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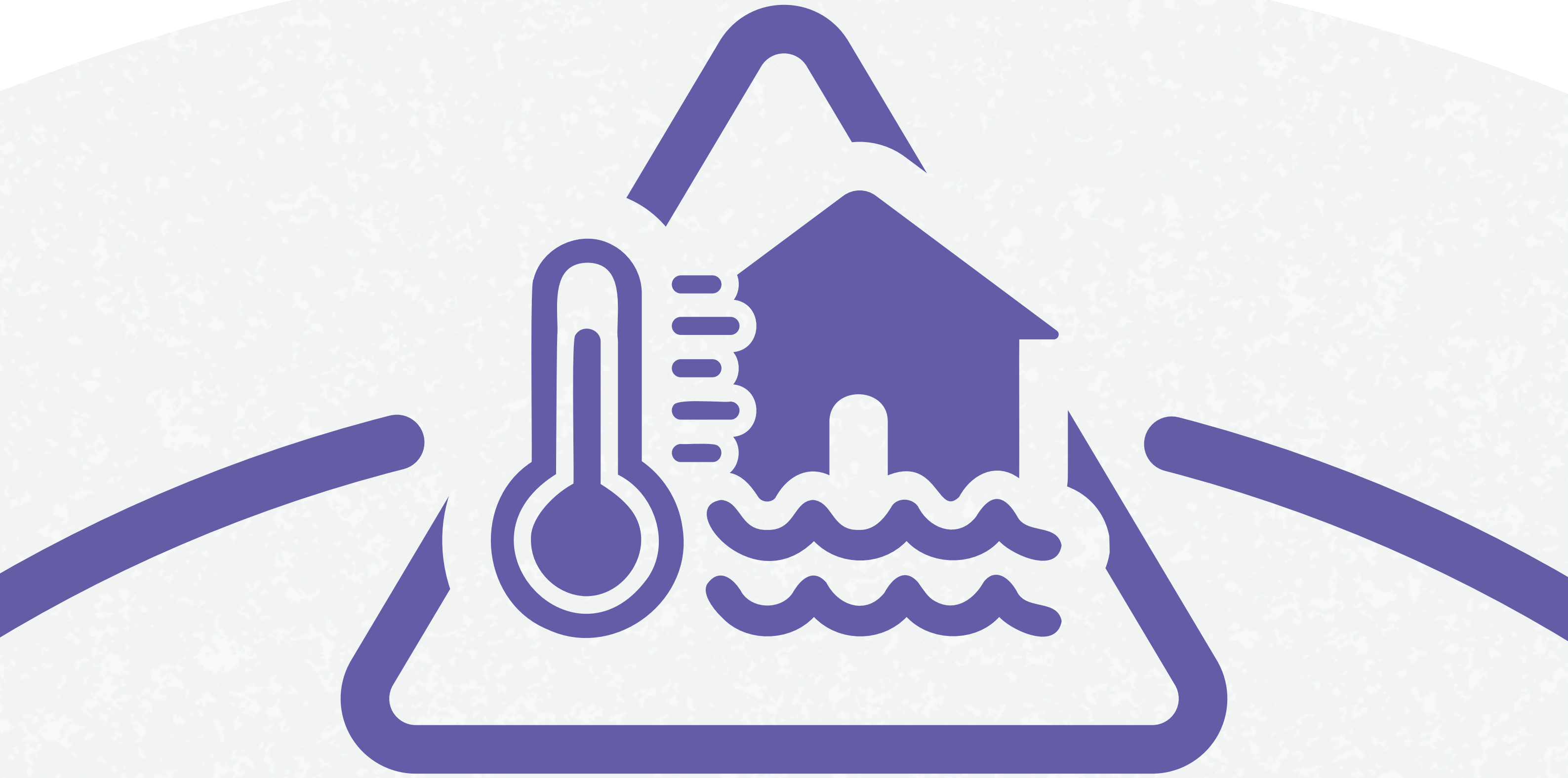
Double jeopardy: Addressing compound flood and heatwave events



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Double jeopardy: Addressing compound flood and heatwave events

Evidence Paper

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About the Zurich Climate Resilience Alliance

The Zurich Climate Resilience Alliance is a multi-sectoral partnership, powered by the Z Zurich Foundation, focused on enhancing resilience to climate hazards. By implementing solutions, promoting good practice, influencing policy and facilitating systemic change, it aims to ensure that all communities are able to thrive. By 2035, alongside like-minded organizations, the Alliance aspires to positively impact 70 million people vulnerable to climate change, and 5.5 million by 2027. The Alliance works to achieve its objectives through long-term, flexible, community-centred programming and a focus on systemic change. The Alliance does this by delivering programmes, conducting evidence-based research, sharing knowledge, and influencing key stakeholders on resilience to climate hazards.

Members of the Zurich Climate Resilience Alliance are funded by the Z Zurich Foundation, with the exception of Zurich Insurance Group. However, the views expressed in this publication do not necessarily reflect the official position of either the Foundation or the company.

Contents

Executive summary

This paper explores the escalating risks of compound heatwave and flood events, a growing phenomenon highly accelerated by climate change and urbanization. These hazards, occurring in close succession or simultaneously, amplify impacts on human health, infrastructure, ecosystems, and livelihoods, often surpassing the damage caused by each event individually. Using current scientific research and case studies, the paper examines the mechanisms driving these events, their increasing frequency, and the implications for climate resilience practitioners.

Three primary forms of compound events are explored: **heatwaves followed by floods, floods followed by heatwaves, and simultaneous occurrences of both**. Urbanization exacerbates these risks through the urban heat island effect, impervious surfaces, and inadequate drainage systems, increasing exposure and vulnerability. Case studies such as Hurricane Beryl in Texas and Pakistan's 2022 floods illustrate how cascading events disrupt essential infrastructure, overwhelm emergency responses, and deepen socioeconomic inequities.

Tailored for practitioners, this paper provides actionable solutions with co-benefits for compound flood and heat wave events, such as nature-based interventions and resilient urban planning. Recommendations include expanding urban green spaces, restoring wetlands, implementing bioswales, and adopting climate-resilient infrastructure. The authors also highlight the importance of **integrated risk assessments, multi-hazard early warning systems, and community-based adaptation measures**. Cross-sectoral collaboration among governments, private sector actors, and communities is essential to implement these strategies effectively.

This work is coauthored by the Red Cross Red Crescent Climate Centre, Z Zurich Foundation, Institute for Social and Environmental Transition-International (ISET-International), International Federation of Red Cross and Red Crescent Societies (IFRC), London School of Economics and Political Sciences (LSE) and Mercy Corps as part of the **Zurich Climate Resilience Alliance** (the Alliance). The Alliance is a multi-sectoral partnership committed to enhancing community resilience to climate hazards. By providing evidence-based insights and practical recommendations, the paper calls on practitioners to adopt holistic, equity-focused strategies that address the dual threats of heatwaves and floods, fostering sustainable and adaptive urban environments in the face of escalating climate challenges.

Introduction

Climate change is posing significant threats to communities around the world. The frequency and intensity of floods and heatwaves has already increased on a global scale due to climate change and will continue in the foreseeable future (IPCC, 2023). In the context of climate change, a new category of extreme events is increasingly prevalent: **compound heatwave and flood events** (Gu et al., 2022). Such back-to-back events can result in significant damage to **human health, livelihoods, agriculture, infrastructure, and ecosystems, and pose unique challenges to adaptation**.

Understanding compounding events and risk

Concept	Definition
Compound events	When two or more weather or climate events occur at the same time, in close succession, or concurrently in different regions (IPCC, 2023).
Compound risk	Compound risks are broadly defined as 'the combination of multiple drivers and/or hazards that contributes to societal or environmental risk' (Zscheischler et al., 2020).

Compound events are more complex and can have more devastating consequences compared to single extreme events, as highlighted in the latest 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2023; Zhou et al., 2024). Compound events can interact in a way that creates more severe outcomes than if they occurred both individually ("1 + 1 > 2"), as multiple stressors can exceed the coping capacity of a system more quickly than individual stressors occurring in isolation. Next to climate change, other factors such as **urbanization** are increasing the likelihood of such events. While adaptation practitioners are familiar with the threat of heatwaves and floods, it is important to assess the compound risks that occur when such events **happen closely after each other** and develop solutions that address such risks.

In this paper, we focus on compound heat and flood events and translate the latest scientific evidence on the compound risks and draw on the experience of the **Zurich Climate Resilience Alliance** to provide actionable recommendations for practitioners on how to adapt to these combined risks.

The key objectives of this paper are to:

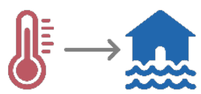
- Identify the potential compound risks that arise when floods and heatwaves occur in close succession, and
- Explore practical solutions that offer co-benefits for reducing these risks.

Compound heatwave and flood events: current and future trends

Compound heatwave and flood events occur when the **two extreme events happen in close succession or even simultaneously.** These types of compound events used to be rare but are occurring more often in the present climate and this trend is likely to continue, creating additional risks beyond the impact of heatwaves or floods alone (Gu et al., 2022). Although most research has focused on flood or heatwave events individually, analyses on compound events are gradually increasing. In addition, as flooding can result from different drivers (e.g. extreme rainfall, tropical cyclones, or high sea levels), the literature on compound heat and flood events looks at these trends separately.

Compound heatwave and flood events can manifest in **three main forms** (Gu et al., 2022):

Heatwave followed by a flood

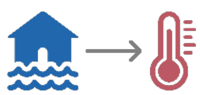


Intense heat can destabilize the atmosphere, fostering conditions conducive to heavy rainfall which leads to floods; studies have shown that the likelihood of extreme rainfall increases locally when preceded by a heatwave. (You and Wang, 2021). Additionally, prolonged periods of heat and drought can dry and compact soils, reducing water infiltration and increasing the risk of flash floods (IPCC, 2023).

This phenomenon is most likely in mid-latitudes (temperate and colder climates), particularly in North America, Europe, Australia, and parts of Asia (Sauter et al., 2023; Zhang & Villarini, 2020). Extreme rainfall tightly preceded by extreme heat has been identified as one of the most common and impactful compound extremes, and are projected to become more frequent, longer in duration, and more intense (Zhou et al. 2024).

Example: *In January and February 2019, extreme heat followed by heavy rainfall in Queensland, Australia, led to the death of half a million cattle and total economic losses of at least $1.2 billion U.S (Zhang & Villarini, 2020).*

Flooding followed by a heatwave



This can happen when weather systems like cyclones cause flooding and are followed by heatwaves. Large-scale weather patterns and interactions between land and sea often play a role in connecting cyclones and heat. Cyclones are increasingly causing major flooding because warmer sea surface temperatures are enabling storms to carry far more moisture. In addition, cyclones are often followed by warm, humid air masses since they originate in the tropics and carry that air inland when they make landfall. Flooding followed by heatwaves is most common in tropical and subtropical regions with active cyclone zones, such as Southeast Asia, the Gulf Coast of the United States, and the Bay of Bengal. These areas are particularly vulnerable due to warm sea surface temperatures that fuel intense storms and create humid air masses.

Example: *In 2018, a sequence of flooding followed by a heatwave struck western Japan, impacting thousands within the span of a week. The initial flooding damaged homes, disrupted power grids, and left populations without electricity or safe drinking water, worsening impacts during the subsequent heatwave (Chen et al. 2021).*

Image 1: 1July 2018 – Japanese Red Cross staff and volunteers arrive in areas hit by record heavy rainfall and landslides to provide vulnerable people with emergency care. Many roads were impassable, and it was necessary to borrow fishing boats to reach the affected communities. Photo: Japanese Red Cross Society.

Heatwave and flood at the same time

In some cases, heatwaves may coincide with coastal flooding, particularly in areas experiencing extreme sea levels (Zhou & Wang, 2024). 87.73% of coastlines globally have been affected by concurrent heatwaves and extreme sea levels from 1979 to 2017 (high tides and storm surges, which can lead to flooding), and 40% of global coastlines have experienced a significant increase in such events over the past decades (Zhou & Wang, 2024). Regions with a higher risk of compound heatwaves and coastal flooding are concentrated in the tropics. While tropical coastlines account for less than half the world's shorelines, they have already experienced over 70% of the compound heatwaves and coastal flooding events worldwide (ibid.). This is especially worrying, as the tropics contain some of the world's poorest countries.

***Example**: In August 2021, the Mediterranean was struck by flooding induced by extreme sea levels while temperatures reached nearly 122 F (50 °C) (Zhou & Wang, 2024).*

Looking ahead, the incidence of floods and heatwaves are both projected to increase on an individual level (IPCC, 2023). The IPCC (2023) reports that with each additional degree of global warming, the frequency, duration, and intensity of heatwaves will continue to increase in all regions around the globe. In addition, flooding is projected to increase, due to increases in both sea level rise and increases in heavy rainfall, including changes in precipitation intensity associated with tropical cyclones. Furthermore, expected increases in dry spells are also projected, which will dry out soils, limiting their ability to absorb water. These changes will increase the likelihood and severity of flooding, especially in areas with inadequate drainage or flood risk management systems.

Studies have shown that compound flood and heatwave events are projected to increase across most catchments worldwide, with the tropics projected to become a global hotspot (Gu et al., 2022). For example, global coastlines are projected to experience 38 days of concurrent heatwaves and extreme sea levels each year in the 2025–2049 period under the highest emission scenario (Zhou & Wang, 2024). While climate projections show this increasing risk, there is a dearth of research on its potential impacts and implications for adaptation.

Climate Resilience Measurement for Communities (CRMC)

The definition of resilience adopted by the Alliance requires specifying "resilience of what to what for what purpose". This means that for each climate hazard we address, we think specifically about resilience to that hazard.

However, it is widely acknowledged that:

1. **there are overlapping areas of resilience across multiple hazards, and**
2. **interventions to enhance resilience can offer co-benefits across several hazards, even if they are not specifically designed to address multiple hazards simultaneously.**

The **Climate Resilience Measurement for Communities (CRMC)** tool and framework, developed by the Alliance, assesses and measures community resilience to climate hazards. The CRMC includes indicators ("sources of resilience") that are based on the five capitals of resilience: human, social, natural, physical, and financial. These sources are a mix of generic and hazard-specific indicators. For instance, 'first aid knowledge,' 'healthcare access,' 'transport system continuity,' and 'local government financial capacity' are general resilience sources that apply across various hazards. Meanwhile, sources like 'large-scale flood protection', 'heatwave protection knowledge', and 'flood insurance' are hazard specific.

The CRMC does not yet explicitly address compounding hazards, including interacting risks and resilience, but it can be run for two or more hazards at a time. This means that relative resilience strengths and weaknesses can be compared for the different hazards, and the implications for hazards occurring simultaneously can be explored. This can then be coupled with active identification of actions that provide benefits for both/all hazards by addressing common or interlinked resilience areas. Moving forward, the Alliance will work with local communities to evaluate the co-benefits and unintended consequences of adaptation actions across the multiple hazards they face. This approach ensures that resilience is built holistically, rather than through isolated measures that address one hazard at a time.

Urbanization and non-climatic compounding factors

Extreme events don't occur in a vacuum. The risk of extreme events is determined by the *hazard* event itself, *exposure* to that hazard (i.e. the people and assets in the path of the extreme event), and *vulnerability* (i.e. the susceptibility of people or infrastructure to harm) (IPCC, 2023). In the near-term, the climate-related risks communities face will largely be shaped by changes in vulnerability, exposure, and the degree of adaptive measures (IPCC, 2023; Simpson et al., 2021).

Rising exposure to floods and heat from rapid urbanization

The world is quickly urbanizing. In 2023, 4.6 billion people live in urban areas (United Nations, 2023), with an additional 2.5 billion people expected to live in urban areas by 2050, of which a large percentage live along coasts (IPCC, 2023). Coastal cities are the at the forefront of climate change. Over the coming decades, expansion of populations living in coastal cities is expected to continue, increasing the number of people vulnerable to coastal floods, sea level rise, and storm surge. In addition, populations living in cities are also more at risk due to the urban heat island effect, which exacerbates the impacts of heatwaves.

The shift from green spaces to concrete

Urbanization and other non-climatic factors are exposing more people to compound flood and heatwave events (IPCC, 2023; Zheng et al., 2024). The rapid growth of urban areas has led to increased concrete and asphalt surfaces, which absorb heat and exacerbate the urban heat island effect, increasing both residents' exposure to heatwaves and the severity of the heatwave hazard. Land use changes, such as deforestation and agricultural expansion alter natural drainage systems, increasing runoff and susceptibility to flooding (Roy et al. 2022). The expansion of impermeable surfaces reduces water's ability to be absorbed into the ground, increasing the urban flooding hazard.

Poor infrastructure in cities

Furthermore, inadequate infrastructure, particularly poorly designed drainage systems, exacerbate flooding in urban areas (Yazdanfar & Sharma, 2015). This increase in both hazard and exposure is often coupled with increased vulnerability caused by aging infrastructure that may not be equipped to handle the increasing frequency and severity of heatwaves and floods. Although urbanization in itself is not a bad thing, its effects depend on how well growing cities are planned and managed. Poorly managed growth can increase vulnerability to climate risks and deepen inequalities, while well-planned urbanization can enhance resilience and sustainability.

There are also multiple **non-climatic factors** that affect people's risk. Socio-economic status and cultural factors affect risk perception and response, influencing people's behavioural responses and therefore preparedness (Hass et al., 2021). Factors such as the effectiveness of emergency preparedness and response systems, policies regarding disaster preparedness, and public health infrastructure are crucial in supporting people to reduce their exposure and vulnerability by setting up shelters, supporting preparedness, and providing critical services, amongst others. Furthermore, it's essential to recognize that risks and impacts from these compound events are not felt equally across different genders and social groups. Women, especially those who are pregnant, children, the elderly, outdoor workers, and low-income communities are often disproportionately affected by climate hazards. Marginalization - due to political affiliation, gender, caste, race, refugee/displaced status - makes people more vulnerable because they are overlooked in any kind of response.

In urban areas, many different actors need to work together in order to address the challenges associated with compound heat and flood events. For example, the power authority needs to work with emergency response agencies and the meteorological and health agencies in order to ensure continuity of electricity during a heat-flood event. No one sector or actor alone can solve the issue, it requires collective, multi-partner action.

Impact pathways

There are a variety of impact pathways that can result from compound heat and flood events. What needs to be considered and planned for is where a key impact pathway related to the response to one hazard has unintended consequences that increase the risk of another hazard. For example, the implementation of grey flood control infrastructure (e.g. flood walls, levees, etc.) can lead to changes in land use and urban design which can increase the urban heat island effect, resulting in elevated ambient temperatures, especially during heatwaves. Another example is people seeking relief from the heat outdoors during a heatwave, exposing them to higher risk from extreme sea levels and flooding (Zhou & Wang, 2024).

Another key impact pathway to consider is linked to the impacts of one hazard increasing the risk of another hazard, through increasing exposure and vulnerability. For example, heatwaves themselves are health hazards and lead to significant heat-related health problems due to the stress heat places on the human body. Beyond that, floods can further exacerbate impacts by affecting water supply (e.g. contaminating drinking water and causing outbreaks of waterborne diseases) or causing infrastructure damage leading to power outages, limiting the use of fans or air conditioning in a subsequent heatwave. This type of critical infrastructure failure from a flood limits adaptive capacity during heatwaves. The Hurricane Beryl case study below shows how this type of scenario can play out.

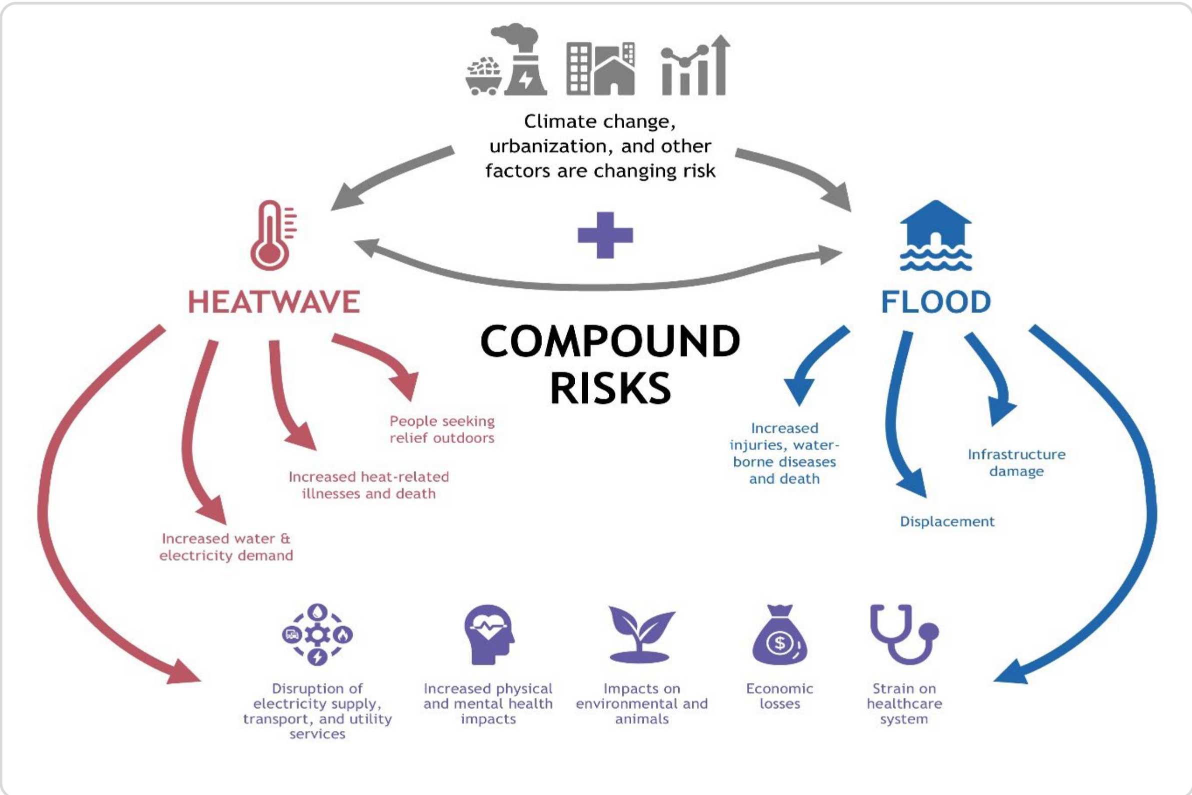


Figure 1: Simplified visual of compound heat and flood events. These events affect all five capitals: natural (e.g., environmental degradation), social (e.g., displacement), human (e.g., health impacts), financial (e.g., economic losses), and physical (e.g., infrastructure damage and/or loss of critical services), underscoring the need for holistic resilience strategies. Source: Red Cross Red Crescent Climate Centre.

Case study 1: The compounding impact of Hurricane Beryl, heatwave and widespread power outages on public health

This case study examines the sequence of events that unfolded during and following Hurricane Beryl's landfall in Texas, highlighting the compounding effects of hurricane-related flooding, widespread power outages, and heatwaves.

Image 2: Currents from Hurricane Beryl were so strong that boats were pushed out of water and into the streets in the Texas Gulf, July 8, 2024. Photo: Matthew Pena/American Red Cross.

Hurricane Beryl made landfall in Matagorda, Texas as a Category 1 hurricane on July 8, 2024. The storm caused extensive damage from Galveston to the Houston metro area and beyond. The power grid suffered massive damage; over 2.7 million customers lost electricity, and trees and utility lines were downed across the region. On July 10, two days after landfall, 1.6 million customers remained without power.

As the storm moved out, a dangerous heatwave settled over the region in which temperatures climbed into the mid-90s Fahrenheit (32.2°C), and heat index values rose above 100°F (37.7° C). The widespread nature of the outages caused by Hurricane Beryl meant that many critical facilities, including community centres and libraries that typically serve as cooling centres, were also without power, leaving residents with few options to escape the heat.

The combination of hurricane damage, prolonged power outages, and the heatwave created a compounding disaster. Hospitals were quickly overwhelmed with patients suffering from heat-related illnesses and carbon monoxide poisoning from running generators indoors. The elderly, sick, and those without means to relocate were particularly susceptible to the dangerous conditions.

Further, the heat complicated recovery efforts, slowing down power restoration and debris removal. The compounding nature of this disaster led to a third of the deaths following the storm being attributed to the heat and a spike in heat-related hospitalisations.

This pattern of heat-related deaths following hurricanes has been observed in previous disasters, such as Hurricane Laura in 2020 and Hurricane Ida in 2021, where heat caused more fatalities than any other single factor associated with the storm. One of the key lessons from Hurricane Beryl is that investing in robust and redundant infrastructure systems and ensuring cities have adaptive strategies for multiple hazards is critical to protecting vulnerable populations in urban areas.

This case study highlights two particularly powerful entry points for building urban resilience:

- **Invest in backup power systems for critical infrastructure** like hospitals and cooling centres to ensure they remain operational during and after extreme events such as floods or heatwaves.
- **Develop emergency response plans that take into account the compounding potential of various risks.** These plans should identify key systems, such as transportation, communication, and power grids, and assess how damage to one system can increase the vulnerability to and impacts of another hazard should they occur concurrently or in rapid sequence of one another.

The Hurricane Beryl case study highlights the way in which the impacts of one hazard on critical infrastructure can increase vulnerability to another, subsequent hazard. It also underscores the urgent need to plan for compound events, including by building redundancy into existing infrastructure, preparing backup power systems even as you increase the robustness of the power grid, and increasing the capacity of medical services to scale up care during a disaster.

Case study 2: The compounding impacts of heatwaves and floods in Pakistan in 2022

In Pakistan, a heatwave followed by extreme floods shows how one hazard can erode people's capacity to respond to additional shocks, thereby creating an environment in which the subsequent hazard can do greater harm.

Image 3: Water collection in the Sindh province, Pakistan, 20 February 2023. Monsoon floods in 2022 damaged and contaminated the already scarce water sources in the region. Photo: Angbeen Sohail/ IFRC.

In March 2022, Pakistan was hit by one of the most severe heatwaves in its history. Temperatures soared to over 50°C (122°F) in some regions, with prolonged periods of extreme heat. This extreme heat dried out soil and overwhelmed the electrical grid, leading to frequent power outages as demand for cooling surged. Water shortages intensified as rising temperatures exacerbated existing scarcity, particularly in major cities like Karachi.

The heatwave was followed by a summer monsoon season that brought unprecedented rainfall – 190% of normal – to Pakistan in July and August. Dried soils were less able to absorb water, and rapid glacial melt from the heatwave meant rivers were already swollen by meltwater when the rains started. The result was the deadliest floods in Pakistan since 2010, affecting more than 33 million people and leaving a third of the country underwater. Critical infrastructure—including more than 8,000 miles of roads and 410 bridges—was damaged or destroyed, hindering emergency response and evacuations, with damage and economic losses of over USD 30 billion.

Cities like Karachi saw an influx of over 50,000 displaced people from rural areas as a result of the flooding, intensifying the strain on already overburdened urban services. Housing shortages forced many into makeshift shelters, increasing the risk of disease outbreaks.

Repeated extreme weather events can give rise to disaster poverty cycles, which occur when disasters deplete households' resources and disrupt livelihoods, preventing full recovery.

In the aftermath of the 2022 Pakistan floods, the national poverty rate is estimated to have risen by up to 4.3 percentage points, equal to an additional 9 million people (Knippenberg et al., 2024).

The case of Pakistan in 2022, which compounded extreme heat and widespread flooding, serves as a critical example of the challenges that can arise when multiple hazards converge, and highlights the importance of:

- **Integrated Risk Assessments**: Understanding how extreme heat can exacerbate flooding risks is crucial. Practitioners should assess multiple hazards collectively rather than in isolation.
- **Infrastructure Resilience**: Enhancing infrastructure to withstand extreme weather events can mitigate impacts. Strengthening power grids, water supply systems, and transportation networks is essential.
- **Adaptive Urban Planning**: Preparing for population influxes during disasters can help cities accommodate displaced people without overwhelming services of creating new hazards.

Both heatwaves and floods can result in economic impacts due to disruptions to business continuity and damage to business or government infrastructure (e.g. transportation, buildings, telecommunications) that can have knock-on effects across other sectors.

Adapting to compound heatwave and flood events

Though there is a growing recognition of the need to build resilience against compound events through better urban planning, flood defences, and climate-resilient agriculture, the costs and technical challenges associated with these measures are significant, particularly for low-income countries.

Adaptation solutions with co-benefits

Fortunately, there are many opportunities to implement adaptation solutions that address both heat and floods, with co-benefits for improving overall quality of life, environmental sustainability, and economic stability.

Nature-based solutions

Urban green spaces: Expanding parks, green roofs and walls, and urban forests can help reduce the urban heat island effect by providing shade and cooling through evapotranspiration. Green walls, parks, and street trees have been well-researched for their urban cooling capabilities and are very effective (e.g. green walls can provide up to 8.2 °C cooling) (Kumar et al., 2024). These green spaces also improve water absorption and reduce surface runoff, mitigating the risk of urban flooding during heavy rains. (Gill et al, 2007). Additional benefits beyond flood and heat mitigation include increased property values, and improvements to health and productivity for those living or working nearby.

Rain gardens and bioswales: These landscaped areas are designed to absorb and filter rainwater, reducing the risk of flooding while also contributing to cooling the surrounding area. They can be integrated into urban landscapes, helping to manage stormwater and reduce the urban heat island effect (Kumar et al., 2024; Davis et al., 2009).

Wetlands restoration: Restoring and protecting wetlands can serve as a natural buffer against floods, as these areas can absorb large amounts of water during heavy rainfall. Wetlands are one of the most effective nature-based solutions in reducing air temperature, acting as natural coolers (Kumar et al., 2024).

Mangrove reforestation: In tropical and sub-tropical coastal areas, mangroves can protect against storm surges and flooding. Mangroves sequester carbon, reduce shoreline erosion, create tourism opportunities and habitats for diverse species offering broad environmental and climate resilience benefits (Alongi, 2008).

Implementing, restoring, and preserving water features: Maintaining and/or restoring (small) water features such as small creeks, ponds, etc. supports the drainage network, provides space for water during intense rainfall, and routes floodwater into larger water bodies. Water features are also effective in cooling the surrounding area (Kumar et al., 2024).

Building and urban design

Rooftop rainwater harvesting: These systems can lower rooftop temperatures, supplement household water supply, manage stormwater and reduce flood risks (Yew and Yew, 2021).

Elevated and flood-resistant buildings: Designing buildings with elevated foundations or incorporating flood-resistant materials (e.g. insulated concrete forms, treated bamboo and compressed earth blocks) can protect against flooding while also improving ventilation and cooling, reducing the heat load on buildings.

Permeable pavements: Replacing traditional concrete and asphalt with permeable materials allows water to infiltrate the ground, reducing surface runoff and the risk of flash floods. These surfaces also reduce the heat retained by urban infrastructure, helping to lower local temperatures (Collins, 2008; Kumar et al., 2024).

Green streets: Incorporating permeable pavements, street trees, and other green infrastructure into road design can manage stormwater more effectively while providing cooling benefits through shading and reduced surface temperatures (Kumar et al., 2024).

Integrated Water Resource Management (IWRM): Implementing IWRM practices that optimize water resource use can help manage both flood risks and water scarcity during heatwaves. IWRM includes retention basins, rainwater harvesting/infiltration basins systems, and efficient irrigation practices that reduce water demand during dry periods while mitigating flood risks (Dey et al., 2024).

Community-based adaptation

Multi-hazard early warning systems: Strengthen and integrate early warning systems that monitor and warn for combined and interrelated extreme heat and flood risks, such as through impact-based forecasting, and early action protocols that consider compounding effects across hazards (UNDRR, 2023; White et al. 2024). Warning systems should include localized flood and heatwave alerts that engage local leaders and organizations to spread coordinated and coherent flood and heat alerts through appropriate channels - with an emphasis on reaching the most vulnerable groups to each hazard type.

Early action based on a warning or forecast: Warnings should lead to appropriate actions, taking into consideration the nuances and implications of different hazard impacts and their compounding effects (Golding, 2022). Considering complementary actions and being aware of maladaptive actions is critical for developing early action protocols that take into account compounding risks. Actions can include checking in on higher-risk individuals such as elderly grandparents or neighbours, evacuating, or going to a flood shelter or cooling centre. It may be that people need resources to take action or need to be incentivized.

Community cooling centres and shelters: Establishing multipurpose centres that can serve as cooling shelters during heatwaves and flood shelters during flooding to protect vulnerable populations from both hazards. These centres can be equipped with solar power, rainwater harvesting, and other resilient infrastructure, both to improve centre performance during hazard events and as demonstrations of available technology and its utility (Kovats & Hajat, 2008).

Public education and awareness: Educating communities about the risks of heatwaves and floods and promoting preparedness measures can enhance resilience. Awareness campaigns can encourage behaviours that reduce both heat and flood risks, such as planting trees, maintaining drainage systems, and using water efficiently.

Social networks and mutual support systems: These systems foster community cohesion, enabling neighbours to share resources, check on vulnerable individuals, and coordinate evacuations during heatwaves, floods, or compound events. They also promote real-time information sharing and collective action, helping communities access cooling centres, distribute emergency supplies, or perform quick recovery efforts.

Important lessons on adapting to compounding risks

Building resilience to heatwaves and floods requires a combination of adaptation strategies, such as green infrastructure, planning, early warning systems, and public education campaigns. Governments, communities, and individuals all play a role in mitigating the compounding risks of these extreme weather events.

Strengthening local governance and decision-making is critical. This includes inclusive planning that ensures local adaptation strategies include voices from all parts of society, particularly marginalized groups. Empowering local neighbourhood councils, leaders, and organizations to actively participate can strengthen governance and fosters community ownership of resilience efforts. Community engagement and education further strengthen adaptive capacity and people's ability to participate in governance mechanisms.

Risk assessment for compound events must be holistic and incorporate multiple sectors (e.g. health, water infrastructure, telecommunications, power, etc.) in order to understand potential areas of vulnerability that require special attention in integrated risk plans. Infrastructure should be climate resilient and have built-in redundancy to ensure continued functionality during crises. For example, cooling systems with backup power and redundant water sources ensure buildings and people can stay cool even if one system fails, safeguarding essential services and community well-being.

In cities, advocating for policy and regulatory frameworks that integrate compound disaster risks into urban planning can ensure that city and national governments align climate adaptation with socio-economic development strategies, leading to sustainable and cost-effective urban growth in flood-prone and heat-sensitive areas.

Lastly, addressing underlying vulnerabilities is essential for managing both compound risks. Enhancing basic access to healthcare, reducing poverty, and fostering social and spatial integration can strengthen community resilience in general and to compound events.

Conclusion

As climate change accelerates, compounding events pose new and complex challenges, demanding immediate, integrated action. Addressing these interconnected threats requires shifting from siloed responses to holistic, systems-thinking approaches that consider both individual hazards and the broader vulnerabilities they expose.

To effectively safeguard vulnerable populations, it is critical to implement targeted policies, allocate adequate resources, and foster coordinated action across all levels of government and society. Protecting communities from these extremes requires a multi-layered approach that engages public, private, and community stakeholders. Particularly in urban settings, this will require much broader partnerships that bring together governments, private industry, civil society, and local communities. These collaborations will drive innovative solutions to promote adaptation, create safer urban environments, and enhance cities' capacities to withstand future extremes.

Recognizing the unprecedented challenges posed by compounding heat and flood events, this paper aims to serve as a blueprint for proactive leadership within the Zurich Climate Resilience Alliance, emphasizing the need to adopt multi-dimensional resilience strategies. We encourage teams to leverage this framework to pioneer adaptive solutions, integrate compound-risk assessments, and lead coordinated resilience actions for both hazards and tailored to the unique vulnerabilities of urban contexts. Sharing knowledge and promoting community-based adaptation, across the Alliance and beyond, plays an important role in addressing climate-induced risks. Making heat resilience a priority and advancing systems change will help build an urban future that is safer and more sustainable for all.

References

Alongi, D. M. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, *76*(1), 1-13.

Chen, Y., Liao, Z., Shi, Y., Tian, Y., & Zhai, P. (2021). Detectable increases in sequential flood-heatwave events across China during 1961–2018. Geophysical Research Letters, 48, e2021GL092549. https://doi.org/10.1029/2021GL092549

Collins, K. A., Hunt, W. F., & Hathaway, J. M. (2008). Hydrologic comparison of four types of permeable pavement and standard asphalt in Eastern North Carolina. *Journal of Hydrologic Engineering*, *13*(12), 1146-1157.

Davis, A. P., Hunt, W. F., Traver, R. G., & Clar, M. (2009). Bioretention technology: Overview of current practice and future needs. *Journal of Environmental Engineering*, *135*(3), 109-117.

Dey, S., Santra, M., Ghosh, A. R., & Samanta, P. (2024). Global solutions for integrated water resources management in cities throughout the world. Developments in Environmental Science, 16, 351-385.

Gill, S. E., Handley, J. F., Ennos, A. R., & Pauleit, S. (2007). Adapting cities for climate change: The role of the green infrastructure. *Built Environment*, *33*(1), 115-133.

Golding, B. (2022). Towards the “Perfect” Weather Warning: bridging disciplinary gaps through partnership and communication (p. 270). Springer Nature.

Gu, L., Chen, J., Yin, J., Slater, L. J., Wang, H.-M., Guo, Q., et al. (2022). Global increases in compound flood-hot extreme hazards under climate warming. Geophysical Research Letters, 49, e2022GL097726. https://doi.org/10.1029/2022GL097726

Hass, A. L., Runkle, J. D., & Sugg, M. M. (2021). The driving influences of human perception to extreme heat: A scoping review. Environmental Research, 197, 111173. doi:10.1016/j.envres.2021

Knippenberg, E., Amadio, M. & Meyer, M. Poverty Impacts of the Pakistan Flood 2022. EconDisCliCha 8, 453–471 (2024). https://doi.org/10.1007/s41885-024-00155-3

Kovats, R. S., & Hajat, S. (2008). Heat stress and public health: A critical review. *Annual Review of Public Health*, *29*, 41-55.

Kumar, P., Debele, S. E., Khalili, S., Halios, C. H., Sahani, J., Aghamohammadi, N., ... & Jones, L. (2024). Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs. The Innovation, 5(2).

Roy, P.S., Ramachandran, R.M., Paul, O. et al. Anthropogenic Land Use and Land Cover Changes—A Review on Its Environmental Consequences and Climate Change. J Indian Soc Remote Sens 50, 1615-1640 (2022). https://doi.org/10.1007/s12524-022-01569-w

Sauter, C., Fowler, H. J., Westra, S., Ali, H., Peleg, N., & White, C. J. (2023). Compound extreme hourly rainfall preconditioned by heatwaves most likely in the mid-latitudes. Weather and Climate Extremes, 40, 100563.

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., ... & Trisos, C. H. (2021). A framework for complex climate change risk assessment. One Earth, 4(4), 489-501.

UNDRR (2023). Words into action: A GUIDE TO MULTI-HAZARD EARLY WARNING SYSTEMS. Available through: https://www.undrr.org/words-into-action/guide-multi-hazard-early-warning

United Nations, Department of Economic and Social Affairs, Population Division. (2023). World Urbanization Prospects 2023: Highlights. New York: United Nations.

White, C. J., Adnan, M. S. G., Arosio, M., Buller, S., Cha, Y., Ciurean, R., Crummy, J. M., Duncan, M., Gill, J., Kennedy, C., Nobile, E., Smale, L., and Ward, P. J.: Review article: Towards multi-hazard and multi-risk indicators – a review and recommendations for development and implementation , Nat. Hazards Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/nhess-2024-178, in review, 2024.

Yazdanfar, Z., & Sharma, A. (2015). Urban drainage system planning and design – challenges with climate change and urbanization: a review. Water Science and Technology, 72(2), 165–179. doi:10.2166/wst.2015.207

Yew, M. C., & Yew, M. K. (2021). Active and passive systems for cool roofs. *Eco-Efficient Materials for Reducing Cooling Needs in Buildings and Construction: Design, Properties and Applications*, 275–288. https://doi.org/10.1016/B978-0-12-820791-8.00012-2

You, J., & Wang, S. (2021). Higher probability of occurrence of hotter and shorter heat waves followed by heavy rainfall. Geophysical Research Letters, 48, e2021GL094831. https://doi.org/10.1029/2021GL094831

Zhang, W. and Villarini, G. (2020), Deadly Compound Heat Stress-Flooding Hazard Across the Central United States. Geophys. Res. Lett., 47: e2020GL089185. https://doi.org/10.1029/2020GL089185

Zheng, K., Xian, Z., Liao, W., & Chen, Y. (2024). Urbanization impacts on sequential flood-heatwave events in the Guangdong-Hong Kong-Macao Greater Bay Area, China. Urban Climate, 55, 101878.

Zhou, M., Wang, S. (2024). The risk of concurrent heatwaves and extreme sea levels along the global coastline is increasing. Commun Earth Environ 5, 144 . https://doi.org/10.1038/s43247-024-01274-1

Zhou, Z., Zhang, L., Zhang, Q. et al. (2024) Amplified temperature sensitivity of extreme precipitation events following heat stress. npj Clim Atmos Sci 7, 243. https://doi.org/10.1038/s41612-024-00796-x

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., ... & Vignotto, E. (2020). A typology of compound weather and climate events. Nature reviews earth & environment, 1(7), 333-347.