LIFELINE
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Review

# Urban lifeline resilience under compound hazards: A review on the cascading failures and systemic risk

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**ABSTRACT:** Core infrastructure systems like water, electricity, transport, and communication are fundamental to modern cities, supporting vital services and everyday societal operations. However, their resilience is increasingly threatened by the occurrence and severity of compound hazards, such as floods that occurs concurrently with power system outages. These risks increase systemic risks that go far beyond the original source of disruption and frequently cause cascade failures throughout interconnected networks. With an emphasis on the dynamics of interdependencies and cascading consequences, this study investigates the resilience of urban lifeline networks under compound hazard situations. To capture the multi-layered vulnerabilities of lifeline systems, the study combines functional dependencies, performance indicators, and hazard scenarios using a network-based modelling technique. The results demonstrate how interruptions in one industry may quickly spread to others, worsening service outages and impairing emergency response capabilities. Key resilience measures—robustness, redundancy, and recovery time—are evaluated to identify vulnerable nodes and routes under compound hazards. The paper also explores mitigation strategies such as advanced monitoring, decentralized energy systems, and adaptive infrastructure design. By linking hazard modelling with resilience assessment, the study advances knowledge and offers practical insights for policymakers and engineers to strengthen urban lifeline resilience. This review uniquely synthesizes recent advances in understanding the interdependencies and cascading dynamics of urban lifeline systems exposed to compound hazards. It provides a comprehensive framework that integrates systemic risk concepts with resilience assessment approaches, offering new insights for urban resilience research and practice. This review contributes to the current body of knowledge by synthesizing existing research on cascading failures and systemic risks affecting urban lifeline systems under compound hazards, and by proposing a conceptual framework to enhance urban resilience planning and risk-informed decision-making.

**KEYWORDS:** Urban lifelines; resilience; compound hazards; cascading failures; systemic risk; critical infrastructure

## 1 Introduction

The fundamental infrastructure that keeps cities functioning and sustains daily social and economic activity is made up of urban lifeline systems, such as water, power, transportation, communication networks, and healthcare. High levels of interconnection and complexity define these systems, and when one service is disrupted, it frequently has instantaneous effects on other services. Power outages, for example, can impair emergency response efforts, paralyse transportation networks, and halt water pumping systems. The dependability of these vital networks becomes more important as cities get denser and more linked, not just to support day-to-day urban life but also to guarantee safety, security, and well-being in time of stress[1-5]. Urban lifeline systems are extremely susceptible to compound hazards, which are situations in which social, technical, and natural threats overlap and interact, notwithstanding their significance. Floods, heat waves, and storms are examples of climate-induced extremes that might occur concurrently with technical malfunctions or cyberattacks, increasing systemic hazards. These risks almost never happen alone; instead, they frequently have cascading impacts throughout networks of infrastructure. For instance, a coastal storm surge might cause disproportionate social and financial losses by flooding transit corridors, upsetting healthcare facilities, and damaging electricity infrastructure all at once. The increasing occurrence and severity of these compound catastrophes highlight the critical need to comprehend how systemic vulnerabilities spread and how lifeline systems function under stress[6-9]. Enhancing urban resilience requires research on systemic risk and cascade failures in vital systems. Conventional risk assessment methods frequently ignore the feedback loops and nonlinear dynamics that cause systemic crises by treating infrastructures and hazards in silos. A systemic risk approach, on the other hand, emphasises how little disturbances may develop into major accidents, endangering the ability of entire urban areas to withstand shocks. To mitigate these risks, governance frameworks that encourage collaboration across industries and scales are just as important as technological solutions like

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redundancy, robustness, and intelligent monitoring. This assessment is situated within the framework of compound hazards, with an emphasis on how cascading failures occur, how risks may be predicted, and what tactics might strengthen urban lifeline systems against upcoming disruptions[10-13].

Emerging risks from compound hazards arise when multiple stressors interact in ways that amplify their impacts on urban lifeline systems. Compound risks, as opposed to single-event disruptions, consist of the sequential or simultaneous occurrence of several shocks that result in nonlinear and frequently unpredictable effects, such as an earthquake causing technology mishaps or a heatwave occurring concurrently with drought. Rapid urbanisation, changing climates, and growing digital connectedness all increase these risks by opening new avenues for disruptions to proliferate. For this reason, standard hazard-by-hazard studies are no longer sufficient to understand the collapse of lifeline systems under compound dangers; instead, a systemic approach that considers their complex and dynamic character is necessary[14-17]. The impact of compound hazards on lifeline systems is sometimes greater than the initial accidents due to cascade failures across linked networks. For instance, flooding that obstructs roads can cause delays in emergency response, while electrical system damage at the same time jeopardises communication and hospital operations. Public safety, economic stability, and social cohesiveness are all at danger due to secondary crises brought on by these interdependencies, which intensify hazards and spread their reach beyond the immediate hazard zone[15,18,19]. An additional layer of risk is introduced by our increasing reliance on digital infrastructure, where systemic disruptions can be amplified by cyberattacks or ICT malfunctions that coexist with physical threats. The significant level of ambiguity around the probability, interactions, and long-term effects of emergent risks resulting from compound hazards is one of their distinguishing characteristics. It is challenging to simulate the behaviour of concurrent or cascading events or create effective resilience tactics due to a lack of previous data[8,20]. Furthermore, most current frameworks for infrastructure planning and catastrophe risk reduction are still compartmentalised, concentrating on specific sectors or risks, and as a result, they fail to consider systemic vulnerabilities across lifeline systems. Policymakers, engineers, and urban planners are unable to foresee problems and take preventative action because of these information gaps. A greater comprehension of compound hazards, their systemic effects, and resilience tactics that go beyond conventional single-hazard techniques are necessary to meet this issue[7,21].

If one element of an urban lifeline system is disrupted, it might lead to the failure of other linked services. This behaviour is known as cascading failures. These failures, which start with a localised shock like a substation outage, a ruptured pipeline, or a flooded transport corridor, spread quickly due to closely linked dependencies. For instance, a power outage may paralyse transportation, shut down communication networks, and immobilise water treatment facilities, all of which increase the scope and length of disruptions. Small beginning disruptions can turn into city-wide disasters in cascading failures, which are distinguished from isolated failures by their nonlinearity and disproportionate effects[22-24]. The possibility that small-scale disturbances might turn into major systemic failures that jeopardise the stability of whole urban areas is known as systemic risk. Interdependencies, resource limitations, and the lack of redundancy in key services all increase systemic risk in lifeline systems. For example, concurrent failures in the digital and electricity infrastructures might jeopardise emergency response and healthcare service, undermining social stability and public trust. The analytical focus is shifted from individual hazards or sectors to comprehending how interconnected infrastructures collectively absorb, transmit, or amplify shocks under compound hazards when systemic risk is recognised. The advancement of urban resilience under compound hazards requires the adoption of a cascading failure and systemic risk approach[25,26]. While resilience in linked urban ecosystems necessitates taking cross-sectoral interconnections and feedback loops into account, traditional engineering techniques frequently place an emphasis on robustness within individual systems. Researchers and practitioners may more accurately predict how disruptions spread, pinpoint crucial points of vulnerability, and create treatments that lessen their consequences by approaching lifeline resilience through the perspective of systemic risk. To stop localised shocks from turning into systemic crises, this viewpoint not only guides technical methods like redundancy and adaptable design, but it also emphasises the necessity of integrated governance and coordination across infrastructure sectors[27-29]

Even though urban resilience is receiving more attention, there are still a lot of unanswered questions about how compound hazards and cascade failures interact to create systemic risks for vital systems. Current research frequently ignores the cross-sectoral interdependencies and nonlinear dynamics that intensify disruptions in favour of concentrating on risks or infrastructure sectors. Additionally, frameworks for assessing resilience that consider both governance issues and physical vulnerabilities in multi-hazard situations are not well integrated. This analysis attempts to fill up these gaps by offering a thorough synthesis of how urban lifeline systems' cascading failures are caused by compound hazards and how resilience design may be influenced by a systemic risk approach. The study intends to identify research gaps in the existing frameworks for resilience assessment, synthesise the literature on cascading failures and systemic risks in urban lifeline systems under compound hazards, and suggest a conceptual model that combines infrastructure interdependencies with hazard interactions. The three specific objectives are to: (i) map the current understanding of compound hazards and their effects on interconnected lifeline infrastructures; (ii) critically assess current frameworks and methodologies for analysing systemic risks and cascading failures; and (iii) identify new approaches, innovations, and policy directions that can improve the resilience of urban lifelines in complex and changing risk environments. This explanation demonstrates how the article enhances both theoretical knowledge and useful tactics for enhancing urban resilience.

## 2 Literature review

### 2.1 Resilience concepts in critical infrastructure

Critical infrastructure resilience is now a multifaceted framework that includes flexibility, recovery, and transformation, rather than an engineering-centric emphasis on robustness. Resilience was first mainly described as an infrastructure's capacity to endure shocks and recover to its initial state. Resilience—that is, the ability to withstand setbacks, adjust to shifting circumstances, and adjust operations in response to persistent difficulties—has been added to the idea as understanding of the complexity and interconnection of urban lifeline systems has grown. In the literature, resilience is frequently conceived in terms of four interconnected dimensions: rapidity (speed of recovery), resourcefulness (ability to mobilise and coordinate resources under stress), redundancy (availability of backup systems or alternative pathways), and robustness (resistance to initial disruption)[30-32]. Since most research still concentrate on single-hazard settings or sector-specific disruptions, these dimensions offer a helpful lens for examining how infrastructures react to shocks, but their application under compound hazards is still restricted. In critical infrastructure, resilience is increasingly seen as a socio-technical capability that extends beyond technical characteristics to include governance, policy, and community involvement[15,23]. Research on urban lifeline systems emphasises that institutional frameworks, decision-making procedures, and cross-sector collaboration influence resilience just as much as technology innovation and physical design. For instance, smart grids and hardened assets are only two characteristics of resilient power systems; other characteristics include regulatory frameworks that facilitate quick resource reallocation and renewable energy integration. Resilient water systems also depend on demand-management strategies that lessen shock susceptibility, modular treatment plants, and supply diversity[33-35]. Dynamic resilience measures that measure infrastructure performance over time while taking systemic interdependencies and cascading consequences into account under compound hazards are crucial, according to recent research. Few studies, however, completely include these viewpoints, exposing a lack of comprehensive frameworks that connect resilience principles to cascading failure analysis and systemic risk in complex urban contexts[29,36,37].

## 2.2 Previous studies on single vs. compound hazards

Historically, a large portion of the research on infrastructure resilience has focused on isolated and single-hazard scenarios, such as earthquakes, floods, hurricanes, or cyberattacks[38-40]. These studies have been helpful in expanding technical understanding of vulnerabilities related to certain hazards, such as flood risk models for water networks, seismic fragility curves for bridges, or reliability evaluations of power grids during severe weather conditions. Robust procedures for assessing the cost-benefit trade-offs of preventive measures, calculating downtime, and modelling physical damage have been established via engineering approaches[41,42]. Since risks are treated separately, these studies frequently understate the actual magnitude and dynamics of risk in intricate metropolitan settings, where infrastructures are rarely subjected to a single danger at a time. Thus, the single-hazard paradigm has come under growing fire for failing to account for interdependencies among vital systems and oversimplifying risk assessments[43,44]. Urban lifeline systems are often vulnerable to compound hazards, when many shocks or pressures interact either sequentially or concurrently, as has been increasingly apparent in recent years. The way that environmental, technical, and social factors combine to increase dangers beyond the sum of their individual components is highlighted by studies on compound hazards. Hurricane-induced floods, for example, can result in power outages, chemical spills, and public health emergencies, while heatwaves that coincide with droughts can put a strain on water supply systems and electrical grids at the same time. Compound hazards are more complicated to foresee and control than single hazards because they produce nonlinear consequences and cascade failures[45,46]. To capture interdependencies, this new body of work has started to integrate probabilistic modelling, network theory, and scenario-based analyses; yet, it is still dispersed across disciplines and has not yet reached a consensus on common frameworks or approaches[47,48]. Despite advancements, there are still few studies comparing single and compound dangers in the context of lifeline systems. Many resilience evaluations are still based on compartmentalised methods, which offers little insight into how resilience tactics that work well for individual risks could operate poorly or not at all in complex situations. For example, redundancy systems designed to survive floods may not work well when coupled with power outages or supply-chain disruptions. Furthermore, there is disagreement on how to systematically evaluate cascading effects across sectors under compound scenarios, and which resilience indicators are most suited for these types of assessments[44,49]. The necessity for integrative reviews that summarise current research, point out methodological flaws, and provide frameworks that specifically take into consideration the dynamics of compound hazards and systemic risks in urban lifeline resilience is highlighted by this gap (as shown in Table 1).

**Table 1 Comparison of single-hazard vs. compound-hazard studies in lifeline resilience research.**

| Dimension | Single-hazard studies | Compound-hazard studies |
|---|---|---|
| Focus | Individual hazard types (e.g., earthquake, flood, hurricane, cyber-attack)[50,51]. | Interactions of multiple hazards (e.g., flood + power outage, heatwave + drought, storm + chemical spill)[52,53]. |
| Approach | Hazard-specific vulnerability and fragility analysis; deterministic or probabilistic models[54,55]. | Scenario-based modeling, network theory, multi-risk frameworks, probabilistic compounding approaches[56,57]. |
| Strength | Provides detailed understanding of infrastructure response to specific hazards; well-established engineering models[32,58]. | Captures nonlinear effects, cascading failures, and cross-sector interdependencies; reflects real-world risk complexity[59,60]. |
| Limitation | Treats hazards in isolation; underestimates systemic risk; limited applicability under multi-hazard conditions[51,54]. | Methodologies remain fragmented; limited empirical data; high uncertainty in modeling interactions[61,62]. |
| Relevance to systemic risk | Often overlooks cascading impacts and interdependencies[63,64]. | Explicitly considers systemic vulnerabilities and amplification of risks across lifeline systems[16,65]. |
| Application to resilience planning | Useful for hazard-specific protection and mitigation strategies[66,67]. | Informs integrated resilience strategies, cross-sector coordination, and governance under complex risk landscapes[68,69]. |

## 2.3 Interdependency in lifeline networks

Urban lifeline systems are intricately linked, and the efficiency of one system frequently relies on the effectiveness of others. These interdependencies fall into one of four categories: logical, geographic, cyber, or physical. When one facility directly depends on another to function, such as when water pumping stations need electricity from the power grid, this is known as physical interdependency. Digital control and communication systems give rise to cyber interdependencies, since operational oversight of transportation, water, and energy systems can be jeopardised by ICT network failures. When a natural disaster, such an earthquake or flood, strikes several adjacent infrastructures at the same time, it creates spatial co-location and geographic interdependencies[70-73]. Coordinated emergency response procedures between hospitals and transportation networks are an example of a logical interdependency that reflects functional or policy-driven interactions. Since failures can spread along several paths, enhancing the effects of even localised disturbances, it is imperative to comprehend these varied interdependencies. The frequency and intensity of cascading failures, which raise systemic risk, are greatly influenced by interdependencies both within and between vital networks. Dependent systems may have partial or complete service outages when one infrastructure fails, setting off a domino effect that may extend across industries and geographical regions. For instance, a power outage might simultaneously impair healthcare services, stop public transit, and cripple water treatment facilities[74-76].

Literature demonstrates that, in the case of catastrophic events, the likelihood of simultaneous failures increases, making highly linked networks especially susceptible to compound hazards. These interdependencies must therefore be specifically taken into consideration in resilience assessments. To do this, critical nodes, possible failure pathways, and intervention points that can lessen systemic vulnerability and cascading effects must be identified using network modelling, scenario analysis, and system-of-systems approaches[52,75]. The interdependence of the power network, communication, and transportation systems is depicted in Figure 1, where each system's seamless operation is dependent upon the others. Although this dependency improves coordination and overall efficiency, it also makes everyone more vulnerable since a disturbance in one system might have a cascading effect on the others. Consequently, these interrelated risks must be taken into consideration in any successful resilience planning.

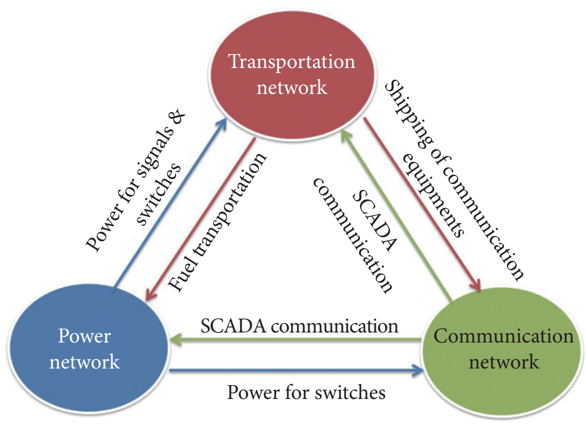


**Fig. 1 Interdependency among power, communication, and transport systems.** Reproduced with permission from Ref. [77], © IOS Press 2014.

• Existing resilience assessment frameworks

The functioning of vital infrastructure under risks has been assessed using a variety of resilience evaluation methodologies. The engineering resilience of physical systems—their robustness, redundancy, and recovery after single-event disruptions—is a common topic of traditional paradigms. Network reliability models, system dynamics simulations that measure downtime, damage, and repair expenses, and fragility-based risk assessments are a few examples. These methods offer important insights into infrastructure vulnerability and mitigation techniques, but they are usually sector-specific and frequently overlook feedback loops, cross-sector interdependencies, and the cascading effects that are typical of complex urban setups[28,78,79]. The integration of multi-hazard and systemic viewpoints has been tried in more recent frameworks, acknowledging that metropolitan lifeline systems are subject to interrelated risks and compound hazards. Interdependencies and cascading failures across many sectors can be simulated by researchers using network theory frameworks, agent-based models, and system-of-systems techniques. The use of probabilistic and scenario-based modelling approaches is growing to reflect nonlinear system responses, dynamic hazard interactions, and uncertainty[51,80,81]. By evaluating not just the infrastructures' immediate robustness but also their adaptive capability, recovery trajectory, and potential to change in response to long-term stresses, these frameworks further highlight the temporal dimension of resilience.

The current frameworks for assessing resilience still have a lot of shortcomings, notwithstanding these improvements. Standardised measures for assessing systemic risk under compound threats or evaluating resilience across various lifeline systems are still lacking in many techniques. Socio-technical elements that might affect infrastructure performance in times of crisis, such as governance, policy coordination, and community reaction, are rarely included in frameworks and empirical validation is frequently lacking. Additionally, there is no advice on how to convert resilience evaluations into practical plans for decision-makers, especially in urban settings with a lot of uncertainty and many interdependencies. These inadequacies highlight the necessity of integrative frameworks that integrate systemic risk assessment, multi-hazard analysis, and useful recommendations for enhancing urban lifeline resilience in the face of compound hazards[82,29,83].

## 3 Methodology

The qualitative synthesis method used in this study is organised around a clear, three-step literature search and screening procedure that guarantees academic rigour and repeatability. A wide range of multidisciplinary evidence, including engineering, urban studies, environmental science, catastrophe risk management, and policy analysis, was captured by the technique.

### 3.1 Database search

Scopus was used for the primary literature search because of its extensive coverage of peer-reviewed research in the social sciences, engineering, and environmental sciences. To cover the range of research on compound hazards, cascade failures, and systemic risks in urban lifeline systems, the search method used keywords and Boolean operators. Keywords like "urban lifeline," "critical infrastructure," "compound hazards," "cascading failures," "systemic risk," "urban resilience," "infrastructure interdependencies," and "disaster risk reduction" were among the main search phrases. To guarantee both historical depth and current relevance, the search was limited to English-language journal papers published between 2000 and 2024. This resulted in 2,964 initial entries. Complementary searches were conducted using the Summon discovery engine (Summon, 2024) to incorporate grey literature, such as technical studies, urban resilience policy documents, and publications from international organisations, to expand the body of evidence. Relevance was carefully assessed for each grey source.

### 3.2 Screening and selection

Explicit inclusion and exclusion criteria were used in the screening process. Studies had to (1) consider lifeline systems (such as energy, water, transportation, communications, and health) in urban settings, (2) specifically look at the effects of single or compound hazards, and (3) offer conceptual, empirical, or modeling-based insights into interdependencies, cascading failures, or systemic risks to be included. Studies that only addressed rural infrastructure, risks with no systemic urban repercussions, or merely technical engineering evaluations that were not integrated with risk or resilience frameworks were filtered out by exclusion criteria. The dataset was whittled down to 164 articles and documents after filtering by title and abstract.

### 3.3 Quality appraisal and full-text review

A systematic quality assessment was conducted in the last phase to assess methodological clarity, scope relevance, and the extent to which each study advanced our knowledge of compound dangers and cascade failures. The only studies that were kept were those that provided empirical evidence, intellectual depth, or insights into applied policy. 93 full-text articles and reports made up the final sample consequently. Hazard types (such as flood-heatwave interactions, earthquake-tsunami sequences, and storm-infrastructure failures), lifeline domains (such as electricity, water, transportation, communications, and healthcare), and resilience dimensions (technical, institutional, or social) were used to methodically classify each source. This classification made it easier to draw comparisons between developed and developing urban settings. The summary offered in this paper was made possible by the analysis, which identified important patterns, prevalent weaknesses, and emerging tactics.

## 4 Results and discussion

### 4.1 Analysis

#### *4.1.1 System performance under single hazard conditions*

Urban lifeline systems in industrialised cities tend to be more resilient and recover more quickly from single hazard scenarios than those in developing ones. Redundancies, real-time monitoring, and adaptable design standards are frequently incorporated into water, electricity, and transportation infrastructures in high-income areas. These features enable systems to withstand shocks with little to no cascade effects. For instance, to minimise widespread blackouts following localised storm damage, modern power systems in regions of North America and Europe usually immediately redirect electricity. Similarly, water companies that have modular pumping stations and sophisticated leak detection systems may continue to provide service even after failures brought on by earthquakes or floods. These actions demonstrate the availability of technical capability to carry out quick, focused recovery as well as long-term investment in hazard-specific readiness[47,84-86]. However, in many developing cities, especially those in South Asia and Sub-Saharan Africa, lifeline systems continue to be extremely vulnerable to the same single hazard circumstances. Even minor disruptions have a greater impact when there are limited financial resources, poor preventative maintenance, and outdated or unofficial infrastructure. When a badly maintained pumping station is flooded, for example, large metropolitan areas may be left without drinkable water for weeks. In the same way, power distribution networks frequently lack redundancy; if one substation fails during a storm, it might lead to prolonged outages over the whole city[12,87,88]. Furthermore, restoration efforts are often delayed by institutional bottlenecks and fragmented administration, which exacerbates socioeconomic disparities because poor populations endure the longest service interruptions. These dynamics highlight how, in developing countries, discrete risks become systemic stresses when there are insufficient safety margins[89,90].

Comparative data also shows that performance under single dangers is a governance and inclusion issue as well as an engineering one. Recovery plans in industrialised cities are frequently supported by social safety nets that protect the most vulnerable populations during interruptions and well-coordinated emergency procedures. On the other hand, households in developing cities, especially those in informal settlements, are more likely to experience disproportionate hardships such tainted water supplies, extended power outages, or limited mobility during floods. These differences show a growing resilience gap: developing cities often face risks as systemic crises, whereas wealthier cities handle individual hazards as brief disruptions. Understanding why compound hazards have disproportionately severe cascading repercussions in urban systems with less resources is based on this difference[91-94].

#### *4.1.2 Compound hazard impacts on lifeline networks*

Situations involving compound hazards, which go well beyond the scope of single-hazard preparedness, test the resilience of urban lifeline systems. Even while industrialised cities frequently have well-resourced infrastructures, established redundancies may nevertheless be overwhelmed by the interaction and simultaneity of hazards, revealing hidden interdependencies and cascading vulnerabilities. In contrast, low redundancy, poor institutional coordination, and resource limitations exacerbate compound risks in developing cities, leading to larger resilience gaps. In this study, interdependency failures that cause cascading disruptions across multiple lifeline sectors are referred to as systemic collapse, while indicators such as recovery time, redundancy levels, and the accessibility of critical services during multi-hazard events are used to define the resilience gap. The research makes a distinction between systemic complexity resulting from interconnected infrastructures and feedback mechanisms and structural inequalities, such as differences in governance ability and resource distribution. Compound hazards have distinct effects on urban lifeline systems in different development situations, and this framing improves analytical clarity and offers a strong comparison perspective. For instance, despite advanced control systems, the combined effects of storm surge floods and strong winds during Hurricane Sandy in New York led to cascading failures throughout the power, transportation, and communication networks[95,96]. In a similar vein, heatwaves and wildfires in California have put a strain on electrical infrastructure due to transmission line damage and an extraordinary need for cooling. These examples show that while sophisticated cities can usually handle single hazards as localised interruptions, compound hazards highlight important interdependencies, where the failure of one system, like energy, quickly jeopardises others, like digital communications, water supply, and health services[88,97-99]. In contrast, systemic vulnerabilities that are already noticeable under single hazard settings are often exacerbated by compound hazards in growing cities. In South Asia, for example, flood-disease interactions frequently impair health and water systems at the same time, with weak drainage systems exacerbating pollution concerns and overburdening already frail healthcare systems. The concept of interacting, compound, interrelated, and cascading risks is depicted in Figure 2, which also demonstrates the causation chains connecting environmental causes, global interdependencies, severe occurrences, and infrastructure disruptions. It draws attention to the fact that hazards are intensified and spread by closely interconnected systems, creating intricate vulnerabilities in the environmental, technical, and human realms.

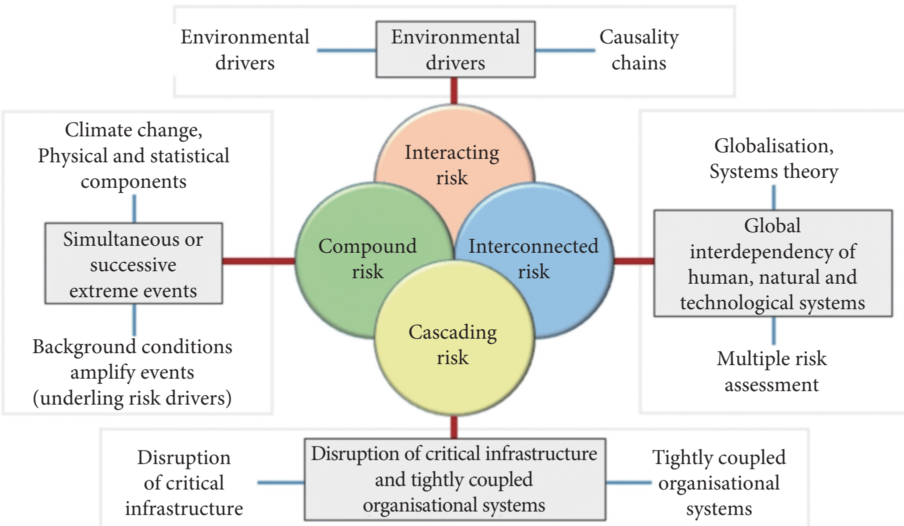


**Fig. 2 Complex, linked, interacting, and escalating catastrophes.** Reproduced with permission from Ref. [100], © The authors 2019.

Similarly, sub-Saharan African cities that experience heat waves and drought at the same time face a series of electricity, water, and food delivery system failures that frequently result in protracted shortages and civil unrest. Compound hazards in these situations are rarely localised phenomena; instead, they become citywide crises with lengthy recovery periods due to a lack of redundancy, informal settlements in high-risk areas, and resource limitations[46,61,101,102].

Comparative study shows that the resilience gap is growing, developing cities suffer systemic collapse due to unfair service distribution and a lack of baseline capacity, whereas wealthier cities primarily struggle with managing complexity and linked failures under compound hazards. Crucially, underprivileged people bear a disproportionate amount of the impact of compound hazards in low-resource environments because they lack the institutional, financial, and infrastructure buffers that enable quicker recovery in affluent metropolitan areas. This discrepancy emphasises that inclusive governance and adaptive capacity building must be incorporated into resilience planning in addition to engineering redundancies, especially in developing cities where compound hazards have long-term social and economic destabilising effects that go beyond infrastructure[47,56,103,104].

### *4.1.3 Propagation of cascading failures*

In lifeline networks, cascading failures frequently start with the breakdown of a single crucial node but spread quickly throughout linked systems, with the effects depending on the level of interdependency and the resilience mechanisms in place. The high level of infrastructure integration and digitisation in modern cities can both reduce and increase cascading hazards. For example, automated control systems and smart grids in North America and Europe enable quick rerouting of energy flows after localised interruptions[105-107]. However, these same interdependencies also create vulnerabilities: a power outage or cyberattack may quickly paralyse communication networks, water pumping facilities, and even emergency services. This trend is best shown by the 2003 Northeast blackout in the United States, in which a localised fault cascaded across state lines, impacting millions of households, transportation, and healthcare facilities because of the close coupling of energy-dependent systems[108,109]. Cascade failures have a propensity to spread more severely in developing cities because of a lack of redundancy, maintenance, and obstacles to stop failure propagation. For example, in South Asia, a flood-induced electrical infrastructure failure might halt water supplies, disrupt hospital operations, and paralyse urban mobility all at once, with insufficient backup preparations to mitigate the effects. In a similar vein, a single substation or bridge collapse after a storm in Sub-Saharan Africa may cut off whole metropolitan regions, depriving people of power, food, medical supplies, and transportation. Figure 3 presents a network diagram showing how an earthquake ($V_1$) can trigger cascading impacts such as building collapses, tsunamis, dam failures, and landslides, which in turn lead to floods, fires, epidemics, and other secondary hazards. Ultimately, these interconnected events contribute to casualties ($V_7$) and widespread disruption to infrastructure, livelihoods, and essential services. Informal settlements and unregulated service expansions, which are not formally integrated into response systems, sometimes make failures in these circumstances worse by leaving huge populations without any recourse during protracted interruptions[110-112]. In contrast, developing cities see cascading failures as systemic breakdowns that span several lifelines with little hope of containment, whereas wealthy cities experience them as intricate networked shocks. In contrast to emerging systems, which are typified by linear dependencies where one disruption always causes another, established systems frequently incorporate feedback mechanisms, backup resources, and institutional coordination to stop failure propagation.

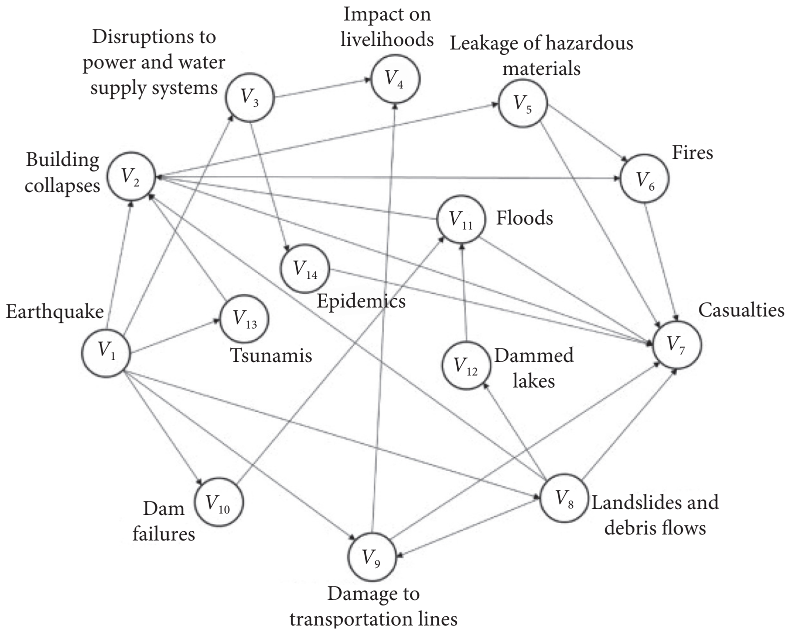


**Fig. 3 Urban infrastructure systems experiencing cascading failures.** Reproduced with permission from Ref. [113], © The authors 2025.

This is where the distinction resides in the resilience buffers. To prevent isolated failures from turning into citywide crises, less-resourced cities must improve redundancy, modularity, and inclusive emergency governance. Advanced urban systems must prioritise managing complexity and cyber-physical interdependencies. This emphasises the significance of context-sensitive resilience strategies[114-116].

#### *4.1.4 Identification of critical nodes and pathways*

The comprehension of how disturbances develop into cascade failures under compound hazard situations depends on identifying important nodes and channels within lifeline networks. Major substations in electricity grids, central data servers for communication systems, or important transportation hubs like airports and metro interchanges are examples of highly centralised and technologically advanced assets that frequently correlate to these nodes in industrialised cities. Real-time digital twin simulations and network theory are two examples of advanced modelling tools that are frequently used to map interdependencies and measure these nodes' susceptibility. For instance, high-voltage substations and water pumping facilities in Germany and Japan have been designated as priority assets for upgrading based on seismic risk assessments since their failure would quickly spread to other vital systems. The possibility of a system-wide failure is decreased by these proactive measures, which allow for focused expenditures in redundancy or hardening[117,118]. Since infrastructure in developing cities is often loosely organized and fragmented, pinpointing and managing critical pathways and hubs becomes more difficult. A single bridge that connects whole districts or a single transformer that serves many highly populated neighbourhoods might serve as a de facto crucial node even if it isn't explicitly acknowledged in planning papers. The thorough mapping of these vulnerabilities is complicated by the absence of comprehensive data, the scarcity of monitoring tools, and the lack of institutional cooperation. Therefore, when threats like floods or heatwaves are added to the breakdown of seemingly insignificant assets, like a modest pumping station or an unofficial road network, they can turn into citywide problems. Furthermore, even when important pathways are identified, investments in resilience enhancements are frequently postponed or deprioritized in favour of immediate demands due to political and governance restrictions[119-121].

The complexity and interconnectedness of these systems present a challenge for developed cities, where failure at a single digital or energy hub can have network-wide repercussions. Developed cities, on the other hand, usually have sophisticated diagnostic tools, integrated data infrastructures, and coordinated administrative frameworks that make it possible to systematically identify and prioritise vital lifeline connections. Evidence-based risk assessments and proactive maintenance techniques are supported by these capabilities. On the other hand, developing cities frequently have insufficient institutional coordination, fragmented data systems, and limited diagnostic capability, which results in the undervaluation and under-protection of critical infrastructure components. As a result, the fragility of nodes spreads through interconnected urban systems, increasing systemic vulnerabilities. This disparity highlights the necessity of context-sensitive approaches: low-resource cities need basic infrastructure audits, community-informed mapping, and governance reforms to identify and secure the nodes and pathways most crucial for survival during compound hazard events, while high-income urban systems need to improve cross-sectoral risk modelling to predict complex hazard interactions[122-125].

#### *4.1.5 Sensitivity analysis of interdependencies*

Sensitivity analysis of interdependencies sheds light on how malfunctions in one vital system affect other systems and how much system performance depends on certain linkages. Advanced modelling frameworks, such as agent-based simulations, network theory, and system dynamics techniques, are frequently used in developed cities for these kinds of evaluations. Planners may use these tools to evaluate various hazard scenarios and determine which interdependencies—like energy-transport, electricity-water, or communication-emergency services—are most likely to cause cascading disruptions. Sensitivity analyses, for example, have shown that even brief power outages in European urban areas severely impair hospital and metro services, underscoring energy as the most vital lifeline. Targeted resilience investments, such decentralised renewable energy integration to reduce reliance on single sources or backup generating capacity for hospitals and metro systems, are informed by this data[60,126,127]. Sensitivity analysis is much less formalised in developing cities, and the potential to quantify interdependencies is constrained by the absence of complete data and modelling capabilities. Rather, post-disaster data, which show extremely sensitive and linear correlations across infrastructures, are frequently used to gain insights. For instance, flooding often interrupts road networks in South Asian cities, which stops food and pharmaceutical supply chains, paralyses waste management, and limits access to medical services. Similar interdependencies exist between power and water in Sub-Saharan African cities: a single substation failure can instantly stop water pumping, leading to secondary health crises in crowded informal settlements. These trends show that even in the absence of sophisticated sensitivity analysis techniques, the visible effects of hazards draw attention to important dependencies that need immediate consideration in resilience planning[128-131].

In contrast, the sensitivity of interdependencies in industrialised cities is typically a result of system complexity, where the risks of cascade failures are increased by closely connected infrastructures. In contrast, the sensitivity in emerging cities is caused by their fragility and lack of redundancies, where an excessive dependence on a single item causes even minor interruptions to quickly worsen. This discrepancy emphasises how crucial it is to contextualise sensitivity analysis techniques: developed cities need to improve scenario-based modelling to predict the effects of compound hazards in intricate networks, while developing cities need practical, resource-appropriate methods—like participatory mapping and basic risk audits—to identify and rank the most vulnerable interdependencies for protection[78,132,133].

### 4.2 Discussion

#### *4.2.1 Systemic risks revealed by compound hazards*

Compound hazards show how closely linked lifeline systems may turn isolated shocks into citywide catastrophes, revealing systemic risks that go well beyond localised infrastructure damage. These systemic hazards frequently show up in industrialised cities as dependency on digital infrastructure and network interdependencies. For instance, the co-occurrence of cyber disruptions with harsh weather in North America and Europe has brought attention to the close interdependence of financial institutions, water utilities, and electricity systems, where a breakdown in one area may quickly destabilise others. For example, during Hurricane Sandy, the concurrent flooding of power substations and the failure of public transport networks not only caused mobility disruptions but also paralysed hospitals and communication systems, increasing the hazards to public health and the economy. These incidents demonstrate how the intricacy of overseeing several interconnected networks in situations of compound hazard can lead to systemic concerns even in cases when redundancies are present[73,119,134,135]. Compound hazards often expose deeper systemic issues in developing cities by interacting with existing structural weaknesses and amplifying their impact. For example, the co-occurrence of disease outbreaks and floods in South Asian megacities has demonstrated how poor waste management, shoddy drainage, and brittle health systems may intensify localised risks into systemic urban disasters. Similarly, extended droughts and heat waves in Sub-Saharan Africa put a strain on electricity and water infrastructures at the same time, leading to food shortages, economic disruption, and occasionally societal instability.

Marginalised communities frequently suffer the most severe and long-lasting effects of these systemic hazards, which are exacerbated by informality, fragmentation of government, and unequal access to services. In this case, systemic risk is more about resolving underlying deficiencies in capacity, redundancy, and social protection than it is about managing technology interdependencies[29,37,91,136,137]. The concept of urban resilience is depicted in Figure 4, which shows how cities may respond to risk events like natural disasters and climate change by promoting resilience, adapting, recovering, and resisting. To develop urban systems through efficiency, creativity, variety, and resource coordination, it highlights five essential dimensions: facility, social, economic, ecological, and system resilience. In contrast, complexity-driven interdependencies are the primary source of systemic hazards in industrialised cities, where managing highly connected infrastructures under multi-hazard stress is a difficulty. However, systemic risks in developing cities are mostly capacity-driven, stemming from underinvestment, brittle institutions, and unequal access, which leave lifeline systems vulnerable to failure when many hazards combine. This distinction highlights the need for context-specific resilience strategies: systemic risk reduction in lower-resource settings necessitates inclusive governance, basic service reliability, and investments in foundational infrastructure to prevent hazards from cascading into existential urban crises, whereas in wealthier contexts, improving cross-sectoral coordination, cyber-physical safeguards, and scenario-based planning is crucial[45,138,139].

#### *4.2.2 Comparative insights: single vs. multi-hazard resilience*

The ways that urban lifeline systems in developed and developing cities handle resilience in single- and multi-hazard scenarios differ significantly, according to a comparative analysis. Due to built-in redundancies, advanced monitoring systems, and efficient emergency protocols, modern cities often demonstrate strong resilience when facing individual hazard events. Even though they might be expensive, disruptions are often restricted inside industries and recovered in a short amount of time. For instance, localised power outages or transportation delays are usually caused by isolated flooding or heatwave disasters in European cities; but systemic collapse is avoided by backup systems and diverse supply chains. However, developing cities struggle even when faced with a single hazard: localised floods can disrupt whole power or water networks for weeks, and recovery is prolonged by institutional and logistical limitations. The change from single to multi-hazard situations is far more destabilising

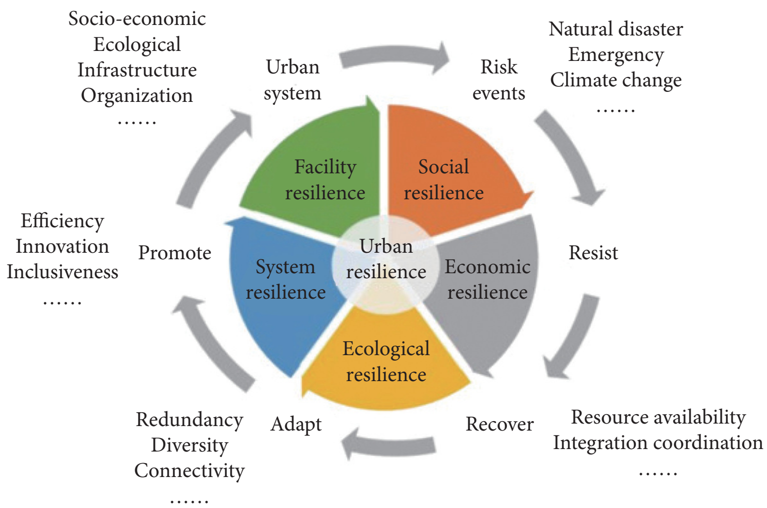


**Fig. 4 Urban resilience showing how cities withstand disruption.** Reproduced with permission from Ref. [140], © The authors 2022.

because of this baseline fragility[141-144]. The disparity in resilience capability increases in response to compound or multi-hazard situations. Managing complex interdependencies—the way disturbances ripple across closely connected infrastructures—is the main problem in industrialised cities. Hurricanes in the United States, for example, have shown how communication breakdowns, power system failures, and storm surge flooding combine to impede emergency response and economic activity. Although redundancies are there, they become less effective when several systems are under stress at once, revealing hidden interdependence. On the other hand, capacity constraints rather than system complexity weaken resilience in emerging cities under multi-hazard situations. Near-total lifeline collapse can result from the co-occurrence of disasters like drought and heatwaves in Sub-Saharan Africa or flooding and disease outbreaks in South Asia, since these regions frequently lack emergency governance systems, protective infrastructure, and basic redundancy. Instead of just cascading, multi-hazard stresses in this situation exacerbate vulnerabilities, turning localised hazards into existential metropolitan catastrophes[132,145-147].

Resilience under single hazards in industrialised cities gives people a false sense of security against dangers from several hazards, which is an important comparative observation. When risks overlap, systems that seem resilient under individual shocks may not function as intended, demonstrating that single-event performance alone cannot adequately measure resilience. Poor performance under single hazards, on the other hand, is a sign of the potential for a systemic collapse under compound hazards in emerging cities. This disparity highlights the need for context-specific resilience planning: in high-income environments, improving risk models and bolstering cross-sectoral coordination are crucial for anticipating intricate hazard interactions, whereas in low-income environments, the emphasis must be on constructing foundational infrastructure, modular redundancy, and inclusive governance to provide even baseline resilience under compound shocks[47,91,148]. In the end, contrasting single-hazard and multi-hazard resilience in urban settings reveals a disparity in resilience worldwide. Developed cities must deal with the problem of handling complexity, while emerging cities must deal with the problem of addressing basic capacity deficiencies. When draughting policies, investments, and international partnerships to increase urban lifeline resilience at a time of compound risks that are becoming more severe, it is imperative to acknowledge this disparity.

### *4.2.3 Practical implications for emergency response*

The comparison between developed and developing cities is evident in the analysis of single and compound hazard dynamics, which highlights important practical implications for emergency response. Advanced technologies like predictive analytics, geographic information systems (GIS), and digital twin simulations are frequently the foundation of emergency response systems in developed urban contexts. These technologies allow authorities to better allocate resources in real time and predict cascading effects. These systems enable coordinated multi-agency responses to compound disasters like hurricanes or wildfires, guaranteeing transportation routes, energy nodes, and medical institutions prioritised attention. However, the very dependence on highly digitalised systems also creates vulnerability; during hazard occurrences, power outages or cyberattacks can impair situational awareness, which lowers the efficacy of even strong reaction measures. This highlights a paradox: whereas technology improves readiness for emergencies, it also introduces new systemic risks that need to be taken into consideration when preparing responses[149-152]. The practical difficulties in responding to emergencies in developing cities stem more from long-term shortages of resources and capability than from a reliance on technology. Interventions during compound hazards are frequently delayed or unequal because of a lack of access to trustworthy early-warning systems, ill-prepared first responders, and disjointed governance structures. For example, floods in South Asian megacities usually overwhelm rescue services, causing coordination to be hampered and relief distribution to take longer due to clogged transport routes and broken communication links. Similarly, the lack of emergency medical facilities and pre-positioned supplies in Sub-Saharan African cities means that when several disasters occur, humanitarian response frequently relies significantly on outside assistance organisations, which slows the rate of recovery overall. These limitations underline the pressing need for capacity-building initiatives that enhance fundamental response capabilities, such as decentralised emergency resources, community-based disaster planning, and inexpensive communication technologies that continue to operate even when infrastructure is stressed[153-156].

Comparative analysis shows that developing cities need measures to establish foundational capability to assure even modest levels of emergency coverage, whereas developed cities must concentrate on improving adaptive coordination—managing complexity across digital, physical, and social systems. This distinction has significant policy ramifications: low-income cities gain more immediate benefits from investments in basic logistics infrastructure, inclusive evacuation planning, and the empowerment of local actors as first responders, while high-income cities should invest in cyber-resilient emergency platforms, cross-sectoral drills, and interoperable communication systems. Ultimately, the alignment of institutional capacity, community participation, and fairness concerns, in addition to technology sophistication, determines how resilient emergency response is under compound threats. To stop cascade failures from turning into systemic humanitarian disasters, these gaps must be closed[157-159].

#### *4.2.4 Alignment with climate change and urbanisation trends*

The interaction of urban lifeline resilience, rising urbanisation, and climate change is becoming more important in determining how vulnerable infrastructure systems are to disasters. Extreme weather events like heatwaves, storms, and flooding have become more frequent and intense in major cities due to climate change, putting even the most sophisticated lifeline systems to the test. Cities become more susceptible to cascading failures due to increased interdependencies brought about by urban densification and the growth of high-tech infrastructure. Urban areas in North America and Europe, for instance, have seen how climate-related flooding or extended heat waves can interfere with digital communications, water distribution, energy and transportation networks, and more. This underscores the necessity of incorporating climate projections into resilience planning and infrastructure design. These cities' forward-thinking urban policies depend more on scenario-based stress testing, green infrastructure, and climate-adaptive designs to foresee multi-hazard consequences and preserve system continuity[47,119,160]. Rapid urbanisation and climate change put further strain on lifeline systems in emerging cities, which are frequently already under stress. Urban regions in South Asia and Sub-Saharan Africa are confronted with the dual challenges of climate-induced disasters like heatwaves, droughts, and floods, as well as population increase in places vulnerable to hazards. Disruptions in essential services like water, energy, sanitation, and transportation may swiftly turn into systemic crises, and informal settlements—which often house a significant number of urban populations—are especially vulnerable to compound risks. Since infrastructure development and regulatory monitoring are frequently outpaced by rapid urban expansion in these settings, lifeline networks are institutionally and physically unprepared for the higher hazard loads brought on by climate change. Resilience planning in emerging cities must thus specifically take into consideration the amplification of hazard frequency and magnitude as well as the spatial demands of urbanisation[3,161,162],

In contrast, poor cities see climate change and urbanisation trends as causes of baseline vulnerability and exposure, whereas developed cities focus on these trends as threats to system complexity and interdependency. In high-income cities, combining robust infrastructure design, predictive climate modelling, and cross-sector cooperation is crucial to preventing cascade failures. This contrast highlights the need for context-sensitive adaptation measures. In contrast, it is imperative to prioritise community-based adaptation solutions, equitable service access, and basic infrastructure upgrades in low-resource urban contexts to mitigate systemic vulnerabilities that are exacerbated by climate change and fast urban expansion. Understanding these distinct forces guarantees that urban resilience plans are proactive rather than reactive, in line with long-term sustainability objectives and the reality of urbanisation in a warming global environment[47,163-165]. Furthermore, the necessity of multi-scalar planning techniques is highlighted by the alignment of resilience measures with urbanisation and climatic changes. In established cities, this entails identifying hazards across the city, coordinating across agencies, and incorporating climate forecasts into infrastructure investment and zoning. Localised, community-informed planning is equally important in emerging cities, with a focus on decentralised energy, water, and transportation networks that improve redundancy, lower exposure, and promote neighborhood-level adaptability. While climate change is a universal driver of hazard risk, the comparative perspective emphasises that its effects on lifeline resilience are mediated by institutional capacity, resource availability, and urban development patterns, requiring customised strategies to protect vital urban functions under compound hazards[166-169].

### 4.3 Mitigation and policy implications

#### *4.3.1 Adaptive infrastructure design*

In the context of compound hazards, adaptive infrastructure design has become a crucial tactic for improving urban lifeline resilience, especially in situations when conventional static design techniques are unable to account for changing threats. Adaptive design concepts are being incorporated more into infrastructure development in industrialised cities because of technology-enabled, modular, and adaptable systems that can react quickly to a variety of threats. For instance, energy networks can isolate problems and continue operations during storms or heat waves thanks to smart grids that include automatic rerouting and real-time monitoring features. In a similar vein, water distribution systems that include variable pressure control and sensor-driven leak detection can continue to function even in the case of a flood or earthquake. By allowing systems to learn from past disruptions, these design techniques not only lessen the possibility of cascading failures but also allow for incremental resilience enhancements. Adaptive infrastructure in high-income cities guarantees that vital urban operations continue to work reliably even in the face of more complex and compound hazard situations by fusing physical redundancy, advanced technology, and scenario-based design[78,170-173].

Although financial limits, institutional capability, and informal urbanisation make adaptive infrastructure design difficult to execute in underdeveloped countries, it is nevertheless an essential tactic for reducing systemic risks. Here, low-cost, modular, and decentralised improvements that improve the adaptability and redundancy of lifeline systems are frequently the focus of adaptive design. For example, elevated or permeable road and drainage networks can lessen transportation interruptions caused by flooding, while decentralised microgrids or solar-powered water pumping stations can continue to provide important services during power outages. Participatory design and community-informed planning are also essential for making sure that solutions match exposure to hazards and local needs. Crucially, adaptive infrastructure in low-resource contexts allows cities to gradually improve resilience without needing significant capital investment by prioritising multifunctional solutions and incremental upgrades, such as green corridors that support urban mobility and mitigate flooding. This comparative viewpoint emphasises that to successfully minimise cascade failures and systemic risks under compound hazards, adaptive infrastructure must be customised to local capacities, hazard profiles, and urban growth patterns[174-178].

### *4.3.2 Decentralised and redundant systems*

One important mitigating technique to improve urban lifeline resilience under compound hazards is the deployment of decentralised and redundant infrastructure systems. Redundancy is frequently included into technologically advanced, highly linked networks in modern cities to stop localised failures from spreading to other systems. To provide uninterrupted service even in the event of a major transmission line failure, electrical grids are increasingly being constructed with numerous substations, microgrids, and automatic rerouting capabilities[47,78,179]. Similar to this, water and wastewater networks use backup pumping stations and parallel pipes to keep running in the case of earthquakes or floods. In these situations, decentralisation also entails the spatial dispersion of vital infrastructure, such as data centres, hospitals, and ERs, which lessens reliance on single points of failure. During overlapping hazard occurrences, mature urban systems may prevent cascade failures, absorb shocks, and preserve key services by intentionally implementing both functional and physical redundancy[132,145,180,181].

Decentralised and redundant systems are equally crucial in emerging cities, although they are frequently limited by institutional capability and resource availability. Small-scale energy microgrids, regional water treatment facilities, and community-level emergency or medical services that function independently of central systems are examples of decentralisation in this context. Modular, scalable infrastructure solutions can provide redundancy by enabling network segments to operate independently if other components fail. For instance, several little drainage canals can stop floods in informal settlements, and decentralised solar-powered water pumping devices can maintain the local water supply during blackouts[182-184]. Crucially, these tactics improve responsiveness and equality in service delivery by empowering local populations to take part in hazard mitigation in addition to enhancing physical resilience. A significant change from linear, centralised infrastructure models to systems that can sustain continuity under complex, compound threats is represented by the integration of decentralisation and redundancy into lifeline planning in both situations[185,186].

### *4.3.3 Monitoring, sensing, and early warning technologies*

Technologies for early warning, sensing, and monitoring are essential for improving urban lifeline resilience because they provide prompt emergency response and proactive risk management. Advanced sensor networks, remote monitoring tools, and integrated data platforms enable authorities in developed cities to monitor the functioning of vital facilities in real time and predict cascade failures under compound danger scenarios. Predictive analytics is used by interconnected energy grids to identify weaknesses prior to system overloads, while smart water networks with pressure and quality sensors can spot leaks or pollution early[187,188]. The probability of system-wide disruptions can be decreased by using early warning systems for floods, storms, or heatwaves to automatically change operations across many lifelines, such as rerouting power, cutting off vulnerable transportation connections, or issuing public advisories. The strategic significance of digital integration in hazard-resilient urban design is highlighted by these technologies, which not only improve situational awareness but also increase the effectiveness of resource allocation and emergency response[119,189].

Due to lack of funding, institutional capacity, and technological know-how, monitoring and early warning systems are still underutilised in developing cities. However, lifeline resilience and hazard preparedness may be greatly enhanced by inexpensive, locally tailored sensor technologies. For example, solar-powered water level sensors, community-operated rainfall gauges, or mobile-based flood warning systems can all send out timely signals to households and authorities, allowing for preventative mitigating measures[190,191]. Similarly, basic automated monitoring tools that identify service interruptions can help decentralised water and energy systems by enabling local teams to act quickly and avert further failures. Beyond the use of technology, community involvement in monitoring initiatives increases local trust and ownership, both of which are critical for efficient disaster response. To move from reactive to proactive resilience methods and make sure that lifeline systems can endure compound threats while minimising cascading and systemic risks, it is imperative that sensing and early warning technology be integrated into both established and emerging cities[154,192,193].

### *4.3.4 Governance and cross-sector coordination*

Mitigating cascade failures and improving urban lifeline resilience under compound hazards need effective governance and cross-sector collaboration. In mature cities, coordination between various authorities, commercial operators, and emergency response units is made easier by strong institutional structures and explicit regulatory requirements. Cities in North America and Europe, for instance, frequently combine transportation, energy, water, and communication organisations into centralised command structures for hazard control[194,195]. By enabling quick information exchange, coordinated operational reactions, and prearranged backup plans, these approaches lessen the possibility that crucial system interdependencies may spread problems. In addition, the implementation of inter-agency exercises and scenario-based planning enhances institutional learning, guaranteeing that decision-makers can effectively distribute resources across sectors in times of emergency and predict intricate hazard interconnections. Therefore, strong governance enhances technical resilience by integrating cross-sectoral cooperation, proactive management, and accountability into urban lifeline design[196,197]. Governance and cross-sector coordination continue to be major obstacles in growing cities because of dispersed institutions, scarce resources, and unofficial urban growth. During compound hazard incidents, lifeline management is frequently dispersed across several organisations with conflicting or ambiguous directives, which can impede prompt action. Floods, for example, frequently reveal coordination gaps between water, transportation, and health authorities, leading to delayed restoration of critical services and heightened socioeconomic vulnerability in South Asian or Sub-Saharan African communities. In these situations, strengthening governance necessitates not just defining institutional roles but also creating cooperative forums including local government, private service providers, and community groups[198-201]. Decentralised decision-making, collaborative hazard mapping, and participatory planning are some of the mechanisms that might facilitate adaptive responses and enhance coordination, especially in informal settlements. Developed cities depend on formal institutional networks and technology-driven coordination, whereas developing cities gain the most from adaptable, inclusive governance structures that can accommodate a variety of players and make up for structural resource constraints. Both strategies emphasise that, in the context of compound hazards, efficient governance is just as important as infrastructure and technology in lowering systemic risk[47,202,203].

#### 4.3.5 Future research directions

Urban lifeline resilience has come a long way, but there are still several research gaps that need to be filled to improve mitigation techniques for compound hazards. One crucial topic is the mathematical modelling of interdependencies across various lifeline systems, especially when risks occur sequentially or simultaneously. Although digital twins, network theory, and scenario-based simulations are being used more in developed cities, little is known about how these approaches may be applied in developing cities with inadequate data. The creation of scalable, contextually relevant modelling frameworks that can represent the dynamics of cascading failures in formal and informal urban networks should be the top priority of future research to produce useful information for resource allocation, emergency preparedness, and infrastructure planning. To further improve these models' prediction capacity and applicability for equitable resilience planning, socioeconomic, demographic, and geographical vulnerability data should be incorporated. Cross-sectoral interdependencies should be given top priority in future study to better understand how disturbances in one lifeline system spread to others under compound risks. Governance and institutional structures that support coordinated risk management and flexible decision-making also require more focus. Furthermore, resilience performance and the prediction of cascade failures might be improved by the development of predictive modelling and simulation tools. The theoretical and practical knowledge of urban resilience under complicated hazard scenarios is advanced by these study directions, which fill up the gaps in empirical data and analytical accuracy.

Another important field of research is evaluating how successfully adaptive and decentralised infrastructure modifications lessen systemic dangers. Critical evidence for policy acceptance and investment prioritisation may be found in empirical studies that compare the performance of modular microgrids, distributed water networks, and multifunctional urban green infrastructure in various urbanisation and hazard scenarios. Similarly, studies on the integration of community-based sensing, monitoring, and early-warning systems can show how low-cost, locally informed technology, particularly in developing cities, can support formal infrastructure and governance procedures. Lastly, to comprehend how institutional arrangements affect resilience results, it is crucial to investigate governance models and cross-sector coordination techniques in various urban environments. To guide more flexible, inclusive, and context-sensitive urban resilience strategies, comparative studies between high- and low-income cities can provide best practices for coordinating institutional, technical, and infrastructure solutions. It will be crucial to address these research avenues to translate findings from single-hazard and compound-hazard studies into practical solutions that improve the resilience of urban lifeline systems throughout the globe.

#### 4.3.6 Limitations of the study

It is important to recognise several limitations even though this evaluation offers a thorough comparison of urban lifeline resilience under single and compound risks. First, there is variation in data quality, methodological methods, and contextual relevance due to the study's heavy reliance on secondary literature, case studies, and previously published empirical findings. Low-income and quickly urbanising cities in Sub-Saharan Africa and South Asia are comparatively under-represented in the literature since most of the research that are currently available concentrate on high-income urban environments, especially in North America, Europe, and East Asia. The generalisability of findings about systemic risk, cascade failures, and the effectiveness of mitigation techniques in situations with limited resources may be limited by this bias. The availability and granularity of public data for emerging cities, particularly with relation to informal infrastructure, community-level adaptation solutions, and local government processes, have thereby limited the capacity to make comparisons.

Second, because lifeline systems are mostly studied in urban environments, the study might not consider how urban and peri-urban or rural systems interact to affect resilience and hazard propagation. For instance, cities' reliance on regional food supply chains, electricity transmission networks, or water sources adds levels of systemic risk that are not completely represented in localised analysis. Furthermore, while the review highlights institutional, technical, and physical aspects of resilience, it could not adequately account for behavioural and social aspects, such as informal networks, cultural practices that influence hazard response, and family coping mechanisms. The study's capacity to offer accurate prediction evaluations of cascading failure probability or resilience thresholds is further limited by its use of a qualitative comparison methodology as opposed to quantitative modelling of compound hazards and interdependencies. Recognising these drawbacks emphasises the necessity of multi-scalar, quantitative, and multidisciplinary study in the future to better understand the intricacy of urban lifeline resilience under compound risks.

#### 4.3.7 Forward-looking recommendations and global implications

This study emphasises the critical need for forward-looking policies that improve urban lifeline resilience in the face of more frequent and complex compound hazards, building on the comparative insights and synthesis of data. Cities throughout the world need to embrace integrated strategies that incorporate advanced monitoring and early warning technology, decentralised and redundant systems, inclusive governance frameworks, and flexible infrastructure design. Using scenario-based modelling, cross-sector cooperation, and investments in cyber-physical protections, developed cities should place a high priority on controlling system complexity, interdependencies, and digital vulnerabilities. However, to guarantee fair service delivery and quick local reaction, developing cities need to employ measures that address basic fragilities, such enhancing fundamental infrastructure, putting low-cost decentralised solutions into place, and encouraging community involvement.

The results have wide-ranging effects on international collaboration, information transfer, and policymaking that go beyond local and regional planning. To facilitate the adaption of best practices across a variety of urban contexts, global urban resilience programs should place a strong priority on context-specific solutions that recognise the different problems faced by high- and low-resource cities. Furthermore, the need for ongoing research, data sharing, and capacity-building to foresee emergent systemic hazards is highlighted by the growing convergence of climate change, expanding urbanisation, and technology interdependencies. Cities around the world can protect vulnerable populations, increase the resilience of vital lifeline networks, and lessen the possibility of cascading failures that jeopardise social, economic, and environmental sustainability by coordinating policy, practice, and research with the realities of compound hazards. This forward-thinking viewpoint frames urban resilience as a proactive, strategic requirement for sustainable urban development in the twenty-first century, rather than just a reactive response to calamities.

## 5 Conclusion

This study advances understanding of urban lifeline resilience by revealing how compound hazards amplify cascading failures and systemic risks across interconnected infrastructures. It introduces a conceptual framework that links hazard interactions with infrastructure interdependencies, providing a basis for more integrated resilience assessment. The analysis also identifies critical research and policy gaps related to governance coordination, data integration, and adaptive planning. Overall, the study contributes both theoretical clarity and practical direction for enhancing urban resilience in increasingly complex risk environments. Key findings show that industrialised cities are vulnerable to disasters when they interact because of the great interconnectedness and complexity of lifeline networks, even if they are typically resilient when faced with a single catastrophe. On the other hand, developing cities are extremely vulnerable to even single hazards, and because of governance limitations, low investment, and a lack of redundancy, systemic collapse is more likely in situations with compound hazards. The comparative perspective highlights that resilience is a multifaceted phenomenon influenced by institutional capacity, governance, social equality, and community participation rather than only being a technical or infrastructure issue. In addition, the study highlights that early warning systems, integrated governance, and technology-enabled, adaptive, and decentralised infrastructure solutions are essential for preventing cascade failures and preserving vital urban services in both situations. The finding of this review offers useful advice for bolstering urban lifeline resilience in the face of compound threats. Prioritising mitigation techniques across infrastructure systems and making risk-informed decisions are supported by the study's identification of significant interdependencies and probable cascading failure paths. The creation of integrated resilience assessment instruments that take systemic risk views into account can be guided by the synthesised frameworks and ideas. Additionally, politicians, urban planners, and infrastructure managers may benefit from the insights offered in developing adaptable solutions to improve readiness, lower vulnerabilities, and foster sustainable urban resilience.

From a theoretical perspective, the study advances knowledge of urban resilience by integrating systemic risk, compound hazards, and cascade failures into a single conceptual framework. It highlights the significance of considering interdependencies, crucial nodes, and sensitivity pathways across different systems and shows that lifeline resilience cannot be properly evaluated using single-hazard analysis. By demonstrating how infrastructure design, decentralisation, monitoring, and governance impact results under complex hazard scenarios, the study empirically offers a cross-contextual comparison that informs urban development for both high- and low-income areas. The results provide practical insights for emergency managers, urban planners, and policymakers: in developed cities, the focus should be on managing interconnectedness and complexity through scenario planning, predictive modelling, and cyber-physical safeguards; in developing cities, investments in decentralised systems, inclusive governance, community-based monitoring, and foundational infrastructure are crucial to preventing localised hazards from spreading into systemic crises. A comprehensive knowledge of urban lifeline resilience is advanced by this study, which bridges theoretical and practical issues. It also lays the groundwork for future studies and policy development targeted at protecting cities from the increasing threat of compound hazards.

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## Author contribution statement

Chukwuemeka Kingsley John contributed to writing—original draft, methodology, resources, and formal analysis, while Jaan Hui Pu contributed to writing—review and editing, resources, supervision, and project management. All authors have approved the final manuscript.

## Data availability

Not applicable.

## Use of AI statement

During the preparation of this work, the authors used Copilot to grammatically correct the manuscript. After using this tool the authors further reviewed and edited the content as needed and takes full responsibility for the content of the publication.

## Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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