vulnerable regions. This could contribute directly to Sustainable Development Goals (SDGs), particularly SDG 9: Industry, Innovation and Infrastructure**,** SDG 11: Sustainable Cities and Communities**,** and SDG 13: Climate Action**.**

Literature Review

The impact of climate change on rural populations in Pakistan is creating the strongest pressure, as the melting of glaciers, the changes in precipitation, and the increase in temperatures during summer turn from scenarios projected by agencies and transformed them into reality (Allan et al., 2023). Monsoon being late can nullify a whole crop, and the collapse of a glacier can destroy houses and animals overnight. These environmental shocks do not merely affect households who are already vulnerable to poverty, having an unstable infrastructure, and being marginalization due to ingrained gender differences (Adger, 2006; Adger et al., 2008).

The usage of Information and Communication Technologies (ICTs) is often mentioned as a possible panacea, but their implementation is not even. An SMS notification about a weather update can save a crop, but a community radio notification about pest outbreaks can influence the decisions related to planting (Ajani & van der Geest, 2021; Rahman et al., 2021). In 2022, there were cases of farmers in Chitral being provided with timely SMS warnings that allowed them to move their cattle uphill, though

others were not provided with this kind of warning due to long periods of power outages or network failures that left the communication infrastructure crippled (Cheong et al., 2023; Drechsel et al., 2022). These gaps depict the weakness of ICTs as a lifeline of mitigating risk.

The larger story is the reflection of trends in the Global South. In Pakistan, the ICTs are not only seen as fringe devices but as essential infrastructures that convey crucial information through which preemptive governance is being facilitated, and a thin slice of preparedness enabled among the underprivileged households (Allan et al., 2023; Rahman et al., 2021). A phone, a footprint of the satellite, or an online market place can all radically change the way agrarian practices are conducted. Almost the same results have been reported in Vietnam, where the use of digital advisory services increased the crop yields significantly (Kaila & Tarp, 2019). In Ghana, ICTs improved food diversity and income (Twumasi et al., 2021). Chinese farmers have used digital platforms to strengthen farming systems and household earnings (Zheng & Ma, 2024). Rogers (2003) would describe these outcomes simply: technologies spread when they show "relative advantage.

Pakistan's experience mirrors this but with limits. Early warnings have been sent, adaptive cropping promoted, farmers connected to extension workers and markets (Saddique et al., 2022). Still many valleys stay in darkness during outages. Besides being weak, internet signals are also costly and inaccessible. In the case of small farmers, the price of data is sufficient to keep them offline (ITU, 2020). The barrier is even greater in terms of social factors. Individuals experiencing disability, the elderly, women, and young people have low access to personal devices and cannot use them (GSMA, 2023). The most deserving ones are the deprived ones.

In this study, two areas are taken into close scrutiny; Chitral and Gilgit-Baltistan. They are both beautiful and dangerous, being isolated in ecological as well as in infrastructural ways. They had been critical locations of the Glacial Lake Outburst Flood Risk Reduction Project Phase II (GLOF-II), which was conducted by the Ministry of Climate Change with the UNDP. The project deployed the satellites to track glacial lakes, alerts through the use of SMS, and relied on community sirens. Such actions create a decent case study of the way digital systems reconnect with more local and traditional means of warning (Rasul et al., 2020; UNDP, 2025).

The study is framed by two structures. The theory of Diffusion of Innovations is used to explain how technological systems can be integrated into social systems and whether they are perceived to be compatible or shared by having networks (Rogers, 2003). Technology Acceptance Model 3 is centered on personal perceptions, i.e., whether a tool is perceived as useful, easy, and even possible to employ in everyday life (Venkatesh & Bala, 2008). The combination of them permits the flow of analysis between the systemic and the personal level.

Although the qualitative research method is adopted in this research, key informant interviews, focus group discussions, and document reviews have been used as evidence. Authorities talked of policy purpose; practical barriers were described in women groups and details of implementation were exchanged by project staff. None of these accounts is complete in itself. But collectively they spill the beans about how the digital climate resilience is being constructed unevenly, imperfectly and how that reflects the inequalities of the larger rural Pakistan.

Rural Pakistan calls out for solutions to climate change the hardest. Its implications include melting glaciers, bursting rains, and hotter summers without any warnings (Allan et al., 2023). Yields can be ruined in a late monsoon. A glacier surge is able to carry off cattle and houses. Whole fields were washed away in the 2022 monsoon in Reshun village, near Chitral. To those households already experiencing poverty, poor infrastructure, and deep-rooted gender disparities, these shocks not only travel, but they also perpetuate, trapping people into extended chains of threat and marginalization (Adger, 2006; Adger et al., 2008).

ICTs are often mentioned as a way out. They can work, but their spread is uneven. A weather alert on a phone may save a crop, while a community radio message about pests can influence planting decisions (Ajani & van der Geest, 2021; Rahman et al., 2021). During the 2022 floods, farmers in Shogram received SMS warnings early enough to move their cattle to higher ground. Others in Yarkhun did not, because electricity had failed for two days and towers were down (Cheong et al., 2023; Drechsel et al., 2022). These gaps tend to make ICTs a fragile lifeline rather than a consistent safety net. The empirical situation in Pakistan reflects these processes across the world but it is surrounded by significant limitations. Early-warning messages have been sent, adaptive-cropping mechanisms have been encouraged, and farmers have been conncted to extension agents and

markets (Tang et al., 2024). However, during power failures, there are many valleys that are covered by darkness. There is a lack and high expense of internet connectivity. Smallholders in Mastuj cannot afford mobile data, which is a deterrent to their connection (ITU, 2020). There are social barriers which make the digital divide worse. Females in the town of Gilgit tend to depend on their male family members to use computers, and the individuals with disabilities seem to be entirely left out of these training programs. Therefore, they are often the most marginalized who need climate intelligence the most.

The available published resources, which focus on specific manipulations like SMS-based weather messages, agricultural advisory applications, remote sensing platforms, etc., emphasize that the effectiveness of ICTs depends not on the technological presence in the market but rather on the ecosystem that allows its application (Kamal & Bablu, 2023). Particularly, the availability or lack of the so-called facilitating conditions, e.g., the affordability of data plans, locally based training, and institutional support, is conclusive in determining the level of engagement with users as defined by the Technology Acceptance Model 3 (TAM3) (Venkatesh & Bala, 2008).

On a Behavioural level, TAM3 provides an imperative suppression to the Diffusion of Innovations framework since it focuses on the fact that perceived usefulness and ease of use are key conditions to the technology adoption. As several articles have emphasized, however, such impressions are often falsified with low digital literacy, especially for the women of rural Pakistan (Alam et al., 2018; UN Women, 2021). Lack of relevant culturally oriented training programs, gender-based learning space, and non-discriminatory policy frameworks, also support and maintain the digital divide Akram (2023) and GSMA (2023).

It is important to note that such community-based projects, as the Community Technology Learning Centres (CTLCs) and the Sarhad Rural Support Programme (SRSP), provide examples to be followed to overcome the barriers of infrastructures and socio-cultural frameworks with the help of a hybrid of renewable energy solutions and digital education (Sarhad Rural Support Programme [SRSP], 2024; UNDP, 2023). They have succeeded in their efforts, which highlights the importance of regional ownership, local teaching, and institutional cooperation as a means of achieving equitable innovation.

Nevertheless, large research gaps remain. Bonke et al. (2018) note that most ICT interventions do not quantify their long-term effects on food security, poverty in households, or the inclusion of value chains. Further, adoption of ICT is often technocratically viewed, without paying enough attention to the social embeddedness or inequitable distribution of risk and opportunity that it can intensify. To fill out these intellectual and practical divisions, the literature is increasingly recommending the use of frameworks that would reflect the overlap between infrastructure, behavior, and governance. At this point, the synergistic application of DOI and TAM3 is especially useful. DOI provides a sense of the role of social networks, trialability and compatibility in terms of spreading innovative ideas, and TAM3 offers a grounded perspective on how people consider usefulness, react to peer pressure and cope with technical complexity. Last, but not least, ICTs have a role to play in anticipatory adaptation.

Asian case studies (Inoue, 2020) and East African researches (Ateeq et al., 2024) indicate that the implementation of the ICT tools can be effectively applied to the workforce as well as to the entire organization. Participatory platforms, remote sensing, and mobile based advice can make a great impact. It is imperative to cut down on losses in farmland and build communal strength. The platforms of sharing knowledge which it implements. Local agency and expand adaptive behavior with social learning process are promoted. (Drechsel et al., 2022). ICTs are not panaceas and yet can be persuasive. Climate resilience facilitators need to be taken into consideration. They must be organized in terms of inclusive, green, participatory and well-endowed ecosystems. Rural vulnerabilities, such as in the case of Pakistan, are historically multi-dimensional, digital, as well as social. Gaps need to be bridged to take advantage of ICTs to transform development.

The current study contributes to existing research in three major aspects. First, it goes beyond previous representations of the rural digital divide in Pakistan by explaining the role played by gendered mobility, trust systems, and weak Information and Communication Technology Infrastructure (ICTI) in forming ICT access, dimensions that have been theorized inadequately. Second, it contributes to climate adaptation knowledge among mountain communities as it shows that mountain residents do not passively receive hazard information, but they instead evaluate, redefine, or resist digital warnings according to the localized credibility frameworks.

Third, it extends the discussion of participatory technology design in a developing context by showing how successful ICT efforts require a translation into the vernacular, a gendered facilitation, and use of trusted community intermediaries - constituents that go beyond traditional co-design paradigms.

Theoretical Framework

The two related theoretical approaches on which the basis of this paper is founded are selected to question the complex processes of ICT uptake in climate prone rural areas. They include, Rogers (2003) Diffusion of Innovations (DOI) theory and the Technology Acceptance Model (TAM3) by Venkatesh and Bala (2008). These frameworks are analytically synergistic, providing macro-level answers on the spread of innovations within social systems, and micro-level insight on how people perceive, negotiate or resist new technologies. The DOI theory developed by Rogers enables one to see the process of spreading innovations within communities in a systemic manner. The framework is based on five perceived attributes such as relative advantage, compatibility, complexity, trialability and observability that determine the way and reason behind the spread of new ideas (Rogers, 2003). These dimensions appear to be particularly relevant in rural and risky areas such as Chitral and Gilgit-Baltistan where community-based confidence and peer support staple a lot. For example, SMS-based early warning system owners could witness, commonly accepted and favorably brought results like evacuation on time or crop protection amongst peers, as a feature of the GLOF-II initiative. It was also facilitated by the availability of community mediators (e.g.: mosque leaders, teachers or local volunteers). When innovations are mediated through the existing social actors and integrated with the existing cultural rhythms, as Eitzinger et al. (2013) and Ajani and van der Geest (2021) remark, their observability and perceived compatibility become dramatic.

Notably, another important point made by DOI is the contribution of opinion leaders and sources of communication to the quickening or delaying of innovation diffusion. In this work, these figures played a critical role in understanding digital tools in a manner that appealed to local epistemologies-turning abstract technologies into useful, trusted instruments for climate resilience. Technology Acceptance Model (TAM3) is a behavioral model that would be discussed in 3.2. DOI is a sociological explanation of the diffusion of innovation, but TAM3 is a supplement, as it

deals with the psychology of individual use of technology on a personal scale. TAM3 has been developed by Venkatesh and Bala (2008) as an extension of the previous models, including the variables of perceived usefulness, perceived ease of use, computer self-efficacy, anxiety, voluntariness, and facilitating conditions. This paradigm is especially relevant when analyzing intra-community differences in up taking ICT. In most Pakistani rural settings, despite the presence of ICT infrastructure, the extent of usage is varied significantly according to digital confidence, gender norms, literacy and previous exposure. For example, some female respondents in this study reported relying on male family members to interpret SMS alerts due to unfamiliarity with text-based content or lack of training—highlighting how perceived complexity and low self-efficacy can stall engagement.

Crucially, TAM3's construct of facilitating conditions as reliable electricity, mobile data affordability, and localized ICT support tend to be proven especially relevant. Community Technology Learning Centers (CTLCs) and SRSP-run digital initiatives demonstrated this as well (UN Women, 2024). They have also identified that where support structures exist, individual apprehensions decrease and behavioral adoption improves.

Theoretical Synergy: DOI and TAM3 in Dialogue

In order to explore the nuanced interplay between systematic enablers and behavioral constraints, DOI and TAM3 provide a comprehensive lens. DOI helps to map out the social architecture of diffusion with a focus on peer influence, trialability and visibility, and TAM3 enables an exploration of the personal architectures of decision-making. This includes what people feel confident using, what they find useful, and what inhibits them from engaging. This dual-theoretical lens is essential in understanding why, even in the same village, ICT adoption may flourish among one group (e.g., digitally literate youth) and stagnate among another (e.g., older women). As Rahman et al. (2021) and Cheong et al. (2023) emphasize, structural access alone is insufficient; cognitive, emotional, and contextual factors also shape adoption behavior.

By weaving these two frameworks together, the study not only explains how ICTs cruise through rural social systems, but also how individuals interpret and navigate them in relation to their lived realities. It also offers a grounded theoretical basis for designing context-appropriate, user-

centered interventions that respect both institutional hierarchies and personal capacities as an imperative for truly inclusive innovation in climate governance.

Core Research Questions

In alignment with the broader aim of investigating ICTs as enablers of climate resilience in Pakistan's glacial melt–prone rural regions, this study is structured around the following research questions:

1. *Integration of ICTs into Climate Adaptation:* How are Information and Communication Technologies (ICTs) being adopted and integrated into climate adaptation strategies in northern Pakistan, particularly in glacially impacted regions such as Chitral and Gilgit-Baltistan?
2. *Systemic and Behavioral Enablers and Barriers:* What structural (e.g., infrastructure, policy frameworks) and behavioral (e.g., perceptions, digital skills) factors facilitate or hinder the effective uptake of ICTs for climate resilience in rural mountainous communities?
3. *Gendered Digital Access and Trust Networks:* How do gender dynamics, levels of digital literacy, and the presence of local trust networks shape the accessibility, usability, and perceived value of ICT tools—especially among women, older adults, and other marginalized groups?
4. *Scalability and Participatory Innovation:* What insights can be drawn from successful, community-led ICT interventions in Chitral and Gilgit-Baltistan that could inform scalable, context-sensitive models of digital adaptation for other climate-vulnerable regions?

Core Argument (Analytical Proposition)

This study argues that ICTs hold important transformative potential for enhancing climate resilience in Pakistan's mountainous northern regions. This potential can only be fully realized by embedding the digital tools and platforms within participatory, trust-based governance systems. This also needs to be aligned with local knowledge systems. This could be strengthened by enabling conditions such as inclusive digital literacy initiatives, culturally relevant training, and institutional coordination.

Grounded in Rogers' Diffusion of Innovations (DOI) theory, and Venkatesh and Bala's (2008) Technology Acceptance Model 3 (TAM3),

the paper contends that the adoption of ICTs is not merely a matter of technical deployment, but a socially and behaviorally negotiated process. Rogers' DOI offers a systemic understanding of how innovations spread through networks based on their trialability, compatibility, and observability.

Whereas TAM3 addresses the issue of individual interactions, since it is important to acknowledge the perception of usefulness and ease as contributory factors of ICT use. This can be empowered with sufficient support and training, that is necessary in the uptake of technology especially among digitally marginalized populations.

Such theoretical synthesis shows that resilience extends beyond access to technology, and co-production of digital agency, trust and institutional scaffolding. This point of view is skeptical of bridging the gender digital gap especially in the context of adaptation and expectations in ICT based solutions. They should not necessarily be only technologically sound but needs to be reasonable that are socially equitable, ethically sensitive, and local-minded.

Methodology

Research Design and Case Selection

It is founded on an embedded qualitative case study design (with references to the interpretivist approach to qualitative research as described by Creswell and Poth, (2017) to explore the adoption, adaptation or resistance to ICTs in glacial melt-prone northern Pakistan. Specifically, two high-altitude regions—Chitral (Khyber Pakhtunkhwa) and Gilgit-Baltistan (GB)—were purposively selected as bounded systems, owing to their climate vulnerability, historic infrastructural marginalization, and active participation in the Scaling-up of Glacial Lake Outburst Flood Risk Reduction (GLOF-II) project, co-led by Pakistan's Ministry of Climate Change and the United Nations Development Programme (UNDP, 2023).

The selected regions are not only ecologically fragile but are also technologically transitional that makes them ideal laboratories for examining how digital tools intersect with community-based disaster preparedness. Within this framework, the study employs a multi-sited comparative case design, allowing for layered analysis across geographies, institutions, and population subgroups.

Data Collection Methods

To ensure methodological triangulation and to capture both systemic and behavioral dimensions of ICT adoption, the study relied on four primary data sources:

- Firstly, Semi-Structured Interviews (n = 26): These were conducted with local farmers, female ICT users, local disaster volunteers, community leaders, and community members. Demographic variables like age, gender, education, household phone access, and involvement in local risk committees were recorded to contextualize ICT usage. It also includes officials from GB Disaster Management Authority (GBDMA), Provincial Disaster Management Authority (PDMA-KP), and NGO personnel associated with GLOF-II and the Sarhad Rural Support Programme (SRSP). Interview questions probed by exploring digital access, perceptions of usefulness, social trust, and infrastructural constraints to gain better insight into the issues.
- Secondly, Focus Group Discussions (FGDs) (n = 4): they were conducted separately for men and women to elicit gendered perspectives on ICT engagement. Key focus was on SMS-based alerts and early warning participation. These discussions highlighted both enabling conditions and social barriers to ICT access.
- Thirdly, Observational Fieldwork: The research team participated in early warning simulation drills, and inspected local hydrometeorological installations. The response of community members toward warning systems and digital platforms was observed.
- Fourth, Document Analysis: Key policy and project documents, including UNDP's (2025), GLOF-II reports ICIMOD hazard assessments and SRSP activity records, were reviewed to situate field data within broader institutional frameworks (Rasul et al., 2020).
- Fifth, A purposive sampling strategy was adopted to identify participants with direct exposure to early warning systems deployed under the Glacial Lake Outburst Flood Risk Reduction Project Phase II (GLOF-II). Recruitment relied additionally on community-mediated access, reflecting gender norms and the central role of local authority figures in high-mountain societies. Upper Chitral and Gilgit District were chosen because they exhibit high GLOF exposure, active ICT installations, and significant variation in digital connectivity and trust

structures.

Case Profiles

Two embedded case studies were developed to probe how ICTs are contextualized and operationalized:

- Case 1: Upper Chitral (Reshun, Buni/Booni): Focused on the implementation of SMS-based flood alerts and the role of community disaster committees in translating digital warnings into culturally relevant actions.
- Case 2: Bagrot and Hunza Valleys, Gilgit-Baltistan: Investigated the participatory deployment of Community-Based Flood Early Warning Systems (CBFEWS), including hydro met stations, solar-powered radio hubs, and local hazard mapping tools.

Analytical Strategy

All qualitative data were thematically analyzed using Braun and Clarke's (2006) six-step framework. Codes were initially generated around themes such as *trialability*, *perceived ease of use*, *social influence*, and *trust*. Deductive codes from Diffusion of Innovations (DOI) (Rogers, 2003), specifically compatibility, complexity, and trialability, and constructs from Technology Acceptance Model 3, (TAM3) such as perceived usefulness, perceived ease of use, and social influence (Venkatesh & Bala, 2008), were integrated with inductive patterns emerging from interview and FGD transcripts.

Recurring analytical motifs—such as women's differential access, localized trust anchors (e.g., mosque leaders, teachers), and infrastructural inconsistencies—were mapped across cases and validated through triangulation.

Ethical Considerations

The researchers placed cultural sensitivity and ethical rigor at the forefront. The purpose of the research was explained to all participants and they agreed to audio recordings or handwritten notes, in exchange of complete confidentiality. Understanding the gendered nature of rural Pakistan, women researchers organized women FGDs in the local languages (e.g., Burushaski, Urdu), and provided a secure environment.

Community trust was negotiated through the local elders and the NGO

partners. The best practices of the inquiry in a vulnerable context were also aligned with the research protocols, which is defined as suitable in a research protocol by Palinkas et al. (2025).

Scope and Reflexivity

The current study is a high-resolution look at ICTs in extreme ecological settings since it focuses on communities in glacial melt alone. That makes it more enriching in depth and provides richness of context, but there are also geographic constraints. In order to determine the responsiveness of ICTs to different climatic issues, research in the future would be required to incorporate other vulnerable regions- such as drought hit Tharpakkar or flood prone regions in the southern part of Punjab.

Findings

This section involves thematic analysis and discussions of the ways information and ICTs are changing climatic resiliency practices. The focused regions were glacial melt-prone areas in north Pakistan, Chitral and Gilgit-Baltistan. The results are expressed through the application of Roger's (2003) theory of Diffusion of Innovations (DOI), and a technology acceptance model (TAM3) proposed by Venkatesh and Bala (2008), which employs the fact that ICTs adoption is determined by a stratified interaction between structural barriers, community networks, behavioural intentions, and gendered realities.

Though the value of the operational utility of Information and Communication Technologies (ICTs) in the form of Short Message Services (SMS) alerts and Community-Based Flood Early Warning Systems (CBFEWS) has been manifestly demonstrated during the recent occurrence of Glacial Lake Outburst Floods (GLOFs), there seems to be a significant imbalance in the real usage of the new technological tools, encompassing households. This implies that although various respondents reported the increased speed of responses and the prompted improved awareness of hazards, eight to ten households per village were reliable to receive and act on these warnings. Further, thirteen out of twenty-six of the interviewees mentioned that they received missed messages because of weak telecommunications infrastructure and in two out of the four women in focus groups mentioned about no direct access to telecommunications gadgets. Concretely, the ICTs can work well as systems, but they cannot be distributed evenly due to the fact that those who can exploit them

meaningfully are defined by connectivity, gender norms, and control over devices.

Diffusion of Innovations (DOI) attributes structured coding matrix: *compatibility* appeared in accounts comparing ICT tools to customary practices; *complexity* emerged where participants described unfamiliar interfaces; and *trialability* featured in narratives about repeated community drills. Technology Acceptance Model 3 (TAM3) constructs were evident in discussions of usefulness (timeliness of alerts), ease of use (network instability), and social influence (validation by teachers and religious leaders).

ICTs as Instrument of Anticipatory Adaptation

ICT integration in climate adaptation strategies: The integration of ICT into climate adaptation strategies offers significant advantages by enabling local governments to apply suitable practices aimed at enhancing climate change management.

Responding to RQ1: (ICT integration into climate adaptation strategies)

At both research sites, ICT came out as not only information delivery frameworks, but proactive means of active adaptation. Flood alerts by SMS, weather applications, and community radio were perceived as very useful in allowing real-time decision-making.

In Chitral, a farmer recalled: "When that SMS came, we didn't wait for the river to rise. We moved our animals and wheat early."

This example revisits the idea of perceived usefulness in TAM3 and validates previous sources that mobile climate services significantly reduce losses experienced in agriculture, and shorten the response turnaround times (Eitzinger et al., 2013). Also, community simulation drills increased familiarity to the tools by its users, which proved the notion of trialability by DOI, and amplified trust and usability over time (Rogers, 2003).

Structural and Institutional Barriers

(Addressing RQ2: Systemic and behavioral enablers/constraints)

In spite of these achievements, there are still infrastructural shortfalls of lack of internet connectivity at certain times, inconsistent electricity supply, and poor mobile signal, thus ensuring that ICT adoption has not been successful in Nigeria. The communities in the upper valleys of Gilgit

Baltistan have been left uncovered to ICT based warning systems due to a huge technological constraint. A district officer remarked: "The support in this case should be based on the actual needs on the ground; it cannot be just deployed sensors without training."

As one elderly participant in Upper Chitral noted, "The message reaches us only if the tower survives the storm; otherwise, we wait for the imam to confirm it." An elderly woman in Gilgit District explained, "I only hear about the SMS alert when my son reads it aloud." However, the young women having higher literacy rates with personal access to smart gadgets are well informed as mentioned by one lady, "We follow mainly the local warning alerts on social media and tend to adapt accordingly". Field observations documented three malfunctioning sirens and delayed telemetry readings, illustrating systemic fragilities in the early warning chain.

Such shortcomings provide a clear illustration of the impairment of observability and facilitative conditions, which are key entities in the Diffusion of Innovation model as well as in the Technology Acceptance Model 3, when using poor infrastructure. Moreover, the inter-institutional disjunctions, particularly between the National Disaster Management Authority (NDMA) and the Provincial Disaster Management Authority of Khyber Pakhtunkhwa (PDMA-KP) and the Gilgit-Baltistan Disaster Management Authority (GBDMA), also result in the partial implementation process, as reported by Rahman et al. (2021) and Cheong et al. (2023).

Social Trust, Gender, and Community Integration

(Addressing RQ3: Gendered digital literacy and trust networks)

The uptake of ICT was realized to be significantly successful in those communities where local actors were operating as a credible mediator. In Chitral, the announcements of the mosque were used to relay digital notifications to illiterate people; recollecting one resident of the area, the mosque loudspeaker ensured that even non-reading people were informed of the threat. This example shows how significant opinion leader and social compatibility are in facilitating diffusion, and these ideas are described by Rogers (2003). Similarly, in Bagrot Valley, GilgitBaltistan, those civilians who participated in the installation of telemetry sensors reported that they felt more trusted by the system. According to one youth volunteer, "our services to assist in fitting the sensors were not in vain. The system is more

trusted by people since they witnessed us being involved in the process. However, women and older people faced more challenges, which is due to the digital illiteracy and established cultural stagnation. As one of the female respondents confessed, her son read out the messages and interpreted them to her. “I want to know, yet somebody do not know how to tell it to us.” This finding is in line with the construct of enabling conditions in TAM3 and it supports the observation made by GSMA (2023) that women are 40 per cent less likely to use mobile-based ICTs because they have less training and because of mobility barriers.

Telemetry-based early warning systems in both the Bagrot Valley and in Chitral have provided a significant input to the community-specific climate-risk preparedness, although through varying community engagement plans. A community-based process of installing and repairing the telemetry sensors was brought about by the skills of youth volunteers, which triggered a sense of local ownership. According to one of the respondents, the villagers put the sensors up themselves, and as a result, they believe in them. This fact is consistent with Roger’s (2003) concerns on observability and social legitimacy in the diffusion of innovations. Contrastingly, community members of Chitral, especially in Reshun and Buni, did not personally install the telemetry equipment as it would need specialized skills. Still, they actively participated in training exercises, location identification, and alert readmission as part of the GLOF- II project (UNDP, 2025.). Their involvement intensified the trust of the community towards the system and improved on the aspect of technological trialability and compatibility dimension, a fact that appealed to the constructs of TAM3, regarding perceived usefulness and facilitating conditions (Venkatesh & Bala, 2008). Therefore, despite the difference of technical implementation, both examples can be described as an instance of how the relational credibility and adaptive capacity of ICT intervention to glacial hazard areas is enhanced through participation integration, be it installation or interpretation.

Across all interviews, 13 out of twenty-six participants reported regular use of ICT based warning systems while approximately 50% of women indicated that access to ICT alerts remained mediated by male relatives.

Comparative Insights: Chitral vs. Gilgit-Baltistan

(Addressing RQ4: Scalable, community-led ICT models)

In Chitral the strategy has been to focus on the usage of SMS messages in association with periodical simulation exercises where disaster committees in the region organize disaster simulation exercises. Conversely, Gilgit and Baltistan has expanded its capacity and has involved 244 telemetry stations and 54 community-based warning posts in the model known as the Community based Flood Early Warning Systems (CBFEWS) (UNDP, 2023). The co-designed alert system in Gilgit-Baltistan has proven to be more observable and has enabled inter-valley learning (exchange between Gulmit and Bagrot) and confidence among the users.

These comparative insights shed light on how scalability is not only a role of the available technological resources, but depends on the flawless coordination with the local systems, strong institutional support, and the co-production with the local actors.

Empirical Reinforcements on Larger Rural Environments

In other areas outside the glacial zone, the study revealed supplementary evidence in arid areas like Tharparkar, where ICT based irrigation systems and solar powered digital hubs have made water use more efficient besides crop planning. The Sarhad Rural Support Programme (SRSP)-based case studies as well as Community Technology Learning Centers (CTLCs)-based case studies confirmed that context-specific training, specifically of women, has not only boosted the rate of adoption but also the confidence rate (Ashden, 2022; UN Women, 2024).

Theoretical Implications

DOI Theory (Rogers, 2003):

- Adoption improved when ICTs aligned with existing communication norms, such as mosque announcements and peer-to-peer learning.
- Trialability—e.g., through simulation drills or co-installation of sensors—strengthened trust and perceived relevance.

TAM3 (Venkatesh & Bala, 2008):

- Perceived usefulness was the highest when ICTs directly addressed local concerns (e.g., flash floods, crop failure).

- Ease of use was enhanced when systems offered localized interfaces and were supported by facilitating infrastructure (e.g., digital literacy programs).

Practical Implications for Policymaking

Policy measures should prioritize stabilizing Information and Communication Technology Infrastructure (ICTI) in Upper Chitral and Gilgit District. This seems to ensure reliable communication during hazard peaks. Gender-responsive interventions such as community-shared devices, women-focused digital skills training, and inclusive emergency-communication committees are necessary to reduce access barriers. Early warning protocols should formally integrate trusted community intermediaries, recognizing their decisive influence on message credibility. Finally, all ICT tools should be co-designed in vernacular languages, embedded within long-term community-based training structures, and aligned with the evolving needs of high-altitude ecologies as postulated in below crux points.

1. *Participatory ICT Design*: Collaborate with village councils and local opinion leaders to co-create culturally resonant ICT tools.
2. *Hybrid Communication Strategies*: Integrate digital platforms (e.g., SMS, apps) with analog systems (e.g., mosque loudspeakers, community boards).
3. *Soft Infrastructure Investment*: Prioritize digital literacy, regional language training, and mentorship—especially for women and older adults.
4. *Institutional Convergence*: Promote coordination across NDMA, PDMA-KP, and GBDMA for seamless ICT integration.
5. *Gender-Sensitive Access Models*: Scale up women-only digital training centers and safe digital spaces to mitigate gender exclusion (GSMA, 2023; UN Women, 2024).

It is shown that the incorporation of Information and Communication Technologies (ICTs) in the high altitude Chitral and Gilgit-Baltistan (GB) areas is not even, but rather influenced at least by the social setting as well as by the technological presence. Regarding the limitations to how communities access Services in Short Message Service (SMS) alerts, satellite-based telemetry systems, and Community-based Flood Early

Warning Systems (CBFEWS), data obtained through interviews and field observations show that low levels of digital literacy, weak Information and Communication Technology Infrastructure (ICTI) and gendered restrictions remain as the present limitations to hinder the community's access to these services. Simultaneously, participants repeatedly mentioned that Community Trust Networks (CTNs), such as local religious leaders, teachers, and youth volunteers, make a strong impact on the views on the credibility (or the safety) of the utilization of such tools. Meanwhile, the comparative accounts propose that ICT interventions are better accepted with the regional actors in the case of co-design, translation of the interventions into the local forms, and provision of the interventions based on inclusive Community-Based Training Architecture (CBTA). On the whole, the results suggest that climate resilience on the basis of ICT is not merely a question of technical implementation but seems to be based on the social legitimacy, participatory practices and ordinary ecologies in which rural users bargain and make sense of technological advances.

This study emphasizes that ICTs, when rooted in community participation, cultural trust, and institutional synergy, transcend their technical form to become adaptive social infrastructures. They enable communities not just to respond to crises but to anticipate, interpret, and co-manage them. The success of such systems, especially in Pakistan's mountainous ecosystems seem to depend less on bandwidth and more upon whether users feel noticed with access, equipped, and empowered to act.

Conclusion

The paper focuses on Information and Communication Technologies (ICTs) and climate resilience intersections in glacial melting regions of Pakistan: Chitral and Gilgit-Baltistan. Environmental insecurity, structural marginality and increasing exposure to glacial burst threats characterize such areas. It is a sobering challenge that requires an effective testing environment. Apparently, it is lacking in elements of inclusivity and community-based digital adaptation.

The theory of diffusion of innovations (DOI) and the Technology Acceptance Model 3 (TAM3) seem to offer a means of visual representation of the stratified process of ICT adoption. It does not appear to be a process of technical implementation. Instead, it might be necessary to create a socially mediated negotiation between infrastructure, cultural norms,

institutional coordination and the individual perceptions. The data indicate that ICTs, such as SMS alerts and satellite-based telemetry, Community-Based Flood Early Warning Systems (CBFEWS), etc. may be of considerable use. Particularly in relation to anticipatory governance when they are adopted in participation frameworks. This may also be attractive to the local social systems to have a successful implementation.

The digital promise does not appear to be neutral or well distributed. The differences in gender, insufficient infrastructure, diffused institutional mandates and non-existence of vernacular training became some of persisting issues in these regions. Indicatively, women and digitally marginalized groups who have long been sidelined in the policy and the programming appear to continue to face structural impediments to their involvement. Even the most well-meaning ICT interventions seem to lack them. TAM3's emphasis on facilitating conditions, and DOI's emphasis on compatibility and trialability are not abstract concepts. They play key roles in signaling success or failure in real resilience efforts in such areas.

Comparative analysis of the cases of Chitral and Gilgit-Baltistan provides more than site-specific information. It has a tendency to indicate a central claim that digital resilience should be co-produced, rather than delivered. There appears to be the urgency to deal with the plausible working systems out there. This can be a mobilizer of community trust via the mosque leaders, youth volunteers, and women-led groups. Technologies would be incorporated into the ordinary life worlds, and not obtruded as external solutions. Some of the models of integration that are in place in Gilgit-Baltistan can serve to illustrate how such integration can foster efficacy and equity. Top down hierarchies have dangers of duplicating the already existing exclusion of the local communities.

Re-configuration of ICTs must be discrete as opposed to relational infrastructures of resilience. This research has theoretical and practical implications. Theoretically, it contributes to the available literature by demonstrating that the ICT-diffusion process in weak ecologies is guided by the same level of the affections and social influences as by technological properties. In practice, it means inclusive co-design policies towards vulnerable populations, culturally oriented pedagogy and inter-agency collaboration as the first priority. ICTs must be put upon contextualized. It must share it with its transformative ability in climate adaptation.

This study tends to confirm that the future of climate resilience in Pakistan, and similar places, does not necessarily only reside in more sensors or faster networks. The systems designed with, and for the people they will be protecting seems to decide the success or failure of the ICTs implementation that could bridge the digital divides existing in such areas. Merely digital transition in climate adaptation is not the issue of information flow. It seems to be the issue of restoring agency, dignity and voice to the face of increasing ecological uncertainty.

Author Contribution

Shahla Riaz: conceptualization, methodology, investigation, data curation, formal analysis, writing – original draft, visualization, project administration. **Farrukh Shahzad:** supervision, validation, writing – review & editing, resources.

Conflict of Interest

The authors of the manuscript have no financial or non-financial conflict of interest in the subject matter or materials discussed in this manuscript.

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