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Addressing sustainable urban flood risk: reviewing the role and scope of theoretical models and policies

Gabriele Oneto * and Maria Canepa

Department of Architecture and Design, University of Genoa, Stradone S. Agostino, 37, Genoa, GE, Italy
*Corresponding author. E-mail: gabriele.oneto@edu.unige.it

GO, 0000-0003-3621-1179; MC, 0000-0003-2464-6757

ABSTRACT

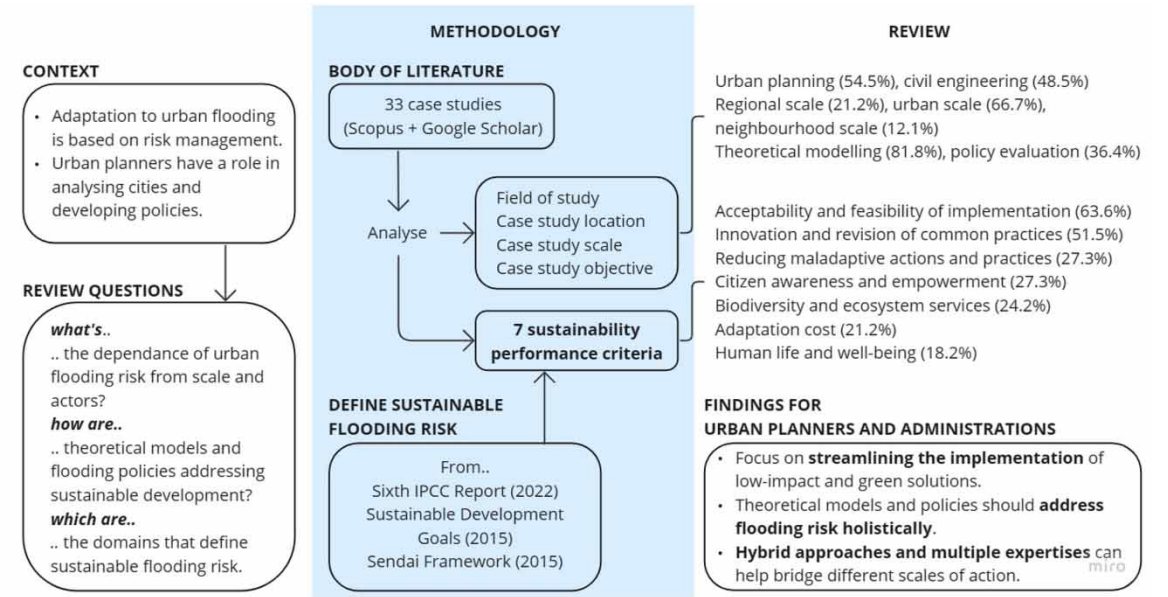
Contemporary adaptation to urban flooding is based on risk management. Urban planners have both an active role in studying cities and a supportive role in helping to define policies. From 33 case studies, this review tries to give insight into how flood risk management fares in confronting international directives on disaster reduction and sustainability, by defining seven sustainability performance criteria. Most studies try to maximize the acceptability and feasibility of implementing solutions in cities (63.6%) and the revision of existing building codes and plans (51.5%), while fewer try to test existing urban practices for weak points (27.3%). Analyses do not fully consider urban habitats as holistic and complex systems, as citizen awareness (27.3%), costs (21.2%), and biodiversity (24.2%) are some of the least recurring and intersecting themes. The main findings should help planners define new lines of action on urban flooding and consider alternative aspects in their frameworks.

Key words: Adaptation feasibility, Conceptual framework, Sustainable Development Goals, Sustainable governance, Urban design, Urban flood management

HIGHLIGHTS

- Contextuality is the most effective measure for the acceptability of LID solutions.
- The sustainability of flood management depends on the scale and objective.
- Streamlining the implementation of existing LID solutions should precede new ones.
- Conceptual models should bridge the scale gap and empower stakeholders.
- New frameworks should cover both physical and socio-economical vulnerabilities.

GRAPHICAL ABSTRACT



INDEX OF NOTATIONS AND ABBREVIATIONS

GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
LID	Low-impact Development
MCDM	Multi-Criteria Decision-Making
RFC	Reasons For Concern
SDGs	Sustainable Development Goals

1. INTRODUCTION

Flood management is traditionally associated with environmental and hydrological engineering, capitalizing on resistance-based strategies to remove or lower the risk to urban settlements (Keskitalo, 2013). Such approaches mislead the administration in believing that resistance-based solutions can effectively confront future flooding events. Exclusive engineering solutions do not fully take into consideration human life, properties, natural assets, and infrastructure (Ludwig, 1996; Dráb & Říha, 2010; Dawson *et al.*, 2011). Modern adaptive resilience approaches rely on the recursive processes that can be coupled with engineering systems but are open to different fields of studies and expertise (Park *et al.*, 2013). Risk mapping is usually considered a basic tool for urban flood monitoring and planning, often being the product of hydrological models and hazard maps. As such, several global flood risk assessment models have been developed in the last decade (Winsemius *et al.*, 2013). The Sixth Intergovernmental Panel on Climate Change (IPCC) Assessment Report described adaptation to water-related risks and impacts as the ones that make up most of all documented adaptation practices. The IPCC report configures flooding under the Reasons For Concern (RFC) framework as extreme weather events that

impact human health, livelihoods, assets, and ecosystems. As such, numerous guidelines for sustainable development are provided: from decreasing maladaptive actions, to increase in community resilience, and strengthening the acceptability of adaptation strategies.

Contemporary planning for disaster risk reduction aims to envision the consequences of development, using tools such as project cycle management and logical and results-based frameworks. The common mainstream process for sustainable risk management contemplates including socio-economic evaluation when updating construction designs and existing building standards (Benson *et al.*, 2007). As such, modern-day urban development and renovation try to adapt to future scenarios while integrating existing physical and cultural assets. Contemporary policies for urban flooding adaptation and mitigation are being developed side-by-side with international directives, originating from the Sustainable Development Goals (SDGs). Urban planning for contrasting flooding is considered in the third objective (Good Health and Well-being), 11th (Sustainable Cities and Communities), 13th (Climate action), and 15th (Life on Land). Such a broad point of view considers a vaster assortment of stakeholders, distancing from the traditional anthropocentric planning that characterized past practices. Tackling flooding risk often incurs difficulties as management is not always designed for integrated management (Kreibich *et al.*, 2022). A gradual transition in both analytically describing the event and legislating around vulnerability and exposure is taking place. As more socio-economical characteristics are being taken into account to better understand and describe human environments, including both anthropic and natural assets, a shift and redistribution of responsibility is occurring (Butler & Pidgeon, 2011). The 2015 Sendai Framework for Disaster Risk Reduction outlines targets and priorities for action to achieve the reduction of disaster risk and losses in human, environmental, and socio-economical assets. Sustainable disaster risk is addressed by understanding and investing in disaster preparedness, risk reduction, and recovery. Cities should strive to make their citizens the active participants in risk assessment, supporting the overarching social safety net and enhancing the local resilience programmes. Moreover, the Framework envisions a shared ground where government and citizens can collaborate on developing context-specific, long-term, efficient mitigation strategies and governances, as in practices for governing without an enhanced institutional capacity to connect multi-scalar initiatives, adaptation efforts could remain reactive short-term solutions (Amundsen *et al.*, 2010).

The state of the art on urban flooding risk management is currently tackling the phenomenon from different perspectives. While a significant body of literature is being developed regarding the tools for modelling, lowering, and predicting the effects of flooding (Mosavi *et al.*, 2018; Venkataramanan *et al.*, 2020; Azizi *et al.*, 2022; Casali *et al.*, 2022; Perosa *et al.*, 2022; Ren *et al.*, 2022), there is currently a lack of information regarding investigating integrated policies and practices (Matczak & Hegger, 2020). Growing conscience regarding the need for preserving human habitats and the sustainable development of cities has brought into question the actual integration of conceptual frameworks in urban flood management. Different actors and scales of operation can induce governments to adopt different practices, but often with similar frameworks. Urban planners that tackle urban climate change adaptation are usually positioned in both an operative and supporting role. Firstly, planners operate analysis to understand the mechanisms that make an urban habitat vulnerable to flooding, for example, by studying urban form and using software based on Geographic Information System (GIS). Secondly, planners support administrations in developing tools and policies. Thus, this review is proposed to evaluate the sustainable performance of theoretical modelling and urban policies in tackling urban flooding, to provide insight into how administrations can improve their operative tools and policies regarding sustainable urban flooding. By conducting a systemic review, this study analyses 33 distinct case studies from different areas of the world and at different operative scales. In addition, the study proposes seven sustainable performance criteria deduced from the Sixth IPCC report, the SDG, and the Sendai Framework, to confront the cases. The study proposes to investigate three main topics:

T1. How is urban flooding risk management discussed depending on the scale and main participants?
T2. How are theoretical models and flooding policies addressing sustainable development?
T3. What are the common domains that define sustainable urban flooding risk management?

Addressing these questions would paint a finite picture of the current direction of the literature for effectively contrasting the phenomenon of urban flooding. Furthermore, defining the most common lines of action for reducing flooding risk, across scales and with different objectives, could provide a common ground for developing new frameworks on the matter. The paper is structured as follows. Section 2 covers the planning and identification criteria for the review. Section 3 describes the results of the selected body of literature. Section 4 discusses the defined performance criteria and confronts the selected papers in that regard. Section 5 concludes the paper, giving insight into the most common features, contrasting aspects, limitations, and future research opportunities.

2. MATERIAL AND METHODOLOGY

This study is proposed to evaluate the role and scope of theoretical models and policy evaluations in addressing the phenomenon of urban flooding, according to the main international directives on sustainable development, to better understand how the administration could profit from integration in their administrative toolkits. Methodologically, the review is based on a three-step process. We first planned the review by defining the eligibility criteria that will be followed during the starting research phase and the following selection. Secondly, through a database search, we selected a relevant body of literature and gave the opportune screening. Finally, the review is conducted, and the results are discussed and charted. The search was conducted in September 2022.

We defined several criteria for paper selection, focusing on publications that are relevant to our analysis of urban flooding and correlated policies (Figure 1).

- Papers must be published in journals, peer-review conference papers, or book chapters, and be written in English.
- Papers must not be older than 2010, so as to focus only on relevant and recent publications.
- Papers must focus on conceptual models or policy analysis for decision-making on adapting to and mitigating urban flooding.
- Papers must be related to building and urban design and form, as the analysis will be under scrutiny from an urban planning point of view.
- Papers must refer to urban flooding risk as a means to reach the governance goals, independently of the location of the case study but limiting the scope at most at a regional scale, or large area.
- Papers applied their methodology to an actual case study, referring to past flooding events as a benchmark.

To form the first batch of literature for this study, the research was conducted using different search engines to lower the risk of bias. The SCOPUS engine was used to make up the bulk of papers needed for the examination. It was built using the following set of keywords as a search query for title, abstract, and keywords: ‘urban’ AND ‘flood’ AND ‘risk’ OR ‘mitigation’ OR ‘prevention’ OR ‘assessment’ AND ‘mapping’ AND ‘planning’. As filters, we selected as language ‘English’ and for the time of publication ‘after 2010’. This gave 286 results. Starting from this cluster, a second integration was conducted on Google Scholar with the same keyword list as before, resulting in 24,200 publications, of which we considered the first 300 to lower the risk of selecting uninteresting papers (Haddaway *et al.*, 2015). After sifting through duplicates and irrelevant articles, we were left with 489 results.

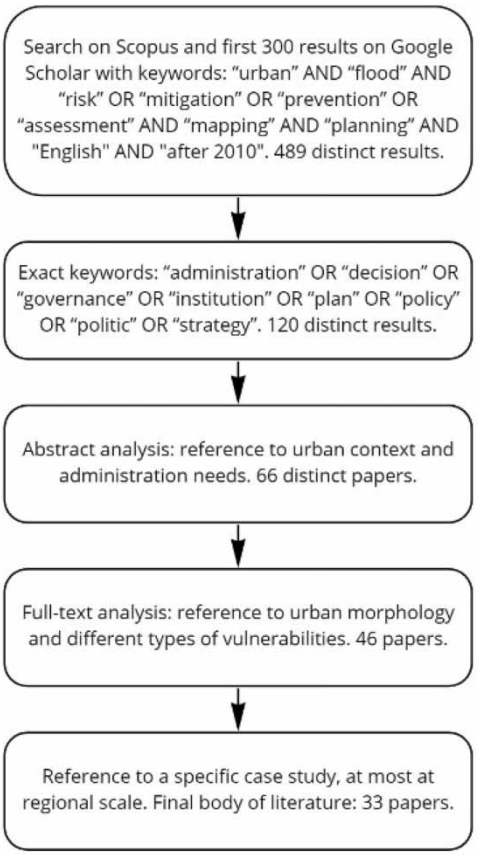


Fig. 1 | Diagram showing the selection process of the analyzed body of literature.

Next, we limited the search to articles with context to the urban environment that gave explicit mention of planning and policy strategies for mitigating and adapting to urban flooding. We screened the associated keywords for 'administration' OR 'decision' OR 'governance' OR 'institution' OR 'plan' OR 'policy' OR 'politic' OR 'strategy', resulting in 120 papers. This permitted us to quickly focus on the administrative and disaster assessment side of flood monitoring. We excluded most of the broader and generic research that eluded the scope of our review.

Of the resulting collection, a first focused analysis was conducted by examining the abstracts to understand the main aims of the publications. Papers discussed risk mapping without giving context or direct reference to the administration's needs. Many publications gave no direct interpretation of the urban implications of their data and models. Most of the articles culled from this selection were from a solely technical standpoint focusing on a particular analysis methodology. For instance, papers that focused on machine learning for urban flooding prediction focused on the used methodology, giving no urban planning insights. Similarly for papers on hydrodynamic modelling, cloud computing, satellite, and unmanned drone monitoring. This filter was not explicitly connected to the presence or absence of urban planners from the authors, as even publications made by only environmental engineers and water scientists considered urban morphology. This exclusion brought the total of papers to 66, of which two were not available for consultation past their open-access abstract.

Parallelly, by analyzing the full text, we observed the presence of urban morphology as one of the investigated parameters. This meant having the mean to compare physical vulnerability to social, economic, ecosystem, institutional, and cultural vulnerability. We excluded research that gave no insight into the correlation of urban form to urban flooding. With this filter, we lowered the total of interesting publications to 46 papers.

Finally, we excluded papers that gave no explicit reference to a case study, limiting the review to practical publications. Among the excluded studies we counted international directives (e.g., European proceedings) and theoretical approaches without a specific case study. We concluded the selection of 33 research papers.

3. CHARACTERISTICS OF THE SELECTED CASE STUDIES

After the collection of a selected body of literature of 33 papers, as for the previously enlisted criteria, we carefully examined the literature for acquiring key information. We were interested in highlighting how different administrations are satisfying the need for adapting to urban flooding. The operative strategy was to catalogue the information with different labels so as to better confront it to find possible patterns, selecting a title, authors, year of publication, the field of study, case study location, the case study scope, and case study purpose. Finally, we read through the body of literature for assessing their sustainability performance regarding tackling urban flooding.

3.1. Field of study

We divided the papers' contributors into different fields of study to better understand the actual mix of experts that are tackling urban flooding and where particular concentrations are taking place. Then, we group the various authors into clusters: civil engineering, ecology, economics, environmental engineering, geoscience, humanities and political science, computer science, urban planning, water science, weather, and climate. During the urban planning process, experts coming from different knowledge fields are called upon for evaluating and giving suggestions to the proposals. A multi-disciplinary panel is generally more effective while reducing the need for intermediary interpretation and loss of information. Urban planning and engineering are the most recurring proficiencies (54.5 and 48.5%), with the latter being more frequent in recent years (Figure 2).

3.2. Case study location

Exposure to climate change and flooding, while being a global hazard, is not equally distributed. Several research centres and groups that are studying the phenomenon are not directly influenced by it and are locating their case studies abroad. We were interested to see if the framework for conducting flooding analysis was dependent on the geographical location.

3.3. Case study scale

City policies and the methodologies behind the formulation of a theoretical model vary based on the dimensions of the considered areas. Usually, the multi-scalability of information comes as a complication during urban planning. For instance, models considering large or regional landscapes cannot easily be scaled down to the street scale. We divided the scope into three levels: regional, urban, and neighbourhood. Doing so, our goal is to find the correlation between different sizes of territorial disaster management and urban flooding. Urban scale is the most frequent operational level (66.7%), while other scales did not show particular correlations with geographical locations (Figure 3).

3.4. Case study objective

The research on urban flooding often considers the reasons for a past event or proposes mitigating and adaptation for better answering hazardous events. This is done by funding a study on a flood inventory, or a forecasting

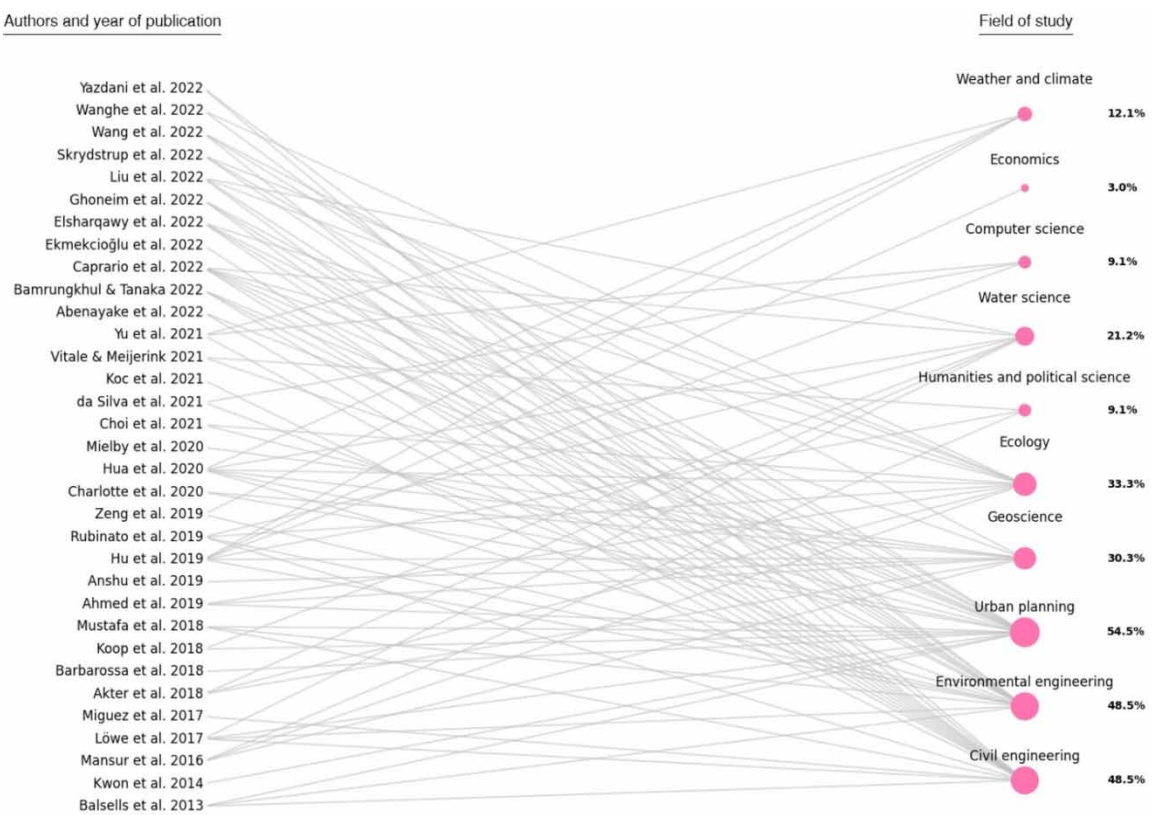


Fig. 2 | Network diagram showing the field of studies of the selected body of the literature that tackles urban flooding risk with theoretical models and policies, organized by the publication year.

methodology. On the operative side, one that is directly affecting the governance process, theoretical models and policies are tools that express a precise intention or the means to interpret the given data. We distinguished between theoretical modelling and policy evaluation. The former was the overwhelming majority (81.8%), while the latter had a minor presence (36.4%). Several cases opted for a hybrid approach, focusing both on the definition of a model and contextualizing it analytically with the local policies (18.2%).

4. REVIEW RESULTS AND DISCUSSION

We examined the main international references on the matter of urban sustainable development for defining common baselines for the different governments. From the SDG, the Sendai Framework for Disaster Risk Reduction 2015–2030, and Sixth IPCC Assessment Report, we obtained a selection of sustainability performance criteria by isolating flood mitigation and adaptation-specific requirements that governance should be following. The criteria are not mutually exclusive and hierarchically ordered, as different administrations can reach for similar objectives following distinct via contrasting paths. We defined the following seven performance criteria: acceptability and feasibility of implementation, adaptation cost, innovation, and revision of common practices, reducing maladaptive actions and practices, citizen awareness and empowerment, human life and well-being, biodiversity, and ecosystem services. While the urban scale and theoretical modelling are the most common, the

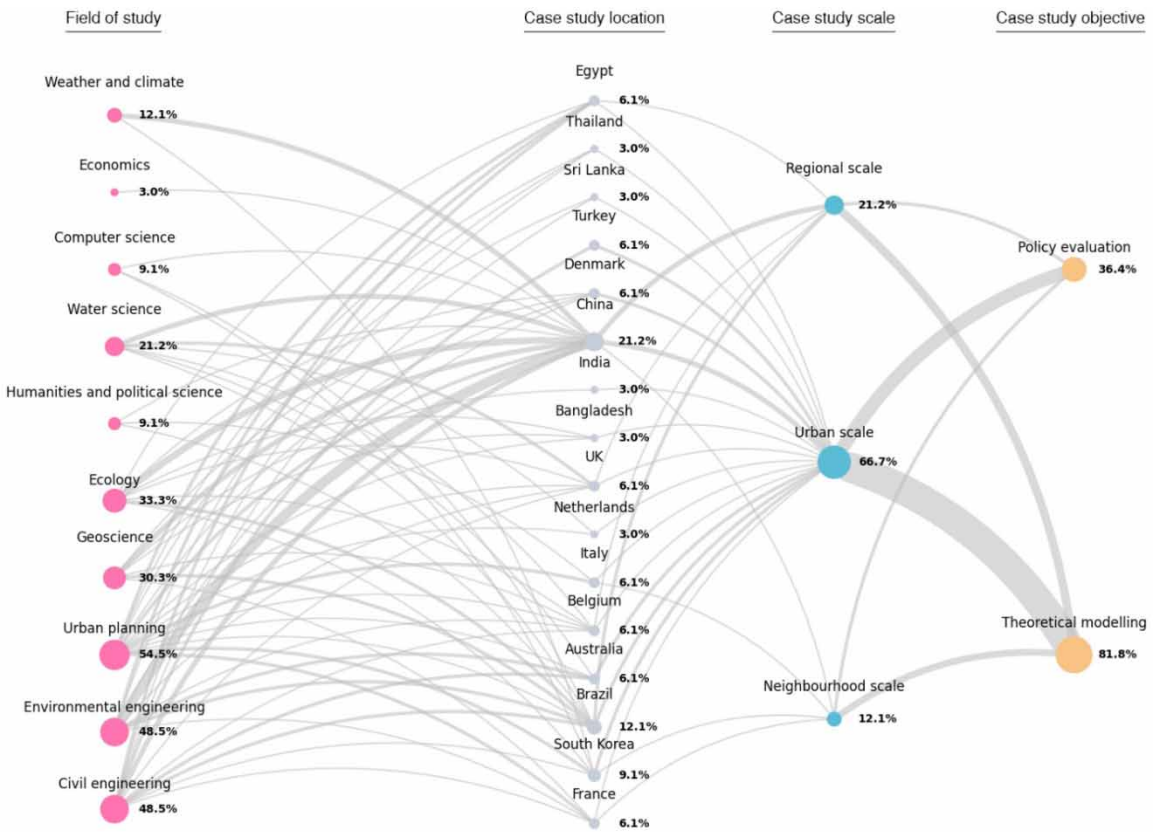


Fig. 3 | Network graph, vertically organized by the investigated category, showing the correlation between the field of study, case study location, case study scale, and case study objective.

distribution of cases is not homogeneous, as acceptability and feasibility of implementation and innovation and revisioning of common practices both are the most common goal for urban-level models. Other results are less predictable: the smallest scale, for example, is not connected with all criteria, showing that costs, welfare, and maladaptive actions are not usually analyzed at the neighbourhood scale (Figure 4).

4.1. Acceptability and feasibility of implementation

An increasing number of adaptation responses already exist for urban systems, but their effectiveness and implementation feasibility are limited by institutional, financial, and technological access and capacity. By lowering these constraints, appropriate responses across physical, natural, and social infrastructure could take place. Secondly, administrations that are struggling to include mitigation and adaptation solutions into their development programmes and agendas should adopt integrated policies and plans towards efficiency and resilience (United Nations 2015; UNISDR 2015; IPCC, 2022). Acceptability and feasibility of implementation were the most frequent performance criteria (63.6%). Generally, most of these studies opted to illustrate how a theoretical model could be of use as a governance tool by more effectively using existing resources in an integrated and holistic way.

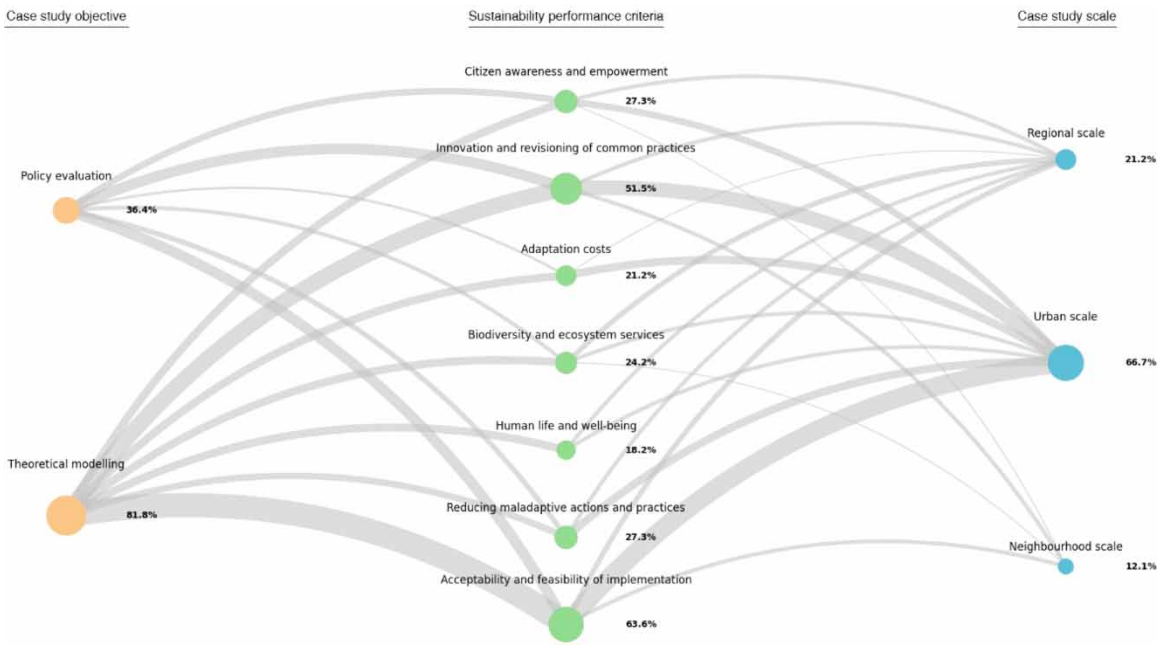


Fig. 4 | Network graph showing the dependence of performance criteria on the case study objective and scale.

At the urban scale, theoretical modelling in support of the decision-making process gives the best results when intersecting heterogeneous data are used. In return giving insight on what type of data can be better optimized. This is the case for patterns of hazardous rainfall mapped on urban areas (da Silva *et al.*, 2021), implementation of grey-green solutions (Wang *et al.*, 2022), and blue-green solutions (Ahmed *et al.*, 2019). Moreover, flexibility in model definition greatly opens up possibilities for reuse and ease of application. This is especially efficient in increasing the feasibility of implementation if cities are regarded as complex systems that need to be synthesized (Koc *et al.*, 2021; Ekmekcioğlu *et al.*, 2022).

Clear visualization and readability of data are often brought up as keys aspect for easier implementation and acceptance. GIS-based solutions are relevant across scales for user interface platforms, in case of planning and management of local flood-emergency (Charlotte *et al.*, 2020; Yazdani *et al.*, 2022), to plan interventions in large areas (Caprario *et al.*, 2022; Wanghe *et al.*, 2022), or to select and prioritize critical infrastructure to develop precise mitigation strategies (Abenayake *et al.*, 2022). Among GIS-based applications, graph models have the advantage of accurately representing the complexity of city management; such sensitivity in modelling can proxy for missing indicators, further increasing a model's adaptability (Liu *et al.*, 2022).

At neighbourhood scale, theoretical modelling has the role of validating and verifying architectural and engineering adaptation solutions, in order to prove that a particular low-impact development (LID) solution has relevance in reducing flooding risk locally (Hua *et al.*, 2020) or to confront different designs (Balsells *et al.*, 2013).

Policy evaluation at urban scale is oriented to simplify the implementation of toolkits and planning methodologies to support resilience and sustainability. Interdisciplinarity in urban hydrogeological studies for comprehensive planning could help local resilience in various ways: from assessing the surface conditions of hazardous areas (Mielby & Henriksen, 2020), to limiting indiscriminate urbanization (Bamrungkhul & Tanaka, 2022), to down-scale and up-scale different levels of planning (Elsharqawy *et al.*, 2022).

Other scenarios showed that accessibility and capacity for adaptation strategies can be obtained by integrating both theoretical modelling and policy evaluation. Knowledge of future urban planning scenarios and of local context can help to successfully implement mitigation and adaptation solutions. For example, when proposing adaptive solutions over one-off investments (Löwe *et al.*, 2017), when assessing the capacity of cities to make use of LID solutions by assessing the acceptability of multiple stakeholders (Koop *et al.*, 2018), and by including social, environmental, and technical performance targets for LID solutions (Zeng *et al.*, 2019). Holistic inquiries are relevant when considering secondary planning options, having in mind that citizens' acceptance could influence the efficiency of the implemented strategies (Kwon *et al.*, 2014). At the neighbourhood scale, an integrated approach is meant to allow more contextual-specific efficient, and systematic building-based management of urban space and land use as part of urban planning measures (Yu *et al.*, 2021). At the neighbourhood scale, an integrated approach is meant to allow more contextual-specific efficient, and systematic building-based management of urban space and land use as part of urban planning measures (Yu *et al.*, 2021).

4.2. Adaptation costs

Optimization in flood mitigation is often applied considering only risk reduction as the main goal. Recent solutions such as green infrastructures and LID can find it difficult to compete with grey infrastructure. Combining social, economic, and environmental responses as co-benefits allows for comparing strategies according to effective costs and benefits in the long term, strengthening urban and regional development planning. Then, the costs for maintenance and reconstruction of urban infrastructure, including the transportation and energy systems, will increase with climate change, projecting disruption particularly in cities (United Nations 2015; UNISDR 2015; Alves *et al.*, 2020, IPCC, 2022). This category was one of the least recurrent (21.2%). We found that studies that cover combined ecosystem-based and structural adaptation approaches often gave no direct insight into the potential lowering of costs for adaptation.

Most cases adopted Multi-Criteria Decision-Making (MCDM) modelling, with supervision from economists. Trade-offs with existing resources and budgets were particularly successful in demonstrating the cost-reduction of mixed grey-green infrastructure (Hu *et al.*, 2019), small-scale, site-specific technologies (Choi *et al.*, 2021), and LID solutions (Koc *et al.*, 2021). A similar budget-oriented investigation has shown to be effective even at a larger scale (Caprario *et al.*, 2022). Finally, the introduction of new indicators, such as the recreational value, has the potential to more appropriately define the benefit of green solutions for citizens (Skrydstrup *et al.*, 2022).

Thematic masterplans can be more accessible to administrators and investors than spatial planning and flood zoning, connecting context-specific vulnerabilities to the whole urban system across scales. These cases are the product of both the theoretical modelling and the policy evaluation. This is the case for locally defined urban-wide interventions, such as renovating large portions of a city's underground water disposal system, and investments, such as the case of urban development in flood-prone areas (Löwe *et al.*, 2017; Bamrungkhul & Tanaka, 2022).

4.3. Innovation and revisioning of common practices

Traditional and existing practices that do not consider climate change as a critical aspect in mid-long-term planning could be exposed to greater risk and especially in areas prone to flooding. While enhancing water retention and flood risk reduction with land planning is commonly considered a fine solution, revisioning and development of new building codes and standards based on local context are often more effective and more applicable. As such, strengthening disaster preparedness for flooding events must be applied in pre-disaster assessment, prevention, and mitigation, and in post-disaster scenarios with effective response, recovery, rehabilitation, and

reconstruction actions (United Nations 2015; UNISDR 2015, IPCC, 2022). This criterion was the second most frequent (51.5%).

Most of the theoretical models were defined at the urban scale. A simple approach in renovating existing administrative toolkits is overriding unreliable processes that could bias the decision recommendation. This can be done just by highlighting the critical limitations of current technologies and imposing a call for renovation (Choi *et al.*, 2021), or by proposing and verifying new flood risk prioritization methodologies (da Silva *et al.*, 2021). A second approach is to identify weaknesses in current spatial planning, firstly by imposing a conservative land use control in flood-prone areas by testing local resilience in various hazardous scenarios (Mustafa *et al.*, 2018), or by using integrated large-scale tools, such as compensation of urban peak runoff by local storage, to limit unregulated urban development (Akter *et al.*, 2018). Afterward, failing links can be patched by redefining building codes based on simulations of building components (Ghoneim *et al.*, 2022) and by allowing combined infrastructural and blue-green (Miguez & Veról, 2017) and LID solutions (Hua *et al.*, 2020). The mobility system is often found as a crucible of critical nodes, and those can be identified by graphs representative of the street network and traffic volume (Abenayake *et al.*, 2022). As a product of modelling, guidelines can inform new building codes across scales and can address different stakeholders.

Policy evaluation exposed the need for more balanced power symmetry between the different fields of studies behind the formulation of planning tools. A dominant engineering resilience discourse could affect the result in a closed decision-making process, weakening proposed solutions (Vitale & Meijerink, 2021). Operatively, this heterogeneity of approach should be obtained both in practitioners, as in trained planners and designers specialized in indigenous conditions and peculiarities (Anshu & Firduai, 2019), and in data analysis based on risk awareness Key Performance Indicators (KPIs) (Rubinato *et al.*, 2019; Mielby & Henriksen, 2020; Elsharqawy *et al.*, 2022). Theoretical modelling informed by local policies is crucial in strengthening land use planning. These are relevant in outputting both short-term measures for minimizing risk and long-term scenarios (Yu *et al.*, 2021), and in multi-scale analysis, by adopting an ecological urban analysis (Barbarossa *et al.*, 2018) or by using large-scale flood zoning to provide correspondence to local adaptation solutions (Löwe *et al.*, 2017).

4.4. Reducing maladaptive actions and practices

Current flood mitigation policies are likely to be maladaptive due to unintended consequences that undermine the effectiveness of the interventions in the long term. Isolated practices can quickly cover short-term necessities and distress but they can have negative impacts in the long run. Integrated flood risk management, as a systemic broad approach that envelopes the infrastructure, the technology advance, the management behaviour, and the risk transfer, could increase climatic resilience and flood risk management (United Nations 2015; UNISDR 2015; Mai *et al.*, 2020, IPCC, 2022). However, these criteria were not commonly found in the analyzed body of literature (27.3%).

Theoretical models that focus on analyzing maladaptive practices and interpreting weaknesses in the adaptation strategies lean mostly on the urban scale, leveraging urban morphology for defining operative measures. Some research opted to analyze why LID solutions were not performing as well as previous estimates envisioned. Coupled systems, i.e., integrating grey infrastructure with LID and green solutions, perform better in the long term, albeit showing slightly lower performance to the most extreme events than traditional grey infrastructure. Generally, coupled systems with decentralization seem to provide the best performance in a trade-off among economic costs, hydraulic reliability, and technological and operational resilience (Wang *et al.*, 2022). Because it is difficult to measure the negative impact of grey infrastructure and the positive benefits of green solutions to the environment, planners typically underestimate both by a large margin. Grey infrastructure usually possesses better protection standards in reducing inundation risks associated with the low return period events

but has a high level of negative impact on ecology and such negative impact is very difficult to quantify (Hu *et al.*, 2019). Spatial planning has proven detrimental for allocating mitigation and adaptation solutions when coming from analyses not holistically conducted. Urban density needs to be modelled not exclusively from a physical point of view, especially in large urban-natural areas, where rapid urbanization takes place (Mansur *et al.*, 2016), or in cities with degraded soils (Mustafa *et al.*, 2018), and with overexposed public assets that needed to be relocated (Ghoneim *et al.*, 2022).

At the regional level, the main criticism of flood risk management policies was their given nature as a reactive practice. Hence, a more proactive approach that includes the integration of land use planning and flood management is strongly recommended by some (Rubinato *et al.*, 2019; Elsharqawy *et al.*, 2022). On top of this, some research stated how solutions like water storage reservoirs were offered as innovative, but remained the task of hydraulic engineers, thereby limiting the interactions with and input from other potential actors who have access to it only through external export remarks. In this regard, authorities are exposed to not being correctly equipped to integrate environmental issues with old expertise and responsibilities (Vitale & Meijerink, 2021). On the end of the spectrum, others featured, through examples, the apathy and laxity of local authorities in urban management and governance practices. This corresponded, again, to flawed land use planning and weak environmental protection, undermining the effectiveness of any solution aimed at making cities resilient (Anshu & Firduai, 2019).

4.5. Citizen awareness and empowerment

Reducing the risk areas can be achieved by directly involving the stakeholders as the active part in the planning process, requiring an all-of-society engagement and partnership. A common approach is devoting a share of damage prevention to citizens, which need to be aware of not only the risk of flooding and its potential consequences, but also of the possibility, effectiveness, and cost of private precautionary measures (Grothmann & Reusswig, 2006). In practice, awareness of policies and measures on climate change mitigation, adaptation, impact reduction and more importantly strengthening early warning systems can lower the vulnerability and loss of lives. A more direct approach is the concept of citizen science, where the citizens act as living, direct sensors that could inform the community at large via data mining systems or direct opinion-oriented strategies. Finally, in contrast to traditional planning, the absence of risk diagrams does not imply the absence of risks within a region. Research that eludes human sensible vulnerability and adaptation behavior incurs the risk of bias (United Nations 2015; UNISDR 2015; Njue *et al.*, 2019; IPCC, 2022). Similarly, to the 4.4 criteria, citizen awareness and empowerment wasn't usually a discussed topic (27.3%).

Regarding theoretical modelling, city level is the main scale of analysis. Empowerment can be obtained in flood modelling by revisioning the weights that are put on human assets. This can be done by involving citizens in the weighting process for MCDM analyses and assessment (Koop *et al.*, 2018; Charlotte *et al.*, 2020; da Silva *et al.*, 2021). Inhabitants bring a very peculiar and refined sensitivity to flooding, otherwise unobtainable (Akter *et al.*, 2018). If not directly confronted for participation and coordination at neighbourhood scale, citizens could prove distrusting and fall off model predictions (Ahmed *et al.*, 2019), resulting in lost opportunities to enrich models with data that reflects investments desires in small private properties (Barbarossa *et al.*, 2018).

Policies at the regional scale address the governance in regard to land use, but proactively by using early warning systems and water-sensitive urban design engagement. Communities need to be involved and communicate their specific interests, while stakeholders have the role of providing a better understanding of what causes pluvial and fluvial flooding in urban areas, identifying different techniques to be incorporated within urban planning (Rubinato *et al.*, 2019; Elsharqawy *et al.*, 2022).

4.6. Human life and well-being

Flooding risk is often associated with marginalized communities, peripheral urban areas, and lower income areas. Flooding damage to critical infrastructure usually cascades into risks to safety and well-being of already weakened neighbourhoods. Addressing water services, from runoff retention to stormwater disposal, can lead to promoting human health and well-being while limiting exposure. This phenomenon is accentuated by the uneven distribution of physical assets or intrinsic frailty of urban morphology (United Nations 2015; UNISDR 2015; De Risi *et al.*, 2020; IPCC, 2022). This theme was originally thought to be a matter mostly of policy analysis. Interestingly, only theoretical modelling tackled anthropic well-being as a direct objective. While we observed a horizontal interest regarding human welfare and exposure reduction, it was never explicitly stated as one of the main focal points. Our impression is that risk to human life is not out of the spotlight, rather is a given topic and not to be put on the discussion. Overall, human well-being was the least common topic (18.2%, 6 papers).

In theoretical modelling, people's vulnerability and exposure are the core weights of the analyses at both urban and regional scales. The introduction of social KPIs can proxy for ecological and economic variables. In dense urban contexts where the deterioration of natural capital is a prime criticality, 'human welfare' can help us to better understand the sustainability of new blue-green infrastructure (Ahmed *et al.*, 2019). 'Community resilience' can help in LID integration in residential and commercial areas (Koc *et al.*, 2021). Introducing social KPI can make traditional risk mapping more sensitive to local characteristics, especially in homogeneous morphological areas at various scales that usually do not represent the real perceived flooding risk (Mansur *et al.*, 2016; Caprario *et al.*, 2022; Liu *et al.*, 2022). Apart from KPI, modelling on people's vulnerability can be appropriate for a particular category of people, such as hospital patients, that need special care in case of flooding events. In the case of hospital patients, an emergency transportation model based on the street network was developed in the case of evacuation to nearby urban facilities (Yazdani *et al.*, 2022).

4.7. Biodiversity and ecosystem services

Urban restoration and development can easily affect biodiversity and ecosystem services, which in turn influence anthropic services. There is substantial literature supporting the positive psychological and physiological effects on human health of exposure to greenness and natural environment. A conservative natural resources management while integrating these resources in traditional planning could productively contribute to risk reduction and to lowering recovery time (United Nations 2015; UNISDR 2015; Sutton-Grier & Sandifer, 2019; IPCC, 2022). Biodiversity was mostly discussed at the regional scale, while the fewer cases that focused on the urban scale viewed biodiversity as a means to simplify and streamline adaptation, without direct concern for the natural stakeholders. This criterion was the third less frequent (24.2%).

The relationship between urban and natural systems can be analyzed by theoretical models in different ways. One approach, in spatial planning, is to appropriately weigh built-up areas and green areas to give the latter more relevance, by adopting specific ecological KPI, such as greenhouse gas emissions and groundwater recharge potential. This facilitates the preservation and enrichment of the inmost ecosystem values, balancing man-made and natural features (Barbarossa *et al.*, 2018; Ahmed *et al.*, 2019; Koc *et al.*, 2021). At the regional scale, not considering ecologic services could severely underestimate the role that ecosystems play in modulating both the hazardous events and the condition for vulnerability, undermining the mitigation strategies. This is the case for large green areas, such as the Amazon Delta Estuary (Mansur *et al.*, 2016), regional urban watershed management, and the Sponge Cities (Wanghe *et al.*, 2022), regional parks development (Ghoneim *et al.*, 2022).

Amidst the policy analyses, water management can be a way to help foster biodiversity if ecosystem services are taken into account while planning. Stakeholders with strong environmental emphasis can account for the

prosperity of natural life, and are especially important for city mitigation strategies and infrastructure development (Rubinato *et al.*, 2019; Elsharqawy *et al.*, 2022).

5. CONCLUSIONS

This study illustrates and gives insight into how new theoretical models, policies and practices for urban flood risk management could be developed for effectively reducing the increasing risk derived from climate change. Seven sustainability performance criteria were defined from interpreting the directives and findings of the Sixth IPCC, the SDG, and the 2015 Sendai Framework. Each criterion followed a path of inquiry to understand how current research is following international objectives, what works best, and what is still lacking.

We defined several correlations between the field of study of the analyses, the scale, the objective, and the sustainable performance criteria. We applied the Pearson's Coefficient with Boolean values for each analyzed variable. Regional scale is strongly correlated ($\rho = 0.7536$) to ecology, while urban flooding analysis is a topic that is rarely discussed from an ecological perspective ($\rho = -0.6196$). Generally, the two scales of analysis are mutually exclusive ($\rho = -0.7536$), indicating a difficulty in dialogue at different levels. Among the field of studies, most variables show no strong correlations, meaning an overall homogeneity. A moderate direct correlation between economy, climate, and IT ($\rho = 0.5601$, $\rho = 0.5316$) shows that they are usually tied, while economy bears a correlation to humanities and political science. The only moderate correlation that comes from the objective is the opposing trend from theoretical modelling and policy evaluations ($\rho = -0.6124$), as most studies do not use a hybrid approach in analyzing risk management. From the sustainable performance, a moderate negative correlation exists between implementation feasibilities and humanities ($\rho = -0.3983$), showing a possible example of missing expertise in tackling human acceptability. Moreover, a moderate negative trend is shown in biodiversity and urban scale ($\rho = -0.4014$), as most ecological analyses are conducted at a larger scale ($\rho = 0.4581$). Operating at a lower scale could be insightful for addressing biodiversity in a more holistic manner. Finally, the reduction of maladaptive practices is mostly not a matter of theoretical modelling ($\rho = -0.4743$) and not put side by side with the feasibility of implementation ($\rho = -0.5610$), potentially being limited to just economic analysis ($\rho = 0.4841$).

The limitations are as follows. The results come from searching papers that explicitly express a correlation to urban design. A different selection could give an alternative meaning to the same sustainability criteria. Moreover, the synthesis of the international directives is intentionally overlapping, but it could provide misinterpretations. A different set of criteria, or reports, could influence the perception of sustainable urban flooding risk.

Future research and reviews could follow a similar approach in examining different kinds of climate change-related risks. In the case of cities overheating, the analysis and practices around urban comfort and the heat island effect could be confronted in a similar way, by addressing maladaptive urban practices and their revisioning. Biodiversity loss in urban habitats could be more effectively confronted by understanding how green solutions fare in terms of acceptability, to better implement existing solutions. Similarly, environmental and landscape planners could profit from a sustainable performance of the most common practices in hydrogeological instability, air pollution, and water quality. In these regards, urban planners have the role of understanding and linking different perspectives that work under the complexity of urban systems. By weighing and orienting the sustainability of the next generation of theoretical models and urban policies, cities should experience fewer extreme events and increase their overall resilience. The main findings should be used by urban planners and policymakers in defining new urban analyses and revising existing ones.

- Acceptability and feasibility of implementation are the main goals for conceptual frameworks that tackle urban flooding risk (63.6%). Mitigation and adaptation strategies are already being developed and effective measures

exist. Instead of developing or optimizing new LID or green solutions, administrators should focus on streamlining and simplifying the adaptation process of existing solutions in development agendas.

- For implementing LID and green solutions in urbanized contexts, administrators should give appropriate criteria to socio-economic aspects and to the environmental response so as to increase their appeal, as this influences their overall effectiveness.
- LID and resilience-based solutions are usually the most competitive designs in term of sustainability and long-term efficiency, while traditional resistance-based solutions could still be considered the better solution against extreme phenomena.
- Clearness and openness of data should be prioritized while tackling data representation, given that a fairer state-of-the-art picture could help different stakeholders understand and participate in designing and verifying the mitigation solutions. GIS-based models are the most common for data visualization, proving to be effective and flexible. Citizens should be brought closer to the development of new tools for tackling urban flooding, as their actions, role and opinions are critical for both acquiring data and accepting the adaptation solutions.
- Land use planning is often the most effective solution for flood risk reduction, in both developed areas and where scarcity of resources is critical. Flood zoning should be prioritized over other solutions, even green ones, as a common administrative framework can actively produce linear long-term stability. Developing new models that innovate on existing building codes and urban planning should be one of the main objectives.
- While most of the theoretical models are developed at the urban scale, there is often a lack of contextuality coming from the difficulties of tying together problems coming from different scales. Policies should aim to ease dialogue at different levels and conceptual frameworks should be oriented in operating both at large and micro scale. Integrating hydrological modelling, MCDM criteria, and graph theory could bridge the gap of scale by adopting context-specific parameters.
- The development of a theoretical model and urban policy should always be oriented to a holistic approach, where physical vulnerabilities are put side-by-side with social, economic, environmental, and cultural vulnerabilities. A more balanced power symmetry between different fields of study should be achieved when formulating planning tools.
- Biodiversity is still in most cases used as a means for increasing the likeability and feasibility of implementation of green solutions. While the benefits of living alongside a natural environment is recognized, natural and animal stakeholders don't appear as a main objective in most models and policies. Administrations that opt to not consider ecosystem services should follow a strictly conservative approach while trying to be more inclusive of natural stakeholders as cities become more sustainable and liveable.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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