

SPATIO-TEMPORAL TRENDS IN INDEX (CCVI) - A CASE OF DISTRICT RAHIM YAR KHAN, PAKISTAN CLIMATE CHANGE VULNERABILITY

TENDANCES SPATIO-TEMPORELLES DE L'INDICE DE VULNÉRABILITÉ AU CHANGEMENT CLIMATIQUE (CCVI) – CAS DU DISTRICT DE RAHIM YAR KHAN, AU PAKISTAN

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ABSTRACT

Climate change is increasingly affecting water, agriculture, and socio-economic systems in developing countries with limited adaptive capacity. Pakistan is among the most climate-vulnerable countries globally, facing recurrent floods, droughts, and extreme temperatures that disrupt livelihoods and strain water resources. This study develops and applies a Climate Change Vulnerability Index (CCVI) for the District Rahim Yar Khan (R.Y. Khan), Punjab, to provide a spatially disaggregated and data-driven assessment of climate vulnerability. The CCVI integrates three dimensions including exposure, sensitivity, and adaptive capacity using socio-economic, demographic, and climate data from 2019-2023. The index is computed across four tehsils including Khanpur, Liaquatpur, Rahim Yar Khan, and Sadiq Abad with rural-urban and gender-disaggregated analysis. Findings reveal significant spatial disparities, as rural areas exhibit persistent vulnerability due to water scarcity, agricultural dependence, and limited access to services. Urban areas are increasingly vulnerable due to utility-driven factors, rapid population growth, inadequate infrastructure, and rising health risks. Tehsil Rahim Yar Khan shows increasing vulnerability trends, while Tehsil Sadiq Abad demonstrates improved resilience through community-driven initiatives. Gender-disaggregated results highlight disproportionate impacts on women, children, and elderly populations. The research contributes a replicable CCVI framework and demonstrates its operationalization through a web-based decision-support tool enabling policymakers to identify vulnerability hotspots. The findings emphasize the need for integrated water management, climate-resilient agriculture, and targeted social protection mechanisms. Aligned with the International Commission on Irrigation and Drainage (ICID) priorities, the research provides actionable recommendations for sustainable irrigation planning, groundwater management, and climate-resilient agricultural systems, as the CCVI approach offers a scalable pathway for strengthening evidence-based planning and resilience in climate-affected regions across Asia and Africa.

Keywords: Spatio-temporal trends; Climate change vulnerability; Water scarcity; Rapid population growth; Climate-affected regions.

RÉSUMÉ

Le changement climatique affecte de plus en plus les systèmes hydriques, agricoles et socioéconomiques des pays en développement dont la capacité d'adaptation est limitée. Le Pakistan figure parmi les pays les plus vulnérables aux effets du changement climatique dans le monde et subit

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des inondations, des sécheresses et des températures extrêmes récurrentes qui perturbent les moyens de subsistance et mettent les ressources en eau à rude épreuve. Cette étude élabore et applique un indice de vulnérabilité au changement climatique (CCVI) au district de Rahim Yar Khan (R.Y. Khan), au Pendjab, afin de fournir une évaluation spatialement désagrégée et fondée sur les données de la vulnérabilité climatique. Le CCVI intègre trois dimensions — l'exposition, la sensibilité et la capacité d'adaptation — à partir de données socioéconomiques, démographiques et climatiques couvrant la période 2019–2023. L'indice est calculé pour quatre tehsils — Khanpur, Liaquatpur, Rahim Yar Khan et Sadiq Abad — avec une analyse ventilée selon le milieu rural ou urbain et selon le genre. Les résultats révèlent d'importantes disparités spatiales : les zones rurales présentent une vulnérabilité persistante en raison de la pénurie d'eau, de la dépendance à l'agriculture et d'un accès limité aux services. Les zones urbaines deviennent de plus en plus vulnérables sous l'effet de facteurs liés aux services essentiels, d'une croissance démographique rapide, d'infrastructures insuffisantes et de risques sanitaires croissants. Le tehsil de Rahim Yar Khan présente une tendance à la hausse de la vulnérabilité, tandis que celui de Sadiq Abad affiche une résilience accrue grâce à des initiatives communautaires. Les résultats ventilés selon le genre mettent en évidence des effets disproportionnés sur les femmes, les enfants et les personnes âgées. La recherche propose un cadre CCVI reproductible et montre sa mise en œuvre au moyen d'un outil web d'aide à la décision permettant aux décideurs d'identifier les foyers de vulnérabilité. Les résultats soulignent la nécessité d'une gestion intégrée de l'eau, d'une agriculture résiliente au climat et de mécanismes ciblés de protection sociale. En cohérence avec les priorités de la Commission internationale des irrigations et du drainage (ICID), la recherche formule des recommandations opérationnelles pour la planification durable de l'irrigation, la gestion des eaux souterraines et les systèmes agricoles résilients au climat ; l'approche CCVI offre ainsi une voie évolutive pour renforcer la planification fondée sur les données probantes et la résilience dans les régions d'Asie et d'Afrique touchées par le changement climatique.

Mots clés : Tendances spatio-temporelles; Vulnérabilité au changement climatique; Pénurie d'eau; Croissance démographique rapide; Régions touchées par le changement climatique.

INTRODUCTION

Climate change is fundamentally altering global development trajectories through its impacts on water availability, food systems, and human livelihoods. Increasing variability in temperature and precipitation patterns has intensified extreme events such as floods, droughts, and heatwaves. These impacts are disproportionately concentrated in developing countries where economies are heavily dependent on climate-sensitive sectors such as agriculture. Pakistan represents a critical case and is consistently ranked among the most climate-vulnerable countries due to high exposure, limited adaptive capacity, and dependence on the Indus Basin Irrigation System (IBIS). The country faces a complex combination of risks, including monsoon flooding, prolonged droughts in arid regions, and extreme heat affecting both agricultural productivity and human health. These challenges are further compounded by rapid population growth, institutional constraints, and resource mismanagement. Despite increasing climate risks, policy responses remain largely reactive and insufficiently localized thereby limiting their effectiveness in addressing district-level vulnerabilities.

District Rahim Yar Khan (R.Y. Khan), located in Southern Punjab, exemplifies these dynamics. Characterized by an agrarian economy, high poverty levels, and limited infrastructure, the district is highly susceptible to climate variability. Rahim Yar Khan covers an area of 11,880 square kilometers (km²) and is home to a substantial population of 5.56 million individuals (male: 2.89 million, female: 2.67 million, transgender: 551) with an average household size of 6.7 and population density/km² of 468.41 (PBS, 2023). This district lies in the vicinity of Rajanpur and Dera Ghazi Khan (D.G. Khan) districts in Punjab and is near Kashmore and Ghotki in Sindh. It is administratively organized into four tehsils: Liaquatpur, Khanpur, Sadiq Abad, and Rahim Yar Khan.

Rahim Yar Khan is classified as a low socio-economic status district due to persistent social, economic, and development challenges (PBS, 2023). The district also experiences extreme climatic conditions, characterized by prolonged hot summers with temperatures reaching 43.4°C and relatively mild winters (PMD, 2023). Its vulnerability has further increased as a host region for climate-induced

migrants following the 2022 floods, placing additional pressure on water resources, food systems, and public services. Despite these growing challenges, existing national-level assessments lack the spatial granularity required to support targeted and evidence-based planning interventions.

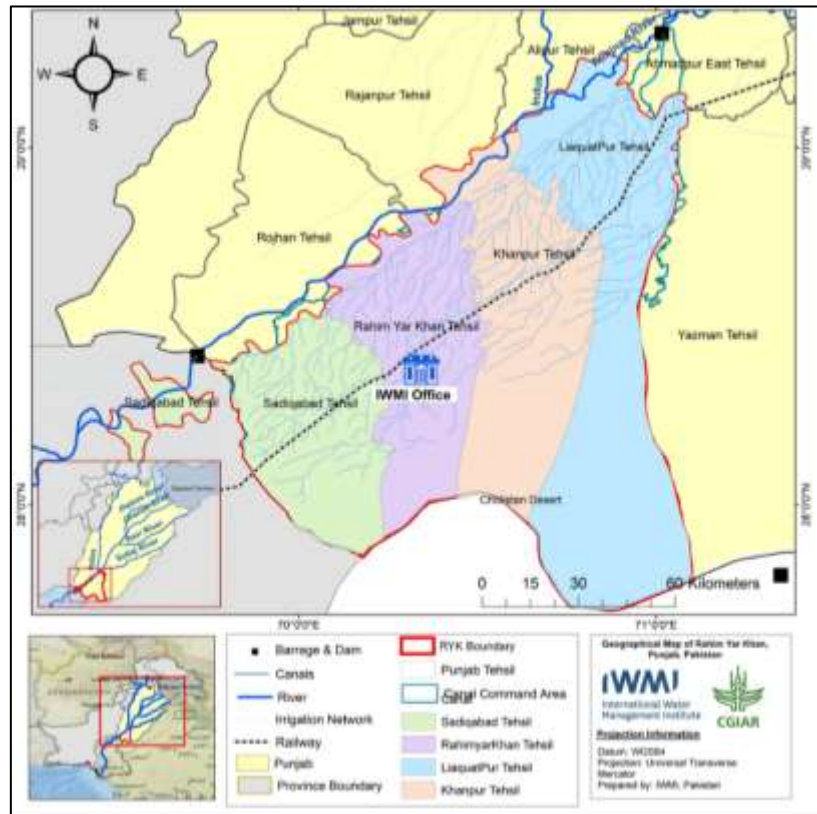


Figure 1. Administrative Location of District R. Y. Khan

Therefore, the research aims to:

1. Develop a district-level Climate Change Vulnerability Index (CCVI).
2. Analyze spatial and temporal vulnerability patterns.
3. Identify key drivers of vulnerability.
4. Provide policy-relevant recommendations for water and agriculture systems.

LITERATURE REVIEW

Climate change vulnerability is increasingly conceptualized as a multidimensional phenomenon shaped by the interaction of exposure, sensitivity, and adaptive capacity. The latest global synthesis underscores that climate change acts as a ‘risk multiplier’, intensifying pre-existing socio-economic and governance vulnerabilities in developing countries (Ali et al. 2024). This perspective shifts the analysis from purely environmental stressors towards systemic interactions between climate, society, and institutions. Climate change affects water systems by altering hydrological cycles, increasing rainfall variability, evapotranspiration, and groundwater depletion (IPCC, 2022). In Pakistan, where agriculture consumes over 90% of available water resources and groundwater supplies nearly 60% of irrigation needs, water availability is a key determinant of climate vulnerability (Khan and Zahid, 2024). This underscores that water insecurity is not only a resource challenge but also a governance and management issue.

The Water-Energy-Food (WEF) Nexus has emerged as an important lens for understanding interconnected climate risks and vulnerability. Climate variability disrupts this nexus by simultaneously affecting water supply, agricultural productivity, and energy systems thereby creating cascading risks across sectors (Ali et al. 2024). In Pakistan, evidence also indicates that weak institutional coordination and inefficient use of resources exacerbate these vulnerabilities (Hassan et al. 2025). The agricultural dimension of climate vulnerability has also been extensively updated in recent research. This is because climate change is increasingly recognized as an existential threat to agrifood systems in tropical and subtropical regions where agriculture is highly climate sensitive. Recent assessments confirm that extreme weather events including floods, droughts, and heatwaves are already disrupting agricultural production, reducing yields, and threatening food security (FAO, 2025). In Pakistan, agriculture contributes significantly to the gross domestic product (GDP) and employment, yet remains highly vulnerable due to reliance on irrigation, inefficient water use, and limited adoption of climate-smart practices (Arshad et al. 2024). Climate-induced variability in rainfall and temperature directly affects crop cycles, productivity, and income stability, hence reinforcing vulnerability among farming communities.

Emerging evidence from Pakistan highlights that vulnerability in agricultural systems is strongly mediated by adaptive capacity rather than exposure alone. Recent empirical studies show that farmers' resilience is shaped by access to irrigation infrastructure, climate information, financial resources, and institutional support systems. However, adaptive responses remain constrained by structural issues, including weak extension services, limited policy integration, and inadequate investment in climate-resilient technologies. The literature also emphasizes the importance of climate-smart agriculture, which integrates productivity, adaptation, and mitigation objectives as a key pathway for enhancing resilience in water-stressed regions.

Social differentiation remains a critical dimension of climate vulnerability, with recent global evidence reinforcing the uneven distribution of climate impacts across populations. Vulnerable groups, including women, children, and low-income households, face disproportionately higher risks due to limited access to resources, services, and decision-making processes (FAO, 2025). In rural contexts, women's roles in water collection and agricultural activities increase their exposure to climate risks, while structural inequalities constrain their adaptive capacity. Similarly, children and elderly populations are more susceptible to health risks associated with water scarcity, malnutrition, and extreme temperatures. These findings highlight the importance of incorporating gender- and age-sensitive indicators into vulnerability assessments to ensure inclusive and equitable adaptation strategies.

The health dimension of climate vulnerability has gained increasing prominence in recent assessments. Pakistan's latest climate and health vulnerability analysis highlights that climate change exacerbates existing health burdens through pathways such as waterborne diseases, heat stress, and food insecurity (WB, 2024). Poor water quality, inadequate sanitation, and limited access to healthcare further intensify these risks in densely populated and resource-constrained areas. This demonstrates that climate vulnerability is not confined to environmental or economic domains, but extends into human well-being and public health systems. Climate-induced migration has also emerged as a critical and increasingly relevant dimension of vulnerability. Recent evidence shows that climate shocks such as floods and droughts are driving large-scale displacement in South Asia. In Pakistan, the 2022 floods affected over 30 million people and triggered significant internal migration thereby placing additional pressure on host communities (Maqbool, 2023). Migration is thus both a coping mechanism and a driver of vulnerability, as it increases demand for water, food, and infrastructure in receiving areas. This creates a feedback loop in which climate change, resource scarcity, and socio-economic pressures interact to amplify vulnerability.

Methodologically, climate vulnerability assessment has advanced significantly with the integration of spatial tools, composite indices, and data-driven approaches. Indicator-based frameworks such as CCVI's remain widely used for their ability to synthesize complex multidimensional data into policy-relevant outputs. Recent studies emphasize the integration of Geographic Information Systems (GIS), remote sensing, and modeling tools to improve spatial resolution and analytical robustness. Advanced

modeling approaches including Water Evaluation and Planning (WEAP) based simulations demonstrate how climate scenarios can be used to project future water demand and vulnerability under different pathways (Khan and Zahid, 2024). These approaches enhance policymakers' ability to identify hotspots, assess risks, and design targeted interventions. Despite these advancements, several gaps persist in literature. First, most studies are conducted at national or regional scales thereby limiting their applicability for district-level planning where interventions are implemented. Second, there is insufficient integration of water, agriculture, health, and migration within a unified analytical framework. Third, while vulnerability indices are widely used, fewer studies operationalize them into decision-support systems for real-time policy use. Finally, institutional and governance dimensions in the context of developing countries remain underexplored.

The present research addresses these gaps by developing a district-level CCVI that integrates climatic, socio-economic, demographic, and water-related indicators within a unified framework. By incorporating gender-disaggregated analysis and migration dynamics, the research provides a more comprehensive understanding of vulnerability patterns. The integration of the CCVI into a web-based decision-support platform further enhances its practical relevance thereby enabling policymakers to identify vulnerability hotspots and design targeted interventions. This aligns with emerging literature that emphasizes localized, integrated, and policy-oriented approaches to climate resilience.

METHODOLOGY

The study adopts a quantitative indicator-based approach to construct a CCVI for district R.Y. Khan with the objective of capturing the multi-dimensional nature of climate vulnerability by integrating climatic, socio-economic, and demographic variables. The analytical design combines cross-sectional and temporal dimensions, utilizing data from 2019 to 2023 to assess not only the spatial distribution of vulnerability, but also its evolution over time. The analysis is conducted at multiple levels including district-wide aggregation and disaggregation across the four tehsils as well as across rural and urban areas. Further disaggregation by gender and age groups is incorporated to capture socially differentiated patterns of vulnerability. The primary dataset used in this study is derived from the National Socio-Economic Registry (NSER) under the Benazir Income Support Programme (BISP), Government of Pakistan (GoP) which provides comprehensive household-level information on demographic characteristics, education, employment, asset ownership, housing conditions, and access to water and sanitation. This dataset is suitable for vulnerability analysis due to its focus on low-income households and its national coverage. Climate-related variables are obtained from secondary sources including the Pakistan Meteorological Department (PMD) and provincial agencies and include indicators such as temperature trends, precipitation variability, and extreme events such as floods and heatwaves. Additional environmental indicators including groundwater depth and water quality parameters such as electrical conductivity are incorporated to reflect water-related stress conditions. Spatial data including administrative boundaries is used to enable geographic analysis and visualization through GIS-based techniques.

Prior to analysis, the dataset undergoes rigorous data cleaning and preprocessing. Missing values and inconsistencies are addressed through standard statistical procedures, and variables are harmonized to ensure consistency across datasets. Since the indicators are measured on different scales, normalization is applied to convert all variables into a common scale. The min-max normalization method is used to transform each indicator to a value between 0 and 1 thereby enabling comparability across variables and preventing any single indicator from disproportionately influences the index due to scale differences. The construction of the CCVI is guided by the conceptual framework of vulnerability, which comprises exposure, sensitivity, and adaptive capacity.

- Exposure reflects the degree to which a system is subjected to climatic hazards and is operationalized using indicators such as temperature variability, rainfall fluctuations, groundwater decline, and water quality deterioration.

- Sensitivity captures the extent to which socio-economic systems are affected by climate stress and is measured through variables such as dependence on agriculture, food and water insecurity, health conditions, and patterns of migration and displacement.
- Adaptive capacity represents the ability of individuals and communities to cope with and recover from climate impacts and is assessed through indicators including education levels, employment status, asset ownership, and access to infrastructure and services.

Each of these dimensions is constructed by aggregating the normalized indicators associated with it. A balanced weighting approach is employed by assigning equal weights to exposure, sensitivity, and adaptive capacity to avoid subjective bias in the absence of strong empirical justification for differential weighting. Within each dimension, indicators are also equally weighted to ensure transparency and replicability. The composite CCVI is then calculated by combining the three dimensions with exposure and sensitivity contributing positively to vulnerability, while adaptive capacity contributes inversely. This relationship is operationalized by subtracting the adaptive capacity component from unity before aggregation thereby ensuring that higher adaptive capacity reduces overall vulnerability. The resulting CCVI values range from 0 to 1 with values closer to 1 indicating higher vulnerability and values closer to 0 indicating lower vulnerability.

The index is computed separately for each tehsil and for rural and urban populations thereby enabling a detailed spatial comparison of vulnerability patterns. Temporal analysis is conducted by calculating the index for each year within the study period, hence allowing for the identification of trends and fluctuations associated with climatic events and socio-economic changes. Additionally, geospatial analysis plays a central role in the methodology, as the computed CCVI values are integrated into GIS to produce maps illustrating the spatial distribution of vulnerability across the district. These maps facilitate the identification of hotspots and provide a visual representation of disparities between different regions. In addition to spatial analysis, the dataset is further disaggregated by gender and age groups to examine how vulnerability varies across demographic categories. This enables a more nuanced understanding of vulnerability thereby highlighting the disproportionate impacts on women, children, and elderly populations.

To ensure the robustness of the results, several validation steps are undertaken. The selection of indicators is informed by established literature and aligned with internationally recognized frameworks thereby ensuring conceptual validity. Temporal consistency is assessed by comparing results across multiple years, while sensitivity analysis is conducted to evaluate the impact of the weighting scheme on the final index values. These steps enhance the reliability of the findings and ensure that the results are not driven by methodological artifacts. The methodology is further strengthened by its integration into a digital decision-support system. CCVI is operationalized through a [web-based dashboard](#) that combines GIS visualization with interactive data analytics, allowing users to explore vulnerability patterns in real time (Figure 2). This platform enhances the index's practical utility of the index by enabling policymakers and practitioners to identify priority areas, assess trends, and design targeted interventions based on empirical evidence.

Despite its strengths, the methodology is subject to certain limitations. The reliance on secondary data may introduce uncertainties in the accuracy and completeness of environmental indicators. The use of equal weighting, while transparent, may not fully capture the relative importance of different factors influencing vulnerability. Additionally, the availability of high-resolution climate data is limited, which may constrain the precision of exposure assessment. Nevertheless, the approach provides a robust and scalable framework for vulnerability analysis thereby offering a balance between methodological rigor and practical applicability. The design of the CCVI framework ensures that it is both replicable and adaptable to other contexts. By relying on widely available data sources and a transparent methodological structure, the approach can be applied to other districts and regions to support comparative analysis and policy planning. Its integration with digital tools further enhances its scalability thereby making it a valuable instrument for advancing evidence-based decision-making in climate resilience, water resource management, and sustainable agricultural development.

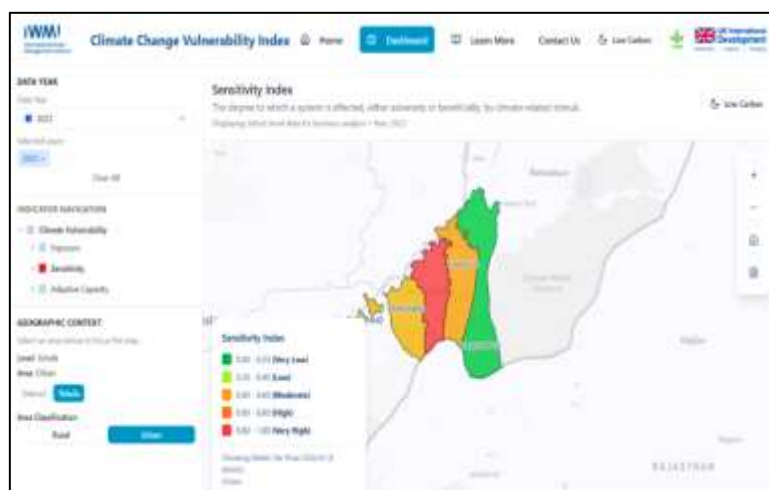


Figure 2. Climate Change Vulnerability Index - Web-Based Dashboard

RESULTS AND DISCUSSION

The CCVI results reveal significant spatial and temporal disparities across the district of R.Y. Khan, further adding that vulnerability is dynamic and varies across four tehsils, rural-urban contexts, and socio-demographic groups. The analysis over the period 2019-2023 indicates that vulnerability is neither static nor uniformly distributed, rather it fluctuates across tehsils and between rural and urban areas in response to both environmental stressors and socio-economic dynamics. Tehsil Rahim Yar Khan shows increasing vulnerability in urban areas driven by rapid population growth and infrastructure strain. The concentration of population in urban centers has led to greater demand for water, sanitation, and healthcare, while the capacity of these systems has not expanded proportionately. Consequently, exposure to climate-related risks, including heatwaves and waterborne diseases, has intensified. In contrast, tehsil Sadiq Abad demonstrates relatively stable or declining vulnerability due to localized adaptation measures, while Khanpur and Liaquatpur tehsils exhibit fluctuating trends linked to climatic variability. These fluctuations highlight limited resilience to sustained shocks.

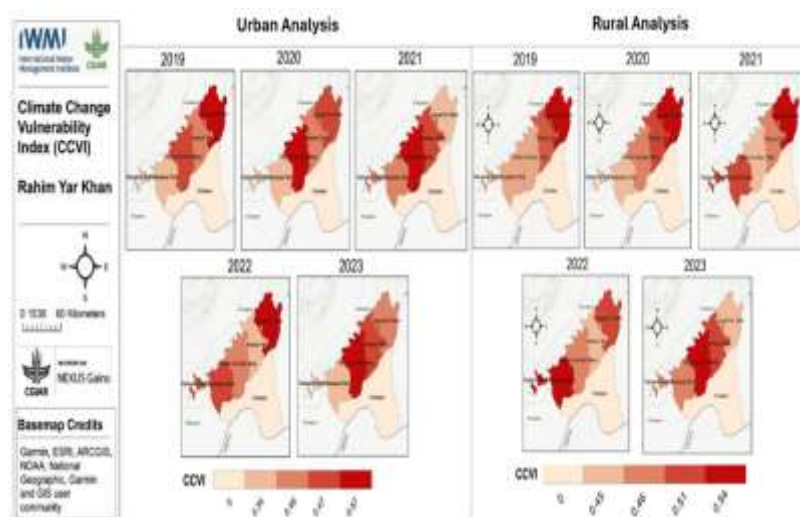


Figure 3. Spatio-temporal Distribution of Climate Change Vulnerability Index (CCVI) for District R.Y. Khan - Urban and Rural Analysis

Rural areas consistently show higher vulnerability due to agricultural dependence, water scarcity, and limited access to services. In addition, rural areas often lack access to essential services such as healthcare, sanitation, and education, further exacerbating sensitivity to climate shocks. Urban areas, while relatively better equipped with economic opportunities enhancing adaptive capacity, are experiencing rising vulnerability due to unplanned growth and infrastructure deficits. Socio-demographic analysis further indicates that women, children, and the elderly are the most disproportionately affected groups. Gender roles increase women's exposure to water stress, while children and the elderly face heightened health risks. Water security emerges as the central driver of vulnerability. Groundwater depletion and deteriorating water quality significantly affect both agriculture and health outcomes. This creates a reinforcing cycle where reduced productivity leads to lower income and diminished adaptive capacity. Furthermore, urban populations are increasingly exposed to extreme heat events due to the urban heat island effect, which compounds existing health and environmental risks. Another important dimension highlighted by the results is the role of climate-induced migration, which further intensifies vulnerability by increasing demand for resources in host communities. The 2022 floods significantly contributed to these dynamics. Temporal analysis shows that resilience gains are often short-lived and reversed by subsequent shocks thereby indicating insufficient structural adaptation. From a policy perspective, the findings highlight several critical gaps including fragmented interventions, weak cross-sector integration, and a lack of localized data tools. Strengthening adaptive capacity requires investments not only in physical infrastructure, but also in human capital, institutional capacity, and technological innovation. Thus, the CCVI dashboard offers a potential solution by enabling evidence-based decision-making.

The following short-, medium-, and long-term interventions are proposed to reduce the adverse effects of future climatic events and enhance resilience by understanding the district's unique vulnerabilities.

Short-Term: Strengthen emergency response systems, improve WASH services, and deploy GIS, remote sensing, and vulnerability mapping tools to identify climate hotspots and support rapid, evidence-based interventions.

Medium-Term: Scale nature-based solutions such as rainwater harvesting and groundwater recharge, promote climate-smart crop zoning, and strengthen local capacities through research, innovation, and knowledge partnerships.

Long-Term: Establish an integrated disaster risk management framework, invest in climate-resilient infrastructure, and foster inter-provincial coordination for sustainable resource management and disaster preparedness.

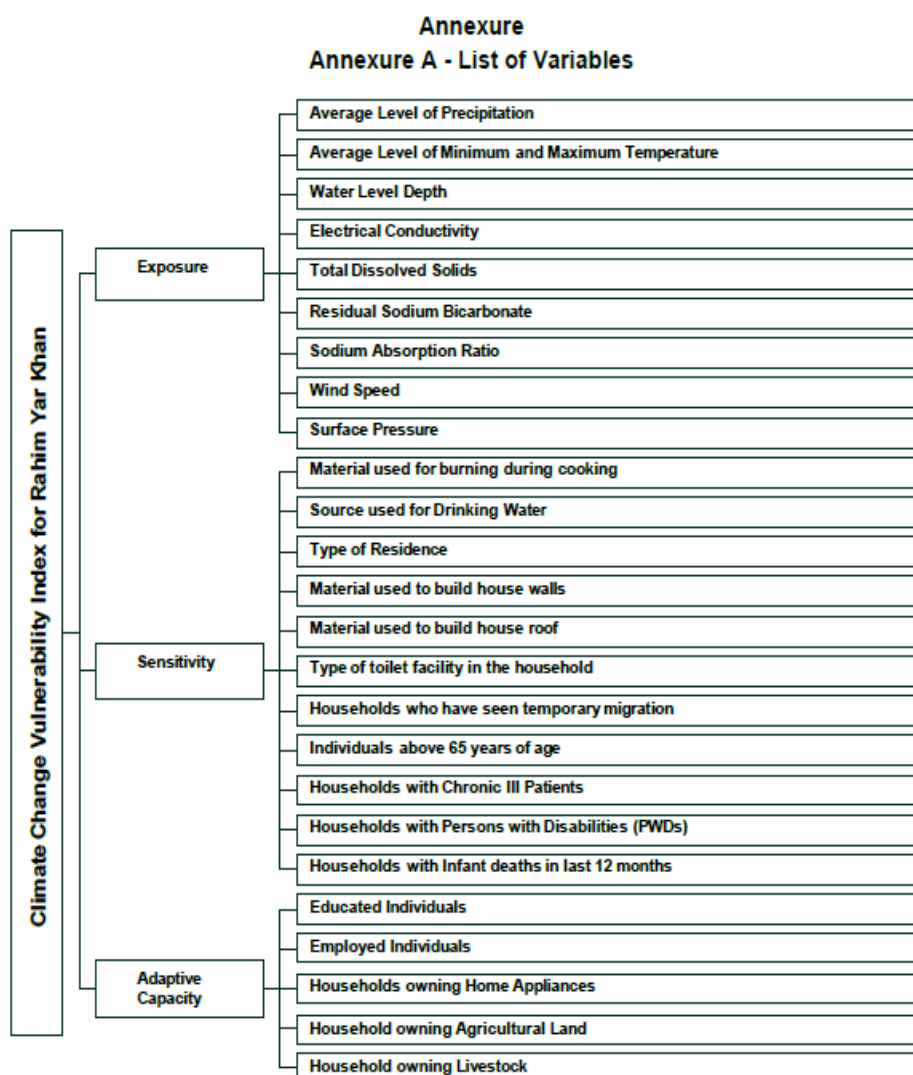
Through its expertise in water, climate, and digital innovation, IWMI can help transform climate vulnerabilities into pathways for resilience, sustainable development, and long-term water security.

CONCLUSION

This study provides a comprehensive assessment of climate vulnerability in the district of R.Y. Khan, demonstrating that vulnerability is multidimensional, dynamic, and unevenly distributed. The CCVI framework highlights water insecurity as the most critical driver influencing agriculture, health, and livelihoods. The findings thus highlight the urgent need to prioritize integrated water resources management (IWRM) as a cornerstone of climate adaptation strategies. Rural populations remain persistently vulnerable, while urban areas are increasingly exposed due to rapid and unplanned growth. These findings challenge the conventional assumption that urban areas are inherently less vulnerable and instead point to the need for more nuanced and context-specific interventions. Vulnerability is further shaped by socio-economic inequalities affecting women, children, and elderly populations. Climate-induced migration adds complexity by increasing pressure on already constrained resources. These findings underscore the need for integrated and localized adaptation strategies.

Methodologically, the CCVI proves to be a valuable tool for synthesizing complex data into actionable insights. Its integration into a digital dashboard enhances usability and policy relevance. Therefore, future research should focus on improving data resolution, integrating advanced modeling techniques, and strengthening institutional analysis. Expanding digital decision-support tools can further enhance climate resilience planning. The CCVI dashboard developed in this research can be further enhanced by integrating real-time data, user-friendly interfaces, and scenario analysis capabilities. Scaling such tools to provincial and national levels would enable more comprehensive monitoring of climate vulnerability and support evidence-based policymaking. Overall, addressing climate vulnerability requires a holistic approach that integrates water management, agricultural development, infrastructure planning, and social protection. The CCVI framework provides a scalable and practical pathway for advancing climate-resilient development in Pakistan and beyond.

Annexure Annexure A - List of Variables



Source: Extracted from NSER-BISP, GoP.

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