Narrative Review Article

The Interaction of Population Density and Flood Infrastructure in Urban Flood Risk Areas: A Narrative Review of Economic Loss and Social Vulnerability

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ABSTRACT

Flooding is one of the most catastrophic natural disasters impacting millions of people worldwide and causing trillions of dollars in annual economic loss. While literature exists on the subject, it often focuses on a limited scope of variables at a time, rather than synthesizing a holistic perspective of factors contributing to flood severity and their consequences. This narrative review synthesizes literature from various contexts to better evaluate how population density and the extent of protective flood infrastructure are related to economic losses due to flooding. The discussion and analysis points include a narrative review and analysis of literature that measures loss assessments, community infrastructure characteristics, urbanization trends, and adaptations within cities across the globe. Across the reviewed studies, a recurring pattern indicates that damage from flooding escalates with population density, but they are significantly reduced where all-encompassing protection infrastructure is present; the addition of green infrastructure and proactive adaptation measures - especially those guided by effective policy - further enhances resilience to flooding. Taken together, the literature consistently highlights population exposure and infrastructure capacity as leading determinants of loss outcomes. This review underscores implications for urban planning, policymaking, and disaster mitigation by emphasizing the need not only to evaluate hazard exposure, but also to adapt the physical urban environment - through infrastructure upgrades and equitable planning - for greater sustainability and resilience. The approach presented in this narrative review synthesizes existing literature to point to opportunities to better combine infrastructure, demographic, and spatial data for enhanced disaster preparedness.

Keywords: Urban flood risk; Population density; Flood infrastructure; Economic flood damage; Social vulnerability; Climate adaption; Green infrastructure; Flood resilience

INTRODUCTION

Floods are among the most potentially devastating and long-lasting natural disasters on the planet, as they can impact millions of people each year and cause billions of dollars in economic damage worldwide. The number and ferocity of flood events have increased over recent years, a trend generally explained by anthropogenic climate change and rising global temperatures. Because these insights are essential for enhancing emergency

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management, resource allocation, and disaster response systems, researchers and other policymakers have been compelled to look into factors that contribute to changes in precipitation regimes and the increased frequency of intense flood events (1). Decision-makers can better predict, prepare for, and reduce infrastructure disruptions and fatalities during flood events by knowing the factors that influence flood risk. Many existing studies have hypothesized and empirically demonstrated that urbanization contributes to the majority of increases in flood risk, especially in rapidly developing regions (2-5). Therefore, variables relating to urbanization have become popular subjects of study in attempts to reduce the impact of severe floods. This review will discuss key themes and findings in the literature regarding relationships between population density, flood infrastructure, and the economic and social consequences of flooding. It will examine how population density and the adequacy of flood infrastructure shape the severity and distribution of economic impacts during urban flood events.

Many existing studies examine population, infrastructure, and hazard conditions in isolation or treat them mainly as control variables, which can obscure how these factors interact in shaping flood impacts. This narrative review instead brings together research from diverse geographic and socioeconomic contexts to discuss how population density, flood infrastructure, and loss outcomes have been discussed together, and considers how these discussions inform broader, multi-factor perspectives on urban flood risk.

BACKGROUND, RATIONALE, AND DRIVERS OF URBAN FLOOD RISK

Why have floods been getting worse?

Existing reviews typically summarize climate and urbanization as parallel drivers of flood risk without making clear their relative quantitative contributions to exposure and loss. One primary cause of the rising contribution of floods over the past few decades is the rise in rainfall extremes and the evolving global climate. The mean global surface temperatures are still on the rise, strengthening the hydrologic cycle and in turn producing more intense, frequent rainfall and increased river flows (6). The latest reviews have found that climate change is responsible for about 21% of the increase in global flood exposure, but urbanization - and especially the concentration of populations and assets in floodplains - is responsible for up to 77% of the increase in risk observed, with the most exposure of vulnerability being among urban and poor populations (2, 5). This means floods are becoming more likely and their consequences are increasingly severe, particularly where people are more crowded in risk-prone areas. A United States-based study showed that urbanization along coastlines outpaces infrastructure adaptation, leading to increased, more populous, and more exposed settlements (7). In poorer countries, this intersection of accelerated development and limited adaptation capacity is the most intense (8).

Why are population density and flood infrastructure important?

Amidst this increased vulnerability, it has come into perspective that population density and the integrity or extent of flood hazard infrastructure are two variables that can have a disproportionate effect on flood damage severity. These are becoming the focus of increasing empirical analysis and policy research, as they are modifiable, policy-relevant levers by which disaster losses may be reduced. Heavy population density can significantly increase the number of exposed people and asset value treated by a single flood event (5). Strong flood risk infrastructure in the form of levees, floodways, drainage, and green adaptation can minimize significant losses even when augmenting hazards (3, 9). Inadequate development or insufficient maintenance of such systems normally accompanies the largest loss ratios, especially as “protection gaps” - defined as deficiencies in insurance and coverage and in the physical reach or quality of flood protection infrastructure - leave massive numbers of people uninsured or under-protected against flood losses (8). There have not been consistent quantitative frameworks established that allow researchers to accurately quantify or compare “protection gaps” in relation to population density across various studies or to identify which measures of infrastructure density and capacity are the strongest predictors of loss outcomes after flooding. In addition, many existing empirical analyses have incorporated a large number of strong but unverified design choices: e.g., measuring average flood losses using coarse administrative averages, analyzing losses associated with single flood events, using binary indicators of protection that may not account for non-linear or “threshold effects”.

Population Density

Population density, in terms of flood hazard, is commonly defined as the number of inhabitants per square kilometer (or mile) of area. Scientists typically calculate this value by using the national census, high-

resolution gridded population datasets (e.g., Global Human Settlement Layer, WorldPop, or GPWv4), or approximated from dynamic sources like mobile phone call data records or satellite imagery. While static census data are a good starting point, more recent studies point towards the necessity of taking population dynamics into account - changes in the number and organization of residents over hours or days - which does impact accurate flood exposure analysis in urban areas. For instance, mobile phone data gives analysts a more accurate exposure estimate of who is exposed to at any given time by enabling them to observe the changing day/night or event-condition population (10). Broader application by researchers is hampered by issues like data privacy, restricted access to real-time or proprietary data, methodological uncertainties, and irregularities in spatial and temporal resolution. Despite its potential, mobile phone data is not yet a standard tool for all flood risk studies because of these obstacles.

Population density is one of the main variables that exacerbates the consequences of flood exposure and disaster severity. When there is flooding, the denser a settlement - the more people, homes, businesses, and property in a given area - the greater the number of people impacted and the higher the total economic losses. Additionally, spatial clustering of affected communities in densely populated, low-lying regions can enhance inequality in flood impacts. When people live close together in low-lying areas that flood easily, the damage hits some communities much harder than others. Studies show that flooding affects poorer neighborhoods more, making existing inequalities even worse (11). In response, accurate measurement and effective planning for urban population density are thus critical for effective flood hazard identification, resource distribution, and disaster response planning.

Flood Infrastructure

Flood risk infrastructure refers to the set of engineered, natural, and physical systems intended to reduce the occurrence and intensity of flooding on assets and people. Common examples include levees, floodwalls, embankments, stormwater drainage infrastructure, retention basins, coastal protection works, and green infrastructure such as wetlands and vegetated buffers, all of which are engineered to deflect, reserve, or dissipate floodwaters (12). The infrastructure for flood risk quality and coverage is usually measured using quantifiable parameters such as the total length of levees and flood walls per square kilometer, drainage capacity and volume, or even green adaptation components (13). While comprehensive global datasets regarding population and hazard exposure are plentiful (e.g., WorldPop, Global Human Settlement Layer), there is a notable scarcity of standardized, open-access data on infrastructure quality at fine spatial scales. This data gap is a key challenge for comparative risk assessment and highlights the need for expanded data infrastructure projects and collaborative initiatives, as called for by recent reviews. In addition, investment in maintenance, per capita expenditure on infrastructure, or normalized resilience indicators - derived using methods such as principal component analysis - are utilized increasingly in comparative flood resilience benchmarking (14). These steps help both policymakers and engineers evaluate how prepared a community's environment is to resist large-scale flooding, both in terms of current protective performance as well as the potential to build resilience into a changing climate risk (15). In the end, those areas with greater infrastructure capacity, higher standards of maintenance, and robust green defense have a much lower flood risk and can recover faster, highlighting the imperative for ongoing investment and adjustment as flood hazards increase around the world.

The quality and maintenance of flood risk infrastructure are some of the strongest determinants of individual and community disaster consequences. In contrast, deficit adaptation or expenditure is associated with increased and deeper losses, such as in cities with rapidly expanding populations but without improvement in levee or drainage infrastructure. Evidence based on empirical analysis has proven that for every dollar spent on infrastructure upgradation, two to five dollars of damages or prevented insurance claims can be saved, mainly in high-risk or densely populated city locations (9, 12).

Motivation for this review

These sections highlight the importance of considering population density, infrastructure capacity, and economic loss together in the context of urban flooding. This narrative review brings these strands of research into conversation, comparing how different authors define and measure these variables and how their assumptions influence discussions of vulnerability and resilience. This review highlights recurring methodological patterns and gaps, and discusses how future flood loss research and policy discussions may better account for the combined influence of population density and flood risk infrastructure.

POPULATION DENSITY AND ITS RELATIONSHIP WITH ECONOMIC FLOOD DAMAGE

Global and Cross-Country Analyses

Devitt *et al*. (2023) have presented a figure (Figure 1A) that illustrates, for each selected country, the relationship between flood hazard sensitivity and population exposure sensitivity across the three main types of floodplains (2). Figure 1A demonstrates that flood exposure is not distributed uniformly across countries but rather reflects differences in settlement patterns relative to flood-prone land. It illustrates the co-variation between population exposure and flood hazard sensitivity, highlighting the role of settlement decisions in shaping flood risk.

Devitt *et al*. (2023) employ Figure 1A to demonstrate contrasting settlement patterns in global floodplain regions and countries (2). While many nations, especially in the developed world, demonstrate their densest populations in areas that rarely flood, a larger number of developing nations, especially in South Asia and Africa, demonstrate populations below the 1:1 line, which means that large portions of the population are settled in the most frequently inundated and at-risk areas of the floodplain. The authors suggest that the reasons for this pattern may be historical constraints to safer land, rapid urbanization without planning, or economic constraints leading the population to marginal land with few other alternatives. Their more general analysis suggests that populations in developed economies largely demonstrate a "learned adaptation" in settling away from frequently flooded areas due to institutional memory, planning codes, or insurance incentives.

However, in developing regions - where urbanization can sometimes outstrip the ability to plan or build the infrastructure required - these adaptive safeguards are less effective. The key difference highlighted in Figure 1A around risk exposure is that it is not evenly spread across the globe, but rather shaped by intersecting pathways of development, policy capacity, and social fragility. The reasons that these vulnerable groups continue to reside next to at-risk floodplains in developing areas have not been adequately documented. Is it a matter of economic necessity, a historical legacy of informal settlement, or a weakness in hazard communication and governance? This gap is an important area for future research, as these underlying drivers must be understood for effective targeted adaptation and equitable risk reduction. Devitt *et al*.'s work recognizes this and represents a clear path for future research: to investigate the socio-economic,

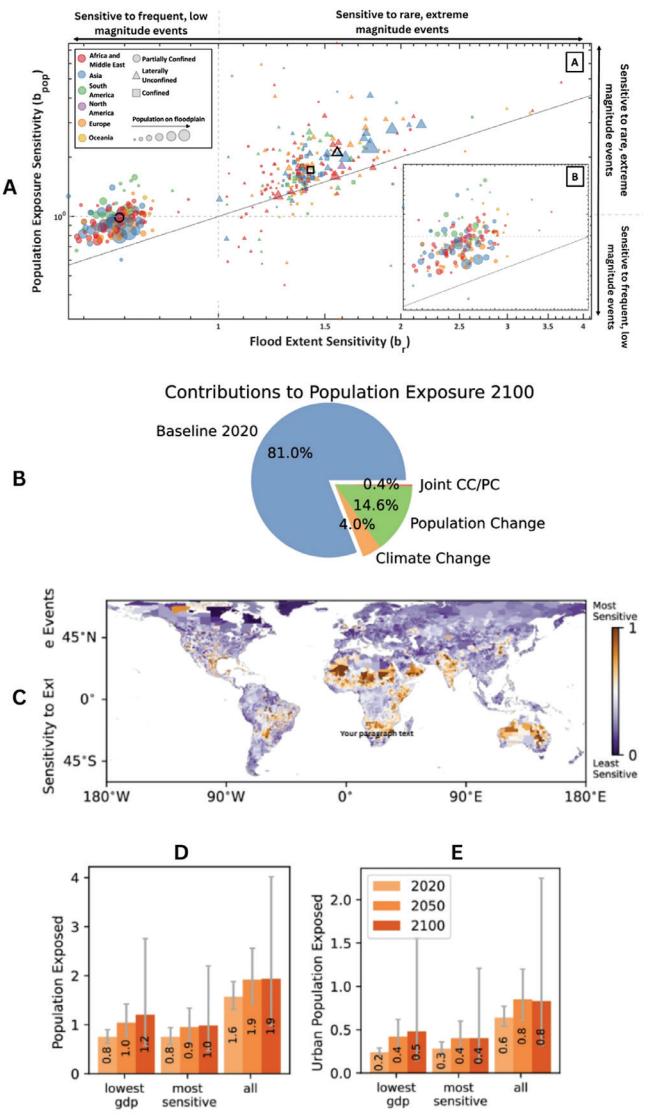

Figure 1. *(A) Interaction between flood hazard and population exposure sensitivity. For each country, flood hazard sensitivity (how quickly flood extent increases with flood magnitude; x-axis) is compared to population exposure sensitivity (how rapidly population exposure increases as flood extent increases; y-axis) (Figure 1A is reproduced from Devitt et al. (2023) under CC BY 4.0 license). (B) Effects of climate change vs population change on population exposure between 2020 and 2100. The projected increase in global population exposed to 100-year flood hazards between 2020 and 2100 into contributions from climate change, population change, and their joint effects. (C) A heatmap of regional flood sensitivity to extreme events displays vulnerability and flood sensitivity to extreme events. (D) Changes over time in the number of people exposed to flooding by GDP per capita tier (low, medium, high), and (E) The same for urban populations (Figures 1B-1E are reproduced from Rogers et al. (2025) under CC BY 4.0 license).*

political, and cultural drivers of where and why vulnerable populations become concentrated in high-risk floodplains and consider how targeted actions might modify those concentrations over time. While the authors of Devitt *et al*. (2023) analyzed alternative settlement or planning scenarios with their results, they did not quantify how much economic loss could have been avoided by using those scenarios. The authors have taken a fixed view of today's patterns and related these to the results that could be expected. There is a lack of literature that discusses the effects of alternative exposure distribution scenarios on future returns or adaptation strategies in practice. This review examines how prior studies link population density and loss outcomes and notes growing interest in modeling approaches that look at population density, damage mapping, and loss mitigation strategies such as land use zoning, relocation, and investment in disaster resilience.

Rogers *et al*. (2025) show that, through Figure 1B, projected flood exposure is shaped by both climate change and population growth, with population change contributing substantially to future risk. It demonstrates that future flood exposure will depend not only on changing hazards but also on how people continue to settle and concentrate in flood-prone areas. In the bar charts in Figure 1C, it is seen that future flood exposure is likely to be concentrated in lower-income and rapidly urbanizing regions. It shows that exposure growth is shaped by socioeconomic conditions as well as geography, reinforcing the uneven distribution of future flood risk. "Most sensitive" countries are those that are projected to experience the greatest changes in exposed population per unit change in flooding or population growth. The "GDP" stratification sorts of countries according to World Bank income terciles, and "rural-urban" solutions are uniformly based either upon spatial classifications or population grid definitions.

Rogers *et al*. (2025), in Figure 1B, present a visualization of changes in global flood exposure from 2020 to 2100 under a variety of scenarios (5). The authors separate the projected increases in population exposed to flooding into the contributions of climate change and the contribution of population growth, and/or urbanization, by combining a global model of flood inundation at high resolution and population projects based on Shared Socioeconomic Pathways (SSP) and running a set of simulations where they held each driver constant in turn and then compared the results. The authors illustrated their results in a pie chart of central estimates with 21% of new global exposure by 2100 attributable to changing climatic hazards only, and 77% due to population growth and urbanization, particularly in low-income and growing regions.

Figure 1B shows that the balance between climate and population drivers varies by region and scenario, reflecting local trajectories of urban growth and development. Across the scenarios considered, a consistent pattern emerges: changes in where and how people settle tend to play a larger role in shaping future flood exposure than changes in hazard alone. This methodological approach, derived from global and U.S. city datasets, highlights the disproportionate role that urbanization and land-use policy will play in future flood risk - and an urgent need for urban floodplains to have forward-looking and effective target adaptation & planning. While existing global projections often view increased population numbers and the provision of related infrastructure as relatively independent of one another, and do not tend to include explicit infrastructure pathways or related policy decisions as part of their scenarios, there appears to be an implicit assumption made about how future exposure growth will occur without any intentional, evidence-driven efforts being made to do so. In this manner, the existing global projections may significantly overestimate the amount of risk that exists for loss of property values due to "locked-in" risk, while significantly underestimating the amount of risk that exists for loss of property values associated with/benefited from strategic planning efforts. An important trajectory emerging from this literature is the call for scenario frameworks that jointly consider changing population density, land-use policies, and infrastructure development when exploring future economic flood loss.

Rogers *et al*'s (2025) findings show that by 2100, the number of people facing significant flood risk will substantially increase relative to 2020 (5). Figure 1C maps where populations are most sensitive to extreme flood events, showing large clusters of highly sensitive areas in parts of South and Southeast Asia, Sub-Saharan Africa, and several major river basins worldwide. Figures 1D and 1E then break down how exposure in these locations is projected to grow between 2020 and 2100, both overall and within urban areas, and stratified by country income and by "most sensitive" regions. Figure 1D and 1E show that future exposure growth in both urban and non-urban areas is expected to be especially pronounced in lower-income countries. The key value of these figures is that they link economic vulnerability to rising flood exposure, rather than treating exposure growth as geographically uniform. Figure 1E also reinforces the idea that urbanization plays

a central role in shaping flood risk and supports the need for city-focused adaptation planning. Together, panels 1C, 1D, and 1E indicate that much of the additional population exposed to 100-year flood hazards will be concentrated in low-GDP countries and in urban centers that are already highly sensitive to extremes, rather than being evenly distributed across regions. This pattern suggests that future flood risk will increasingly reflect underlying demographic, economic, and policy trajectories, reinforcing the need for urban planning, adaptation, and poverty-responsive disaster policy that specifically targets these high-exposure, low-resource settings.

National and Regional Case Studies

Swain *et al*. (2020) find empirical support for the notion that urban population growth is exceeding adaptation rates for flood protection in U.S. coastal metropolitan regions (7). Their scenario modeling predicts that population growth in highly exposed coastal zones will outpace flood protection adaptation from 2020 to 2050, leading to increased per capita flood losses in rapidly growing urban centers such as Miami and Houston. Overall, this case study demonstrates one of the common themes that emerges: that urban flood losses are increasingly driven by both evolving risks and an imbalance between urbanization and protective adaptation. Nevertheless, many regional analyses rely on simplified assumptions regarding adaptation processes, suggesting the necessity for comparative analysis based on standardized metrics.

Other studies in India (20) and Bangladesh (21) employed detailed, geographically granular analyses - often described as fine-scale because they examine administrative units or localized areas rather than broad regions. These studies used longitudinal statistical analyses that track changes across time within these units while controlling for multiple variables. They also explored scenario-based projections of flood impacts and consistently found that districts with higher population densities experienced more direct economic damages per event, even when accounting for infrastructure and flood hazard intensity (20, 21).

Figure 2 illustrates flood fatalities in relation to flooded areas for prominent flooding disasters between 1974 and 2017, showing a declining trend in deaths over recent decades. The authors claim this declining trend in deaths does not truly indicate a reduction in underlying risk because the total risk exposure has been increased with rapid population growth and settlements expanding into flood-prone areas. It indicates that declining fatality rates do not necessarily mean flood risk is decreasing. The figure supports the broader argument of this review that increasing exposure can offset gains in preparedness and hazard mitigation. While relative casualty rates due to floods have decreased, likely due to improved early warning and response, the absolute number of deaths during catastrophic flood events remains high. In other words, flood control and preparedness efforts may have reduced a certain loss, but the rapid accumulation of people in hazard zones has resulted in greater risks to larger numbers of people and assets.

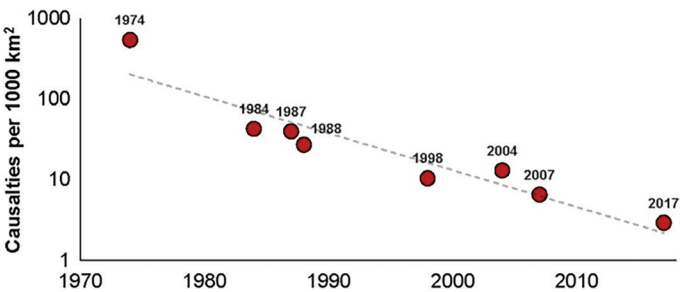

Figure 2. *Flood fatalities in Bangladesh, normalized by flooded area (casualties per 1,000 km2), for major flooding events between 1974 and 2017 (This figure is reproduced from Ferdous et al. (2020) under CC BY 4.0 license).*

Figure 3 shows a sequence of spatial and temporal snapshots of settlement expansion and embankment in Gaibandha and Sirajganj towns between 1989 and 2014 (top panels) and a robust plot of population growth between 1901 and 2011 (bottom panel). Figure 3A demonstrates how settlement expansion into flood-prone areas can intensify flood exposure over time, while Figure 3B shows that population density increased substantially over time in both towns, especially in Sirajganj. Both figures are important because it links urban growth, land use change, and flood protection limits in a way that helps explain why some towns become increasingly vulnerable despite existing embankments. It demonstrates how long-term demographic growth can raise flood risk even when protection infrastructure is available and present. These trends illustrate how, in this case study, population growth outpaced infrastructure maintenance and planning, increasing local vulnerability to flood loss. (21). Nonetheless, the metrics and spatial scales used to represent both density and infrastructure differ markedly across these case studies, which complicates direct comparison and limits how confidently these patterns can be generalized.

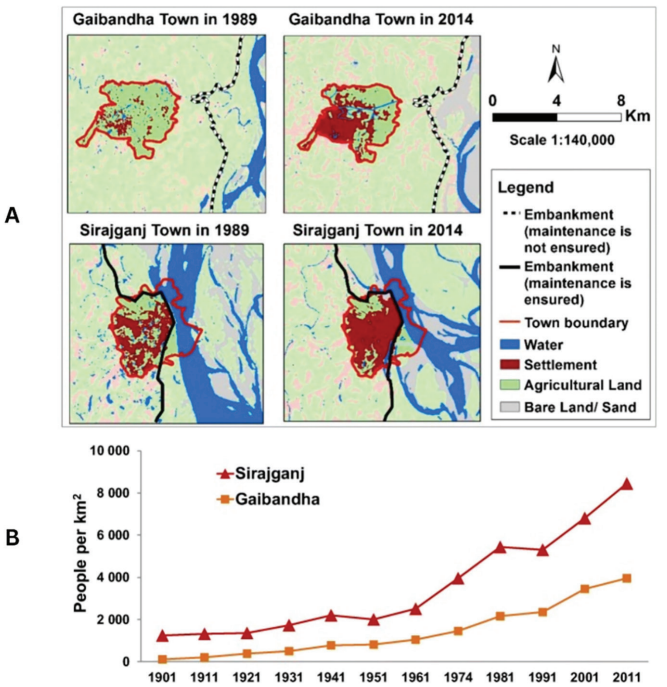

Figure 3. *(A) Spatial evolution settlements in Gaibandha and Sirajganj between 1989 and 2014, showing expansion into surrounding agricultural floodplain areas and position of embankments. (B) Long-term change in population density for Gaibandha and Sirajganj from 1901 to 2011, illustrating sustained, faster growth in Sirajganj (Figures 3A-3B are reproduced from Ferdous et al. (2020) under CC BY 4.0 license).*

Social Vulnerability and Inequity

Population density has been found to interact with various socioeconomic vulnerabilities and inequalities in flood loss, as demonstrated in other research. For example, Sanders *et al*. (2024) investigate how flood losses are distributed unevenly among urban populations using Lorenz curves and Gini coefficients, tools that describe the degree of inequality in loss distribution (11). The authors note that population groups sustaining residency in floodplains with the highest density typically have low adaptive capacity due to low incomes, lower recovery resources, and lower access to insurance or protective infrastructure, as observed across neighborhoods in their research. They conclude that the combination of these conditions results in significant inequality in flood loss in urban areas, as the dense, resource-limited group bears the brunt of flood losses (11).

Population density's impact extends past bodily exposure. Deria *et al*. (2020) and Hemmati *et al*. (2021) illustrate, through social and spatial vulnerability indices, how high density is often accompanied by socioeconomic marginalization, forming "risk traps" where flood effects disproportionately fall upon the marginalized (21, 23). For example, Hemmati *et al*. (2021) demonstrate that in flood-prone areas of Iran, densely populated, low-income neighborhoods suffer from limited access to recovery resources and protective infrastructure, which exacerbates their vulnerability. Such accounts show that periods of recovery and economic dislocation are intensified in zones of low-income urban concentration, where clustering strains available resources and deepens long-term social exposure. In their case studies, marginalized communities in dense neighborhoods experienced longer recovery times and higher economic setbacks after flooding compared to wealthier, less dense districts, directly supporting this broader claim (21, 23).

Sanders *et al*. (2024) use Lorenz curves and Gini coefficients to show that flood losses are unevenly distributed across populations. The figure is important because it demonstrates that flood risk is not only about total damage, but also about who bears that damage, which is central to understanding vulnerability and equity. It not only shows that flood losses are larger in dense urban areas, but also more unevenly distributed across social groups. Figure 4 strengthens the argument by showing that flood impacts are concentrated among more vulnerable populations, supporting that population density interacts with income, adaptive capacity, and access to protection. It supports the conclusion that flood risk is not simply a matter of exposure, but also of social burden. Using the Lorenz curve and Gini coefficient, the authors show that densely populated, low-income neighborhoods carry a disproportionate share of damage from urban flooding, revealing how settlement patterns encode social inequality in disaster risk. However, the majority of past assessments address population density as a static context, not considering how population density interacts dynamically with housing markets, infrastructure development, and public policy decisions. This raises the possibility of unintentionally perpetuating the idea that low income, high population density neighborhoods will remain permanent, while neglecting that the governance and investment patterns have the power to change such areas. A possible area for future research would be to incorporate Lorenz/Gini-type analyses with longitudinal data on neighborhood development to evaluate how interventions or infrastructure improvement projects alter both population density patterns and equity in the impacts of flood loss over time.

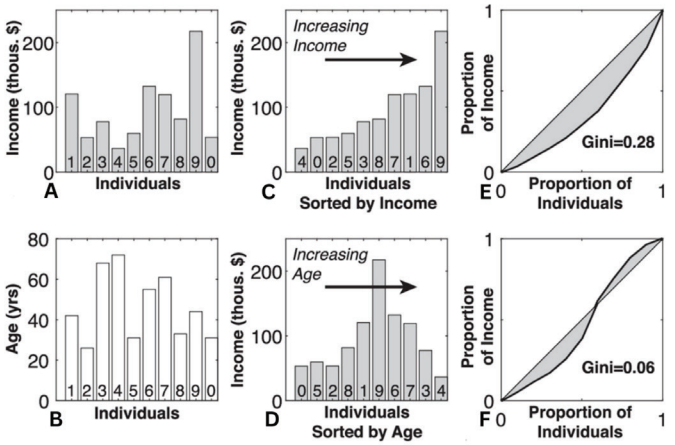

Figure 4. *(A) Example distribution of income across individuals. (B) Corresponding ages for the same individuals. (C) Income bars reordered from lowest to highest income. (D) Income bars reordered from youngest to oldest age. (E) Lorenz curve of the income distribution in (C); the shaded area between the curve and the 45° line illustrates inequality (Gini = 0.28). (F) Lorenz curve of the income distribution in (D), showing a more even income distribution when ordered by age (Gini = 0.06) (Figures 4A-4F are reproduced from Sanders et al. (2024) under CC BY 4.0 license).*

According to Vestby *et al*. (2024), population density emerged as an important predictor of displacement and asset loss, with urban populations found to be at greater risk than rural populations because of higher concentrations of people and assets (2024). Urban areas are more complex systems than rural areas, characterized by higher population density, limited evacuation options, and increased risk of significant disruptions to critical services and infrastructure - referred to as operational damage - posing multifaceted challenges. In addition, their findings revealed that flood-related displacement is highly variable across the world, experiencing greater severity in low-income regions and in conflict-affected areas with limited governance or recovery capabilities. These dimensions can exacerbate the negative effects of population density, worsening vulnerabilities which suggests population density may be a social vulnerability measure after floods and not just a method of exposure measurement. Taken together, these findings support a re-interpretation of population density not only as an exposure metric but as a composite social vulnerability indicator that encodes constraints on mobility, recovery, and access to protection. This review builds on that reframing by examining which existing studies already treat density in this dual role and where models still rely on overly simplistic exposure-only formulations.

A wide range of supplementary research, which includes case studies, supports this notion: flood impacts, when disaggregated - meaning analyzed independently by characteristics of the affected populations (e.g., renters versus homeowners, income strata, or insurance access) - indicate that dense neighborhoods with higher proportions of renters, or economically vulnerable residents, are experiencing the most severe and inequitable damages (25). Taken together, these studies indicate that the intersection of density with socioeconomic status is a major driver of social inequity in flood risk, underscoring the need for targeted mitigation and adaptation funding and urban policy that serves those most vulnerable to flooding.

Population Density in urban Flood Risk and Economic Loss

Across cross-national and multi-scalar studies, population density consistently appears as an important factor associated with flood and economic loss. More densely populated urban locations tend to experience greater losses than less dense counterparts, reflecting the concentration of people and assets in spaces where protective capacity may be insufficient. Moreover, population density worsens social disparities in flood damage, disproportionately affecting vulnerable groups of individuals who are geographically aggregated in hazard-prone areas. Taken together, these patterns underscore a strong association between higher population density and more severe economic flood damages and highlight the importance of integrating demographic spatial data into flood risk models and urban adaptation measures. Thus, population density also serves as a primary criterion for flood risk assessment, in addition to being a basic reference for population-driven adaptation and urban planning frameworks at risk.

FLOOD RISK INFRASTRUCTURE AND ITS RELATIONSHIP WITH ECONOMIC FLOOD DAMAGE

Comparing Infrastructure and Economic Outcomes

Several studies across diverse global regions have measured the quality and extent of flood control infrastructure and its impact on economic losses. For example, Fan *et al*. (2025) contrasted cities globally and found that those with stronger flood protection experienced substantially lower direct losses than those

relying on outdated or incomplete systems, affirming the role of infrastructure in economic resilience (3).

Figure 5 shows that infrastructure performance depends on hazard intensity, not just infrastructure presence. It supports that flood risk management cannot rely on a single protection layer, especially in rapidly urbanizing areas where drainage systems, green space, and land-use planning must work together. The figure explains why the relationship between population density and flood loss becomes more severe when the infrastructure is overwhelmed by larger or more frequent events. Possible reductions in grey infrastructure effectiveness during extreme climate events, such as climate change-induced rainfall, may result in urban flooding risk. In these contexts, flood management may require strategies that extend beyond conventional grey infrastructure alone. Planning for resilience in a warming climate conveys the challenge that climate change is increasing the frequency and intensity of extreme climate rainfall events, which matter for the amount and extent of flooding. Urban flooding will become increasingly difficult to manage, as conventional approaches typically account only for historical or current climate trends and infrastructure performance, making them inflexible and insufficient to address the challenges of more frequent and intense extreme rainfall events under climate change. This necessitates a shift toward climate-resilient solutions that integrate adaptive and forward-looking strategies. Many prior studies examine individual infrastructure components in isolation, but fewer evaluate how combined protection strategies perform across different hazard intensities This review highlights that gap and points to figure work comparing portfolios of grey, green, and policy-based approaches under moderate to extreme rainfall to identify combinations that are most effective at limiting economic losses.

Green infrastructure has well-documented benefits in mitigating flood damage over time. In a longitudinal coastal Texan city analysis, Sohn *et al.* (2021) demonstrated that neighborhoods with higher levels of green infrastructure - i.e., vegetated buffers or urban forests - had much reduced flood damages over multiple major events (27). The longitudinal datasets found that, irrespective of population accumulations and stream inventories, communities with greater

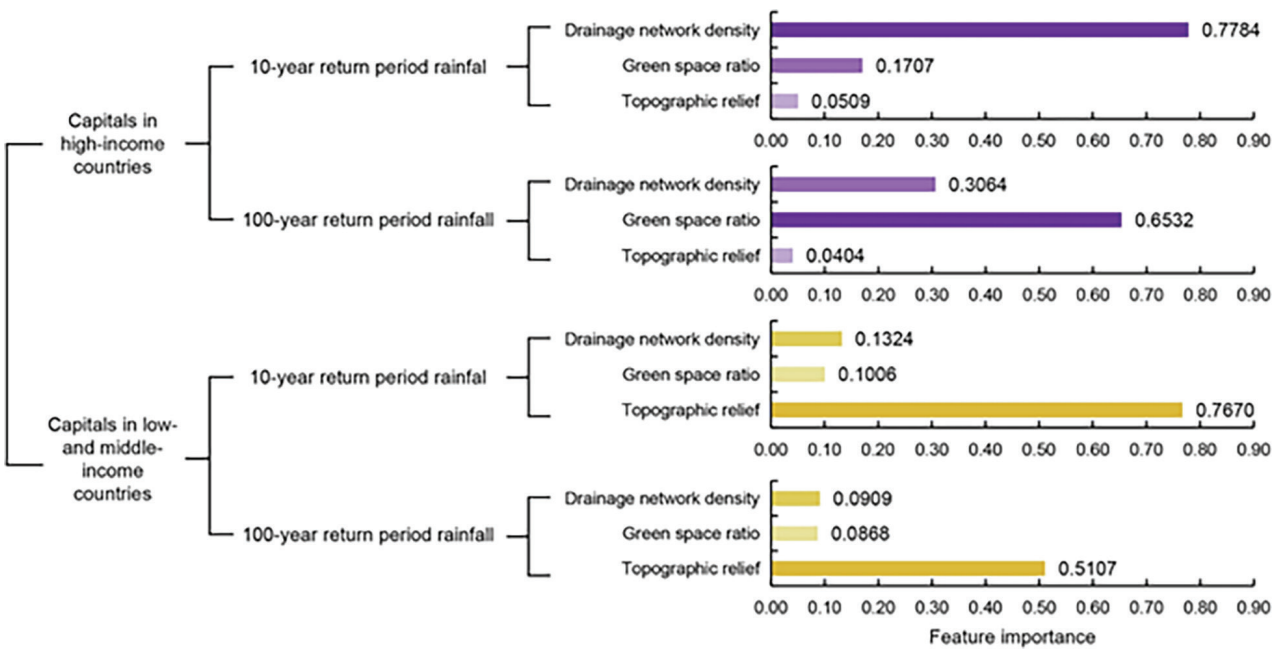

Figure 5. *The impact of drainage network density, green space ratio, and topographic relief on inundation ratio under varying levels of economic damage. The projected changes in flood exposure and vulnerability depict flood exposure in terms of the number of people at risk under future climate and socioeconomic scenarios, highlighting spatial distributions and temporal trends. Key variables include population counts exposed to flood hazards, degrees of vulnerability based on economic and infrastructural factors, and regional breakdowns to show geographic variability in exposure and risk (This figure is reproduced from Fan et al. (2025) under CC BY 4.0 license).*

green infrastructure incurred lower flooding damages following intense rainfall. The more distinctive impact of green infrastructure is its ability to improve infiltration and slow drainage, in addition to the ecological co-benefits that green infrastructure adds to traditional grey infrastructure. All of this adds evidence for green infrastructure being a vital complementary strategy to existing grey infrastructure for flood risk reduction.

The quality and design of drainage systems are important. According to a comprehensive review by Guo *et al*. 92021, coupled 1D/2D drainage modeling plays an important role in appraising and managing urban surface flood water. Models that omit drainage flow often overestimate flood depth and duration, especially in local events, and can misrepresent risk. Implementation of hydrological and hydrodynamic coupling models enables cities to explore various drainage network enhancements and assess their potential to reduce flood risk. This approach has gained increasing empirical support and has been incorporated into urban flood planning policies in regions including the U.S., Europe, and Asia, as evidenced by multiple case studies demonstrating improved flood resilience through such models, as mentioned in the article (14).

Figure 6 depicts the modeling procedure for urban flood risk analysis with a division of the area under study into zones of hydrology and zones of hydraulics. To explain the process of water getting into the storming urban catchment, hydrographs and hydro methods are used to model the rainfall and the runoff process. Outputs made in these domains will be further processed in the hydraulic domains, where a model based on shallow water will dynamically simulate the flood waters' traveling the accumulation on urban surfaces, and the consideration of the drainage infrastructure and street networks is also made. It suggests how hydrological processes and urban infrastructure must be modeled together to understand flood risk ideally and realistically. In the context of this review, the figure supports the broader argument that drainage systems, street networks, and surface runoff interact to shape where flood losses accumulate, helping identify where infrastructure upgrades may most effectively reduce damage. It emphasizes the fact that the value of coupled modeling as a decision-support tool for comparing adaptation strategies and targeting investment in flood-prone urban areas.

Products of such coupled modeling are important for identifying where to invest in infrastructure improvements - such as drainage upgrades, retention basins, or floodwalls - that will yield the most significant economic loss reduction benefits in flood hazard areas. For example, Guo *et al*. (2021) describe how urban flood risk assessments using coupled hydrological and hydrodynamic models, as represented in Figure 6, simulate detailed floodwater flow and interactions with drainage infrastructure across urban catchments (24). This modeling enables identification of critical locations of floodwater accumulation and drainage system constraints, guiding targeted investments in infrastructure upgrades such as stormwater system enhancements or flood barrier placements. These detailed outputs assist policymakers and planners in prioritizing flood mitigation measures that are likely to reduce economic losses and improve urban resilience. This modeling approach provides policymakers and urban planners with a sophisticated decision-support tool, showing the limitations of more traditional hydrologic models based on special assumptions that do not include urban hydraulics. It demonstrates the necessity of combined hydrodynamic simulations for addressing flood risk management planning more completely. For example, the ability to simulate flood water accumulation and movement over urban land and drainage operation can inform where flood mitigation investments are likely to be most effective. For this reason, Figure 6 highlights the urban flood processes and how the quality and design of infrastructure predominantly relate to the economic impacts of flooding. Many of the current coupled models

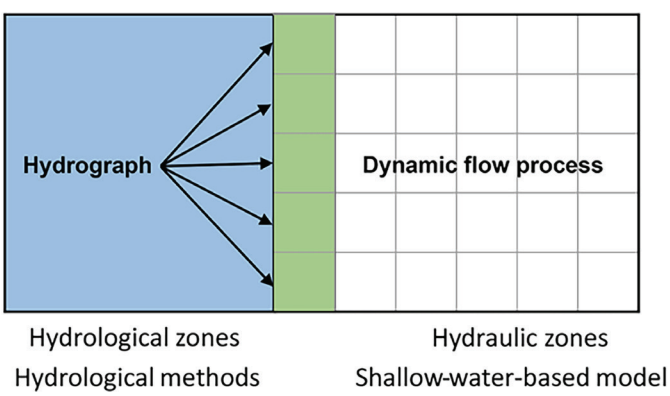

Figure 6. *Divided study area of a coupled hydrological and hydrodynamic urban surface model. The partitioning of the study area into two sections: hydrological zones (where rainfall and runoff are conceptualized using hydrograph and hydrological processes) and hydraulic zones (where shallow-water equation models simulate dynamic moving floodwater flows and accumulate on the urban surface) (This figure is reproduced from Guo et al. (2021) under CC BY 4.0 license).*

still incorporate simplified assumptions regarding drainage conveyance capacities, boundary conditions or infrastructure performance under stress, and do not systematically link outputs to the actual drainage loss comparison database. Thus, the current models do not provide sufficient empirical evidence concerning the hydrologic realism of infrastructure performance variability in relation to economic impacts or comparative evaluations between various design standards. Future research directions are indicated by this review through further enhancements of the coupled modelling systems with standardized economic loss function comparatives and scenario-testing on infrastructure improvement alternatives; in addition to allowing for more direct comparisons of cost-effectiveness and equity results between different design options.

Green Infrastructure and Flood Damage Mitigation

Green infrastructure (GI) - including urban forests of the modern era, vegetative buffers, and wetlands - functions as a natural flood resilience by enhancing processes such as infiltration, increasing soil water retention capacity, and slowing surface water movement. These natural hydrological processes exemplify effective flood management techniques, leading to significant reductions in flood impacts (13). Base *et al*.'s longitudinal spatial panel analysis tested GI conditions in coastal Texas cities and reported a strong negative relationship between green infrastructure connectivity - defined as the degree to which green spaces are physically and functionally linked to reduce runoff pathways and enhance hydrological continuity - and normalized flood damage. It suggests that higher connectivity not only mitigations the severity of flooding but also the economic loss that accompanies it.

Additionally, a case study by the Center for Policy Research on Energy and the Environment (25) extends this line of work by combining ecosystem service valuation with flood risk modeling to show how green infrastructure can reduce flood exposure while simultaneously providing benefits such as biodiversity conservation and urban cooling. The authors' approach uses coupled valuation and flood risk models to link flood risk-reduction with broader ecosystem resilience.

Green infrastructure is increasingly adopted as a complement to traditional flood risk management due to its multiple benefits. However, the existing quantitative studies still tend to be site-specific and lack standard measurements, limiting comparability across studies and with traditional flood protection measures.

Advanced Urban Flood Modeling and Infrastructure Planning

Urban flood modeling development follows the growing complexity and needs to simulate flood behavior in more populated and hydrologically engineered environments. Coupled hydrologic-hydrodynamic models are the current paradigm for this development, integrating rainfall-runoff response with the spread and storage of floodwater across urbanized areas, such as drainage systems, stormwater infrastructure, and natural water bodies. Guo *et al*. (2021) describe a modeling framework that spatially discretizes cities into hydrologic zones where precipitation is converted to runoff using rainfall-runoff models and hydraulic zones where shallow water equations simulate flood propagation with the consideration of urban infrastructure such as roads, retention basins, and drainage networks (14). Figure 6's representation of such spatial models can be seen in their framework diagrams, which visually display the separation of hydrologic and hydraulic zones. These models provide ways of dealing with and planning around complex spatial heterogeneity - such as the organization of impervious surfaces and topographic depressions - allowing hotspots of flooding and the influence of infrastructure capacity or deficits to be detected. Accurate modeling is therefore critical for designing or upgrading infrastructure to mitigate these risks effectively.

Complementary work by Ceola *et al*. (2022) applies satellite remote sensing data coupled with large-scale hydraulic models to track floodplain dynamics over long timescales and large extents in Australia's Murray-Darling basin (1). Spatiotemporal precision of flood mapping is enhanced by the integration of high-resolution synthetic aperture radar observations to facilitate model calibration and post-event validation, which is essential for operational decision-making and evaluating flood defense effectiveness. This approach enables scenario testing of various hypothetical infrastructure investments, such as green-gray hybrid systems that combine traditional engineered structures with ecological features, guiding adaptive management under climate variability.

An example is from Figure 7 of Ceola *et al*. (2022), which tracks changes in built-up urban land by flood risk classes across the Murray-Darling Basin, from 1973 to 2014. It shows that development often continues to expand into flood-prone areas over time, even where risk is already recognized. For this review, the figure helps demonstrate that flood exposure is shaped not

only by hazard maps but also by land-use choices, urban growth, and the extent to which planning redirects development away from high-risk zones. It therefore reinforces the need to connect infrastructure planning with land-use policy if future losses are to be reduced. The data presented illustrates that locations that are currently at risk of floods are expanding because of urban development encroaching into flood-prone land. This highlights a need for integrated land-use and infrastructure planning to minimize economic losses. In many studies of (future) development trajectories and protection standards (e.g. business as usual versus high adaptation), researchers and planners define development trajectories; instead of deriving these from actual behavior or co-designing with affected communities and decision-makers, researchers define these as either "business-as-usual" or "high adaptation". As a result, most studies have little to no means by which they can assess how confident the recommendations made by them can realistically translate into real-world situations. Furthermore, this paper identifies a future area of exploration for researchers where there is empirical evidence available for how high-risk areas have actually been developed, and this evidence is combined with the use of either participatory planning tools (such as stakeholders' workshops or stakeholder-developed scenarios), or optimization tools (such as models designed to identify the most effective combinations of zoning, retreating, and infrastructure investment under given constraints). Therefore, researchers' efforts are being directed towards identifying strategies that can effectively and realistically redirect future growth away from the highest-risk zones (1).

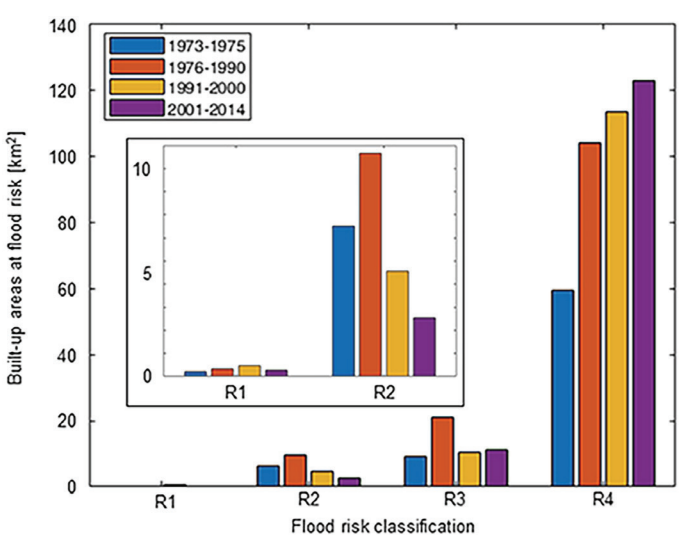

Figure 7. *The temporal evolution of the spatial extent of built-up areas classified into different flood risk categories within the Murray-Darling Basin from 1973 to 2014. The variables represent the total area of urban land (built-up surface) in each flood risk class, defined based on percentile thresholds combining flood hazard and exposure. The inset zooms in on the lower risk classes for a detailed view (This figure is reproduced from Ceola et al. (2022) under CC BY 4.0 license).*

Property-Level Flood Risk Adaptations: Efficacy and Socioeconomic Considerations

Flood risk reduction interventions extend beyond urban infrastructure to include household-level adaptations. Wet-proofing - making water-resistant structures and elevating them above ground - and dry proofing - using barriers or closing openings - are examples of methods that directly reduce susceptibility to flood damage. A global meta-analysis by McClymont *et al.* (2020) concluded that property-level interventions can substantially reduce damage across flood types, geographical settings, and social/economic conditions (12). The paper combines hundreds of field studies undertaken after post-flood field studies and audits, concluding that wet and dry proofing also reduces disruption to livelihoods, mitigates mental health impacts such as stress and anxiety, and accelerates recovery for affected populations. These benefits support planners' adoption of Property-Level Flood Risk Adaptation (PLFRA) measures into subsidized retrofitting programs, tax incentives, or insurance premium discounts to encourage widespread adoption.

The effectiveness of such interventions is subject to the existing socioeconomic status, however. Deria *et al.* (2020) illustrated that unevenly allocated access to adaptation measures - be it due to low income, lack of education, or physical barriers - can render the total damage greater by raising the risk in the most vulnerable regions (22). Addressing these disparities through public investment, outreach programs, and inclusive building codes is essential for promoting equitable distribution of adaptation benefits and enhancing community resilience.

Household-level adaptation may work more effectively when it is aligned with municipal flood management. Previous studies showed that combining local adaptation measures, such as those at the household level, with municipal-scale drainage improvements can enhance protection. However, these measures are often studied in isolation, limiting understanding of their interactions and system-level effectiveness.

Economic Growth and Municipal Fiscal Sustainability Derived from Infrastructure

Flood risk infrastructure investment spurs economic activity by creating direct jobs, supply chains, and ensuring business continuity in affected urban centers. The 2024 Economic Impact Report gives it a dollar value: $1 million in FEMA mitigation creates 40 jobs and four new businesses, spreading benefits out of construction into ancillary service and retail Most importantly, these benefits persist beyond the early stages of infrastructure. Continued investment generates skills and local partnership formation, increasing aggregate demand and regional business innovation. Infrastructure also builds confidence to undertake external investment and real estate development necessary for long-term economic planning.

Economic research by the Bank of Japan confirms broader linkages between flood infrastructure and macroeconomic stability, finding localities with robust flood protection schemes to be more resistant to GDP shocks and better able to respond to disaster-induced recessions by preserving industrial capacity and consumer markets (28).

Municipal budgets are no different. Unterberger *et al*. (2018) demonstrates that municipalities with proactive investment in infrastructure boast better post-disaster budget balances, reduce emergency borrowing, and avoid severe public service cuts (29). These financial capacities enable more thoughtful reinvestments, accelerate recovery trajectories, and allow a stronger public to have confidence in local government, raising adaptive capacity for future flood seasons. As summarized schematically in Figure 8, their analysis links flood hazard, exposure of public assets, and the vulnerability of municipal finances to show how infrastructure damage translates into fiscal strain. Figure 8 links flood risk to more than physical damage, showing how infrastructure investment also shapes economic stability and municipal fiscal resilience. In the context of this review, the figure supports that flood protection effects not only exposure and losses, but also recovery capacity, budget balance, and the ability of local governments to plan ahead. It reinforces the broader point that infrastructure spending is an adaptive strategy with economic and governance benefits beyond immediate hazard reduction

The direct budgetary costs of flood damage to public infrastructure are shown in Unterberger *et al*.'s regression results for Upper Austrian municipalities, which indicate that substantial flood damage is associated with large decreases in current income balances and annual outcomes, together with declines in asset and transaction management balances (29). These effects persist for several years after the event, which indicates that the fiscal burden persists longer than physical rehabilitation. Importantly, local governments with more successful pre-flood land use and investment controls have reduced fiscal impacts and quicker budget stabilizations. This underscores the preventive economic advantages of resilient infrastructure: the findings provide empirical support for the review that preparedness and adaptation are key both to damage reduction and to maintaining healthy municipal finances. Yet, fiscal impact studies often rely on single-country or single-region datasets and use differing indicators, limiting cross-context comparability and the ability to generalize how infrastructure investment

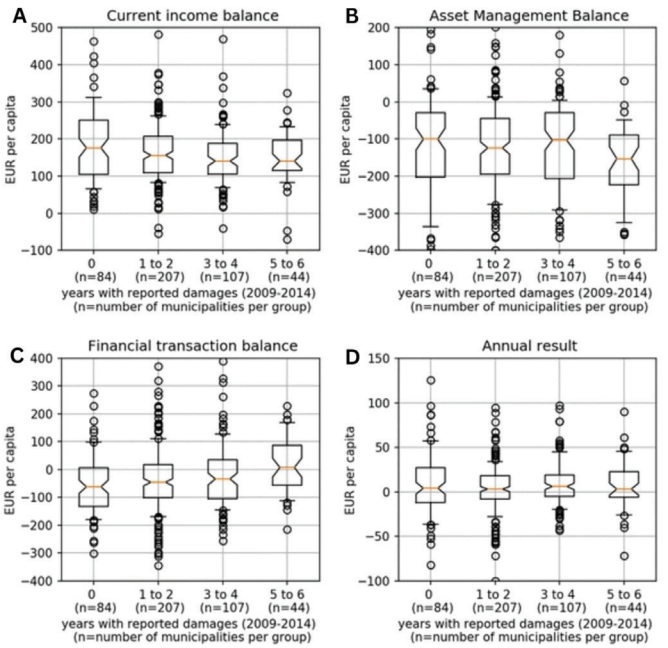

Figure 8. *(A) Conceptual diagram of flood hazard, indicating the occurrence of damaging flood events that affect municipal infrastructure. (B) Conceptual diagram of exposure, showing public infrastructure and assets located in areas that may be affected by floods. (C) Conceptual representation of vulnerability, emphasizing municipal budget structures and their sensitivity to flood-related damage and recovery costs. (D) Integrated schematic linking hazard, exposure, and vulnerability to illustrate how flood damage to public infrastructure translates into fiscal impacts to municipalities (Figures 4A-4D are reproduced from Unterberger (2017) under CC BY 4.0 license).*

patterns translate into budget resilience. There is a clear opportunity for more standardized, cross-national analyses that link pre-disaster infrastructure quality, loss outcomes, and post-disaster fiscal trajectories, providing stronger quantitative guidance for municipal budgeting and national adaptation finance mechanisms.

Climate change worsens flood risks by increasing both the frequency and magnitude of extreme precipitation events, thus increasing the strain on existing infrastructure and municipal resources. Furthermore, without ongoing investments in physical construction, maintenance, and adaptation of infrastructure to a changing climate, cities cannot avoid increasing economic losses and public fiscal distress. Budgeting mechanisms must therefore facilitate both the growth of the economy and a long-term resilience strategy to protect urban centers to accommodate the future patterns of flood risk, while also protecting physical assets from flood risk and diminishing fiscal sustainability. As climate change and urban growth increase exposure, the economic value of sustained infrastructure investment becomes more significant. Cities require not only initial flood protection spending, but also long-term maintenance and upgrade cycles that support both fiscal stability and resilience.

Urbanization, Social Vulnerability, and Infrastructure Effectiveness

The effectiveness of flood risk infrastructure also depends on who is exposed and how protection is distributed. Rogers *et al.* (2025) found that urbanization has emerged as a primary factor in global increases in flood exposure (5); however, while flood exposure matters, social vulnerability, infrastructure disparities, and the uneven ability to adapt have significant roles in determining where flood damage is most severe. For this reason, under-resourced communities are frequently hit by floods repeatedly and recover more slowly even when flood protection infrastructure exists.

The emphasis in current research and policy frameworks for planning, such as the Global Commission on Adaptation (30) and the United Nations Office for Disaster Risk Reduction (UNDRR) Sendai Framework (31), is on adaptive and inclusive planning that treats equity and vulnerability as explicit outcomes of infrastructure decisions. More emphasis on adaptive and inclusive flood management has been placed on recently planning frameworks, which can treat vulnerability and equity as more explicit outcomes of infrastructure-based decisions. Several approaches are commonly recommended, including targeted funding for high-hazard, underserved communities; participatory flood mapping and planning; resilience standards for new development; and the strategic use of decentralized/nature-based measures. Nevertheless, there is still a significant lack of integration between the equity-focused frameworks and the models used to determine how and where to construct infrastructure. Consequently, a primary need identified from his review is the development of methodologies that evaluate not only overall reduced loss but also those that can determine who is receiving the benefits of the protection and who remains at risk of flooding.

Integrated Flood Risk Infrastructure and Economic Loss Reduction

This multi-facetted and interdisciplinary body of research suggests that integrated flood risk infrastructure - combining grey engineering, green ecological infrastructure, and property-level adaptations - can reduce economic flood damages while supporting socioeconomic resilience. Grey infrastructure continues to provide essential flood defense capabilities, while green infrastructure offers ecological benefits such as stormwater management, habitat provision, and urban cooling, which become increasingly critical under escalating climate extremes. Complementing these, home-based adaptations contribute to reducing vulnerability at the household level. Studies suggest that investments in these combined approaches can generate jobs, support enterprise growth, promote fiscal balance, and support faster, more resilient recoveries. These findings support long-term investment in flood risk strategies that are adaptive, equitable, and responsive to concentrated social exposure.

Although there are quantitative studies on grey, green, and household-level measures, most analyze these interventions separately or implicitly assume that all types are equally effective, regardless of the very different social and institutional contexts in which they are implemented. Prior studies point toward an integrated "multi-layer plus equity" perspective that considers infrastructure performance alongside economic losses and their distributional impacts. The literature highlights potential for using comparable metrics across studies to inform future research designs that integrate coupled models, empirical loss datasets, and socioeconomic indicators, helping policymakers develop infrastructure portfolios and financing strategies that balance economic viability with equity for disadvantaged populations.

INTERACTION BETWEEN POPULATION DENSITY AND FLOOD INFRASTRUCTURE

Whereas the above sections have discussed population density and flood infrastructure individually, the literature shows that flood damage can be better accounted for if both factors interact rather than one factor alone. Population density intensifies exposure by concentrating people, buildings, infrastructure networks, and economic assets into relatively small spaces, while flood protection infrastructure determines how effectively that concentrated exposure can be protected. In this sense, therefore, urban flooding risk cannot be defined simply by whether or not a city has a high or low density, or whether or not a city has infrastructure, but by whether or not the capacity, form, and spatial distribution of infrastructure are adequate relative to the scale and spatial concentration of human populations (2, 3, 5).

A key pattern that emerges from integrating these findings is that infrastructure effectiveness may decline in highly dense urban areas, particularly when urbanization outpaces adaptation. The issue is that, especially highly, the level of imperviousness, runoff volume, and drainage demands may actually increase, indicating that even the best flood defense measures may actually become inadequate, especially because such measures are supposed to protect a smaller number of people than are actually exposed to risks (3, 7, 14). This, therefore, means that the performance of such infrastructure is actually context-dependent, and this is why, for instance, some cities that are highly urbanized still experience high levels of damage, especially because such cities actually have nominal flood defense measures in place.

Previous studies also suggest a possible phenomenon of thresholds, whereby a point exists after which a certain level of urban density and asset concentration renders the provided infrastructure insufficient. Although such thresholds are yet to be quantified, several studies suggest that a point exists after which a flood event overwhelms a drainage system, flood protection measures do not reduce flood damage proportionally, or adaptation investments do not keep up with exposure growth (5, 7, 14, 26). This phenomenon has a particular relevance to developing and poor urban areas, which population growth and expansion into flood-risk areas occur more rapidly than improvements in protection and maintenance. This implies that future flood risk studies should consider thresholds and not just whether protection exists, but whether such protection exists in adequate quantities to match urban density growth.

This is especially the case with urban planning and land use policy, as they mediate this relationship over time. Dense urban growth is not inherently problematic from the perspective of flood resilience, and risk only becomes an issue when dense growth is allowed to occur in areas prone to hazards without proportional investment in protection, drainage retention, or adaptive design standards. Planning decisions, such as zoning, floodplain development, building codes, retreat, preservation, and infrastructure financing, all play a role in whether density becomes a factor in creating urban resilience of driving escalating loss (5, 30, 31). Therefore, the literature is increasingly moving towards an approach that promotes a shift from the current perspective of density and infrastructure as separate and independent factors and towards an understanding of them as part of an urban system where density, protection, and decision-making are coupled in determining the outcome of flood risk.

Overall, this perspective reinforces the main purpose of this review, that the determination of loss from floods is not solely determined by the hazard but is, in fact, determined by the interaction between concentrated populations and protective services, or the mis-match between the two.

CONCLUSION

This is a narrative review that investigated the interplay between population density and flood risk infrastructure and its resultant effect on economic flood loss and social vulnerability. The literature revealed a clear trend that, as the population density increases, the flood loss also increases, since the number of people and assets is concentrated in hazard-affected areas. The flood loss, however, does not entirely depend on the population density, as its extent also depends on the availability and suitability of flood risk infrastructure. The literature, therefore, indicates that flood risk is a product of exposure, infrastructure capacity, and social vulnerability, and these three factors are interlinked rather than acting as separate factors.

These results underscore the need to consider flood risk management in land use planning and infrastructure investment, as well as social policies. In urbanizing areas, unchecked development in flood-prone areas without a corresponding strengthening of flood defenses, drainage systems, and flood retention and adaptation measures

can result in increasing protection gaps and losses. To mitigate flood losses effectively, structural measures are just part of the solution, and social measures are equally important in prioritizing areas with high flood risk and disadvantaged populations. Multi-faceted approaches to flood risk management, which include structural measures and household-level adaptation measures, are likely to yield the most benefits in reducing overall losses and inequalities in losses.

At the same time, these practical implications also emphasize some important gaps in the current literature that future research should address. Future studies need to look beyond the analysis of the two variables individually and move towards the development of models that test the interaction between the two variables. There is also the need to develop standardized metrics that can be compared and contrasted, such as infrastructure capacity per capita, expected annual flood loss per capita, equity-adjusted recovery, and protection coverage relative to exposed populations. There is also the need to look into the threshold effects in highly dense urban areas, the evaluation of the effects of planning and policy decisions, and the integration of social equity into the assessment of flood risk. All these areas are likely to take the analysis of urban flood resilience to more realistic and equitable levels.

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CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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