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Weaving equity into infrastructure resilience research: a decadal review and future directions

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Infrastructure resilience plays an important role in mitigating the negative impacts of natural hazards by ensuring the continued accessibility and availability of resources. Increasingly, equity is recognized as essential for infrastructure resilience. Yet, after about a decade of research on equity in infrastructure resilience, what is missing is a systematic overview of the state of the art and a research agenda across different infrastructures and hazards. To address this gap, this paper presents a systematic review of equity literature on infrastructure resilience in relation to natural hazard events. In our systematic review of 99 studies, we followed an 8-dimensional assessment framework that recognizes 4 equity definitions including distributional-demographic, distributional-spatial, procedural, and capacity equity. Significant findings show that (1) the majority of studies found were located in the US, (2) interest in equity in infrastructure resilience has been exponentially rising, (3) most data collection methods used descriptive and open-data, particularly with none of the non-US studies using human mobility data, (4) limited quantitative studies used non-linear analysis such as agent-based modeling and gravity networks, (5) distributional equity is mostly studied through disruptions in power, water, and transportation caused by flooding and tropical cyclones, and (6) other equity aspects, such as procedural equity, remain understudied. We propose that future research directions could quantify the social costs of infrastructure resilience and advocate a better integration of equity into resilience decision-making. This study fills a critical gap in how equity considerations can be integrated into infrastructure resilience against natural hazards, providing a comprehensive overview of the field and developing future research directions to enhance societal outcomes during and after disasters. As such, this paper is meant to inform and inspire researchers, engineers, and community leaders to understand the equity implications of their work and to embed equity at the heart of infrastructure resilience plans.

Infrastructures are the backbones of our societies, connecting people to essential resources and services. At the same time, infrastructure systems such as power, water, and transportation play a pivotal role in determining whether a natural hazard event escalates into a disaster[1]. Driven by the combination of accelerating climate hazards and increasing vulnerability, a 2022 Reuters report indicated that natural hazards caused infrastructure and building losses between $732 and $845 billion dollars internationally[2]. In another report by the World Bank (2019), the direct damage to power and transportation systems had an estimated cost of $18 billion annually[3]. Not only do infrastructure disruptions result in economic losses but they also lead to health issues and a decline in quality of life[4]. Since infrastructure systems secure the accessibility and availability of water, health, and electricity, among other critical services, disruptions of infrastructure exacerbate disasters. For example, the Nepal earthquake (2015) caused the collapse of 262 micro-hydropower plants and 104 hospitals, which further weakened the community's ability to recover from the hazardous event[5]. Hurricane Maria (2017) in Puerto Rico led to year-long power disruptions which contributed to the 2975 estimated human fatalities[6]. Therefore, infrastructure resilience is becoming increasingly prominent in research, policy, and practice.

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The National Infrastructure Advisory Council defined infrastructure resilience as the ability of infrastructure systems, to absorb, adapt, or recover from disruptive events such as natural hazards[7,8]. From an engineering viewpoint, infrastructure resilience ensures no significant degradation or loss of system performance in case of a shock (robustness), establishes multiple access channels to infrastructure services (redundancy), effectively mobilizes resources and adapts to new conditions (resourcefulness), and accomplishes these goals in a timely manner (rapidity)[9]. From these origins, infrastructure resilience has evolved to include the complex interactions of technology, policy, social, and governance structures[10]. The United Nations Office for Disaster Risk Reduction discusses the need to use transdisciplinary and systemic methods to guide infrastructure resilience[11]. In their Principles of Resilient Infrastructure report, the principles of infrastructure resilience are to develop understanding and insights (continual learning), prepare for current and future hazards (proactively protected), positively work with the natural environment (environmentally integrated), develop participation across all levels of society (socially engaged), share information and expertise for coordinated benefits (shared responsibility), and address changing needs in infrastructure operations (adaptively transforming)[12].

Based on the argument of Schlor et al.[13] that "social equity is essential for an urban resilience concept," we also argue that equity in infrastructure resilience will not only benefit vulnerable populations but also lead to more resilient communities. Equity, in a broad sense, refers to the impartial distribution and just accessibility of resources, opportunities, and outcomes, which strive for fairness regardless of location and social group[14,15]. Equity in infrastructure resilience ensures that everyone in the community, regardless of their demographic background, geographic location, level of community status, and internal capabilities, have access to and benefits from infrastructure services. It would also address the limitations of infrastructure resilience, which brings short-term benefits to a specific group of people but ultimately results in long-term disaster impacts[16]. A failure to recognize equity in infrastructure resilience could exacerbate the disaster impact and lock in recovery processes, which in turn, reduces future resilience and leads to a vicious cycle[17].

Even though infrastructure resilience has important equity impacts, the traditional definition of infrastructure resilience is antithetical to equity. Socially vulnerable populations (such as lower income, minority, indigenous, or rural populations) have traditionally been excluded from the development, maintenance, and planning of infrastructure resilience[18]. For instance, resilience strategies do not conventionally consider the unique needs and vulnerabilities of different communities, leading to inadequate one-size-fits-all solutions[19]. Conventional approaches to restoring infrastructure after hazard events are based on the number of outages, the number of affected customers, and extent of damage within an area, depending on the company preferences, and rarely prioritize the inherent vulnerability of affected individuals and areas[20]. Thereby, those who are most dependent on infrastructure systems may also be most affected by their outages. Several reports, such as National Institute of Standards and Technology[21], United Nations Office for Project Services[11], United Nations Office for Disaster Risk Reduction and Coalition for Disaster Resilient Infrastructure[22], and the Natural Hazards Engineering Research Infrastructure[23] have recognized the importance of considering vulnerable populations in infrastructure resilience.

Furthermore, infrastructure resilience efforts often require significant investment at individual, community, and societal levels[24]. For instance, lower income households may not be able to afford power generators or water tanks to replace system losses[25,26], which means they are more dependent on public infrastructure systems. Wealthier communities may receive more funding and resources for resilience projects due to better political representation and economic importance[27]. Improvements in infrastructure can also lead to gentrification and displacement, as an area perceived with increased safety may raise property values and push out underrepresented residents[28]. Infrastructure resilience may not be properly communicated or usable for all members of the community[29]. Research has also shown an association between vulnerable groups facing more intense losses and longer restoration periods of infrastructure disruptions due to planning biases, inadequate maintenance, and governance structures[18]. Due to the limited tools that translate equity considerations, infrastructure managers, owners, and operators are unlikely to recognize inequities in service provision[20]. Finally, resilience planning can prioritize rapid recovery which may not allow for sufficient time to address the underlying social inequities. This form of resilience planning overlooks the range of systematic disparities evident in infrastructure planning, management, operations, and maintenance in normal times and hazardous conditions[18].

The field of equity in infrastructure resilience has sparked increasing interest over the last decade. First, researchers have distinguished equal and equitable treatment for infrastructure resilience. As stated by Kim and Sutley[30], equality creates equivalence at the beginning of a process whereas equity seeks equivalence at the end. Second, the term has been interpreted through other social-economic concepts such as social justice[16], sustainability[31], vulnerability[32], welfare[33,34], and environmental justice[35]. Third, equitable infrastructure is frequently associated with pre-existing inequities such as demographic features[36,37], spatial clusters[38–40], and political processes[41]. Fourth, studies have proposed frameworks to analyze the relationship of equity in infrastructure resilience[42,43], adapted quantitative and qualitative approaches[44,45], and created decision-making tools for equity in infrastructure resilience[31,46].

Despite a decade of increasing interest in integrating equity into infrastructure resilience, the research gap is to systematically evaluate collective research progress and fundamental knowledge. To address this gap, this paper presents a comprehensive systematic literature review of equity-related literature in the field of infrastructure resilience during natural hazards. The aim is to provide a thorough overview of the current state of art by synthesizing the growing body of literature of equitable thinking and academic research in infrastructure resilience. From there, we aim to identify gaps and establish a research agenda. This review focuses on the intersection of natural hazard events, infrastructure resilience, and equity to answer three overarching research questions. As such, this research is important because it explores the critical but often neglected integration of equity into infrastructure resilience against natural hazards. It provides a comprehensive overview and identifies future research opportunities to improve societal outcomes during and after disasters.

1. What are the prevailing concepts, foci, methods, and theories in assessing the inequities of infrastructure services in association with natural hazard events?
2. What are the similarities and differences in studying pathways of equity in infrastructure resilience?
3. What are the current gaps of knowledge and future challenges of studying equity in infrastructure resilience?

To answer the research questions, the authors reviewed 99 studies and developed an 8-dimensional assessment framework to understand in which contexts and via which methods equity is studied. To differentiate between different equity conceptualizations, the review distinguishes four definitions of equity: distributional-demographic (D), distributional-spatial (S), procedural (P), and capacity (C). In our study, "pathways" explores the formation, examination, and application of equity within an 8-dimensional framework. Following Meerow's framework of resilience to what and of what?[47], we then analyze for which infrastructures and hazards equity is studied. Infrastructures include power, water, transportation, communication, health, food, sanitation, stormwater, emergency, and general if a specific infrastructure is not mentioned. Green infrastructure, social infrastructure, building structures, and industrial structures were excluded. The hazards studied include flood, tropical cyclone, drought, earthquake, extreme temperature, pandemic, and general if there is no specific hazard.

The in-depth decadal review aims to bring insights into what aspects are fully known, partially understood, or completely missing in the conversation involving equity, infrastructure resilience, and disasters. The review will advance the academic understanding of equity in infrastructure resilience by highlighting understudied areas, recognizing the newest methodologies, and advising future research directions. Building on fundamental knowledge can influence practical applications. Engineers and utility managers can use these findings to better understand potential gaps in the current approaches and practices that may lead to inequitable outcomes. Community leaders and advocates could also leverage such evidence-based insights for advocacy and bring attention to equity concerns in infrastructure resilience policies and guidelines.

Background

Infrastructure resilience in the broader resilience debate

To establish links across the resilience fields, this section embeds infrastructure resilience into the broader resilience debate including general systems resilience, ecological resilience, social resilience, physical infrastructure resilience, and equity in infrastructure resilience. From the variety of literature in different disciplines, we focus on the definitions of resilience and draw out the applicability to infrastructure systems.

Resilience has initially been explored in ecological systems. Holling[48] defines resilience as the ability of ecosystems to absorb changes and maintain their core functionality. This perspective recognizes that ecosystems do not necessarily return to a single equilibrium state, but can exist in multiple steady states, each with distinct thresholds and tipping points. Building on these concepts, Carpenter et al.[49] assesses the capacity of socioecological systems to withstand disturbances without transitioning to alternative states. The research compares resilience properties in lake districts and rangelands such as the dependence on slow-changing variables, self-organization capabilities, and adaptive capacity. These concepts enrich our understanding of infrastructure resilience by acknowledging the complex interdependencies between natural and built systems. It also points out the different temporal rhythms across fast-paced behavioral and slow-paced ecological and infrastructural change[50].

Social resilience brings the human and behavioral dimension to the foreground. Aldrich and Meyer focuses on the concept of social capital in defining community resilience by emphasizing the role of social networks and relationships to enhance a community's ability to withstand and recover from disasters[51]. Aldrich and Meyer argues that social infrastructure is as important as physical infrastructure in disaster resilience. Particularly, the depth and quality of social networks can provide crucial support in times of crisis, facilitate information sharing, expedite resource allocation, and coordinate recovery efforts. Resilience, in this context, is defined as the enhancement and utilization of its social infrastructure through social capital. It revolves around the collective capacity of communities to manage stressors and return to normalcy post-disaster through cooperative efforts.

Since community resilience relies on collaborative networks, which in turn are driven by accessibility, community and social resilience are intricately linked to functioning infrastructures[52]. To understand the relationships, we first examine the systems of systems approach thinking. Vitae Systems of Systems aims to holistically resolve complex environmental and societal challenges[53]. It emphasizes strategic, adaptive, and interconnected solutions crucial for long-term system resilience. Individual systems, each with their capabilities and purposes, are connected in ways such that they can achieve together what they cannot achieve alone. Additionally, Okada[54] also shows how the Vitae Systems of Systems can detect fundamental areas of concern and hotspots of vulnerability. It highlights principles of survivability (live through), vitality (live lively), and conviviality (live together) to build system capacity in the overall community. In the context of infrastructure resilience, these approaches bring context to the development of systems and their interdependencies, rather than focusing on the resilience of individual components in isolation.

Expanding on the notion of social and community resilience, Hay's applies key concepts of being adaptable and capable of maintaining critical functionalities during disruptions to infrastructure[55]. This perspective introduces the concept of "safe-to-fail" systems, which suggests that planning for resilience should anticipate and accommodate the potential for system failures in a way that minimizes overall disruption and aids quick recovery.

As such, the literature agrees that social, infrastructural, and environmental systems handle unexpected disturbances and continue to provide essential services. While Aldrich's contribution lies in underscoring the importance of social ties and community networks, Hay expands this into the realm of physical systems by considering access to facilities. Infrastructure systems traditionally adapt and change slowly, driven by rigid physical structures, high construction costs, and planning regulations. In contrast, behavioral patterns are relatively fast-changing, even though close social connections and trust also take time to build. Yet, infrastructures form the backbone that enables—or disrupts—social ties. By adopting resilience principles that enable adaptation across infrastructure and social systems, better preparedness, response, and recovery can be achieved.

Given the dynamic, complex nature of resilience, infrastructure resilience, by extension, should not just be considered through the effective engineering of the built environment. Rather, infrastructure resilience must be considered as an integral part of the multi-layered resilience landscape. Crucial questions that link infrastructure to the broader resilience debate include: How will it be used and by whom? How are infrastructure resilience decisions taken, and whose voices are prioritized? These critical questions necessitate the integration of equity perspectives into the infrastructure resilience discourse.

Equity in infrastructure resilience ensures all community members have equitable access to essential services and infrastructure. In her commentary paper, Cutter[56] examines disaster resilience and vulnerability, challenging the prevalent ambiguity in the definitions of resilience. The paper poses two fundamental questions of *"resilience to what?"* and *"resilience to whom?"*. Later, Meerow and Newell[47] expanded on these questions in the context of urban resilience, *"for whom, what, where, and why?"*. They also stress the need for "resilience politics," which include understanding of how power dynamics shape resilience policies, creating winners and losers[47].

In a nutshell, resilience strategies must proactively address systemic inequities. This can also be framed around the concept of Rawls' Theory of Justice principles, such as equal basic rights and fair equality of opportunity[57,58]. Rawls advocates for structuring social and economic inequalities to benefit the least advantaged members of society. In the context of infrastructure resilience, the theory would ensure vulnerable communities, such as lower-income households, have priority in infrastructure restoration. Incorporating Walker's Theory of Abundant Access, this could also mean prioritizing those most dependent on public transit. Access to public transit, especially in lower-income brackets, allows for greater freedom of movement and connection to other essential facilities in the community like water, food, and health[59,60]. At the same time, Casali et al.[61] show that access to infrastructures alone is not sufficient for urban resilience to emerge. Such perspectives integrate physical and social elements of a community to equitably distribute infrastructure resilience benefits. Table 1 summarizes the selected definitions of resilience.

Definitions of equity

Equity in infrastructure resilience ensures that individuals have the same opportunity and access to infrastructure services regardless of differing demographics, spatial regions, involvement in the community, and internal capacity. Equity is a multifaceted concept that requires precise definitions to thoroughly assess and address it within the scope of infrastructure resilience. Based on the literature, our systematic literature review proposes four definitions of equity for infrastructure resilience: distributional-demographic (D), distributional-spatial (S), procedural (P), and capacity (C). Distributional-demographic (D) equity represents accessibility to and functionality of infrastructure services considering the vulnerability of demographic groups[62]. Distributional-spatial (S) equity focuses on the equitable distribution of infrastructure services to all spatial regions[63]. Procedural (P) equity refers to inclusive participation and transparent planning with stakeholders and community members[31]. Capacity equity (C) connect the supporting infrastructure to the hierarchy of needs which recognizes the specific capacities of households[64].

Table 1 | Selected definitions of the concept of resilience

Source	Definition
Holling[48]	Resilience is the ability of ecosystems to absorb changes and maintain their core functionality
Carpenter et al.[49]	Resilience is the capacity of socioecological to withstand disturbances without transitioning to alternative states
Hipel et al.[53]	Resilience is a property of systems which is crucial in proactively planning for effective responses to natural disasters.
Okada[54]	Resilience is grounded in a broad understanding of sustainability risks and the need for a comprehensive approach that integrates various dimensions of coping capacity, including physical, social, and economic aspects.
Aldrich[51]	Resilience is the ability of a community to withstand and recover from disasters through the enhancement and utilization of its social infrastructure, notably social capital
Cutter[56]	Resilience is conceptualized with a focus on its dynamic aspects rather than as a mere return to a pre-disaster state. It involves enhancing the capacity of various systems—such as social, governance, and economic systems—to cope with, adapt to, and recover from disturbances.
Meerow and Newell[47]	Resilience as a boundary object, which serves to initate multidisciplinary dialog.
Wenar and John Rawls[57]	Resilience is the capacity of systems to absorb disturbances, adapt to pressures, and maintain functionality despite external shocks. It also addresses social vulnerabilities by focusing on how different community populations withstand and recover from environmental and societal challenges.
Hay[55]	Resilience is defined as the ability of infrastructure systems to absorb stress, maintain critical functions, and ensure service continuity during disruptions. It emphasizes adaptability and the maintenance of essential operations beyond mere robustness.
Casali et al.[61]	Resilience is defined as the capacity of urban systems to absorb, adapt, and fundamentally transform in response to disturbances, emphasizing not just recovery but also the proactive enhancement of system sustainability and robustness.

Distributional-demographic (D) addresses the systemic inequities in communities to ensure those of differing demographic status have equitable access to infrastructure services[37]. The purpose is to equitably distribute the burdens and benefits of services by reducing disparity for the most disadvantaged populations[42]. These groups may need greater support due to greater hardship to infrastructure losses, greater dependency on essential services, and disproportionate losses to infrastructure[43,65,66]. In addition, they may have differing abilities and need to mitigate service losses[33]. Our research bases distributional-demographic on age for young children and elderly, employment, education, ethnicity, people with disabilities, gender, income, tenure of residence, marginalized populations based on additional demographic characteristics, intergenerational, and general-social inequities[67].

Distributional-spatial (S) recognizes that the operation and optimizations of the systems may leave certain areas in isolation[68–70]. For example, an equitable access to essential services (EAE) approach to spatial planning can identify these service deserts[46]. Urban and rural dynamics may also influence infrastructure inequities. Rural areas have deficient funding sources compared to urban areas[17] while urban areas may have greater vulnerability due to the interconnectedness of systems[71]. Our research labels distributional-spatial as spatial and urban-rural. Spatial involves spatial areas of extreme vulnerability through spatial regression models, spatial inequity hotspots, and specific mentions of vulnerable areas. Urban-rural references the struggles of urban-rural areas.

Procedural (P) equity ensures the inclusion of everyone in the decision-making process from the collection of data to the influence of policies. According to Rivera[72], inequities in the disaster recovery and reconstruction process originate from procedural vulnerabilities associated with historical and ongoing power relations. The validity of local cultural identities is often overlooked in the participation process of designing infrastructure[73]. Governments and institutions may have excluded certain groups from the conversation to understand, plan, manage, and diminish risk in infrastructure[74]. As argued by Liévanos and Horne[20], such utilitarian bureaucratic decision rules can limit the recognition of unequal services and the development of corrective actions. These biases can be present in governmental policies, maintenance orders, building codes, and distribution of funding[30]. Our research labels procedural equity as stakeholder input and stakeholder engagement. Stakeholder input goes beyond collecting responses from interviews and surveys. Rather, researchers will ask for specific feedback and validation on final research deliverables like models, results, and spatial maps, but they are not included in the research planning process. Stakeholder engagement are instances where participants took an active role in the research deliverables to change elements of their community.

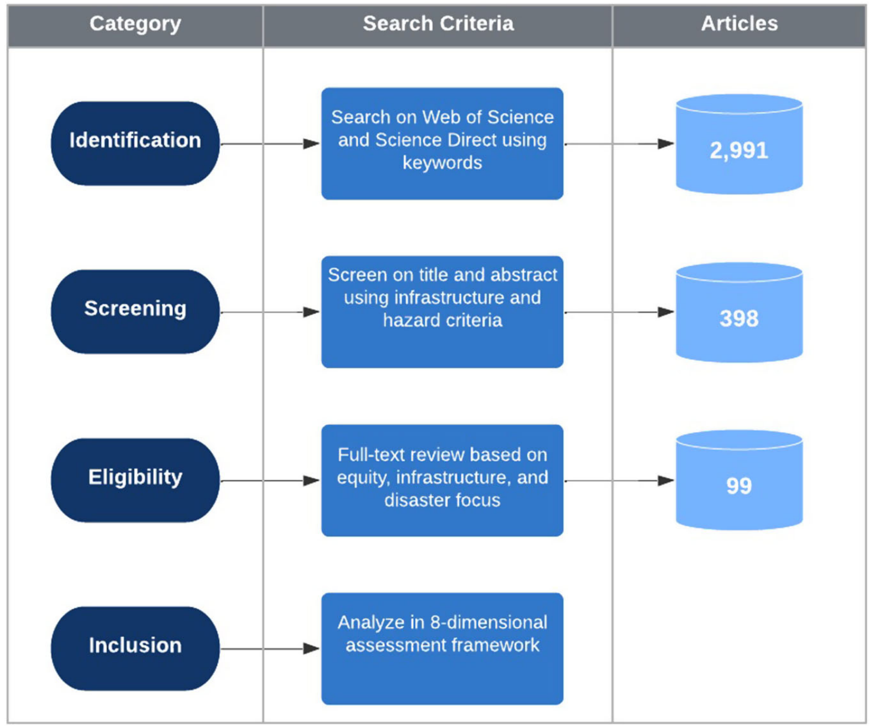
Capacity (C) equity is the ability of individuals, groups, and communities to counteract or mitigate the effect of infrastructure loss. As mentioned by Parsons, et al.[75], equity can be enhanced through a network of adaptive capacities at the household or community level. These adaptive capacities are viewed as an integral part of community resilience[76]. Regarding infrastructure, households can prepare for infrastructure losses and have service substitutes such as power generators or water storage tanks[77,78]. It may also include the household's ability to tolerate disruptions and the ability to perceive risk to infrastructure losses[66]. However, capacity can be limited by people's social connections, social standing, and access to financial resources and personal capital[79]. Our research categorizes capacity equity as adaptations, access, and susceptibility. Adaptations include preparedness strategies before a disaster as well as coping strategies during and after the disaster. Access includes a quantifiable metric in reaching critical resources which may include but is not limited to vehicles, public transportation, or walking. Susceptibility involves a household internal household capability such as tolerance, suffering, unhappiness, and willingness-to-pay models. Although an important aspect of capability, the research did not include social capital since it is outside the scope of research.

Methods of systematic literature review

Our systematic literature review used the Covidence software[80], which is a production tool to make the process of conducting systematic reviews more efficient and streamlined[80]. As a web-based platform, it supports the collaborative management of uploaded journal references and processes journals through 4-step screening and analysis including title and abstract screening, full-text screening, data abstraction, and quality assessment. The software also follows the guidelines of PRIMSA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis), which provides a clear, transparent way for researchers to document their findings[81]. PRIMSA includes a 27-item checklist and 4-phase flow diagram of identification, screening, eligibility, and inclusion. Figure 1 summarizes the PRIMSA method we followed during our review process by showing the search criteria and final selected articles at each stage, including identification, screening, eligibility, and inclusion.

Identification. The search covered Web of Science and Science Direct due to their comprehensive coverage and interdisciplinary sources. To cover a broad set of possible disasters and infrastructures, our search focused on the key areas of equity ("equit- OR fair- OR justice- OR and access-"), infrastructure ("AND infrastructure system- OR service-"),

Fig. 1 | Filtering of systematic literature review generated using PRISMA on COVIDENCE. The figure shows the 4-step screening process of identification, screening, eligibility, and inclusion as well as the specific search criteria for each step. From the initial 2991 articles, 99 articles were selected.



and disasters (" AND hazard- OR, cris- OR, disaster- OR"). We limited our search to journal articles published in engineering, social sciences, and interdisciplinary journals during January 2010 to March 2023. Excluding duplicates, the combined results of the search engines resulted in 2991 articles.

Screening. The articles were screened on their title and abstract. These had to explicitly mention both an infrastructure system (water, transportation, communication, etc.) and natural hazards (tropical cyclone, earthquake, etc.) The specific criteria for infrastructure and natural hazard is found in the 8-dimension framework. This initial screening process yielded 398 articles for full-text review.

Eligibility. The articles were examined based on the extent of discussion in infrastructure, natural hazard, and equity dimension. Insufficient equity discussion means that the paper did not fall within the distributional-demographic, distributional-spatial, procedural, or capacity forms of equity (98). Studies were also excluded for not directly including equity analysis in the infrastructure system (19). Limited infrastructure focus means that the article may have focused on infrastructure outside the scope of the manuscript such as industrial, green, building, or social infrastructure (74). Limited disaster focus means that the article did not connect to the direct or indirect impacts of disasters on infrastructure systems (45). Wrong study design included literature reviews, opinion pieces, policy papers, and unable to access (56). This stage yielded 99 final articles.

Inclusion and assessment framework. To analyze the 99 articles, we designed an 8-dimensional assessment framework (see Fig. 2) to analyze the literature. In Fig. 2, the visualization focuses on equity, infrastructure, and natural hazards since these are the 3 main dimensions of the systematic literature review. The icons on the bottom are the remaining 5 dimensions which add more analysis and context to the first 3 dimensions. Here, we refer to research question 1: what are the prevailing concepts, foci, methods, and theories, in assessing the inequities of disrupted infrastructure services? The framework distinguished the concepts (equity dimensions, infrastructure system, and natural hazard event), foci (geographical scale, geographic location, temporal scale), methods (nature of study and data collection), and theories (theoretical perspective) (Fig. 2). The following details each subquestion:

Equity. *How is equity conceptualized and measured?* First, we label equity into 4 definitions (DPSC). Second, it summarizes the equity conclusions.

Infrastructure type. *Which infrastructure services were most and least commonly studied?* This category is divided into power, water, transportation, communication, health, food, sanitation, stormwater, emergency, and general if a specific infrastructure is not mentioned. Studies can include more than one infrastructure service. Green infrastructure, social infrastructure, building structures, and industrial structures were excluded.

Hazard event type. *Which hazard events are most or least frequently studied?* This category includes flood, tropical cyclone, drought, earthquake, extreme temperature, pandemic, and general if there is no specific hazard. To clarify, tropical cyclones include hurricanes and typhoons while extreme temperatures are coldwaves and heatwaves. It determines which studies are specific to hazards and which can be applied to universal events.

Geographic location. *Which countries have studied equity the most and least?* This category is at the country scale such as the United States, Netherlands, China, and Australia, among others.

Geographic scale. *What geographic unit of scale has been studied to represent equity?* Smaller scales of study can reveal greater insights at the household level while larger scales of study can reveal comparative differences between regional communities. It ranges from individual, local, regional, and country as well as project. To clarify, 'individual' can include survey respondents, households, and stakeholder experts; 'local' is census block groups, census tracts, and ZIP codes equivalent scales; 'regional' is counties, municipalities, and cities equivalent; 'project' refers to studies that focused on specific infrastructure/ construction projects.

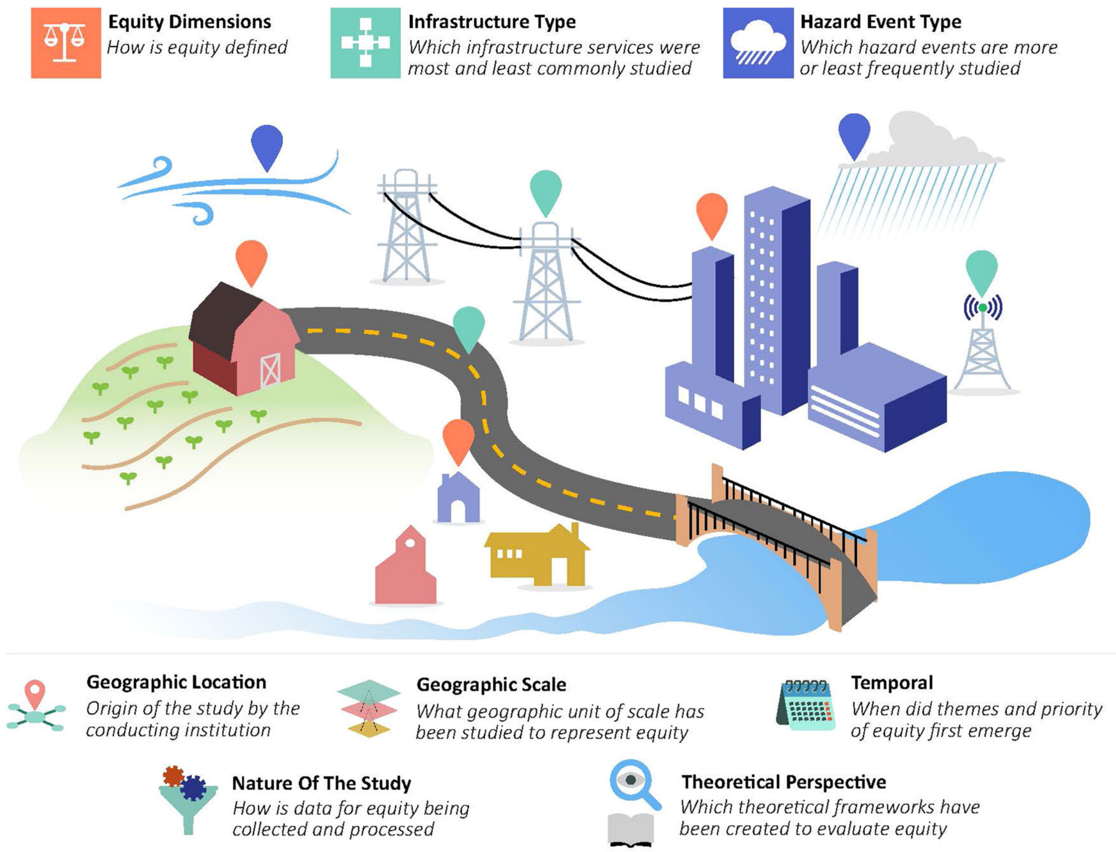


Fig. 2 | 8-dimensional assessment framework evaluating studies related to equity in infrastructure resilience. Equity dimensions, infrastructure type, and hazard event type are the main 3 dimensions while geographical location, geographic scale, temporal, nature of the study, and theoretical perspectives are the remaining 5 dimensions which add more information and context.

Temporal scale. *When did themes and priority of equity first emerge?* This category determines when equity in infrastructure research is published and whether these trends are increasing, decreasing, or constant.

Nature of the study. *How is data for equity being collected and processed?* This category analyzed data types used including conceptual, descriptive, open-data, location-intelligence, and simulation data. To clarify, conceptual refers to purely conceptual frameworks or hypothetical datasets; descriptive refers to surveys, questionnaires, interviews, or field observations performed by the researcher; open-data refers to any open-data source that is easily and freely attainable such as census and flood data; location-intelligence refers to social media, human mobility, satellite and aerial images, visit data, and GIS layers; and finally, simulation data can be developed through simulation models like numerical software, Monte-Carlo, or percolation methods. Second, the data can be processed through quantitative or qualitative methods. Quantitative methods may include correlation, principal component analysis, and spatial regression while qualitative methods may include validation, thematic coding, participatory rural appraisal, and citizen science. We focused on analysis explicitly mentioned in the manuscript. For example, it can be assumed that studies of linear regression discussed correlation analysis and other descriptive statistics in their data processing.

Theoretical perspective. *Which theoretical frameworks have been created and used to evaluate equity?* This category summarizes the reasoning behind the theoretical frameworks which may have informal or formal names such as a service-gap model, well-being approach, and capability approach.

Results

Based on the 8-dimensional assessment framework, the research first examines the spatiotemporal patterns as well as data and methods to evaluate equity. Then, it investigates the definitions of equity to the intersections with infrastructure and hazards. It concludes with a discussion of theoretical frameworks. We use the term "pathways" to identify how equity is constructed, analyzed, and used in relation to the 8-dimensional framework. For instance, the connection between equity and infrastructure is considered a pathway. By defining specific "pathways," we are essentially mapping out the routes through which equity interacts with various dimensions of a framework, such as infrastructure. The following analysis directly addresses research question 1 (prevailing concepts, focuses, methods, and theories, in assessing the inequities of disrupted infrastructure services) and research question 2 (similar and different pathways of equity). Supplementary Figures 1A–12A provide additional context to the research findings and can be found in the Supplementary Information.

Spatiotemporal patterns of equity

Overall, there is an increasing number of publications about equity in infrastructure management (Fig. 3). A slight decrease observed in 2021 could be because of the focus on COVID-19 research. Spatially, by far the most studies focus on the US (69), followed by India (3), Ghana (3), and Bangladesh (3) (Fig. 5). This surprising distribution seems to contradict the intuition that equity and fairness in infrastructure resilience are certainly global phenonmena. Besides the exact phrasing of the search term, this result can be explained by the focus of this review on the intersection of infrastructure resilience and inequity. For infrastructure resilience, prominent reports, such as the CDRI's 2023 Global Infrastructure Resilience Report[82] still fail to address it. Even though research has called for increasing consideration of equity and distributive justice in infrastructure and risk assessment, inequity is still all too often viewed as a social and economic risk[83]. At the same time, persistent imbalances in terms of data availability have been shown to shift research interest to the US, especially for data

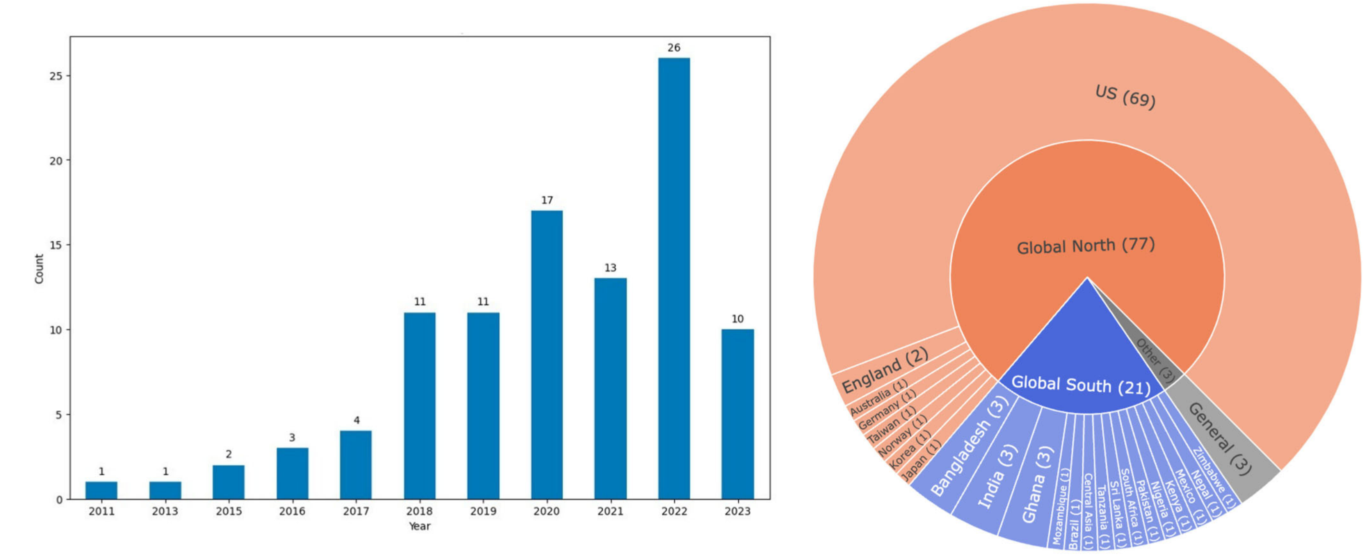


Fig. 3 | Publishing frequency and spatial distribution of selected articles of equity in infrastructure resilience. The bar graph shows an overall increasing from 2011 to 2023 in publications about equity in infrastructure resilience during natural hazard events. The pie chart shows that countries in the global north with United States (US), England, Australia, Germany, Taiwan, Norway, South Korea, and Japan and global south with Bangladesh, India, Ghana, Mexico, Mozambique, Brazil, Tanzania, Sri Lanka, Pakistan, Nigeria, Kenya, Nepal, Zimbabwe, Central Asia, and South Africa.

intense studies on urban infrastructures[84]. Finally, efforts to mainstream of equity and fairness across all infrastructures as a part of major transitions may explain why equity discussion is less pronounced in the context of crises. For instance, in Europe, according to the EU climate act (Article 9(1))[85], all sectors need to be enabled and empowered to make the transition to a climate-resilient society *fair* and *equitable*.

Data and methods to interpret equity

Our Sankey diagram (Fig. 4) sketches the distribution of data collection pathways which connects quantitative-qualitative data to data type to scale. Most studies start from quantitative data (120) with fewer using mixed (34) or qualitative (18) data. Quantitative studies use descriptive (58), open-data (50) location-intelligence (36), simulation (19), and conceptual (9). The most prominent spatial scale was local (66) which consisted of census tract, census block group, zip code, and equivalent spatial scale of analysis. This was followed by individual or household scale (64) which largely stems from descriptive data of interviews, surveys, and field observations. Within the context of infrastructure, equity, and hazards, non-US studies did not use human mobility data, a specific type of location-intelligence data. This could be due to limitations in data availability and different security restrictions to these researchers such as the European Union's General Data Protection Regulation[86]. Increasingly, the application of location-intelligence data was used to supplement the understanding of service disruptions. For example, satellite information[87], telemetry-based data[37], and human mobility data[88] were used to evaluate the equitable restoration of power systems and access to critical facilities. Social media quantified public emotions to disruptions[89,90].

As shown in Fig. 5, there are distinct quantitative and qualitative methods to interpret equity. Most quantitative methods were focused on descriptive analysis and linear models which can assume simple relationships within equity dimensions. Simple relationships would assume that dependent variables have a straightforward relationship with independent variables. Regarding quantitative analysis, descriptive statistics were correlation (12), chi-square (6), and analysis of variance (ANOVA) (5) means. Spatial analysis included geographic information system (GIS) (15), Moran's-I spatial autocorrelation (6), and spatial-regression (5). Variables were also grouped together through principal component analysis (PCA) (9) and Index-Weighting (9). Logit models (13) and Monte-Carlo simulations (7) were used to analyze data. Thus, more complex models are needed to uncover the underlying mechanisms associated with equity in infrastructure. In analyzing quantitative data, most research has focused on using descriptive statistics, linear models, and Moran's I statistic which have been effective in pinpointing areas with heightened physical and social vulnerability[25,91,92].

However, there has been a less frequent yet insightful use of advanced techniques like machine learning, agent-based modeling, and simulation. For example, Esmalian, et al.[66] employed agent-based modeling to explore how social demographic characteristics impact responses to power outages during Hurricane Harvey. In a similar vein, Baeza, et al.[93] utilized agent-based modeling to evaluate the trade-offs among three distinct infrastructure investment policies: prioritizing high-social-pressure neighborhoods, creating new access in under-served areas, and refurbishing aged infrastructure. Simulation models have been instrumental in understanding access to critical services like water[43], health care[92], and transportation[33]. Beyond these practical models, conceptual studies have also contributed innovative methods. Notably, Clark, et al.[94] proposed gravity-weighted models, and Kim and Sutley[30] explored the use of genetic algorithms to measure the accessibility to critical resources. These diverse methodologies indicate a growing sophistication in the field, embracing a range of analytical tools to address the complexities of infrastructure resilience.

Regarding qualitative analysis, the methods included thematic coding (7), validation of stakeholders (9), sentiment (4), citizen science (5), conceptual analysis (3) participatory rural appraisal (2), document analysis (2), participatory assessment (1), photovoice (1), and ethnographic (1). Qualitative methods were used to capture diverse angles of equity, offering a depth and context not provided by quantitative data alone. These methods are effective in understanding capacity equity, such as unexpected strategies and coping mechanisms that would go otherwise unnoticed[95]. Qualitative research can also capture the perspectives and voices of stakeholders through procedural equity. Interviews and focus groups can validate and enhance research frameworks[96]. Working collaboratively with stakeholders, as shown with Masterson et al.[97] can lead to positive community changes in updated planning policies. Qualitative methods can narratively convey the personal hardships of infrastructure losses[98]. This approach recognizes that infrastructure issues are not just technical problems but also deeply intertwined with social, economic, and cultural dimensions.

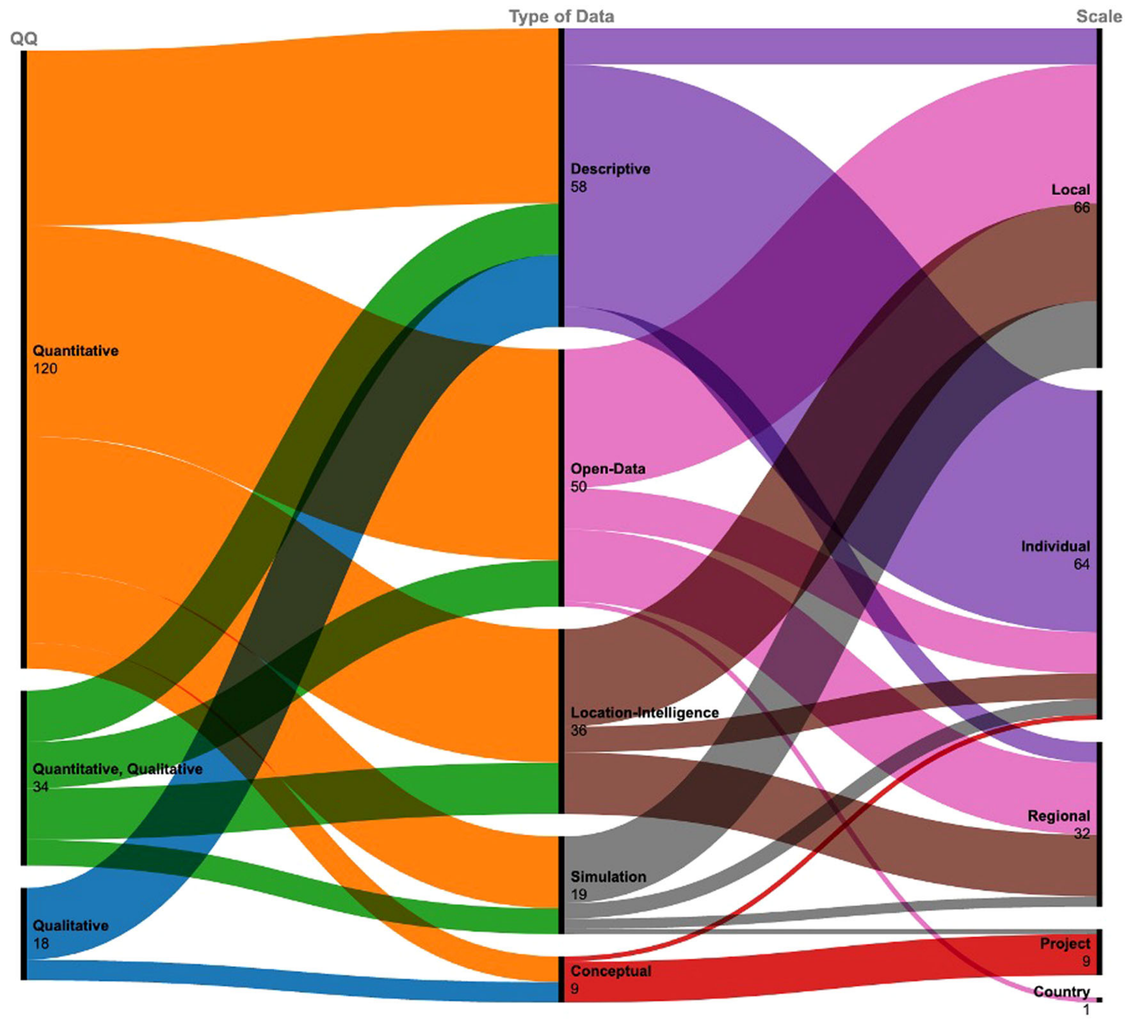


Fig. 4 | Pathways of quantitative-qualitative data, type of data and spatial scale to assess equity in infrastructure resilience. The Sankey diagram shows the flow from studies containing quantitative, qualitative, or quantitative–qualitative data to the specific type of data of descriptive, open-data, location-intelligence, simulation, and conceptual to spatial scale of data of local, individual, regional, country, and project.

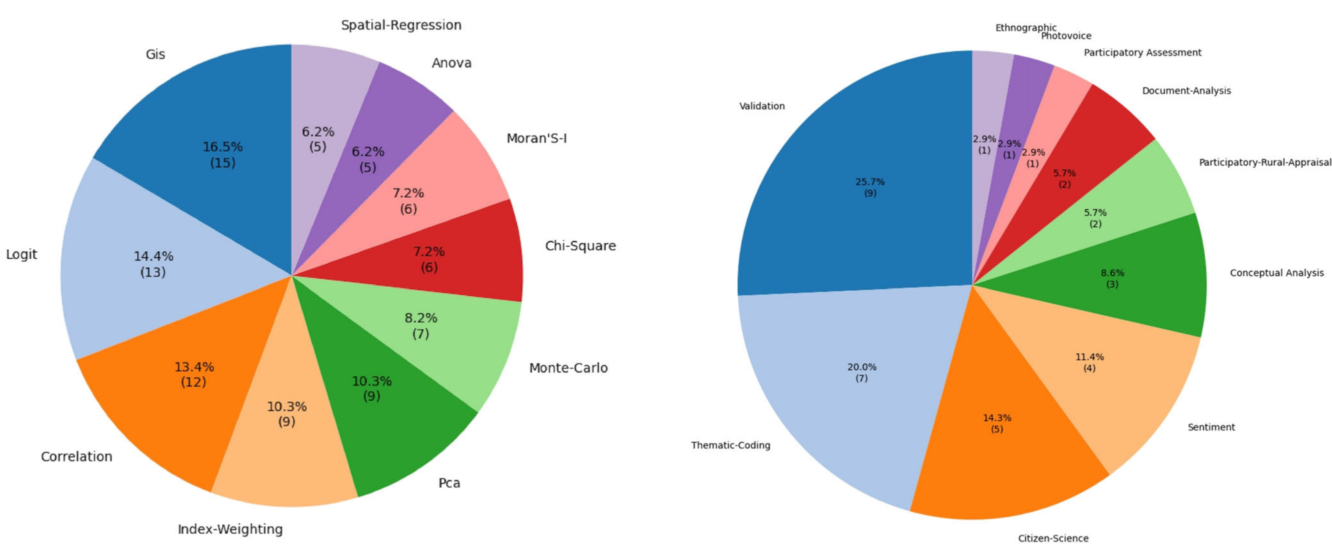


Fig. 5 | Percentage of the top ten types of quantitative and qualitative methods to evaluate equity in infrastructure resilience. The quantitative pie chart has geographic information system (GIS), logit model, correlation, index-weighting, principal component analysis (PCA), monte-carlo simulation, chi-square, Moran's-*I* spatial autocorrelation, analysis of variance (ANOVA), and spatial regression. The qualitative pie chart has validation, thematic coding, citizen science, sentiment analysis, conceptual analysis, participatory rural appraisal, document analysis, participatory assessment, photovoice, and ethnographic.

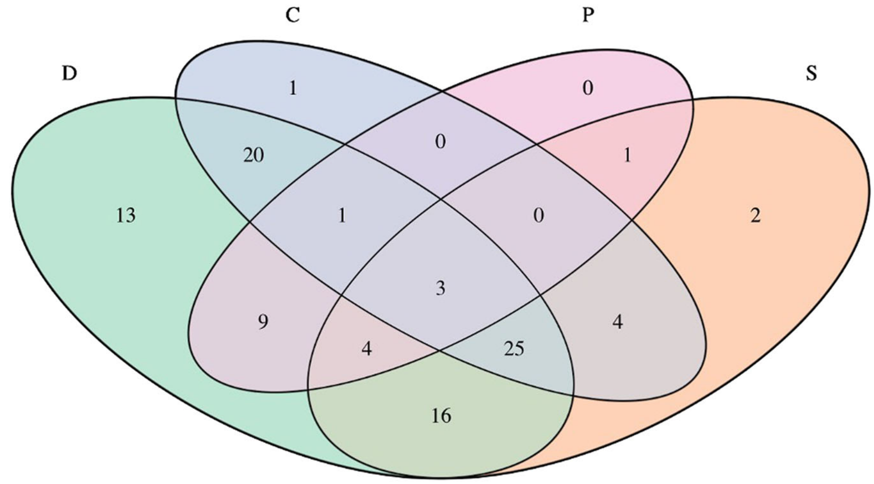


Fig. 6 | Linkages between distributional-demographic, distributional-spatial, procedural, and capacity (DSPC) dimensions of equity. Distributional-demographic had the highest number of studies and the greatest overlap with the remaining equity definitions of capacity, procedural, and distributional-spatial. Only 3 studies overlapped with the four equity definitions.

Table 2 | Frequency of sociodemographic variables for distributional-demographic equity

Distributional-Demographic	P	W	T	F	H	ST	C	SW	E	G	Total
Income	34	30	23	16	18	9	7	5	3	3	148
Ethnicity	31	17	19	16	14	5	7	1	2	3	115
Age	29	23	21	15	14	6	6	4	2	2	122
Disability	18	13	14	10	7	4	5	2	-		73
Tenure	14	14	8	9	8	4	4	2	-		63
Education	14	18	12	9	10	8	5	3	1	1	81
Gender	13	18	6	7	7	4	3	2	1	2	63
Employment	9	6	7	2	6	2	1	1	-	1	35
Marginalized	-	3	-	2	-	-	-	-	-		5
Intergenerational	-	-	-	-	-	-	-	-	-	1	1
General-social	3	5	2	2	2	1	-	3	-	4	22
Total	165	147	112	88	86	43	38	23	9	17	728

Interlinkages of equity definitions

As shown in Fig. 6, the frequency of type of equity was distributional-demographic (90), distributional-spatial (55), capacity (54), and procedural (16). It is notable to reflect on the intersections between the four definitions of equity. Between two linkages, the top three linkages between DC (20), DS (16), and DP (9), which all revealed a connection to distributional-demographic equity. There were comparatively fewer studies linking 3 dimensions except for DSC which had 25 connections. Only 3 studies had 4 connections.

Distributional-demographic equity was the most studied equity definition. Table 2 shows how pathways of demographic equity relate to the different infrastructure systems and variables within distributional-demographic, including 728 unique pathways. As a reminder, pathways explore equity across an 8-dimensional framework. In this case, the distributional-demographic equity is connected to infrastructure, treating these connections as pathways Pathways with power (165), water (147), and transportation (112) were the most frequent while those with stormwater (23) and emergency (9) services were the least frequent. Referencing demographics, the most pathways were income (148), ethnicity (115), and age (122) while least studied were gender (63), employment (35), marginalized populations (5) and intergenerational (1). Note the abbreviations for Tables 2 and 3 are power (P), water (W), transportation (T), food (F), health (H), sanitation (ST), communication (C), stormwater (SW), emergency (E), and general (G). Regarding distributional-demographic, several research papers showed that lower income and minority households were most studied in comparison to the other demographic variables. Lower-income and minority households faced greater exposure, more hardship, and less tolerance to withstand power, water, transportation, and communication outages during Hurricane Harvey[99]. These findings were replicated in disasters such as Hurricane Florence, Hurricane Michael, COVID-19 pandemic, Winter Storm Uri, and Hurricane Hermine, respectively[65,91,100,101]. Several studies found that demographic vulnerabilities are interconnected and compounding, and often, distributional-demographic equity is a pre-existing inequality condition that is exacerbated by disaster impact[102]. For instance, Stough, et al.[98] identified that respondents with disabilities faced increased struggles due to a lack of resources to access proper healthcare and transportation after Hurricane Katrina. Women were often overburdened by infrastructure loss as they were expected to "pick up the pieces," and substitute the missing service[103,104]. Fewer studies involved indigenous populations, young children, or considered future generations. Using citizen-science methods, Ahmed, et al.[105] studied the struggles and coping strategies of the Santal indigenous group to respond to water losses in drought conditions. Studies normally did not account for the direct infrastructure losses on children and instead concentrated on the impacts on their caretakers[106]; however, this is likely due to restrictions surrounding research with children. Lee and Ellingwood[107] discussed how, "intergenerational discounting makes it possible to allocate costs and benefits more equitably between the current and future generations" (pg.51) A slight difference in discounting rate can lead to vastly different consequences and benefits for future generations. For example, the study found that insufficient investments in design and planning will only increase the cost and burden of infrastructure maintenance and replacement.

Table 3 | Frequency of variables in distributional-spatial, procedural, and capacity equity

Distributional- Spatial	P	W	T	F	H	ST	C	SW	E	G	Total
Spatial Clusters	20	8	19	10	13	4	3	3	2	1	83
Urban-Rural	7	8	3	2	2	2	-	1	-	1	26
Total	27	16	22	12	15	6	3	4	2	2	109
Procedural	**P**	**W**	**T**	**F**	**H**	**ST**	**C**	**SW**	**E**	**G**	**Total**
Stakeholder Input	1	7	3	1	3	2	-	2	-	1	20
Stakeholder Engagement	-	1	-	-	-	-	-	4	-	1	6
Total	1	8	3	1	3	2	-	6	-	2	26
Capacity	**P**	**W**	**T**	**F**	**H**	**ST**	**C**	**SW**	**E**	**G**	**Total**
Adaptation	12	15	5	7	6	4	2	1	-	2	54
Access	3	4	10	11	10	2	2	-	-	1	43
Susceptibility	14	8	10	4	5	3	4	1	2	2	53
Total	29	27	25	22	21	9	8	2	2	5	150

Distributional-spatial equity was the second most studied aspect, which includes spatial grouping and urban-rural designation, particularly given the rise of open-data and location-intelligence data with spatial information. Table 3 shows the pathways of spatial equity connected to different infrastructures and variables. In total, 109 unique pathways were found with spatial (83) and urban-rural (26) characteristics. Power (27), transportation (22), water (16), and health (15) systems were the most frequent pathways with stormwater (4), emergency (2), and communication (3) the least frequent. Urban-rural studies on communication and emergency services are entirely missing. Distributional-spatial equity studies, including spatial inequities and urban-rural dynamics, were often linked with distributional-demographic equity. For example, Logan and Guikema[46] defined "access rich" and "access poor" to measure different sociodemographic populations' access to essential facilities. White populations had less distance to travel to open supermarkets and service stations in North Carolina[46]. Esmalian et al.[108] found that higher income areas had a lower number of stores in their areas, but they still had better access to grocery stores in Harris County, Texas. This could be because higher income areas live in residential areas, but they have the capability to travel further distances and visit more stores. Vulnerable communities could even be indirectly impacted by spatial spillover effects from neighboring areas[26]. Regarding urban-rural struggles, Pandey et al.[17] argued that inequities emerge when urban infrastructure growth lags with respect to the urban population while rural areas face infrastructure deficits. Rural municipalities had fewer resources, longer restoration times, and less institutional support to mitigate infrastructure losses[95,109,110].

Capacity was the third most studied dimension and had 150 unique pathways to adaptations (54), access (43), and susceptibility (53). In connecting to infrastructure systems, power (29), water (27), transportation (25), and food (22) had the greatest number of pathways. There were interesting connections between different infrastructures and variables of capacity. Access was most connected to food (11), transportation (10), and health systems (10). Adaptations were most connected to water (15) and power (12) systems. This highlights how capacity equity is reflected differently to infrastructure losses. Capacity equity was often connected with distributional-equity since different sociodemographic groups have varying adaptations to infrastructure losses[78]. For example, Chakalian, et al.[106] found that white respondents were 2.5 more likely to own a power generator while Kohlitz et al.[95] found that poorer households could not afford rainwater harvesting systems. These behaviors may also include tolerating infrastructure disruptions[111], cutting back on current resources[112], or having an increased suffering[113]. The capabilities approach offers a valuable perspective on access to infrastructure services[94]. It recognizes the additional time and financial resources that certain groups may need to access the same level of services, especially if travel networks are disrupted[114,115] and travel time is extended[33]. In rural regions, women, children, and lower income households often reported traveling further distances for resources[105,116]. These disparities are often influenced by socioeconomic factors, emphasizing the need for a nuanced understanding on how different communities are affected by and respond to infrastructure losses. As such, building capacity is not just increasing the preparedness of households but also accommodating infrastructure systems to ensure equitable access, such as the optimization of facility locations[69].

Procedural was the least studied equity definition with only 26 unique pathways, involving stakeholder input and stakeholder engagement. Pathways to communication and emergency systems were not available. The greatest number of pathways were water services to stakeholder input (7) and stormwater services to stakeholder engagement (4). Stakeholder input can assist researchers in validating and improving their research deliverables. This approach democratizes the decision-making process and enhances the quality and relevance of research and planning outcomes. For instance, the involvement of local experts and residents in Tanzania through a Delphi process led to the development of a more accurate and locally relevant social resilience measurement tool[117]. Stakeholder engagement, such as citizen science methods, can incorporate environmental justice communities into the planning process, educate engineers and scientists, and collect reliable data which can be actively incorporated back to the community[118–120]. Such participatory approaches, including citizen science, allow for a deeper understanding of community needs and challenges. In Houston, TX, the success of engaging high school students in assessing drainage infrastructure exemplified how community involvement can yield significant, practical data[119]. The data was approximately 74% accurate to trained inspectors, which were promising results for communities assessing their infrastructure resilience[119]. In a blend of research and practice, Masterson, et al.[97] illustrated the practical application of procedural equity. By interweaving equity in their policy planning, Rockport, TX planners added accessible services and upgrades to infrastructure for lower-income and racial-ethnic minority neighborhoods, directly benefiting underserved communities.

Pathways between equity, hazard, and infrastructure

For the hazards, tropical cyclones (34.6%) and floods (30.8%) make up over half of the studied hazards (Supplementary Figure 2A) while power (21.2%), water (19.2%), transportation (15.4%), and health (12.0%) were the most frequently studied infrastructure services (Supplementary Figure 3A). A pathway is used to connect equity to different dimensions of the framework, in this case, equity to infrastructure to hazard (Fig. 7). When considering

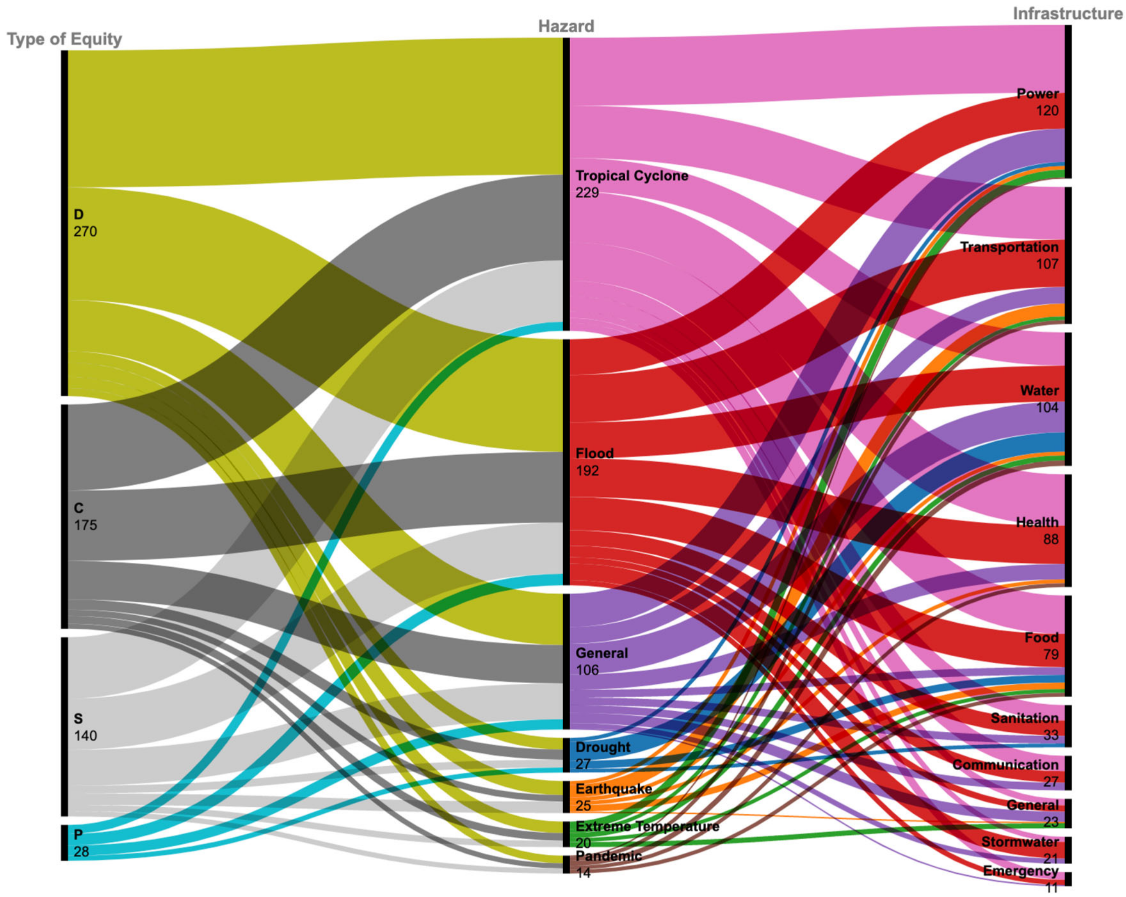


Fig. 7 | Pathways between type of equity, hazard, and infrastructure. The Sankey diagram shows the flow from the different types of equity, or equity definitions, of distributional-demographic (D), capacity (C), distributional-spatial (S), and procedural (P) to hazard of tropical cyclone, flood, general, drought, earthquake, extreme temperature, and pandemic to infrastructure of power, transportation, water, health, food, communication, general, stormwater, emergency, and sanitation.

these pathways, distributional-demographic (270) had the most pathways followed by capacity (175), distributional-spatial (140), and procedural (28). The most common pathway across all infrastructure services was a tropical cyclone and flooding with distributional-demographic equity (Supplementary Figures 6A–8A). As shown in Fig. 7, tropical cyclone (229) and flood (192) had the most pathways while extreme temperatures (20) and pandemic (14) had the least. Although pandemic is seemingly the least studied, it is important to note that most of these studies were post COVID-19. Power (120), transportation (107), and water (104) had the most pathways whereas sanitation (33), communication (27), stormwater (21), and emergency (14) had the least pathways. The figure shows specific gaps in the literature. Whereas the other three equity definitions had connections to each hazard event, procedural equity only had connections to tropical cyclone, flood, general, and drought. There were only pathways from health infrastructure to tropical cyclone, flood, general, earthquake, and pandemic. There were 106 pathways connecting equity to general hazards, which may suggest the need to look at the impacts of specific hazards to equity in infrastructure resilience.

Research frameworks

Regarding research question 2, this research aims to understand frameworks of equity in infrastructure resilience. As an exploration of the frameworks. we found common focus areas of adaptations, access, vulnerability, validation, and welfare economics (Table 4). The full list of frameworks can be found in the online database that was uploaded in DesignSafe Data Depot. Supplementary Information.

Adaptations. Household adaptations included the ability to prepare before a disaster as well as coping strategies during and after the disaster. Esmalian et al.[111] developed a service gap model based on survey data of residents affected by Hurricane Harvey. Lower-income households were less likely to own power generators, which could lead to an inability to withstand power outages[111]. To understand household adaptations, Abbou et al.[78] asked residents of Los Angeles, California about their experiences in electrical and water losses. The study showed that when compared to men, women used more candles and flashlights. People with higher education, regardless of gender, were more likely to use power generators. In a Pressure and Release model, Daramola et al.[112] examined the level of preparedness to natural hazards in Nigeria. The study found that rural residents tended to use rechargeable lamps while urban areas used generators, likely due to the limited availability of electricity systems. Approximately 73% of participants relied on chemist shops to cope with constrained access to health facilities.

Access. Other frameworks focused on the accessibility to resources. Clark et al.[94] developed the social burden concept which uses resources, conversion factors, capabilities, and functioning into a travel cost method to access critical resources. In an integrated physical-social vulnerability model, Dong et al.[92] calculated disrupted access to hospitals in Harris County, Texas. Logan and Guikema[46] integrated spatial planning, diverse vulnerabilities, and community needs into EAE services. In the case study of Willimgton, North Carolina, they showed how lower-income households had fewer access to grocery stores. In a predictive recovery monitoring spatial model, Patrascu and Mostafavi[26] found that the percentage

Table 4 | Summary of theoretical frameworks as it relates to infrastructure, hazard, and equity

Citation	Framework	Infrastructure	Hazard	Equity	Focus Areas
Clark et al.[94]	Social Burden Metric	General	Tropical Cyclone, Extreme Temperature	DC	Access
Dong et al.[92]	Integrated Physical-Social Vulnerability Assessment	Health	Tropical Cyclone, Flood	DSC	Access
Logan and Guikema[46]	Equitable Access to Essential Services	Food, Health, Power, Water, Sanitation, Communication	Tropical Cyclone	DSC	Access
Patrascu and Mostafavi[26]	Predictive Recovery Monitoring	Food, Health	Tropical Cyclone, Flood	DSC	Access
Blondin[115]	Sheller's Mobility Justice Perspective	Transportation, Health, Food	Flood	DSC	Access
Esmalian et al.[111]	Service Gap Model	Power	Tropical Cyclone	DSC	Adaptation
Abbou et al.[78]	Household Adaptations	Water, Power, Communication	General	DC	Adaptation
Daramola et al.[112]	Pressure and Release Model	Water, Power, Health	General	DSC	Adaptation
Dominelli[103]	Gendered-Caring	General	Extreme Temperature	DC	Adaptation
Atallah et al.[36]	ABCD Roadmap	Health	General	DP	Validation
Hsieh and Feng[122]	DEMATEL	Transportation, Health	General	DSP	Validation
Sweya et al.[117]	Social Resilience Tool	Water	Flood	DSPC	Validation
Toland et al.[43]	Community Vulnerability Assessment	Power, Water, Transportation, Food	Earthquake	DS	Vulnerability
Coleman et al.[65]	Anatomy of Susceptibility	Water, Transportation, Power, Health, Food, Sanitation	Tropical Cyclone Flood	DC	Vulnerability
Oswald Beiler and Mohammed[121]	Transportation Justice Threshold Index Framework	Transportation	Flood	DS	Vulnerability
Esmalian et al.[25]	Disruption Tolerance Index	Power, Transportation	Tropical Cyclone, Flood	DSC	Vulnerability
Esmalian et al.[66]	Human-Hazard Nexus	Power	Tropical Cyclone, Flood	DC	Vulnerability
Millington[41]	Willingness to pay	Water	Drought	DSC	Welfare economics
Ulak et al.[126]	Prescriptive resilience model	Power	Tropical Cyclone	D	Welfare economics
Stock et al.[125]	Willingness to pay and unhappiness models	Water, Power	General	DC	Welfare economics
Baeza et al.[93]	Governance scenarios	Water, sanitation	General	DSP	Welfare economics
Lee & Ellingwood[107]	Intergenerational Discounting	General	Earthquake	D	Welfare economics
Wang et al.[123]	Willingness to pay	Transportation	Flood, Tropical Cyclone	DC	Welfare economics
Islam et al.[124]	Willingness to pay	Water	Tropical Cyclone	DC	Welfare economics

of Black and Asian subpopulations were significant features to predict recovery of population activity, or the visits to essential services in a community.

Vulnerability. Several of the infrastructure resilience frameworks were grounded in social vulnerability assessments. For instance, Toland et al.[43] created a community vulnerability assessment based on an earthquake scenario that resulted in the need for emergency food and water resources. Using GIS, Oswald and Mohammed developed a transportation justice threshold index that integrated social vulnerability into transportation understanding[121]. In a Disruption Tolerance Index, Esmalian et al.[25] showed how demographic variables are connected with disproportionate losses in power and transportation losses.

Validation. Additional studies were based on stakeholder input and expert opinion. Atallah et al.[36] established an ABCD roadmap for health services which included acute life-saving services, basic institutional aspects for low-resource settings, community-driven health initiatives, and disease specific interventions. Health experts were instrumental in providing feedback for the ABCD roadmap. Another example is the development of the social resilience tool for water systems validated by experts and community residents by Sweya et al.[117]. To assess highway resilience, Hsieh and Feng had transportation experts score 9 factors including resident population, income, employment, connectivity, dependency ratio, distance to hospital, number of substitutive links, delay time in substitutions, and average degenerated level of services[122].

Welfare economics. Willingness-to-pay (WTP) models reveal varied household investments in infrastructure resilience. Wang et al.[123] showed a wide WTP range, from \$15 to \$50 for those unaffected by disruptions to \$120–\$775 for affected, politically liberal individuals. Islam et al.[124] found households with limited access to safe drinking water were more inclined to pay for resilient water infrastructure. Stock et al.[125] observed that higher-income households showed greater WTP for power and transportation resilience, likely due to more disposable income and expectations for service quality. These findings highlight the need to consider economic constraints in WTP studies to avoid misinterpreting lower income as lower willingness to invest. Indeed, if a study does not adequately account for a person's economic constraints, the findings may incorrectly interpret a lower ability to pay as a lower willingness to pay.

In terms of policy evaluation for infrastructure resilience, studies like Ulak et al.[126] prioritized equitable power system recovery for different ethnic groups, favoring network renewal over increasing response crews. Baeza et al.[93] noted that infrastructure decisions are often swayed by political factors rather than technical criteria. Furthermore, Lee and Ellingwood[107] introduced a method for intergenerational discounting in civil infrastructure, suggesting more conservative designs for longer service lives to benefit future generations. These studies underscore the complex factors influencing infrastructure resilience policy, including equity, political influence, and long-term planning.

Synthesis

This systematic review is the first to explore how equity is incorporated into infrastructure resilience against natural hazards. By systematically analyzing the existing literature and identifying key gaps, the paper enhances our understanding of equity in this field and outlines clear directions for future research. This study is crucial for understanding the fundamental knowledge that brings social equity to the forefront of infrastructure resilience. Table 5 summarizes the primary findings of this systematic review of equity in infrastructure resilience literature, including what the studies are currently focusing on and the research gaps and limitations.

Discussion

Our findings show a great diversity of frameworks and methods depending on the context, in which equity is applied (Table 5). Moreover, we identify a lack of integrative formal and analytical tools. Therefore, a clear and standard framework is needed to operationalize inequity across infrastructures and hazards; what is missing are analytical tools and approaches to integrate equity assessment into decision-making.

Referring to question 3, we will further explore the current gaps of knowledge and future challenges of studying equity in infrastructure resilience. In elaborating on the gaps identified in our review, we propose that the next era of research questions and objectives should be (1) monitoring equity performance with improved data, (2) weaving equity in computational models, and (3) integrating equity into decision-making tools. Through principles of innovation, accountability, and knowledge, such objectives would be guided by moving beyond distributional equity, recognizing understudied gaps of equity, and inclusion of all geographic regions, and by extension stakeholders (Fig. 8).

The first research direction is the monitoring equity performance with improved data at more granular scales and greater representation of impacted communities. Increased data availability provides researchers, stakeholders, and community residents with more detailed and accurate assessment of infrastructure losses. Many studies have used reliable, yet inherently approximate data sources, for infrastructure service outages. These sources include human mobility, satellite, points-of-interest visitation, and telemetry-based data (such as refs. 69,100). Private companies are often reluctant to share utility and outage data with researchers[127]. Thus, we encourage the shift towards transparent and open datasets from utility companies in normal times and outage events. This aligns with open-data initiatives such as Open Infrastructure Outage Data Initiative Nationwide (ODIN)[128], Invest in Open Infrastructure[129], and Implementing Act on a list of High-Value Datasets[130]. Transparency in data fosters an environment of accountability and innovation to uphold equity standards in infrastructure resilience[131]. An essential aspect of this transparency involves acknowledging and addressing biases that may render certain groups 'invisible' within datasets. These digitally invisible populations may well be among the most vulnerable, such as unhoused people that may not have a digital footprint yet are very vulnerable to extreme weather[132]. Gender serves as a poignant example of such invisibility. Historical biases and societal norms often result in gender disparities being perpetuated in various facets of infrastructure design and resilience planning[133]. Women are frequently placed in roles of caregiving responsibilities, such as traveling to reach water (as shown in refs. 105,116,134) or concern over the well-being of family members (as shown in refs. 103,135), which have been overlooked or marginalized in infrastructure planning processes.

If instances of social disparities are uncovered, researchers and practitioners could collaboratively cultivate evidence-based recommendations to manage infrastructure resilience. At the same time, approaches for responsible data management need to be developed that protect privacy of individuals, especially marginalized and vulnerable groups[136]. There is a trade-off between proper representation of demographic groups and ensuring the privacy of individuals[45,67]. Despite this, very few studies call into question the fairness of the data collection in capturing the multifaceted aspects of equity[137], or the potential risks to communities as described in the EU's forthcoming Artificial Intelligence Act[138].

By extension, addressing the problem of *digitally invisible populations* and possible bias, Gharaibeh et al.[120] also emphasizes that equitable data should represent *all* communities in the study area. Choices about data collection and storage can directly impact the management of public services, by extension the management of critical information[139]. For example, a significant problem with location-intelligence data collection is properly representing digitally invisible populations as these groups are often marginalized in the digital space leading to gaps in data[132,140]. Human mobility data, a specific type of location-intelligence data derived from cell phone pinpoint data, illustrates this issue. Vulnerable groups may not afford or have frequent access to cell phones, resulting in a skewed understanding of population movements[141]. However, other studies have shown that digital platforms can be empowering for marginalized populations to express sentiments of cultural identity and tragedies through active sharing and communication[142]. Ultimately, Hendricks et al.[118] recommend a "triangulation of data sources," to integrate quantitative and qualitative data, which would mitigate potential data misrepresentation and take advantage of the online information. Moving ahead, approaches need to be developed for fair, privacy-preserving, and unbiased data collection that empowers especially vulnerable communities. At the same time, realizing that data gaps especially in infrastructure-poor regions may not be easy to address, we also follow Casali et al.[84] in calling for synthetic approaches and models that work on sparse data.

Few studies, such as refs. 45,66, have created computational models to capture equity-infrastructure-hazards interactions, which are initial

Table 5 | Summary of the major focuses and gaps of equity literature

Dimension	Majority Focus	Research Gaps & Limitations
Geographic Location	• United States	• non-US Countries, particularly in the Global South
Geographic Scale	• Individual and local scales	• Cross-regional and country comparisons
Temporal	• Increasing trend of publications • Identified several timescales that integrate with disaster management cycle	• Vagueness in the researched methods in applying to different timescales
Nature of the Study	• Open-data and descriptive data • Descriptive statistics and linear regression	• Simulated and location-intelligence • Agent-based modeling, gravity network, generative modeling
Hazard Event Type	• Flooding and tropical cyclone	• Wildfire
Equity Dimension	• Distributional-demographic and distributional-spatial	• Procedural
Infrastructure Type	• Power, water, and transportation	• Stormwater, emergency, and sanitation
Research Perspective	• Evidence for social and spatial inequities • Conceptualization of access	• Analytical tools to integrate equity • Development of decision-making tools

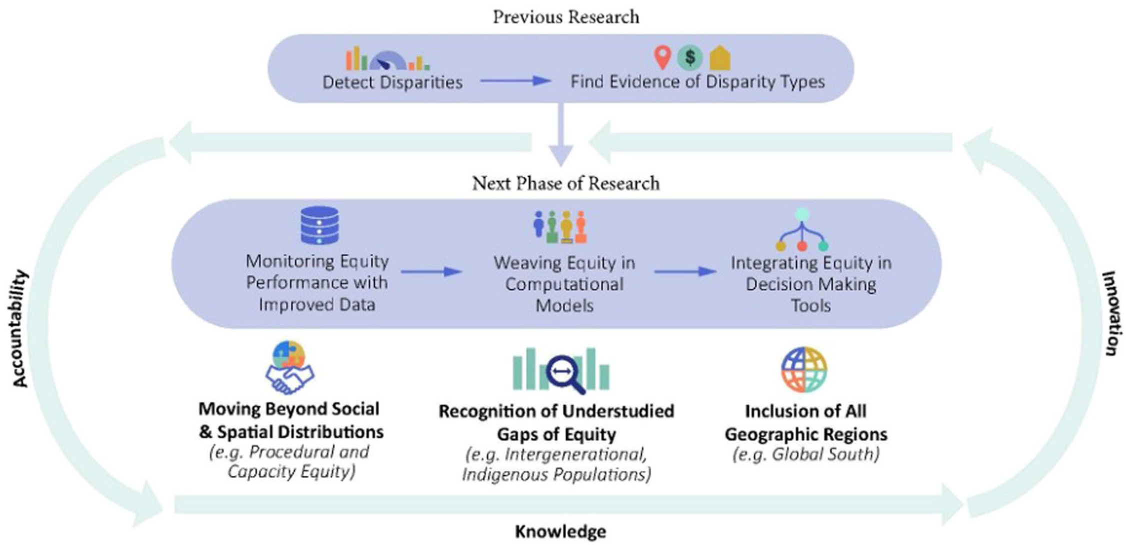


Fig. 8 | Future directions to guide research in equity of resilient infrastructure management. The figure demonstrates that previous research has focused on detecting and finding evidence of disparity in infrastructure resilience in hazard events. It supports that the next phase of research will monitor equity performance with improved data, weave equity in computational models, and integrate equity in decision making tools in order to move beyond social and spatial distributions, recognize understudied gaps of equity, and include all geographic regions.

attempts to quantify both the social impacts and the physical performance of infrastructure. This is echoed in the work of Soden et al.[143] which found only ~28% of studies undertake a quantitative evaluation of differential impacts experienced in disasters. To enhance analytical and computational methods in supporting equitable decision-making, it is imperative for future studies to comprehensively integrate social dimensions of infrastructure resilience. Therefore, the next research direction is the intentional weaving of equity in computational models. Where the majority of studies used descriptive statistics and non-linear modeling, complex computational models—such as agent-based simulations—offer the advantage of capturing the nonlinear interactions of equity in infrastructure systems. These tools also allow decision-makers to gain insights into the emergence of complex patterns over time. These simulation models can then be combined with specific metrics that measure infrastructural or social implications. Metrics might include susceptibility curves[144], social burden costs estimates[94], or social resilience assessment[76]. Novel metrics for assessing adaptive strategies, human behaviors, and disproportionate impacts (such as[113]) could also be further quantified through empirical deprivation costs for infrastructure losses[145]. These metrics also are a stepping-stone for formalizing and integrating equity into decision-making tools.

Another research direction is the integration of equity into decision-making tools. Key performance indicators and monitoring systems are essential for clarifying equity processes and outcomes and creating tangible tools for infrastructure planners, managers, engineers, and policy-makers. In particular, the literature discussed the potential for using equity in infrastructure resilience to direct infrastructure investments (such as refs. 93,126,146). Infrastructure resilience requires significant upfront investment and resource allocations, which generally favors wealthier communities. Communities may hold social, cultural, and environmental values that are not properly quantified in infrastructure resilience[147]. Since traditional standards of cost-benefit analyses used by infrastructure managers and operators primarily focus on monetary gains or losses, they would not favorably support significant investments to mitigate the human impacts of infrastructure losses on those most vulnerable[148]. This limitation also delays investments and leads to inaction in infrastructure resilience, resulting in unnecessary loss of services and social harm, potentially amplifying inequities, and furthering societal fragmentation. To bridge this gap, we propose to measure the social costs of infrastructure service disruptions as a way to determine the broad benefits of resilience investments[147].

As the literature review found, several studies are following a welfare economics approach to quantify social costs associated with infrastructure losses such as the evaluation of policies (such as ref. 93) and willingness-to-pay models (such as ref. 125). Such economic functions are preliminary steps in quantifying equity as a cost measure; however, these models must avoid misinterpreting lower income as a lower willingness to invest. Lee and Ellingwood[107] proposed using intergenerational discounting rate; however, it is important to recognize the flexibility of options for future generations[149]. Teodoro et al.[149] points to the challenges of using (fixed) discount rates and advocate for a procedural justice-based approach that maximizes flexibility and adaptability. Further research is needed to quantify the social costs of infrastructure disruptions and integrate them into infrastructure resilience assessments, such as calculating the deprivation costs of service losses for vulnerable populations.

Our review shows that certain demographic groups such as indigenous populations, persons with disabilities, and intergenerational equity issues have not been sufficiently studied[150]. This aligns with the conclusions of Seyedrezaei et al.[151], who found that the majority of studies about equity in the built-environment focused on lower-income and minority households. Indigenous populations face significant geographical, cultural, and linguistic barriers that make their experiences with disrupted infrastructure services distinct from those of the broader population[152].

Even though intergenerational justice issues have increasingly sparked attention on the climate change discussion, intergenerational equity issues in infrastructure resilience assessments have received limited attention. We argue that intergenerational equity warrants special attention as infrastructure systems have long life cycles that span across multiple generations, and ultimately the decisions on the finance, restoration, and new construction will have a significant impact on the ability of future generations to withstand the impact of stronger climate hazard events. Non-action may lead to tremendous costs in the long run[149]. It is the responsibility of current research to understand the long-term effects of equity in infrastructure management to mitigate future losses and maintain the flexibility of future generations. As a means of procedural justice, these generations should have the space to make choices, instead of being locked in by today's decisions. Future studies should develop methods to measure and integrate intergenerational inequity in infrastructure resilience assessments.

Given the specific search criteria and focus on equity, infrastructure, and natural hazard, we found a major geographic focus on the United States. Large portions of the global north and global south were not included in the analysis. This could be due to the search criteria of the literature review; however, it is important to recognize potential geographic areas that are isolated from the academic studies on infrastructure resilience. Different infrastructure challenges (e.g., intermittent services) are present through data availability in the region. A dearth of studies on equitable infrastructure resilience could contribute to greater inequity in those regions due to the absence of empirical evidence and proper methodological solutions. This aligns with other findings on sustainable development goals and climate adaptation broadly[153]. Global research efforts, along with common data platforms, standards and methods (see above), that include international collaborations among researchers across the global north and global south regions can bridge this gap and expand the breadth of knowledge and solutions for equitable infrastructure resilience.

Finally, while significant attention has been paid to distributional demographic and spatial inequity issues[151], there remain several underutilized definitions of equity. Procedural and capacity equity hold the greatest potential for people to feel more included in the infrastructure resilience process. Instead of depending directly on the infrastructure systems, individual households can adapt to disrupted periods through substituted services and alternative actions (such as ref. 78). To advance procedural equity in infrastructure resilience, citizen-science research or participatory studies can begin by empowering locals to understand and monitor their resilience (such as ref. 76) or failures in their infrastructure systems (such as ref. 120). As referenced by Masterson and Cooper[154], the ladder of citizen power can serve as a framework for how to ethically engage with community partners for procedural equity. The ladder, originally developed by Arnstein[155], includes non-participation, tokenism, and citizen power. Table 3 shows that most research falls into non-participation: survey data and information are extracted without any community guidance. Limited studies that have branched into community involvement still stay restricted in the tokenism step, such as models that are validated by stakeholders or receive expert opinions on their conceptual models. Future studies should expand inquiries regarding the procedural and capacity dimension of equity in infrastructure resilience assessments and management. For instance, research could map out where inequities occur in the decision-making process and targeted spatial regions as well as allocate of resources for infrastructure resilience. It could also continue pursuing inclusive methodologies such as participatory action research and co-design processes. It should investigate effective methods to genuinely integrate different stakeholders and community members from conception through evaluation of research.

Conclusion

Although the primary audience of the literature review is academic scholars and fellow researchers, the identified gaps are of importance for practitioners, governmental agencies, community organizations, and advocates. By harnessing the transformative power of equity, studies in infrastructure resilience can transcend its traditional role and develop equity-focused data, modeling, and decision-making tools which considers everyone in the community. The integration of equity aspects within the framework of infrastructure resilience not only enhances the resilience of infrastructure systems but also contributes to the creation of inclusive and resilient communities. Infrastructure resilience would not just be a shield against adversity but also a catalyst for positive social and environmental change.

Data availability

The created excel database which includes information on the key parts of the 8-dimensional equity framework will be uploaded to DesignSafe-CI.

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Author contributions

All authors critically revised the manuscript, gave final approval for publication, and agree to be held accountable for the work performed therein. N.C. was the lead Ph.D. student researcher and first author, who was responsible for guiding data collection, performing the main part of the analysis, interpreting the significant results, and writing most of the manuscript. X.L. was responsible for guiding data collection, figure creations, and assisting in the manuscript. T.C. and A.M. were the faculty advisors for the project and provided critical feedback on the literature review development, analysis and manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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