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CLIMATE CHANGE IMPACTS ON CIVIL INFRASTRUCTURE: RESEARCH GAPS AND ADAPTATION PATHWAYS FOR CLIMATE-RESILIENT INFRASTRUCTURE

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Abstract
This paper presents the review of climate change impacts on civil infrastructure of Pakistan. Pakistan has faced climate hazards driven by rising temperatures, melting glaciers and erratic monsoon patterns. These hazard including floods, heatwaves, droughts and water scarcity, and sea level rise have directly affected the structural integrity and service quality of civil infrastructure. Several studies have documented the impact of climate change on the occurrence frequency of natural hazard. However, limited studies have identified the vulnerability of existing civil infrastructure towards these hazards. Therefore, this study is designed to review the literature on climate change impacts to identify the research gaps and vulnerabilities in existing planning, design, construction and operation practices of civil infrastructures and housing units towards climate hazards. Identified research gaps are used to determine engineering priorities for adaptation pathways leading towards climate resilient infrastructure. Analysis of reported damages revealed that climate hazards has severely impacted communication infrastructure, houses, hydraulic structures, WASH projects etc. in the past decades. The vulnerabilities of civil infrastructure against natural disasters were found in various fields of civil engineering such as geotechnical, structural, material, hydraulics and hydrological domains. A review of upgraded design codes and policies to cope the adverse impacts of climate change revealed that the updates are limited in scope to address multifaceted climate hazards. Therefore, engineering priority is required to address the research gaps in developing: flood risk assessment maps, multilevel governance framework, protocols for climate risk knowledge into enforceable practice, real time decision framework, construction with durable materials, climate smart infrastructure. Addressing these research gaps will lead towards adaptation pathway resulting in improved hazard maps with asset inventories, climate informed design standards, integrated planning and implementation across building, water and transport for disaster risk reduction. A climate-resilient infrastructure in Pakistan requires action across the full infrastructure lifecycle.

INTRODUCTION

Changes in long term environmental conditions including temperature, humidity, rainfall patterns, sea level, snow mass and occurrence frequency of extreme weather events can be called as climate change [1]. Monitoring of these changes are crucial in Pakistan because these variations affect the performance of built civil infrastructure and allied civil services. Impacts of climate change are visible in Pakistan in the form of rising of temperature, health issues due to changing environment, droughts, floods, inconsistent weather pattern [2], [3], changing rainfall pattern, variations in river discharges and ground water flows [4], accelerated glacier melt and rising sea levels [5]. Despite being contributor of 0.8% of global carbon emission [6], Pakistan is highly vulnerable to the climate change. However, Pakistan's CO_2 emissions could reach 277.9 Mt by 2035 if cleaner energy transitions are not strengthened [6].

Studies have pointed out that developing countries like Pakistan are confronting water scarce conditions [7], [8], experiencing water shortages, which are projected to get worse in future [9] Pakistan is rank third among the countries with water scarcity issues [10]. Pakistan is not only prone to climate change impacts [3], [11], [12], it has been placed among the top ten list of climate vulnerable countries [13], [14], [15], [16], [17], [10] because approximately 10,000 fatalities has been reported due to 152 climate related events with a financial loss of above $37,00 million in Pakistan [13]. Since 1990 Pakistan has face around 14 major floods and has been exposed to frequent GLOFs because of melting glaciers at an accelerated pace [10].

A review paper by [17] pointed out the threats of multiple climate related hazards in Pakistan including flash floods, riverine floods, urban flooding, snowmelt floods, glacier retreats, heatwaves, droughts, sea-level rise, coastal erosion, and saline-water intrusion. These climate-change induced hazard affect various civil infrastructures. For instance, urban floods have already stressed drainage systems, riverine floods are continuously damaging bridges, roads and the embankments, Glacial Lake Outburst Floods (GLOF) are threatening downstream village and town infrastructures in northern areas, sea-level rise and salinity intrusion is increasing the exposure of coastal infrastructure in the Indus delta.

National Flood Protection Plan IV reported that the super food of 2010 has caused damages amounting to US$10 billion [18]. This flood has destroyed 1.6 million homes beside destruction of civil infrastructure affecting over 20 million people in the entire country. Moreover, flash floods and landslides have caused severe infrastructure damage [19]. Similarly Pakistan faced worst flood in 2022 due to extreme monsoon rainfall [20]. According to Federal Flood Commission (FFC), pluvial, torrential / flash, and riverine flooding occurred simultaneously which has caused more damage than 2010 flood [20] with 1739 human live lost, and reported economic losses approximately equal to $US 30 billion [21]. The flood damaged around 24000 schools [15] inundating one third land of Pakistan, affecting 33 million people with 8 million displaced people [22]. Recent remote sensing evidences have indicated that major cities of Pakistan including Islamabad, Lahore and Karachi became more vulnerable to urban pluvial flooding (UPF), because of expansion of urban impervious surface (UIA). UIA has resulted in increased runoff generation due to reduction in infiltration capacity [23], [24].

In the absence of planning, design and construction according to climate change resilience and adaptation principles, Pakistan housing sector has been paying high energy cost to achieve thermal comfort in summer and winter. The energy consumption will continue to rise in future [25], in order to satisfy the demand of growing urban population, which has already doubled between 2000 and 2025 and it is projected to reach 255 million by 2050 [26]. Consequently, more housing will be required to accommodate urban population. Energy inefficient buildings are likely to consume more energy to achieve thermal comfort resulting in more GHG emission [27]. Therefore, unless future construction design and operations adapt to climate change impact, the consumption of less energy for achieving thermal comfort would not be possible [16].

Increasing civil infrastructure and housing units' damages because of floods, rising energy demand to achieve thermal comfort in private and public buildings, ascending water scarcity for agriculture and domestic use, salinity intrusion and sea level rise, degrading water quality with depleting ground water reserves are pointing towards poor adaptation and resilience towards climate change induced hazards. This adaptation towards climate change impact is not possible without proper analysis of weaknesses of civil infrastructure to withstand climate change impacts. Without overcoming these weaknesses, the housing and civil infrastructure shall remain vulnerable to negative impacts of climate change. Number of studies have covered various impacts of climate change that have either enhanced the magnitude or the frequency of natural hazards. However, limited studies have been performed to identify the vulnerabilities of existing civil infrastructure to mitigate the harmful impacts of climate change. Therefore, this research is focused on reviewing the scientific literature and reports related to climate change impacts on civil infrastructure and housing to identify the vulnerabilities of existing planning, design, construction and operation practices of civil infrastructures and housing units towards adverse climate change impacts. Moreover, the identified research gaps are used to determine engineering priorities for adaptation pathways leading towards climate resilient infrastructure.

Methodology

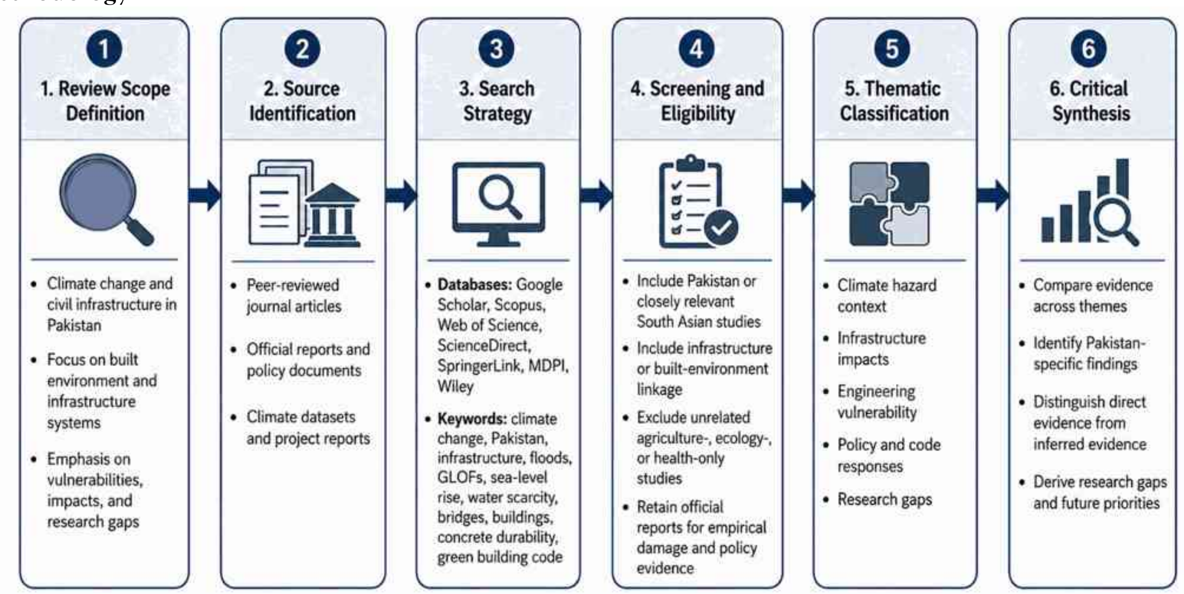

Figure 1 Methodological framework for the structured narrative review

This research adopted a structured narrative review approach in order to synthesize evidence of climate change impacts on civil infrastructure in Pakistan (Figure 1). Relevant literature was selected through focused searches on Google Scholar, Scopus, Web of Science, Science Direct, Springer Link, MDPI, Wiley, and official institutional repositories like data bases.

The search included terms such as climate change, Pakistan, infrastructure, floods, GLOFs, water scarcity, bridge scour, buildings' energy demand, global warming, and green building code. Peer reviewed studies were supplemented with official reports, policy documents, climate datasets, and post-disaster assessments where they provided empirical evidence on infrastructure damage, hazard exposure, or adaptation planning.

Those sources were selected which have a clear link to climate change impact on civil infrastructure or the built environment in Pakistan. The chosen literature was grouped thematically into climate hazards, infrastructure impacts, engineering vulnerability, policy/code responses, and research gaps. A critical synthesis was then used to identify evidence-supported gaps and future engineering priorities to reduce vulnerability and enhance climate change adoption.

3. Results and Discussions

3.1. Climate hazard towards Pakistan's infrastructure

Pakistan faces severe climate hazards driven by rising temperatures, melting glaciers and erratic monsoon patterns. The specific hazards related to civil infrastructure include floods, severe heatwaves, droughts and water scarcity, and Sea level rise. Reported wide spread damages to the infrastructure in the recent floods of 2010, 2012 and 2022 indicate the vulnerability of Pakistan to the floods[28] driven by climate change and global warming [29], [30]. The unusual intense rainfall, particularly in Sindh and Baluchistan resulted in combined flooding (including riverine flows, hill torrents, pluvial flooding, and urban flooding) [21], [12], [15]. Reportedly, August, 2022 Pakistan received 243% more rainfall than above average making it wettest August since 1996. According to data gathered by some climate model suggests that 50% increased rainfall may have been due to climate change [20]. Moreover, in urban area like Islamabad, Lahore and Karachi, impervious surface has increased by 16.8%, 23.5% and 16.4% respectively. And pluvial flooding risk has increased with intense rainfall and the expansion of impervious land [23].Climate change is altering flood generation process by affecting precipitation phase, accelerating glacier melt process, and increasing the probability of extreme rainfalls. Intense rainfall on steep mountainous slope limits the early warning to few hours, consequently making northern infrastructure extremely vulnerable to flash floods, debris flows, landslides, and GLOF-related hazards [31]. GLOF report is providing evidence that northern Pakistan Valleys are at Glacial Lake Outburst Flood GLOF risk. In Gilgit-Baltistan GB and Khyber Pakhtunkhwa KP, GLOF risk requires monitoring systems which is essentially different from the conventional lowland riverine flooding monitoring method. GLOF monitoring system requires lake and river water-depth gauges, automatic weather stations, rain gauges, warning posts, satellite communication, GIS based hazard mapping, and glacial lake inventories [32]. This report's estimated 800 GLOF related deaths in previous 20 years together with US$ 21.078 million loss in economic asset highlighting the need to treat northern mountain valleys as critical infrastructure-risk zones rather than peripheral rural areas [32].

Zachariah et al [33] reported that the climate change due to human intervention caused heat wave 30 times more likely to happen in 2022 as compared to pre-industrial climate [33]. A study by Khan et al [34] stated that recent increase in global warming has also increase the temperature in Pakistan, which has resulted in increased intensity and frequency of heat waves.

Pakistan is facing water scarce conditions [7], [8], with acute water shortages in some areas which is projected to get worse in the future [9]. Pakistan is among the top three countries with water scarcity issues [10] as per IMF. Water availability is continuously declining per capita since 1947, water availability has declined from 5600 m^3 in 1947 to around 1000 m^3 in 2010 and may fall to around 660 m^3 by 2025 and it will be close to 575 m^3 in 2050 [35]. Despite decreasing water availability, the water retention capacity remained at 14.46 MAF against mean annual inflows of 144 MAF. This supports the idea that more planning and investment is needed in the climate smart and resilient infrastructures for water storage, flood control, ground and surface water management [10].

Rise in global warming results in intense precipitations due to change in global hydrological cycle [16]. According to Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6), increase of approximately one meter of mean sea level may reach by around 2110 under RCP 8.5 [14], [36].

3.2. Climate change impacts on infrastructure and built environment

Post disaster assessment reports indicate extensive damages to Pakistan due to 2010 and 2022 flooding (Figure 2). Flood of 2010 reported more than 1.6 million damaged houses, including 913307 completely destroyed house and 694878 partially damaged units. The report recommended that reconstruction should be based on flood resistant design and construction [19].

FFC official data of 2022 flood shows that the damage was not limited to river embankment. Flood reached across irrigation drainage, and caused damage to the roads and bridge. Damages report revealed the damage to 6006 irrigations, drainage and flood protection structure with estimated restoration cost of more than 154 billion [21] to be incurred on 6700 km of road, 269 bridges and 1460 health facilities [20]. The study by [15] reported that authorities like NDMA and provincial institutes did not take robust actions to strengthen the embankments of the water ways or clear major drains. These findings indicate the vulnerability of hydraulic structures in Pakistan due to weak maintenance, drainage dysfunction and lack of preparedness.

NFPP-IV report provided engineering evidence of Pakistan's hydraulic infrastructure vulnerability which has been observed in 2010 flood because all the bridges on the Swat and Kabul rivers were overtopped, while many bridge approaches were washed away. This Report also mentioned the low flood passing capacity of some barrages and bridges resulted in upstream afflux [18].

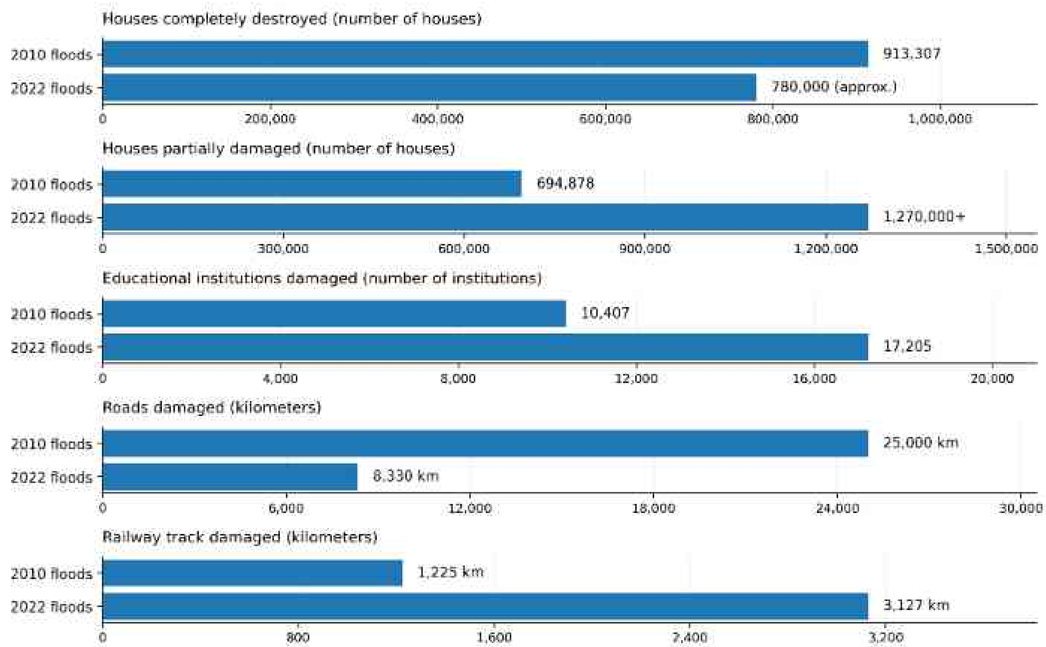

Figure 2 Comparative physical impacts of Pakistan's 2010 and 2022 floods on selected infrastructure and social-service assets [19], [22]

Moreover, infrastructures located along the coastline of Pakistan including ports, power plants, industrial area, storm water drainage pipes, residential and commercial area are exposed to rising of mean sea level [14]. Figure 3 presents the valuation of damages on selected infrastructure and social-service assets including transport and communication facilities, irrigation schemes, WASH infrastructure, education, health and energy projects because of 2022 floods. It also shows the finances required for the recovery and reconstruction.

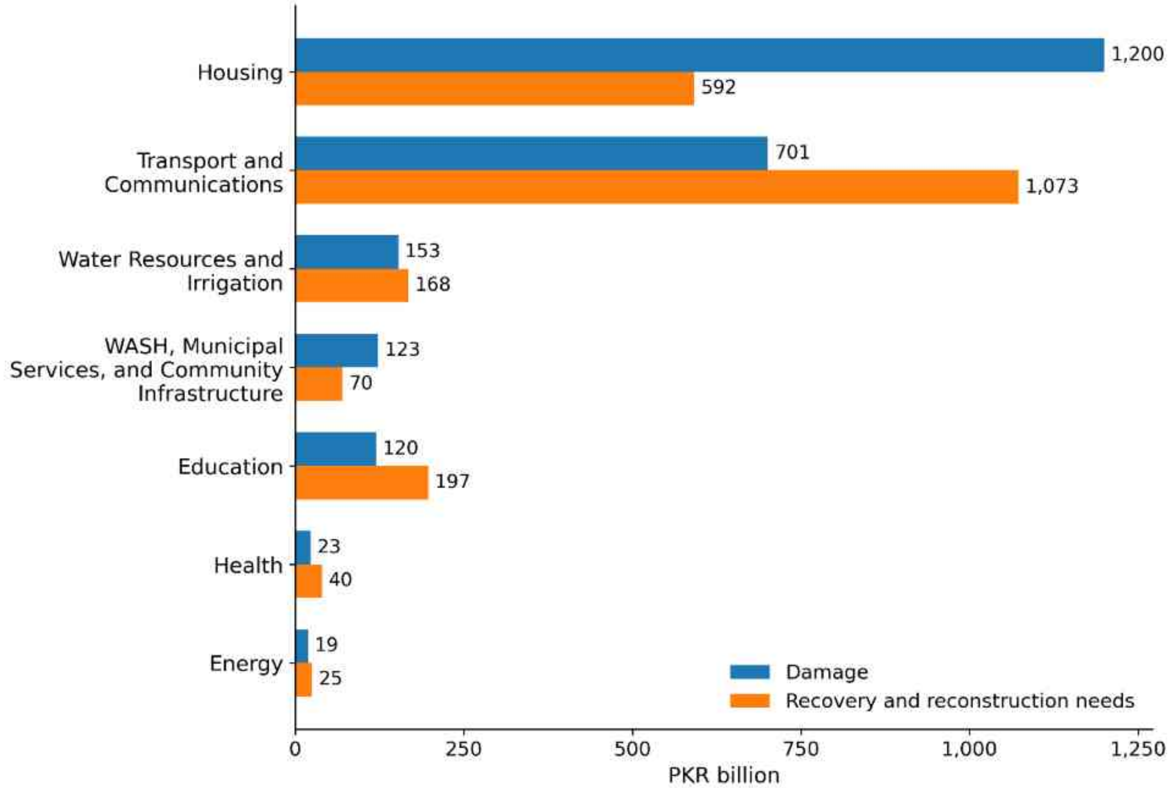

Figure 3 Sector-wise damage and recovery needs after the 2022 Pakistan floods [22]

Mountain flood hazards are linked to geotechnical instability, permafrost degradation contribute to slope movement, debris flow and GLOFs. This is dangerous for infrastructure because high energy flows from the steep mountains can damage the roads, bridges, hydro power facilities while also altering channel morphology [31]. For instance, Chitral is a multi-hazard mountain district where flash floods, landslides, avalanches, and GLOFs interact with steep terrain and river-adjacent settlements which create recurrent risks to the roads, irrigation channels, crops, and local infrastructure [12].

Similarly, Pakistan is also confronted by the tectonic instability. The sea height during 1945 tsunami was 3-6 m at Gawadar, 9 m at Pasni and 0.5-2 m at Karachi. Since, Pakistan is at a junction of Indian, Eurasian, and Arabian plates, therefore sea level is influenced by tectonic instability, uplift and tsunami hazards, which makes costal infrastructures planning depended on sea level projection [14].

3.3. Engineering vulnerabilities due to climate change impacts

The vulnerabilities of civil infrastructure due to climate change impacts in Pakistan has been reported in various fields of civil engineering such as geotechnical, structural, material, hydraulics and hydrological vulnerabilities. The geotechnical vulnerabilities have been discussed in the form of permafrost loss [37], [38] slope instabilities [39], [40] and liquification risks [41], [42]. Karakorum permafrost loss has been reported by [37] in a Hunza River basin. It has been found that permafrost has occupied about 85% of the catchment above 3525 m with a destabilization that has posed direct risk to the downstream infrastructure. Karakorum Highway landslide has been reportedly damaged a retaining wall and threatened highway stability due to rainfall and fault-triggered slides [39]. Similarly, annual rainfall has been identified as a primary trigger behind the risk of Huna-Nagar valley landslide [40].

The structural vulnerabilities have been reported due to scour erosion [43], [28] and coastal battering [44], [45]. The scour has been identified as a major factor behind the failure of 35 flood-affected bridges in Baluchistan due to monsoon flood of 2022 [43]. Similarly, a study by [28] has found that several rural bridges in KPK required immediate scour protection following the 2010, 2012 and 2022 floods. Karachi tide gage analysis by [44] has underscored the rising coastal flooding hazard for shoreline structures.

Material vulnerabilities due to climate change impacts have been found in the form of bitumen softening [46], [47] and chloride intrusion [48]. Lab evaluations of HDPE–Bakelite dual-modified asphalt mixtures by [46] found that conventional 60/70 bitumen suffers severe rutting due to extreme summer temperatures of Pakistan. Natural marine exposure testing of ASTM A615 Grade 60 rebar by [48] found that the humid and saline climate (with high chloride deposition rate) of Karachi in combination with other local conditions have depassivate steel even before embedment in concrete that has caused the tensile-strength degradation.

Climate change can increase carbonation and chloride induced corrosion. Analysis has revealed that rising CO_2 concentration, temperature, and humidity changes can increase carbonation depth. It is reported that carbonation related damage may increase by more than 16% by 2100, that means up to one in six concrete structures may experience additional costly corrosion damage. This corrosion could put the civil infrastructure like reinforced concrete bridges, frame structure, drainage structures, hydraulic works, and coastal infrastructure, at additional risk of corrosion. Therefore, increasing frequency of intense weather, humidity, flooding, salinity, and urban pollution are most likely to intensify durability demands [49].

Hydraulic and hydrologic vulnerabilities have been reported in the form of outfitted drainage capacity [50], [51] Spillway overtopping [52] and silt accumulation [53], [54]. Pluvial flooding of 2022 was caused due to high intensity rainfall on highly impervious urban catchment that has overwhelmed the inadequate drainage capacity of Karachi [50]. Similarly, an analysis by [51] found that undersized and underdeveloped drainage network of Karachi in combination with poor urban planning resulted in widespread flooding during monsoon storms. A study by [52] found that inadequate spillway management under compounded high inflows and precipitation peaks because of climate change could lead to overtopping.

Major limitation in the estimation of flood risk assessment in changing climate is lack of available data of desired quality and resolution. Lack of data cause difficulties in define the damaging thresholds. This supports the need for improvement in monitoring, river mapping, flood simulation and vulnerability hazard mapping of mountainous infrastructure [31]. Pakistan official report [18] has mentioned the limitation in the availability of real time data, low density of hydro metrological gauges and weak spatial temporal monsoon forecasting. For instance, Chitral lacks flood susceptibility assessment and mapping. Moreover Pakistan flood risk mapping is not unified across national multi hazard vulnerability atlas [12]

3.4. Design codes and policies to cope the adverse impacts of climate change

After the flood of 2022, gaps in flood protection planning have been observed, which were corrected by implementing National Flood Protection Plan-IV (NFPP-IV) [21]. The institutional preparedness gap has been indicated by [15] in reference to 2022 flood. It was found that despite warnings from metrological department response coordination was weak and haphazard from federal and provincial authorities. For instance, the embankments were not properly prepared. National Flood Response and Coordination Centre was established later in August, 2022, after the occurrence of disaster.

Post Disaster Needs Assessment (PDNA) 2022 [22] stated that despite investment in post 2010 disaster risk recommendations several institutional issues persisted. The recommendations covered relocation from five-year flood plain, and flood resistant construction design beside long term policies like NFPP-IV.

However, the report identified persistent shortcomings, including (i) lack of operationalization of existing plans, (ii) inadequate financing, (iii) limited use of risk assessments in infrastructure investment and land usage planning, (iv) poor urban planning, (v) weak water resource management, (vi) insufficient infrastructure maintenance systems, (vii) complex governance arrangements, and (viii) limited disaster risk reduction capacity. These findings suggest that Pakistan's principal challenge lies not in the absence of policy frameworks, but in translating disaster risk knowledge into effective implementation and enforceable engineering practice[19], [22]

GLOF II report [32] has mentioned that climate resilient infrastructure guidelines were developed for GB in 2024 which included hazard mapping and zoning, building codes, regulation, and climate resilient construction practices. However, the report highlighted the policy gap because the guidelines were for limited geographical boundary rather than its fully integration with national infrastructure code, such as building code, NHA standards, bridge manuals or provincial engineering design codes [32]. Although, updated design codes and policies like GBCP-2023, NFPP-IV, and GLOF-II were drafted to cope climate change impacts but still their effectiveness is constrained due to limited scope of the codes and lack of proper implementation.

3.5. Research gaps and Engineering Priorities

AHP GIS model developed by Khoso et al [12] for Larkana District using nine flood conditioning factor including rainfall, distance to river, slope, elevation, land use/land cover, topographic wetness index, NDVI, soil type, and curvature. The results of the study revealed that rainfall, river proximity, slope, and elevation were contributing towards 80% of flood risk [12]. Such studies are important for local emerging flood mapping however, these hazard zonation tools are not yet integrated with infrastructure asset condition, drainage-capacity assessment, structural fragility, or climate-informed design prioritization. Therefore, the absence of flood risk and vulnerability assessment and zonation across Pakistan is likely to cope with multifaceted climate change impacts increasingly difficult.

Adaptation need of climate smart construction design codes for development and reconstruction of infrastructure was highlighted by [15]. The GLOF-II project was a practical hybrid model which has combined physical infrastructure, early warning systems, ecosystem-based measures, community preparedness, gender sensitive facilities, livelihood diversification, and institutional capacity-building. This shows that practical adaptation in Pakistan is already in progress [32]. However, multilevel governance framework would be required to build strong coordination between federal, provincial and local government along with private sector and community stakeholders. Nationwide climate policy would be required to clearly define the roles of federation and the provinces [17].

Literature review revealed that Pakistan’s infrastructure gap to cope climate change impacts is not simply the absence of policy documents but also the weak translation of climate risk knowledge into enforceable engineering practice. For instance, Pakistan Floods 2022 Post Disaster Needs Assessment [22] indicated that despite post 2010 planning of disaster, major challenges left from the implementation of plans, financing, and the use of risk assessments in infrastructure investment. Similarly, National Flood Protection Plan IV [18] has also proposed flood management through structural and nonstructural measures which included floodplain mapping, zoning, forecasting, watershed management, and flood protection infrastructure. However, Pakistan Post Disaster Needs Assessment 2022 (PDNA) [22] reports persistent challenges which have limited the implementation includes financing, infrastructure maintenance, and the application of risk assessments.

Another gap concerns the integration of hydro metrological monitoring networks in real-time decision support. National Flood Protection Plan IV [18] emphasized the strengthening of flood forecasting systems through floodplain mapping, and better data acquisition and transmission systems. For mountainous regions, [55] has documented the need for gauges, warning posts, GIS/HVRA mapping, and early warning systems, while [14] highlights the need for stronger sea level evidence and coastal decision support systems. It was found by [14] that there is no systematic way of acquiring real-time sea-level data for coastal risk assessment. Therefore, development of sea level data portal was recommended to support coastal flood mapping. High resolution flood inundation modeling was recommended for sea level rise and flooding and erosion risk. It was also suggested to distribute the acquired water level data among the multiple organization including PMD, the National Institute of Oceanography, the Pakistan Navy Hydrographic Department for tacking sea level rise and taking robust actions. These studies have shown that the monitoring systems exist in some parts, but they are not fully connected to asset level infrastructure decisions.

The research studies also identified major gaps related to the fragility of civil infrastructure to face the natural disaster. For instance, National Flood Protection Plan IV [18] described that problem of urban flooding is linked with inadequate storm water drainage, clogging, encroachment, undersized drains, and poor urban planning. Pakistan Floods 2022 Post Disaster Needs Assessment (PDNA) official reports [19], [22] has shown that the floods damaged roads, bridges, irrigation systems, drainage systems, flood protection works, WASH systems, and transport infrastructure. However, most of these losses were reported at sectoral or provincial scale. They were systematically analyzed to determine the asset level fragility curves and failure mechanism classifications. However, the work required to link the post disaster damage records with the hydraulic performance assessment of the infrastructure such as drains, canals, embankments, bridges, barrages, head works, and urban storm water systems.

Moreover, rural, mountainous, and coastal infrastructure reportedly remained underdeveloped. The GLOF report [55] documented the situation of practical adaptation in vulnerable valleys through early warning systems, gauges, warning posts, GIS/HVRA mapping, gabion walls, irrigation channel rehabilitation, slope stabilization, access routes, safe havens, and community preparedness.

Additionally, material durability and heat-resilient construction in reference to climate change are not exhaustively discussed in the context of Pakistan. Stewart et al [49] provided strong international evidences that rising CO_2 concentration, temperature, and humidity can increase carbonation and chloride induced corrosion risk in reinforced concrete. However, these findings are not independently verified in the context of construction in Pakistan. Local data is still needed on carbonation depth, chloride and sulfate exposure, corrosion rate, concrete cover quality, flood exposure, humidity, salinity, and construction quality for various buildings in Pakistan including bridges, hydraulic structures, Water, Sanitation, and Hygiene (WASH) facilities and coastal assets.

Another identified gap is the limited usage of the knowledge of climate science into practical infrastructure design guide. For instance, Otto et al [20] linked the 2022 flood event with extreme rainfall and climate change influence. This study has provided valuable climate load evidence but the engineering literature has not yet consistently used such information in the design of future IDF curves, design storms, drainage capacity standards, bridge and culvert design inputs, reservoir scenarios, or nonstationary flood frequency criteria. This indicate the gap in using climate projections and event attribution findings in better engineering design inputs for the civil infrastructure.

Additional research gap is related to the consideration of civil infrastructure as a service-continuity problem in addition to asset-damage problem. Pakistan Floods 2022 Post Disaster Needs Assessment [22] documented widespread service disruption after the 2022 floods, while IPCC report [56] has emphasized that poor water and WASH infrastructure can increase vulnerability among women, girls, elderly people, children, and other vulnerable groups. Bhutta et al [15] further highlighted the service consequences of the 2022 floods. Therefore, the infrastructure vulnerability should be assessed in the context of service continuity.

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Figure 4: Transforming knowledge into climate resilient infrastructure through stepwise movement from climate hazards to engineering solutions

The steps from climate hazards to engineering solutions are illustrated in Figure 4. The impacts of climate hazards like floods, heat waves, extreme rainfalls and sea level rise are confronted by the civil infrastructure including communication infrastructure, hydraulic structures, buildings, WASH projects and coastal infrastructure. Many past natural hazards have severely damaged this civil infrastructure necessitating the need for filling the research gaps related to design codes, policies, vulnerability mapping, implementations coordination in order to reach climate resilient infrastructure.

3.6. Adaptation Pathways for climate resilient infrastructure

Table 1 outline the impacts of climate changes that have tested the resilience of buildings and infrastructure in Pakistan. This table cover total seven important issues including flood extent, urban flooding, heat stress and building's energy demand, water scarcity, renewable energy demand, and communication infrastructure. These issues were reported in various research studies and partially addressed in GBCP-2023 [57]. GBCP-2023 has addressed several building and site scale risks but broader civil infrastructure systems were partially covered, the detail of which is given in Table 1.

Table1: Selected climate hazards as addressed in GBCP 2023 and remaining gaps

Literature-identified issue	Evidence from reviewed literature / reports	GBCP 2023 response [57]	Remaining gap
Flood exposure	The 2022 PDNA has reported that one third of Pakistan was under water with 33 million people affected and nearly 8 million displaced. It has been taken as an evidence of Pakistan's high climate vulnerability [22].	GBCP 2023 prohibited development on land that is below 5 ft to 100-year flood elevation and within flood limits of rivers, streams, nallahs, and natural drainage systems. It has required floodplain / inundation mapping approved by Authority Having Jurisdiction (AHJ). AHJ strictly enforce the Green Building Code of Pakistan.	GBCP 2023 has strong addressed the issue at building-site scale, but it remained dependent on floodplain maps, 100year flood levels, and enforcement. Moreover, It did not directly cover roads, bridges, barrages, or embankments.
Urban pluvial flooding and impervious surfaces	FFC noted that urbanization replaces permeable soil with roads, roofs, parking lots, and sidewalks that has reduced infiltration and accelerated runoff. It has also highlighted that urban flooding in overcrowded cities is also due to inadequate storm water drainage [21].	GBCP 2023 required site storm water management using infiltration, evapotranspiration, rainwater harvesting, storage, and storm water collection; greenfield sites must retain the 24 hours 95^{th} percentile precipitation event or maintain predevelopment water balance.	The recommendations are useful for plot scale runoff control but insufficient for citywide drainage basin planning unless integrated with municipal storm water systems.
Heat stress and building energy demand	PDNA 2022 has identified heatwaves in Punjab, Sindh and reported that the 2022 floods followed a severe heatwave, drought emergency with temperatures above 45°C and power outages. The anti-solar roof study added building level evidence on high cooling bills due to roof heat gain with roof temperatures of 60 to 70°C [22]	GBCP 2023 introduced passive solar design, green roofs, heat island mitigation, roof solar reflectance, wall shading, building envelope provisions, energy efficient lighting, and automation systems to promote energy efficiency in the buildings.	GBCP 2023 has addressed the design direction, but it lacked Pakistan-specific long term testing of cool roofs, coatings monsoon exposure, thermal cracking, and cost-benefit performance.
Water scarcity	The scientific literature has shown declining per capita water availability with increasing water stress that necessitated the need for	GBCP 2023 provided water saving technologies, low flow fixtures, rainwater harvesting, greywater reuse,	It has strongly addressed building scale water efficiency, but does not solve the issues of basin scale water allocation,

	conservation and reuse [11], [10].	smart irrigation, and water consumption monitoring.	groundwater depletion, irrigation losses, or rural water supply vulnerability.
Energy transition and renewable integration	Lin and Raza [6] analyzed Pakistan power sector CO_2 emissions and showed the need for cleaner energy technologies, Adnan et al [10] supported renewable energy as part of Pakistan's climate response.	GBCP 2023 required on-site photovoltaic systems based on unshaded roof area for solar radiation of 4 to 6 kWh/m^2/day.	It did not fully address grid resilience, and the issues of solar performance under dust, heat, flooding, battery backup.
Infrastructure systems beyond buildings	The 2010 DNA [19] documented the damages to roads, bridges, embankments, railways, airports, and telecommunication infrastructure due to flooding. Whereas, PDNA 2022 [22] identified the issues of infrastructure-investment, maintenance, governance. Kashif et al [28], showed the need for hydraulic risk assessment specific to bridge.	GBCP 2023 has mainly regulated buildings and building sites. Although, its intent includes resilience and resource efficiency, but its scope remains building focused.	Pakistan still needs climate informed standards for roads, bridges, culverts, barrages, embankments, drainage networks, rural lifeline infrastructure, mountain corridors, and coastal systems.

GBCP 2023 [57] should therefore be interpreted as an important but partial regulatory response to Pakistan's climate-infrastructure vulnerability. Its strongest contribution is at the building and site scale, where it introduces floodplain restrictions, storm water retention, rainwater harvesting, heat island mitigation, roof reflectance, water efficient fixtures, smart irrigation and renewable energy usage. These provisions show that Pakistan has begun translating climate concerns into formal code language. However, the code does not fully close the wider engineering gap because it does not provide detailed climate relevant design standards for roads, bridges, culverts, barrages, embankments, rural lifeline infrastructure, GLOF prone mountain corridors, or coastal systems. Therefore, future code reform should essentially connect GBCP 2023 [57] with asset level vulnerability mapping, updated flood and drainage design criteria, Pakistan relevant material durability data, and enforceable standards for non-building infrastructure.

Emerging climate change related pressures in Pakistan as listed in Table 1 are summarized in Figure 4 along with the aspects that are already addressed in GBCP 2023 [57] and the priority areas that require further research and action. Most of the climate pressures related to buildings planning, design and operation are already covered in GBCP 2023. However, the wider infrastructure gaps related to communication structures, hydraulic structures, essential rural and coastal infrastructure and asset level vulnerability mapping and monitoring could be addressed through focused research and follow-up action in the corresponding priority areas. The adaptation pathway, therefore, required Pakistan specific durability research, improved hazard maps with asset inventories, climate informed infrastructure design standards, integrated planning and

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implementation across building, water and transport in disaster risk reduction (DDR).

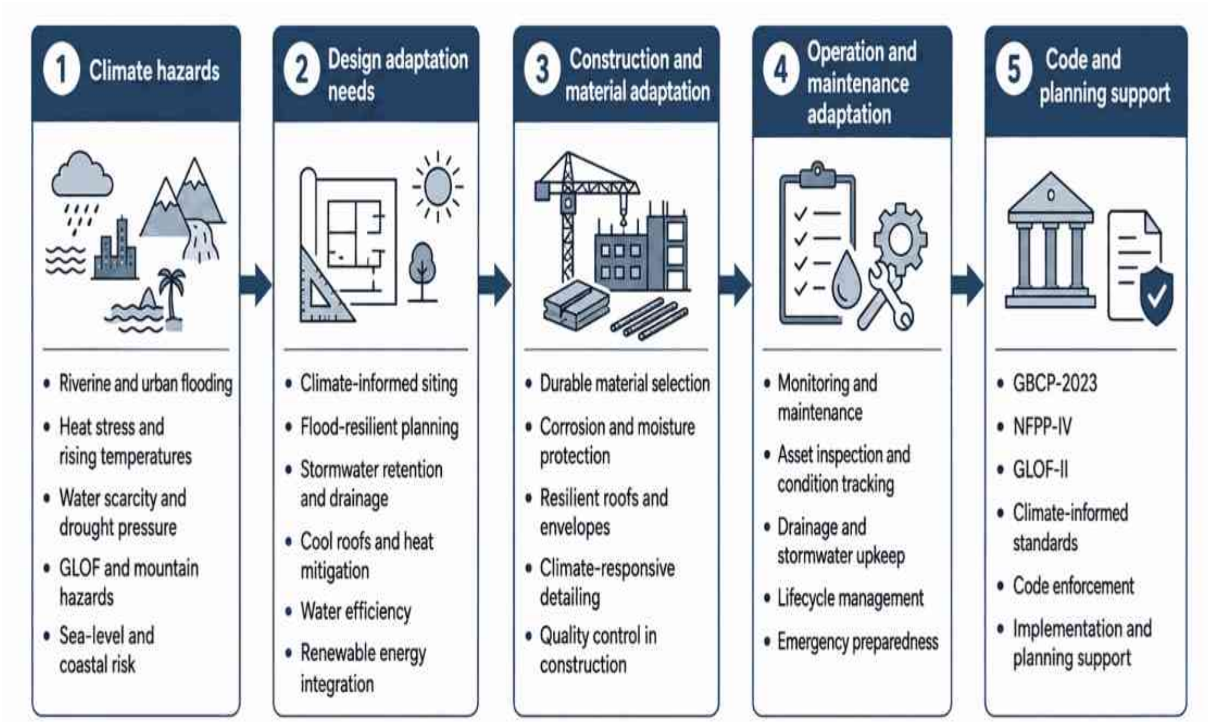

Figure 4 Adaptation pathways for climate-resilient infrastructure design and construction in Pakistan [14], [18], [22], [35], [49], [55], [57].

Figure 5 summarizes the adaptation pathway emerging from the reviewed literature. The evidence indicates that climate-resilient infrastructure in Pakistan requires action across the full infrastructure lifecycle rather than only post-disaster reconstruction. At the design stage, adaptation requires climate-informed siting, flood-resilient planning, stormwater retention, heat mitigation, water efficiency, and renewable-energy integration. At the construction stage, material durability, corrosion protection, resilient envelopes, and quality control become central. During operation, monitoring, inspection, drainage upkeep, lifecycle management, and emergency preparedness are needed to sustain performance under changing hazards. Existing instruments such as GBCP-2023, NFPP-IV, and GLOF-II provide important starting points, but broader implementation and climate-informed standards for infrastructure systems remain necessary.

Conclusions and Recommendations

Pakistan is prone to climate change impacts [3], [11], [12] and it has included in top ten climate vulnerable countries [13], [14], [15], [16], [17], [10] because approximately 10,000 fatalities has been reported due to 152 climate related events with a financial loss of above $37,00 million [13]. Moreover, It is rank 3rd among the countries with water scarcity issues [10].

Impacts of climate change are widely reported in the form of rising of temperature, droughts, floods, frequent heat waves, inconsistent weather pattern [2], [3], changing rainfall pattern, variations in river discharges and ground water flow [4], accelerated glacier melt and rising sea level [5].

Pakistan is threatened by multiple climate related hazards including flash floods, riverine floods, urban flooding, snowmelt floods, glacier retreats, heatwaves, droughts, sea-level rise, coastal erosion, and saline-water intrusion [17].

Analysis of reported damages by structured narrative review approach revealed that climate hazards have severely impacted communication infrastructure, houses, hydraulic structures, WASH projects, energy and health infrastructure in the past decades. For instance, flood of 2010 reported more than 1.6 million damaged houses, including 913307 completely destroyed house and 694878 partially damaged units [19]

The vulnerabilities of civil infrastructure against natural disasters were found due to climate change impacts on various fields of civil engineering such as in geotechnical, structural, material, hydraulics and hydrological domains.

A review of upgraded / new design codes and policies such as GBCP-2023, NFPP-IV, and GLOF-II to cope the adverse impacts of climate change revealed that these codes and policies are limited in scope and lack proper implementation to address multifaceted climate hazards. Therefore, revision and enhancements in codes, standards and policies are required to address all the issues concerning climate hazard for disaster risk and vulnerability reduction.

Research gaps were found in developing: flood risk and vulnerability assessment maps across Pakistan, multilevel governance framework including federal and provincial government to address natural hazards, protocols for applying climate risk knowledge for damage risk reduction, real time decision framework on the basis of monitoring network, heat resilient construction with durable materials and climate smart infrastructure design.

Adaptation pathway for sustainable climate-resilient infrastructure in Pakistan should include development of: i) improved hazard maps with asset inventories, ii) climate informed design standards and policies iii) monitoring network to support databased decision making, iv) integrated planning and implementation across building, water and transport in disaster risk reduction.

Development of sustainable climate-resilient infrastructure in Pakistan should require action across the full infrastructure lifecycle rather than only post-disaster reconstruction.

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The authors declare no conflicts of interest to report regarding the present study.

AUTHOR CONTRIBUTIONS

Conceptualization, M.K.S; methodology, M.K.S. and M.W.H.R; software, M.W.H.R; validation, M.W.H.R; writing M.K.S. and M.W.H.R; writing review and editing, M.K.S.

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Not applicable.

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Not applicable.

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Data is available on reasonable request.

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