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Enhanced urban adaptation efforts needed to counter rising extreme rainfall risks

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Record-breaking rainfall events are occurring more frequently in a warming climate. Impacts on lives and livelihoods disproportionately occur in traditionally underserved communities, particularly in urban areas. To influence policy and behavioral change at the community level, climate services must be developed specific to extreme rainfall events and subsequent floods in urban environments.

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MORE FREQUENT EXTREME RAINFALL IN A WARMING WORLD

Record-breaking rainfall events impact millions of people worldwide, often leading to mass casualty events and resulting in devastating social and economic consequences. The significant level of impact from recent events is yet another indicator showing that existing mitigation measures are insufficiently protecting people from floods, especially in urban and peri-urban areas.

In considering the expected rise in exposure in a rapidly urbanizing world, and with amplified extremes in a changing climate, the most vulnerable populations continue to be at risk of disproportionate impact from urban flooding even as policies have been implemented.

Record-breaking rainfall extremes, and in particular intense short-duration events, are becoming more frequent in a warming climate due to thermodynamic factors such as an increase in the rate of evaporation and a warmer atmosphere's capacity to hold moisture[1–4]. Moreover, potential changes in the atmospheric circulation also contribute to the rising risk of extreme rainfall events. Slow-moving weather systems cause longer-duration rainfall that amplifies flood risk. As an example, Hurricane Harvey remained stationary over Texas for multiple days guided by a persistent meander in the jetstream leading to extreme flooding in Houston in 2017. It has been suggested that global warming leads to a slow-down in the mid-latitudinal summer circulation which would make such events more likely[5,6].

The combination of changes in climate and socioeconomic activity has and will continue to demand a higher resolution for risk assessment. We are at a critical juncture as floods in urban and rapidly urbanizing regions continue to both accelerate in terms of frequency and evolve in complexity and magnitude. Fortunately, resilience plans, once rare, are becoming more commonplace in urban planning, providing a platform to integrate solutions to both extreme rainfall flooding and disproportionate impact from those and other events.

EXEMPLARY HIGH IMPACT RAINFALL EVENTS IN 2021

Globally, precipitation extremes led to a record number of flood disasters in 2021. Severe urban flooding leading to devastating social and economic consequences occurred not only in locations that are accustomed to these types of events, but increasingly in urban and peri-urban areas that have not seen significant flooding in the past[7]. Furthermore, even in urban areas that have adapted to certain types of flooding (such as coastal flooding from storm surge or king tides), there is an increasing risk of different flood types, to which community resilience may not exist (such as rapid onset flooding from intense rainfall or flooding from long-duration events[8]). Herein, we provide details of five destructive extreme rainfall events that attracted public, scientific, and media attention, including setting new records for hourly or short-duration rainfall.

Extreme flooding in the Northeast, USA: the Northeast United States experienced record-breaking rainfall in August and September of 2021. Tropical storm Henri in late August brought hourly rainfall of 1.94 inches, setting a the hourly record for New York City's Central Park weather station, leading to widespread floods and disruption of daily life, disproportionately impacting lower-income communities[9]. Just a week later, the recently set hourly rainfall record was broken when the remnants of Hurricane Ida interacted with an extratropical weather system, leading to severe short-duration rainfall of 3.15 inches in a single hour[10]. This led to severe consequences due to high winds and extreme urban floods from the southern to northeastern United States, resulting in $75 billion in damage[10]. While urban and peri-urban flooding occurred in various areas across gradients of socioeconomic status, non-white lower-income neighborhoods experienced higher fatality rates, with many occurring in illegal basement and surface-level apartments.

Extreme rainfall flooding in Germany, China, and Italy: unprecedented rainfall over Western Europe on July 12–15, 2021, caused severe flood damage[11]. Some parts of Germany received 2 months of rain in approximately 24 to 48 hours, which caused rivers to overtop their banks and led to flash flooding through many urban areas resulting in hundreds of missing people, destruction of social and economic infrastructure, and mandatory evacuation of residents in multiple regions within affected cities. This extreme event resulted in record-breaking insured losses of $4.7–$5.9 billion from the floods in western Germany alone[12]. Just a week later, over the period of July 17–31, 2021, severe flooding occurred in Henan Province in central China after receiving 15.0 inches—a little over half of its average annual

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precipitation of 25.2 inches—in only 6 h on July 20 and more than 25.2 inches during a short period of 4 days[13]. In this flooding event, severe property damage was reported, public transportation was halted, and businesses were shut down, causing an estimated $18 billion in direct economic losses[14]. A Medicane (a quasi-tropical cyclonic system occurring in the Mediterranean Sea with impacts similar to a hurricane) led to extreme rainfall in northern and central areas of Italy on October 4, 2021[13]. On this day, Liguria (northwestern Italy) had received 7.1 inches in 1 h and over 35.4 inches in a 24-h period[13]. These cities experienced severe damage to buildings and physical infrastructure such as roads and bridges, and social infrastructure such as schools and public places. While occurring in different parts of the world, one element each of these events has in common is that most of the impact was felt in urban areas.

EQUITABLE ADAPTATION TO INCREASING FLOOD RISKS

Urbanization, driven by population growth and economic development, is a compounding factor relative to climatic aspects, which can lead to exponential increases in flood risk with even modest changes in climate risk. Even in areas with small amounts of increased extreme rainfall probability, if urbanization is uncontrolled, the impact can be just as high if not worse compared to areas that have higher changes in climate risk[15]. Urbanization changes the geology and hydrology of the region by adding more impervious surfaces, decreasing permeability, and increasing runoff[15,16]. Therefore, leading to changes in how "floodplain" is defined, which likely increases the overall area within an urban context that is at risk of floods. This further leads to changes in the expected flood depth and flood extent and makes potentially existing mitigation measures less effective. Urban growth and informal development can lead to increased exposure of people and assets, in particular to already underserved populations with lower coping capacities[15]. Therefore, mitigation and adaptation measures need to be developed proactively, acknowledging changing urban landscapes and implemented with a focus on the rising risk to urban communities. Even if significant mitigation actions are taken now to decrease the impacts of floods in the future, we would still need to implement adaptation and disaster risk reduction activities as soon as possible to assess rapidly evolving flood risks, and develop forecast and risk-based anticipatory action programs in the short and medium term.

Mitigation measures that increase the resilience of urban communities to various flood types can be categorized into two groups: structural and nonstructural. Structural strategies refer to engineered systems—such as dams, levees, and floodwalls that focus on controlling the hazard[15]. Those protective structures are often designed under consideration of contemporary or historic flood threats. Given the rising frequency and intensity of floods due to climate change, such approaches may be inadequate to protect from future floods that could lead to overtopping or infrastructure failure[15]. Also, structural mitigation measures often create an illusion of safety, leading to unwanted effects such as promoting further growth in or near "flood-protected" areas[17], and a lack of adequate risk perception at the individual, institutional, and government levels. The so-called nonstructural flood mitigation measures, on the other hand, include public policy planning programs, such as zoning, buyout, land-use regulation, and socioeconomic incentives[18]. These policies are applied to control the exposure of risk and are most effective in urbanizing communities; however, they have been shown to be not always effective in reversing the tendency of people to choose to live in flood-prone areas[18].

As consequences from extreme rainfall events continue to rise, we must rethink the design of flood mitigation measures. Floods from extreme rainfall commonly occur in highly urbanized regions, where water cannot properly be absorbed on the ground due to the impermeability of pavements, roads, and lack of green spaces. Therefore, using proper structural measures such as stormwater management systems and green and blue structures can be highly effective in controlling the onset of severe runoff in a community[15]. In addition, buyout programs, as a form of nonstructural mitigating actions, can convert highly susceptible areas into parks and green spaces, increase the permeability of the soil and reduce flood risk; however, the social justice implications must be kept central to designing and implementing these programs. On the other hand, other nonstructural flood actions such as early impact-based forecasting, early warning, and anticipatory action systems can potentially help to mitigate the losses and fatalities in highly urbanized communities, however they must be sustainable and linked to standard operating procedures. For urbanizing cities, land use and zoning regulations can also be adopted by the creation of less dense neighborhoods upstream that use more green spaces for more water to be absorbed, leading to lower volume toward downstream neighborhoods including those that are denser and may have higher costs in restructuring the built environment, especially when social justice elements must be considered[15].

Recent disproportionate socioeconomic impacts of flood events in urban areas (e.g., as observed in the Northeast USA in August and September 2021) demonstrate that the current mitigation and adaptation measures are not enough to strengthen and build communities that are resilient and sustainable for all types of climate shocks, for all residents. As rainfall extremes evolve and become more complex and difficult to forecast, we are at a critical juncture to convene across disciplines to address various critical questions:

- What are the tradeoffs involved regarding implementing structural and nonstructural measures to provide future communities the best opportunity to become more resilient to extreme rainfall events?
- How should these measures capture the dynamics associated with flood risk due to climate change, urbanization, and human behavior? What is our responsibility to be more specific in representing the most extreme rainfall events in urban resilience activities and building standards?
- To what extent do these measures support one group of people more than others? And is this disproportionate benefit leading to the disadvantaged populations becoming relatively more disadvantaged?

In response to record-breaking rainfall events, we have a responsibility to be proactive as not only climate change increases the risk of more such rainfall events but also factors such as urbanization and human behavior lead to higher risks of socioeconomic inequality in urban areas[19–21]. Herein, we outline three suggestions (Fig. 1) to encourage the urban sustainability community to not only address flood risk caused by these repeated extreme events from a social justice perspective but also, incentivize more substantive action to occur now as the risk is rapidly evolving especially in urban settings. The suggestions presented here are designed to be merged with other recommendations to ensure action is taken to address extreme rainfall events in urban being mindful of their contribution to rising socioeconomic disparities[22–29].

SUGGESTIONS FOR BUILDING RESILIENT COMMUNITIES TO EXTREME FLOODING

Developing resilience and preparedness plans for extreme rainfall events

The rising socioeconomic consequences from record-breaking rainfall events in urban communities demonstrate that future

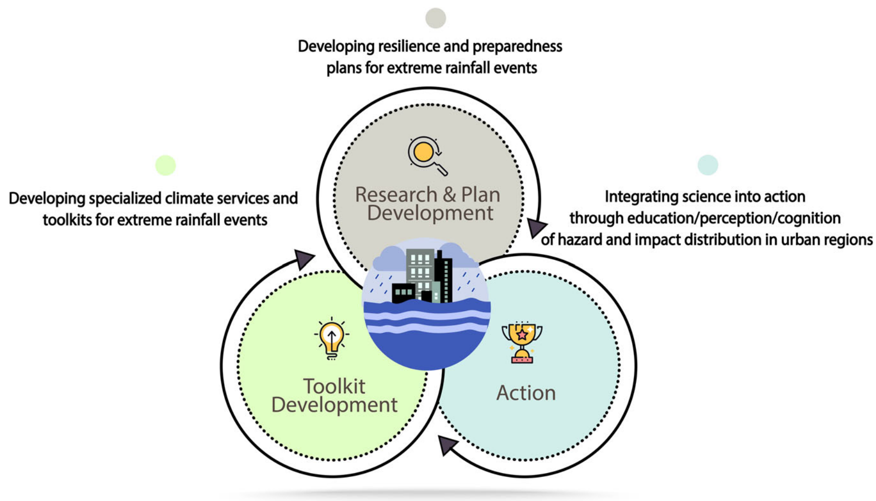

Fig. 1 Diagram showing elements to be considered for building communities resilient to extreme urban flooding induced by extreme rainfall events.

resilience and preparedness plans, which should be designed specifically for extreme rainfall events, must account for the dynamic and evolving nature of flood risk due to climate change, urbanization, and human behavior. If these are not updated, there is an increasing risk that "unprecedented impact" will become normalized. Accurate prediction of record-breaking rainfall extremes in terms of their potential intensity and duration that are evolving due to climate change, and their rising impacts brought by city expansion and human dimension in urban regions are major challenges. As a first step to develop resilience and preparedness plans, there is an immediate need for conducting more research on understanding and predicting rainfall extremes, and their impacts in designing systems for both alerting the public and for prioritizing the neighborhoods where anticipatory action is most needed. Moreover, most resilience and preparedness plans are designed to protect urban communities in the worst plausible flood events. As the worst plausible flood events may either be affected by climate change or underestimated due to both known and unknown inherent uncertainties, urban floods that are far more severe than what is stated as the worst-case scenario may happen in future[17]. Consequently, this will lead to increased impacts in urban areas more so than in other areas due to the relatively tighter vulnerability gradients—which lead to significantly more people being either prioritized or de prioritized for anticipatory action based on shifts in risk[30].

Therefore, minimum standards for the development of future resilience plans must include language to allow for initial versions to capture the probability of the most extreme events and must allow for future revisions to address evolving risk. These plans must also account for urban morphology impact on these extremes itself as some urban environments may influence convective behavior. Other factors that must be considered include building footprint, changes in land cover and population density, and proximity to large water sources[31]. Acknowledging the fact that forecasts for intense convective rainfall are "more uncertain" in some urban areas can be useful in understanding our ability to design and implement preparedness actions and resilience plans[32]. On the other hand, mitigation and adaptation actions, either in the form of structural and/or nonstructural measures, shape urbanization through time, influence land use and land cover, and consequently affect urban flood risk. One of the critical challenges in designing effective resilience plans is to examine how and to what extent policymakers should employ these plans to build resilient urban communities in extreme rainfall events. To do so, policymakers must consider the tradeoffs between costs and benefits of future land development in achieving sustainable and resilient cities considering the uncertainties in the performance of the built environment in extreme rainfall events. An additional underlying factor in changing the nature of flood risk is that the policies are usually adopted without considering the human behavior aspect[33]. While risk perceptions and socioeconomic status vary across all types of communities, gradients of these factors are extremely tight in urban areas, leading to potentially exponential differences in coping capacity from block to block. Therefore, the human behavior elements related to the perception of risk must be addressed in preparedness and resilience plans so that they not only target a wide range of people with different risk perceptions and socioeconomic statuses but also include specific actions that prioritize and reach the populations whereby various factors, such as the lack of services, have led them to become most vulnerable.

Developing specialized climate services and toolkits for extreme rainfall events

Policymakers should access services and toolsets to help them in developing resilience and preparedness plans in urban communities. From a climate perspective, considering the accessibility of high-resolution satellite imagery, there are opportunities in developing Machine Learning algorithms to be used along with climate models to predict atmospheric dynamics and weather systems leading to record-breaking rainfall events in urban areas. Such models should take urban morphology into account to increase the accuracy of the predictions. For an existing conurbation, the development of context-dependent indicators for detecting the most vulnerable neighborhoods will result in prioritizing the needs and consequently diminishing the socioeconomic consequences of flooding induced by record-breaking rainfalls. The current state of urban data is valuable for addressing the climate change challenges in an urban context; however, climate risk-related decision making in an urban context can be improved, and more closely aligned with sustainable development goals, if regularly up to date information on human behavior and perceptions is available[34,35]. Recent advances in technologies including remote sensing, high-resolution satellite imageries, OpenStreetMap, and Google Street view along with traffic and social media datasets can reveal where social vulnerability is relatively higher[34–36], as well as allow for improved understanding of spatiotemporal extent of urban floods. From a long-term perspective, as urbanization evolves, zoning, and land use regulations, as well as socioeconomic incentives such as tax policies, can be adopted in urban development plans so that it promotes urban development in regions that are less susceptible to urban flooding induced by severe rainfall events[15]. The development of local simulation models allows for policymakers to test various structural and nonstructural policies and visualize the consequences of different extreme rainfall scenarios[15]. However, these tools, while containing "simple" interfaces, will convey complex data with inherent uncertainty; therefore, climate science translators and trusted brokers should be included in the process[36]. Finally, as successful policy implementation heavily relies on human behavior and how well they respond to the adopted policies and preparedness plans, we must improve data assimilation and acquisition so local authorities have up to date information on shifts in risk perception, trust, and ability to take action of people in the most at-risk communities. Accordingly, performing local surveys and using data science can provide information about how, when, and why people take short-term anticipatory actions and make longer-term adaptation decisions.

Integrating science into action through education, perception, and cognition of hazard and impact distribution in urban regions

Developing early warning systems based on the reliable prediction of extreme rainfall events can save lives; however, if the design of these systems culminates in only an alert, the necessary anticipatory actions will likely not occur in the communities that are most in need. While this gap between the presence of early warning alerts and the use of the alert to motivate action is present in all contexts, in urban areas the challenges are more pronounced[37]. This is due to various factors including administrative border-based alerting that leads to a high number of people being over warned, as well as the inter-urban dynamics of population movements. For example, challenges in understanding where people are and how many people are exposed at specific points during the day, which is most important relative to early warning and anticipatory action programs to address sudden-onset extremes such as flash floods and mudslides. In the NYC severe urban flooding event in September 2021, although the authorities warned the public about the incoming hazard, people, especially those within the most socially vulnerable and underserved communities, either did not receive an alert, did not perceive the risk was of a sufficient level to warrant action and/or did not have the resources to take action. Moreover, incentivizing and funding community-level and community-led activities is key in providing urban communities the resources they need to become more risk-aware and be prepared for such events and recover from them faster. Such programs do not replace the need for structural changes, across each infrastructure, policy development, and social network—whereby each currently reinforces the social fracturing that leads to disproportionate impact from disasters, and in particular, impact from sudden-onset extremes[38]. Early warning systems must be linked to specific actions and integrated within standard operating procedures of the organizations with the roles, responsibilities, and capacity, as well as trust in communities, to take those actions. As taking action demands resources be available and accessible, we must also create incentives for private industry to engage in the programs that are specifically designed for the preparedness and resilience of the most vulnerable communities.

CONCLUSION

Urban communities face amplified flood risks due to compounding effects of increasing rainfall extremes from global warming and escalating exposure from urbanization, leading to rising socioeconomic impacts from such events. Therefore, resilience and adaptation plans for urban areas must improve the ways they incorporate risks of extreme rainfall events, including sudden-onset events. From an urban sustainability perspective, we provide three suggestions for improving future urban resilience and adaptation plans to tackle the rising socioeconomic consequences of record-breaking rainfall events. Namely, the development of specialized resilience and preparedness plans, the development of services and toolkits, and integrating science with action particularly for extreme rainfall events. Doing so will make progress towards closing a critical gap in planning for record-breaking rainfall events that have increasingly become the norm. The intention of this paper is to provide insight for community leaders, city planners, governments, and private sector stakeholders in achieving sustainable and resilient cities for all inhabitants, which will only be accomplished if the most vulnerable and traditionally underserved populations are centered in all solutions, and their risk for the most extreme rainfall events adequately addressed.

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M.H., K.K., and A.K. conceived and developed the idea for this article. M.H. wrote the initial draft of the paper. M.H., K.K., and A.K. edited the manuscript and wrote the subsequent and final drafts.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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