

Opinion

Understanding and Mitigating Urban Flood Risk

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Abstract: This opinion paper aims to clarify the interacting elements that affect the substantial consequences of urban floods. The main goal is to elucidate the assessment of risk and its mitigation by examining relevant elements, including the comprehension of the causes and characteristics of urban floods. This analysis addresses the challenges of informed urban flood management, emphasizing intelligent planning, operational efficiency, and community preparedness, with the objective of ensuring timely, resilient, and effective responses that maintain social and environmental equity. Ultimately, the unresolved issues that hinder decision makers from making informed decisions are succinctly delineated.

Keywords: urban floods; risk; mitigation; preparedness; resilient responses; flood modeling; flood forecasting

1. Introduction

Urban flooding refers to the inundation of land or property in densely populated areas due to excessive rainfall, overwhelmed drainage and stormwater systems, river surges, or other hydrological factors. It contrasts with rural or coastal flooding, as it primarily occurs in urban settings where impermeable surfaces, including roads, pathways, and structures, prevent water from permeating the soil. This leads to rapid runoff, increasing the likelihood of water accumulation and flooding in low-lying areas. Furthermore, in urban settings, there are few locations available to function as water-holding zones that can alleviate storm surges. Understanding urban flooding is crucial for risk management and alleviating its impact on lives, infrastructure, and the economy. This comprehension enables anticipatory planning, targeted interventions, and the development of robust urban risk management systems.

2. Characteristics and Causes of Urban Floods

Urban flooding can occur due to intense precipitation events (pluvial floods), river inundation (fluvial floods), or a combination of these elements. Pluvial floods arise from excessive precipitation that surpasses the soil's absorption capacity and/or drainage capability. They primarily occur in urban areas due to impermeable surfaces and insufficient drainage infrastructure. They may also occur in rural areas when severe storms affect saturated soils. Fluvial floods occur along riverbanks and floodplains when rivers overflow due to significant precipitation and/or the melting of snow and ice in the upstream catchment area. Tidal forces can significantly affect riverine floods, either by directly inducing tidal inundation or by reducing river discharge into the sea due to heightened tides. Other adverse circumstances may encompass the narrowing of the riverbed due to landslides, the collapse of bridges, or the blockage of their spans by material transported by the current, including trees uprooted upstream by the water's force.



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Pluvial floods predominantly arise from localized thunderstorms or cloudbursts rather than from breaches or the overtopping of river levees. Consequently, because of the limited size of the contributing area, urban floods generally demonstrate a sudden start and rapid intensification. As a result, they demonstrate significant intensity and localized impacts but can disproportionately endanger life and property due to population density, human habitation, and assets [1].

Primary factors contributing to urban flooding

During the latter half of the twentieth century, substantial population concentrations were present across all continents, leading to the establishment of large urban centers accommodating millions of inhabitants, often marked by rampant urbanization, which highlighted the emergence of significant urban flooding challenges. This does not suggest that analogous occurrences cannot occur, though these may be smaller in less populated or rural areas; nonetheless, it is the density of population that markedly increases risk.

Urbanization replaces natural landscapes with concrete and asphalt, significantly reducing water penetration and the soil's ability to absorb rainfall, thus increasing both the volume and speed of surface runoff. Furthermore, the limited vegetation commonly present in urbanized areas substantially reduces evapotranspiration losses. In a flood, asphalt road surfaces become watercourses with significantly reduced friction, far lower than that of natural watercourses' roughness.

The increased propensity for thunderstorms to develop over metropolitan areas led to extensive investigations into the effects of urbanization on precipitation [2]. In contrast to verdant grass and tree canopies, urban environments are characterized by gray infrastructures, including buildings and roads, which absorb solar radiation and elevate temperatures in metropolitan regions, particularly at night. This results in the creation of urban heat islands (UHIs), where temperatures in cities exceed those of surrounding areas, and, coupled with the roughness of structures in urban environments, modify wind patterns in and around the city. The sealed surfaces result in reduced local atmospheric water availability, yet vertical movements occur more rapidly due to enhanced sensible heat transfer. The repercussions include heightened storm development and prolonged cloud cover over metropolitan regions, which, combined with the heightened sealing of urban surfaces, results in less transpiration and infiltration while augmenting direct runoff, hence causing a rise in discharge peak and discharge volume, together with a decrease in lag time.

In a torrent, where the stream gradient exceeds 1/1000, the water runs swiftly. Thus, the risk of urban flooding is evident, as city streets can display gradients exceeding several percent (e.g., 1–2/100), nearly ten times greater than those differentiating torrents from rivers, along with considerably lower roughness compared to the natural features of torrents.

Genoa, Italy serves as a quintessential example, having experienced numerous victims and considerable damage due to the flooding of its waterways (Bisagno, Fereggiano, Sturla, Polcevera), which are confined between buildings and streets, often capped, and reduced to resemble sewers over long distances. These waterways possess attributes typical of nearly the entire hydrographic network that directly discharges into the Ligurian Sea, such as moderately sized contributing catchments, steep gradients of the riverbed in the upstream sections, and the final segment with gentler slopes traversing densely populated areas.

Numerous events since the 1970s and 1990s, as well as in 2011 and 2014, have characterized the critical circumstances in Genoa, with precipitation levels nearly reaching 500 mm within a few hours in 2011.

Urban expansions often demonstrate inadequate drainage infrastructure, intensifying flood dangers regarding probability and increased water levels. Accelerated development

sometimes involves encroachment upon rivers, marshes, and floodplains, which serve as natural defenses against flooding. The degradation or modification of these ecosystems undermines the city's ability to manage water flow. In urban settings, the capacity for natural water storage frequently declines, resulting in negligible (1–2 mm) water layers on rooftops, roadways, and plazas, in addition to the generally insufficient stormwater storage allocated inside the sewage system. Coastal areas experience increased susceptibility to flooding due to storm surges and rising sea levels, which can impair the drainage effectiveness of sewers and intensify urban flooding during storms.

Population density. Increased concentrations of people, housing, and infrastructure in urban areas enhance the probability of harm to property, livelihoods, and human life during flooding events, hence escalating exposure, susceptibility, and risk. Moreover, many big cities suffer from insufficient urban planning, which considerably impacts exposure and vulnerability.

Climate change is exacerbating the conditions. Climate change is primarily exacerbating weather patterns, leading to a heightened severity and frequency of brief, localized downpours. These intense precipitation episodes overwhelm urban drainage systems. The formation of urban heat islands, due to concentrated energy release, leads to localized climate changes, influencing precipitation patterns and intensifying storm systems in urban regions. Ultimately, climate change leads to increased weather unpredictability, limiting urban preparedness and response to flooding events.

3. Impacts of Urban Floods

The concentration of population, human endeavors, and expensive housing and infrastructure in metropolitan regions can result in significant social, economic, and environmental repercussions of flooding.

Social consequences stem not only from casualties and fatalities but also from probable population displacement, job losses, and the deterioration of relationships and social cohesiveness. Health hazards may arise from sewer overflows and spills, stagnant water, and the lack of potable water due to the failure of fragile water-distribution systems.

Economic repercussions may result from damage to infrastructure, residential dwellings, and business establishments. The costs related to recovery will substantially impact the budgets of municipalities and governments.

Urban flooding frequently leads to environmental repercussions, intensifying the pollution of rivers, lakes, and groundwater. In many cases, the extended ecological decline of urban green spaces may also occur.

4. Flood Risk

As seen in Figure 1, risk is currently defined [3] as the amalgamation of three components: hazard, exposure, and vulnerability, typically denoted as

$$Risk = Hazard \times Exposure \times Vulnerability$$

Hazard refers to the likelihood of an event occurring, representing a potential source of harm or undesirable impacts of a specific size; in the context of urban flooding, a hazard may include the probability that significant rainfall events cause rivers or inadequate drainage systems to overflow.

Exposure denotes the extent to which individuals, property, and assets are situated in areas susceptible to hazards; greater exposure, shown by closeness to a watercourse, amplifies the potential impact of a hazard.



Figure 1. Risk descending from the interaction of hazard, exposure, and vulnerability.

Vulnerability denotes the susceptibility of individuals, communities, infrastructure, or systems to harm from hazards; the presence of individuals with disabilities, childcare facilities, educational institutions, or storage places for hazardous materials intensifies this vulnerability. Vulnerability depends on factors such as poverty, weak infrastructure, and lack of preparedness.

Risk factors include increased rainfall events, the frequency and severity of which are intensified by climate change; high population densities combined with chaotic urbanization; expanded impermeable surfaces (such as roads and buildings); insufficient drainage and stormwater infrastructure and management; and varying levels of preparedness and resilience.

Multiple strategies can be employed to alleviate the risk of urban flooding, such as strategic urban planning and development, enhanced disaster preparedness and response, the fortification of infrastructure resilience, adaptation to climate change, the advancement of social and environmental equity, and financial risk management.

5. Urban Flood Risk Management

Urban flood risk management is conventionally approached via prevention and the four phases of emergency management: mitigation, preparedness, response, and recovery [4].

Prevention is an essential phase in reducing the risk of flooding. A fundamental paradigmatic shift is essential to connect with the concept of sustainability, switching from existing planning and design techniques focusing on “return periods” to those focused on “human life” [5]. Prevention must alleviate flood risks by protecting and rehabilitating natural drainage systems, green spaces, and wetlands.

Mitigation is essential through the planning and execution of advanced flood alleviation infrastructures and strategies, including improved drainage systems, underground flood detention facilities, and flood barriers. Furthermore, the incorporation of green infrastructure, including parks, wetlands, rain gardens, and green roofs, aids in the absorption of surplus water, potentially mitigating the immediate impacts of thunderstorms.

Preparedness is a vital element that reduces exposure, vulnerability, and ultimately, risk. Community awareness efforts must inform citizens that the probability of encountering a flood in their lifetime is significant; therefore, they should be informed and prepared to face such a disaster. A considerable number of individuals drown by entering their garages to obtain their vehicles instead of staying on the top floors of their homes; it is essential that they receive thorough guidance on proper behavior during flood events.

Therefore, emergency plans must be developed using thorough flood models to determine evacuation routes, make shelter arrangements, and create resource-allocation strategies during calamities. Early warning and flood warning systems should be created, developed, deployed, and evaluated with resident involvement through the analysis of their reactions to mobile-phone alert messages.

Responses must be swift and based on established flood-response plans developed through detailed flood maps, facilitating the dynamic identification of exposure and danger, along with efficient evacuation protocols reliant on accessible escape routes that are regularly updated.

Recovery includes all measures required to restore normalcy, evaluate the management of the flood event, identify mistakes, and execute the post-disaster reconstruction of structures, infrastructure, and socio-economic systems, with a focus on resilience.

6. Urban Flood Risk Assessment

To achieve preparedness, it is essential to assess the risk associated with the urban area by evaluating the hazard, exposure, and vulnerability.

6.1. Assessing the Hazard

In accordance with the definition of “risk”, it is evident that an initial requirement is the development of hazard maps, specifically flood maps, which correlate the probability of occurrence with the magnitude of potentially catastrophic events. In urban settings, these events are defined by the maximum height and velocity of floodwaters across different urban areas. In addition to these two essential variables, especially for vegetated and cultivated peri-urban areas, we must also consider the water residence period, which affects the potential for harm to plants and crops.

The development of hazard maps necessitates the utilization of one- and two-dimensional hydraulic models that are challenging to construct due to the intricate detail required to depict flooding phenomena and the complexity of obstacles, such as roads, buildings, and underpasses, which serve as singular points within models spanning several tens, if not hundreds, of square kilometers. This complexity demands localized mesh refinements comprising hundreds of thousands of elements to accurately represent the water propagation phenomenon. Cea et al. [6] provide an extensive overview of the present status of urban pluvial flood modeling, encompassing not only a detailed exposition of mathematical methodologies but also the critical factors that must be incorporated into the modeling process, the validation studies conducted thus far, and our perspective on the modeling challenges that require attention in the imminent future.

The initial step involves assessing the likelihood of an event’s occurrence through probabilistic models of extreme values, such as, for instance, the Generalized Extreme Value (GEV) [7] distribution or the Peak Over Threshold (POT) [8] approaches, and establishing the probability levels to be linked with the risk maps. It is essential to interject and highlight that traditionally, this issue has been approached through the concept of return period, which I believe is both deceptive and inadequate to ensure the appropriate safety levels for urban neighborhoods. In engineering practice, the probability of an extreme event is characterized by the return period $T = 1/P^*$, defined as the inverse of the probability that a value of rainfall or flow is greater in a year than a pre-established threshold value $p^* = Prob\{x \geq X^*\}$, with x being the value of rainfall or flow and X^* denoting the predetermined threshold value. Thus, the anticipated damage over a duration of T years is determined by correlating the probability $P^* = 1/T$ with the damage assessed based on the intensity of the triggering rainfall or discharge event X^* . The concept of the return time is susceptible to misconceptions and misapplications that are widely recognized yet

nevertheless prevalent, attributed to a fundamental conceptual misunderstanding [9,10]. For instance, if we use a design return period of $T = 200$ years, as suggested by the EU for urbanized regions [11], the damage level will be determined using X_{*200} , which represents an event that has a probability of $P_* = 1/200$ of being exceeded in a single year. It is theoretically established that the expected interval between two successive events is 200 years, leading us to conclude that a protective measure with a return period of 200 years is adequate to ensure the safety of an individual with an average lifespan of approximately 80 years. It is straightforward to illustrate that this assertion is incorrect, as an event with a probability of $1/200$ in a single year has a cumulative probability of occurrence of 33% over 80 years, which is not insignificant. This is why Borgman [5] advocated a clearer criterion, the “encounter probability”, which is the probability that a structure will encounter a hazardous event during its life. The concept can be easily extended to human life [10]. Moreover, decision theory [12–14] advocates substituting the notion of risk linked to return period, as delineated by the traditional single-value exceedance probability, with the anticipated loss resulting from the most significant event that could transpire over a duration of $N = 80$ years [10]. Evaluating the maximum anticipated loss over a designated timeframe is crucial, as it is a metric that can be juxtaposed with the expenditures decision makers are prepared to bear. This necessitates evaluating the complete probability distribution of the most significant event during a time frame of N years, rather than merely a singular 1-year maximum for probability $P_* = 1/T$; nonetheless, we believe the resultant risk indicator is far more resilient.

All currently employed extreme value methodologies rely on an implicit assumption of stationarity, which is very problematic in light of climate change. Adapting existing results to a non-stationary environment presents a significant challenge in contemporary research [15].

6.2. Assessing Risk

The full probability distribution of the largest occurrence over a time frame of N years can thereafter be discretized to calculate the expected value of damages in a discrete form rather than a continuous one. Inundation maps must be created for each specified probability level utilizing the aforementioned hydraulic models to evaluate the maximum water elevation, velocity, and time of residence at each point. Specifically, flood pathways and local depressions that could exacerbate damages and casualties must be identified and highlighted [1].

Subsequent maps must be generated to identify both the potential presence of individuals in public spaces (such as schools, offices, and factories) and private residences, along with the degree of vulnerability (including nurseries and nursing homes) of those at risk from floods, as well as the types and categories of assets within the territory (economic and environmental) [16].

Risk maps can be generated for each discretized probability step by synthesizing all the information gathered, as outlined in Section 4, and the expected risk will ultimately be assessed as $E\{D\} = \int_0^\infty D(x)f(x)dx$ which can be discretized and approximated, for example, as

$$E\{D\} \cong (P_{x_0} - P_{x_1}) \frac{D_{x_1}}{2} + (P_{x_1} - P_{x_2}) \frac{D_{x_1} + D_{x_2}}{2} + \dots + (P_{x_{n-1}} - P_{x_n}) \frac{D_{x_{n-1}} + D_{x_n}}{2} + P_{x_n} D_{x_n}$$

given that $D_{x_0} = 0$ and $D(x = \infty) \cong D_{x_n}$ for $P_{x=\infty} = 0$, due to the flattening of the upper tail of the damage curve.

$D(x)$ represents the damages as a function of the event magnitude, associated with the exceedance probability $P_x = \int_x^\infty f(x)dx$, and x_0 denotes the threshold event above which

damages occur. Additionally, D_{x_i} signifies the damages resulting from an event equal to x_i with an exceedance probability $P_{x_i} = \int_{x_i}^{\infty} f(x)dx$.

7. Urban Strategic Planning

7.1. Informed Urban Planning and Development

A crucial aspect of urban design and development must prioritize the mitigation of flood risk by reducing vulnerability. Therefore, it is imperative to identify flood-prone areas, allowing planners to designate development zones and guarantee that critical infrastructure and residential regions are not situated in high-risk zones [17].

Flood protection structures must be carefully designed and constructed to reduce risks, an essential element of risk, by assessing the expected probability of flooding events throughout a human lifespan or the lifespan of the structure [5–10].

To develop effective and sustainable drainage systems that can handle extreme weather events, it is crucial to understand existing rainfall patterns and runoff behavior, together with their future projections.

Detention volumes for surface and subsurface water must be suitably located and developed, with management through real-time controls to alleviate flood peaks [18,19].

Green infrastructures should be included in urban settings to improve infiltration and evapotranspiration losses. The purpose should concentrate on “sponge cities” by devising and executing urban development strategies that integrate rainwater systems with specific ecosystem conservation and restoration or remediation initiatives [20]. Aiming to preserve or restore the sponge-like capacity of natural landscapes to absorb and retain precipitation in the face of development, thereby reducing flood risk, diminishing runoff pollution, and improving water availability for many applications, including environmental purposes [21].

7.2. Augmented Catastrophe Preparedness and Response

Structural measures must be augmented by non-structural interventions, including warning systems, the management and control of defense works, and public engagement during and after events.

Proactive establishment of comprehensive flood models and emergency plans is essential for evaluating effective evacuation routes, shelter locations, and resource-distribution systems during flood disasters.

It is imperative to build advanced forecasting and alert systems to furnish citizens and authorities with critical lead time for action, a substantial and ongoing challenge that remains today.

Information must be broadcast through social media and mobile devices to apprise folks of the situation and promote active participation instead of a passive approach. In this context, it is essential to implement instructional campaigns about flood hazards and emergency responses, especially through operational drills and simulation exercises.

7.3. Enhancing Infrastructure Resilience

Design criteria could be improved based on the expected probability of the largest flooding events during a lifetime instead of the conventional “return period.” Understanding urban flooding guides the construction of structures, highways, and utilities to withstand flooding events for a duration suitable for human occupancy.

Identifying vulnerable areas in energy, water, and transportation networks enables planned improvements to mitigate disruptions during floods.

7.4. Social and Environmental Equity

Urban flooding disproportionately affects economically poor populations. Understanding the phenomena helps reduce vulnerability and implement fair methods to safeguard disadvantaged groups.

Comprehending flood dynamics underscores the imperative of preserving wetlands and natural river systems, which function as natural barriers to floods.

7.5. Strategies for Climate Adaptation and Mitigation

Comprehending the relationship between climate change and urban flooding aids cities in establishing climate-resilient infrastructure and policies.

Understanding urban flooding promotes the transition to sustainable development models that harmonize urbanization with environmental conservation.

7.6. An Example of a Holistic Methodology

In 2011, Copenhagen had a 1000-year storm event, a cloudburst, which inundated the city with three feet of water, resulting in damages exceeding USD 1 billion. The City of Copenhagen initiated a Cloudburst Management Plan, a thorough strategy that combines traditional engineering with nature-based solutions to alleviate the impacts of pluvial flooding, which is expected to increase due to climate change, particularly from cloudbursts, while promoting a more resilient and sustainable urban environment.

The design seeks to safeguard against a centennial storm event. In addition to flood protection, the plan seeks to promote urban livability, establish additional recreational areas, and improve the city's microclimate. The plan (Figure 2) integrates (1) blue-green solutions aimed at absorbing, storing, and gradually releasing water, thereby establishing new green spaces and recreational areas; (2) gray infrastructures featuring improved sewer systems and substantial pipes engineered to direct water to the harbor in densely populated regions; and (3) surface solutions that include stormwater roads, detention roads, detention areas, and green roads.

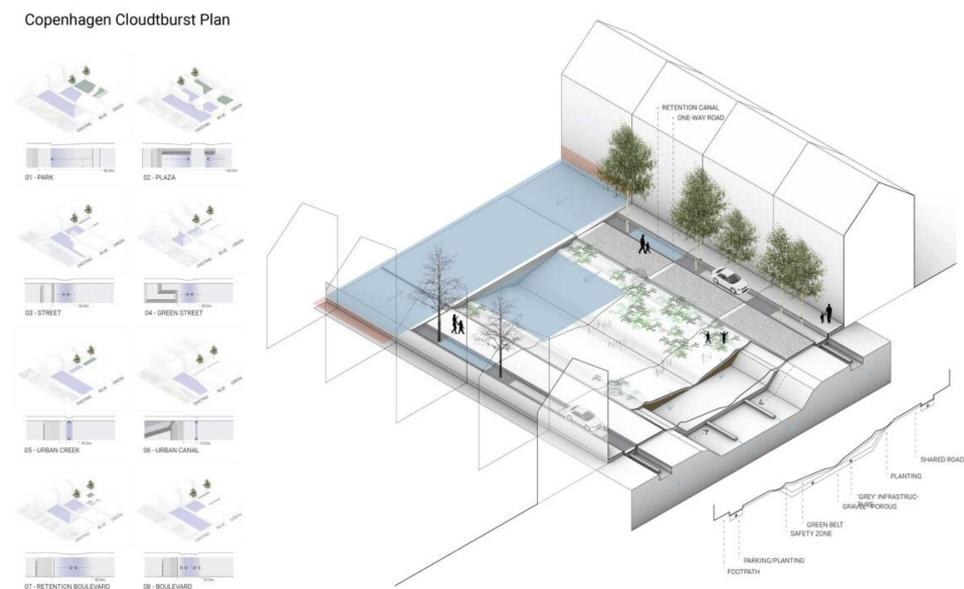


Figure 2. Copenhagen Cloudburst Plan, Copenhagen, Denmark, 2012. Realized/envisoned by the City of Copenhagen. Scale: 21,810 acres; 26 feet above sea level. Drawing: Lucas Dobbin, Nastassja Lafontant, Donguk Lee. <https://www.gsd.harvard.edu/project/copenhagen-cloudburst-plan/> (accessed on 3 June 2025).

8. Urban Flood Forecasts Toward Flood Risk Alleviation

No flood prevention system can completely eradicate the risk of flooding. Consequently, real-time flood-forecasting systems are crucial instruments for enabling decision-makers to mitigate risk before and during emergencies. Although river floods can be predicted several hours or even days in advance for larger rivers, pluvial floods frequently manifest as flash floods, happening in under six hours and occasionally in less than one hour, thereby providing emergency management with less time to formulate a response. The prediction of pluvial urban flooding remains inadequately addressed due to its complexity, which necessitates high-resolution temporal data collection and sampling in urban settings, alongside diminished concentration times that constrain the decision-making window for mitigating flood risk or managing emergencies. Rainfall must be collected and measured at brief intervals, such as every 5 min, necessitating the integration of many measurement sources, including rain gauges and radar. Instances of such combinations that enhance the reliability of forecasts are documented in [22].

Diverse methodologies exist for predicting river flow and urban drainage networks, involving the comprehensive integration of (i) meteorological forecasts, (ii) conventional hydrologic or data-driven artificial intelligence methods, and (iii) hydraulic deterministic models [23], or simpler cellular automata approaches [24], which, while less rigorous in terms of differential equation integration, are more amenable to parallel computation. A compelling analysis of these models is presented in [25].

Alongside traditional flood-forecasting models for riverine floods, Georgakakos [26,27] introduced worldwide the Flash Flood Guidance System, which seeks to predict the likelihood of flood level overtopping based on precipitation forecasts, specifically tailored to anticipate flash-flood occurrences, thereby providing decision makers with adequate time for intervention. An example of its application in conjunction with a detailed hydraulic model, the Urban Flash Flood Warning System (UFFWS), applied to a small community with dense housing and steep terrain in Tegucigalpa, Honduras, is given in [28].

Recently, surrogate models based on Physics-Informed Neural Networks (PINNs) for hydrodynamic simulators governed by shallow-water equations have also been developed to enhance the applicability of detailed hydrodynamic models over extensive regions and facilitate their use for nowcasting [29].

The selection of the suitable approach mostly hinges on the availability of spatial and temporal data, as well as the urgency of the forecast delivery. While numerous modelers advocate for the application of data-driven methods and artificial intelligence in scenarios of “scarce data,” these techniques are highly effective only when enough temporal observations are accessible to provide dependable training, calibration, and validation. Frequently, the absence of severe events within the observational range diminishes their reliability in predicting future occurrences that may surpass the most significant prior event. Conversely, when time-series data is limited, it is advisable to depend more on physically meaningful models, which necessitate substantial spatial data that is readily accessible in map form and can be calibrated with fewer temporal observations.

In urban flooding scenarios, the intricate geometry comprising rivers, canals, edifices, gardens, streets, plazas, sewer systems, and drainage facilities necessitates the utilization of sophisticated and detailed 1-2D hydraulic models to evaluate critical hazard parameters, specifically maximum water elevation, peak velocity, and residence time. Except for rare instances [23], while awaiting the efficacy of surrogate models [29] in real-time operations, as all hydraulic models are exceedingly time consuming and thus unsuitable for real-time applications, it is standard practice to compile a repository of inundation maps and relevant intervention strategies during the planning phase, based on varying magnitudes

of potential events. This approach restricts forecasting to the anticipation of flood event magnitude, either in terms of river flow or rainfall intensity and duration.

Regardless of the model or methodology employed for forecasting, a primary misconception is the necessity for probabilistic predictions. The majority of contemporary flood-forecasting systems offer anticipated future values of flow and water levels, yet they neglect the full “predictive probability density”, which delineates the likelihood of a future outcome based on all available information, typically represented in one or more model forecasts [30]. The predictive probability density is typically perceived negatively as a measure of “uncertainty” and employed to establish “uncertainty bands”, rather than being regarded positively as the “maximum of knowledge” derivable from available information, which does not exacerbate uncertainty but rather improves the decision-making process, as advocated by decision theory [12–14] and widely applied in economics [31]. According to [32], in order to fully profit from real-time flood forecasts, paradigm shifts are currently required. No significant improvement in quality will occur unless decision makers fully comprehend the potential benefits of incorporating predictive density into the decision-making process.

Despite the existence of effective approaches for generating and employing probabilistic predictions in decision making, water resource authorities and decision makers have seldom adopted them. This hesitance can be ascribed to the conservatism of governmental agencies [33] and a deficiency in awareness concerning the potential benefits, such as the increased resilience of the Bayesian decision-making framework (which lowers the probability of erroneous decisions) and the mitigation of losses descending from those decisions. Several aspects of the problem are, in fact, still misconceived or unclear, such as

- While not explicitly articulated, deterministic forecasts are implicitly regarded as “exact”, often resulting in erroneous decisions.
- Probabilistic forecasts do not augment our uncertainty; rather, they can diminish it when appropriately utilized within a Bayesian decision framework.
- Hydrological and meteorological ensembles produced by altering model parameters alongside initial and boundary conditions do not accurately reflect predictive uncertainty.
- Utility functions must be formulated in conjunction with decision makers to articulate their subjective preferences. Conversely, when utility functions are undefined, deterministic thresholds ought to be transformed into probabilistic thresholds.

9. Conclusions

A thorough comprehension of urban flood risk is crucial for the creation of secure, sustainable, and resilient cities. Rosenzweig et al. [34] present examples of pluvial flooding in six cities across the United States, illustrating the current susceptibility of urban areas lacking comprehensive pluvial flood management strategies. They also highlight the difficulties in conducting pluvial flood research due to existing data deficiencies and delineate critical research challenges that the interdisciplinary water research community should prioritize to enhance urban resilience practices.

Forecasting in advance the possibility and the potential effects of flooding, urban stakeholders may diminish damages, protect lives, and foster adaptive development in response to increasing environmental challenges.

A repository of flood maps must be created in advance to allow decision makers to estimate risk, formulate strategies, and promptly monitor conditions during events affecting areas susceptible to water inundation, flow velocity, and exposure duration. This involves employing a combination of statistical models to determine the probability of precipitation or flooding events, in conjunction with hydrological and 1-2D hydraulic models to evaluate hazards.

Real-time flood-forecasting systems are also crucial, but in many instances, especially with pluvial floods, the restricted contributing region and the abrupt occurrence of the event result in lead times that are insufficient for practical use. In many scenarios, 24 h forecasts generated from satellite imagery and advanced meteorological predictions may be more advantageous. Nonetheless, the emergence of AI methodologies and the accessibility of drone imagery now facilitate the creation of short-term projections to assist decision makers in the real-time management of urban flood disasters.

However, the appropriate applications of probabilistic forecasting appear to be in the nascent phases of the Diffusion of Innovations process described by Rogers [35], who outlines critical attributes that promote the successful adoption of innovation, such as (i) the extent to which an innovation is regarded as superior to its predecessor; (ii) its alignment with the existing values, prior experiences, and needs of prospective adopters; (iii) its clarity and user-friendliness; and, ultimately, (iv) the visibility of the innovation's outcomes to others.

Hydrologists must endeavor to effectively communicate the appropriate application of predictive uncertainty to decision makers, who need to acknowledge the benefits of informed decisions that arise from incorporating probabilistic forecasts into Bayesian decision frameworks, thereby maximizing the use of all available information [36].

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