Chapter 1
An Introduction to Multi-hazard Risk Interactions Towards Resilient and Sustainable Cities

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Abstract The relationship between disaster resilience and sustainability in the context of urban risk has gained significant attention in recent years as the research and technical community work towards a safer, more sustainable way of living. Urban risk is a complex matrix that involves multiple elements at risk, hazards, temporal scales, and vulnerabilities, and this is why traditional risk assessment approaches that focus on addressing the impacts of a single hazard are inadequate for effectively assessing and managing urban risk, particularly in the current climate change context. With this in mind, the present chapter provides an introduction to the concept of multi-hazard risk and its relevance to resilient and sustainable cities by listing and briefly discussing the types of natural hazards that impact cities the most and examining the importance of risk assessment and management in reducing the risks posed by these hazards. The chapter also explores strategies for building resilience in cities, including the strengthening of physical infrastructure and the enhancement of social and economic resilience, and concludes by discussing future directions for research and practice in multi-hazard risk management for resilient and sustainable cities.

Keywords Multi-hazard risk · Risk assessment · Risk management · Resilience · Sustainable cities

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1 Introduction

Since the global framework for disaster risk reduction [44] was defined and approved in Sendai, Japan, there has been a greater focus on linking disaster resilience and sustainability through policies and tools that support risk-informed sustainable development. The relationship between the concepts of disaster resilience and sustainability in the context of urban risk has also been developing, and their role towards a safer, more sustainable way of living is now understood in a clear and more comprehensive way by the research and technical community working in this field [11].

Urban risk is a multi-dimensional matrix that often includes multiple elements at risk, such as people, buildings, and infrastructures, multiple hazards, multiple temporal scales, as well as multiple types of vulnerabilities. For this reason, unlike current practice, addressing the impacts of one single hazard is not sufficient when assessing and managing urban risk, and it is, therefore, necessary to replace current single-hazard approaches with multi-hazard risk assessment.

Multi-hazard risk refers to the potential impacts and consequences of multiple hazards on a particular location or system [24]. These hazards can be natural, human-induced, or socioeconomic in nature and may include events such as earthquakes, floods, landslides, fires, industrial accidents, terrorism, financial crises, and pandemics. Understanding and managing multi-hazard risk is critical for building resilient and sustainable cities, as it enables planners and policymakers to identify and assess potential hazards and vulnerabilities, develop risk management strategies, and implement measures to reduce the impacts of hazards on communities and infrastructure. In this chapter, we will be focusing particularly on natural hazards, although some of the considerations provided here also apply to other types of hazards.

The importance of considering multi-hazard risk in urban planning and development cannot be overstated. As extensively discussed in literature—see, for example, Lau et al. [25] or Pelling [33]—urbanization and population growth have led to the concentration of people and assets in cities, making them more vulnerable to the impacts of hazards. At the same time, cities also provide important economic, social, and cultural benefits, and are key drivers of global development and progress. Ensuring the resilience of cities is therefore essential for protecting communities, preserving economic, social and cultural assets [38], and promoting sustainable development.

This chapter aims to provide an introduction to the concept of multi-hazard risk and its relevance to resilient and sustainable cities—the topic of the project "MIT-RSC—Multi-risk Interactions Towards Resilient and Sustainable Cities", funded by the Portuguese Foundation for Science and Technology (FCT) under the MIT Portugal Program at the 2019 PT call for Exploratory Proposals in "Sustainable Cities", which was the basis for this book. The chapter begins by discussing the types of hazards that can impact cities and then discusses risk assessment and management strategies for reducing the impacts of these hazards. Finally, it concludes by exploring strategies for building resilience in cities, and identifies key directions for future research and practice in this area.

2 Natural Hazards in Urban Settings

Cities are exposed to a variety of hazards that can have significant impacts on communities and infrastructure. As mentioned earlier, these hazards can be natural, human-induced, or socioeconomic in nature, and can include very different types of events. Understanding the types of hazards that cities are exposed to is a critical first step in developing effective risk assessment and management strategies. Understanding the types of hazards that cities are exposed to is crucial for developing risk assessment and management strategies that effectively reduce their impacts. This is because specific hazards have different characteristics and impacts that need to be considered in the risk assessment process. As discussed in detail by Dickson et al. [10], tailored risk management strategies can then be developed based on the hazards that the city is exposed to. For example, a city exposed to earthquakes may need to focus on strengthening buildings and infrastructure, while a city exposed to floods may need to improve drainage and flood protection systems. This targeted approach helps to ensure that resources are used effectively and efficiently, as risk management measures will be focused on the hazards that pose the greatest risk to the city.

According to the Federal Emergency Management Agency [12], "*natural hazards are defined as environmental phenomena that have the potential to impact societies and the human environment*". These hazards, which are being increasingly influenced by climate change, can have significant impacts on cities, including physical damage to buildings and infrastructure, loss of life, and disruption of essential services. As previously mentioned, understanding the types of natural hazards that cities may be exposed to is essential for designing efficient risk assessment and management strategies. That is why it is probably worth including at this point a brief definition of the hazards that most commonly affect urban settings. It is also worth noting that the hazards listed below are the ones that will be addressed and discussed in greater detail in the following chapters of this book.

2.1 Earthquakes

Earthquakes are sudden, violent shaking of the ground caused by the movement of tectonic plates in the Earth's crust. They can cause damage to buildings and infrastructure, particularly in areas with a high concentration of unreinforced masonry or poorly constructed buildings (Fig. 1). Earthquakes can also trigger landslides, which can further damage buildings and infrastructure and block roads, disrupting transportation.

Fig. 1 Examples of urban masonry buildings damaged by earthquakes

Robert Mallet and John Milne were pioneers in studying how and why buildings were damaged during earthquakes. According to Cousins and Smith [7], on 13 October 1900, John Milne (1850–1913) wrote regarding his 1892 book on earthquakes: "*if you compare the contents of this volume with its reproduction, and a companion volume called 'Seismology' issued in 1898, you will realize the rate at which a neglected study is advancing*." In his observations, Milne noted that some societies had developed solutions for resisting earthquake damage and incorporated them into local construction practices, while in others, architects and engineers were unaware of the need to design for future shaking, a phenomenon that can be partially explained by the frequency of earthquakes in certain regions and the corresponding risk perception and seismic culture of the populations in those regions [27]. In his catalogue of destructive earthquakes [31], Milne estimated that over 12 million people had been killed by earthquakes in the 2,000 years prior to 1900. As noted by Bilham [7], he would have been astonished to see that, even with the advances in earthquake engineering that occurred in the century following his words, earthquakes would claim an additional 2 million lives.

2.2 Floods

Floods are the most frequent type of natural disaster and occur when an overflow of water submerges land that is usually dry. They can be caused by heavy rainfall, rapid snowmelt, or a storm surge from a tropical cyclone or tsunami in coastal areas. Depending on their extension and magnitude, floods can cause widespread devastation, resulting in loss of life and damage to personal property.

According to the United Nations Office for Disaster Risk Reduction [43], floods have affected more than 2 billion people worldwide between 1998 and 2017 alone (Fig. 2). People who live in floodplains or non-resistant buildings or lack warning systems and awareness of flooding hazards are particularly vulnerable to floods.

Fig. 2 Floods in Bingley, England, in 2015 (left) and in Venice, Italy, in 2018 (right)

Floods can also disrupt essential services, such as public health infrastructure, transportation, communication, and power, which can be particularly meaningful in urban areas, as discussed in great detail by Jha et al. [22] or Hammond et al. [19].

2.3 Landslides

Landslides, or mass movements, are the movement of rock, soil, or debris down a slope. As noticed by Alexander [2] in his pioneering article on urban landslides, landslides are often triggered by other hazards, such as earthquakes, storms, or heavy rainfall, and per se, rarely cause disasters that attract international attention. However, in many countries, smaller-scale landslide disasters, which involve damage valued at hundreds of thousands of dollars and may cause a few fatalities, are both numerous and frequent [2].

It is plausible to believe that the occurrence and impact of urban landslides will tend to increase in future due to two main reasons. Firstly, as a result of the pressures created by population growth—a topic that has already been widely treated in literature applied to different types of hazards; see, for example, Radeloff et al. [20], Hemmati et al. [21], He et al. [35]. Secondly, people are attracted to building on hillsides due to their natural beauty. In Olshansky's words [32], "*Hillsides pose unique problems for the construction and maintenance of human settlements. They are prone to natural hazards, and they topographically constrain the design of settlements. For these reasons, hillside lands often remain vacant long after adjacent valley floors are urbanized. Despite the constraints, they are attractive places to live because of the views and because of the sense of being close to nature.*" Thus, much urban expansion is expected to take place in hillside areas, and consequently, ground failure by landsliding will likely be one of the most significant geological hazards affecting urban settings in future [37].

2.4 Urban Fires

Urban fires are a significant concern in cities around the world. The already mentioned high concentration of buildings, people, and resources in urban areas makes them particularly vulnerable to the impacts of fires. Urban fires can have a range of causes, including electrical malfunctions, accidents resulting from human activities such as cooking, smoking, using open flames, candle usage, or arson. Urban fires can also be triggered by natural hazards, such as earthquakes. Post-earthquake fires are a low-probability phenomenon but can have high consequences in terms of human loss and severe damage to property [23]. According to Cousins and Smith [8], fire losses are usually zero for most earthquakes. However, when a fire does occur after an earthquake, the losses can surpass those caused by the earthquake itself. The San Francisco earthquake in 1906 is a prime example of this—over 80% of the reported damages were due to fire, and more than 28,000 buildings were destroyed [36].

However, the consequences of urban fires per se can be devastating. They can cause significant damage to buildings and infrastructure and lead to injuries and fatalities. According to the World Bank [1], more than 180,000 people die each year in fires or from burn-related injuries worldwide, with 95% of those deaths occurring in low- and middle-income countries where risks rise proportionally with rapid urbanization (Fig. 3). Inadequate urban planning, infrastructure, and construction practices related to fire are among the top factors that contribute most to the potential for conflagration, ignition, and the spread of fires in buildings and urban spaces [13]. In addition, urban fires can have significant environmental impacts, as they release pollutants into the air and can alter local ecosystems.

Effective prevention and management of urban fires is critical to minimizing their impacts. This can include measures such as building codes and regulations that aim to reduce the risk of fires through the implementation of active and passive fire mitigation measures, as well as fire prevention education and outreach programs.

Fig. 3 Urban fires in Leeds, England (left), and in Hargeisa, Somalia (right), both in 2022

3 Multi-hazard Risk Interactions

As mentioned in the introductory section of this chapter, urban risk is a multifaceted concept that involves multiple elements at risk, multiple temporal scales, multiple vulnerabilities, and multiple hazards. This means that cities are often exposed to multiple hazards at the same time, and these hazards can interact in complex ways to create new risks or amplify existing ones. These multifaceted risk interactions can be difficult to predict and can have significant impacts on communities and infrastructure. Therefore, understanding the ways in which hazards can interact and the risks that these interactions create is crucial in developing effective risk assessment and management strategies.

As awareness of the complexities associated with multifaceted risk interactions has grown, a wide variety of terms have emerged to describe them [9, 46]. In an effort to clarify this diversity, Tilloy et al. [42] have reviewed and categorized the various terms into five main types of hazards:

1. Independent: As the name suggests, independent hazard events are events that overlap in space and time but are unrelated to one another. An example of this might be the occurrence of wildfires during the COVID-19 pandemic—they were coincident in spatial location and time, but were completely unrelated. Some authors also include in this category cases where two unrelated hazards impact the same area, at different times (e.g., a flood occurring a few weeks after an urban fire, or an earthquake after a cyclone).
2. Triggering (cascading): Triggering or cascading events occur when one hazard triggers another hazard, creating a chain reaction of events, meaning that triggering events always imply a primary and a secondary hazard. According to [17], any natural hazard might trigger none, one or more than one secondary hazard. For example, an earthquake can trigger a landslide, which could then block a river and cause a flood. The secondary hazard can be the same as or different from the primary hazard [42]. Cascading events can have significant impacts on cities, as each hazard in the chain reaction can cause damage and disruption on its own, and the combined effects of all of the hazards can be much greater than the sum of their individual impacts (e.g., post-earthquake fires, as discussed in Sect. 2.4).
3. Change conditions: Change conditions occur when a primary hazard changes the probability of a second hazard occurring by altering environmental conditions. For example, the impact of wildfires on the risk of landslides or flooding events is a good example of this phenomenon.
4. Compound (association): Compounding hazards involve the simultaneous occurrence of different hazards that are dependent on one another and, when combined, create new or amplify existing risks. In this case, there is no primary and secondary hazard as the different hazards occur simultaneously [42]. For example, a hurricane could produce heavy rainfall that causes a flood, which, in turn, could damage buildings and infrastructure, making them more vulnerable to future hazards. The compound effect of these hazards can have significant

impacts on cities, as the risks resulting from the combination of the hazards can be much greater than the individual risks of each hazard, like in the case of cascading events.

5. Mutual exclusion: Two natural hazards are said to be mutually exclusive if they have a negative dependence on one another. For example, heavy rain may help to extinguish a wildfire. As noticed by Tilloy et al. [42], since a negative dependence of two hazards does not lead to increased impact (which would be a positive dependence), there is less literature on this type of hazard interaction.

From the set of examples provided above, it is clear that understanding the ways in which hazards can interact, and the risks that these interactions create is a crucial step in developing effective risk assessment and management strategies that can reduce the impacts of multiple hazards (as will be discussed in the next section). By considering the potential interactions between hazards, cities can develop risk management measures that address the combined risks of multiple hazards, rather than just the individual risks of each hazard.

4 Risk Assessment and Management

Risk assessment is the process of identifying, analyzing, and evaluating the risks to which a city is exposed in order to understand the likelihood and potential impacts of these risks. On the other hand, risk management involves developing and implementing strategies to reduce these risks in order to minimize the likelihood and potential impacts. It is essential that risk management be based on a comprehensive and accurate understanding of the risks to which cities are exposed (obtained in the risk assessment stage). Otherwise, the efficiency of the strategies implemented during the risk management stage may be compromised. Only by ensuring that the risk is comprehensively and accurately assessed and that the results of this assessment are processed, integrated, and considered in the risk management stage can we develop and implement strategies that can efficiently reduce the risks to which a city is exposed, contributing to more resilient and sustainable urban areas.

Risk assessment and management strategies for cities should consider the potential interactions between hazards as well as the individual risks of each hazard. By considering the potential interactions between hazards, decision-makers can develop risk management measures that address the combined risks of multiple hazards, rather than just the individual risks of each hazard. As discussed in Sect. 3, the combined risks of these hazards can often be much greater than the individual risks of each hazard, so it is key to accurately assess the risks resulting from multiple hazards in areas that are potentially exposed to multiple hazard events.

There are many different approaches to assessing and managing risk in urban settings. However, in general, urban risk assessment is usually described as a four-step process involving: the identification and characterization of hazards that can

Fig. 4 Four steps of risk assessment

potentially affect the city, the assessment of the exposed elements, and the evaluation of the vulnerability of those elements—as illustrated in Fig. 4.

Hazards are typically represented on maps that show the locations and intensities of all the hazards that can potentially affect the city. These maps serve a purpose beyond simply representation, as they are key tools for understanding the risks that these hazards pose to a city. They are fundamental, for example, for identifying the exposed elements in the second step of the risk assessment process, see Fig. 4. When the elements exposed to the hazards considered in the assessment are identified, it is necessary to assess their vulnerability, i.e., to identify the factors that make these elements vulnerable to those hazards, such as the age and condition of buildings and infrastructure, and the demographics and socioeconomic status of the population. It is worth noting that exposure must be disaggregated by individual hazard, as vulnerabilities are hazard-specific, i.e., a specific building or infrastructure can be vulnerable to an earthquake but not to a flood.

Finally, the risk assessment stage involves analyzing the likelihood and potential impacts of the hazards, based on the magnitude and extent of the identified hazards and the vulnerability of the exposed elements to these specific hazards, in order to understand the risks to which a city is exposed.

Once the risks to which a city is exposed have been identified and understood, risk management strategies can be developed and implemented in order to reduce these risks. These strategies can include measures such as strengthening buildings and infrastructure to make them less vulnerable to hazards [15, 28], developing evacuation and emergency response plans [5, 45], and implementing land use and zoning regulations. Risk management strategies should also consider the potential impacts of climate change, which can drastically increase the extent, magnitude, and types of hazards to which cities are exposed. This is particularly important for coastal cities, which are especially threatened by the impacts of sea level rise.

5 Creating More Resilient Urban Areas

The popularity of the word "resilience" has increased significantly in both academic and policy discourse in recent years, with numerous explanations for this dramatic rise [29]. Probably one major reason for this is that resilience theory provides insights into complex socio-ecological systems and their sustainable management, particularly with respect to climate change, see, for example, Leichenko [26], Solecki et al. [34], Pierce et al. [41]. In particular, resilience has become an attractive perspective with respect to cities, often theorized as highly complex, adaptive systems [4, 18], as noted by Meerow et al. [29], who define urban resilience as "*the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity*."

In the context of the present review, this complex definition of urban resilience can probably be simplified to "the ability of a city to withstand, recover from, and adapt to the impacts of natural hazards." Regardless of the definition we choose to use, it is clear that enhancing the resilience of urban areas is a critical step in reducing the risks posed by natural hazards and creating more sustainable and livable communities.

There are many different strategies that cities can use to build urban resilience, and the most appropriate strategies will depend on the specific hazards that a city is exposed to, as well as its resources and capabilities. One key strategy for building resilience in cities is to strengthen the physical infrastructure of the city, such as buildings, roads, bridges, and utilities—which, in other words, means making it less vulnerable. As mentioned before, this can involve retrofitting existing infrastructure to make it more resistant to hazards, or building new infrastructure to higher standards of performance. For example, buildings can be designed and constructed to be more resistant to earthquakes and storms using isolation [40], structural reinforcing [6, 14, 16, 30], and wind-resistant design [39]. Infrastructure can also be designed and constructed to be more resilient to floods, using techniques such as elevation, flood walls, and flood gates [3].

In addition to strengthening the physical infrastructure of a city, it is also crucial to consider the social and economic resilience of the city. Building the capacity of communities to withstand and recover from the impacts of hazards is a critical aspect of social resilience. This can involve building the capacity of communities to respond to disasters, such as through training and education programs, or building the capacity of communities to adapt to changing hazards, such as through economic diversification and diversification of livelihoods. For instance, communities can be trained in disaster preparedness and response techniques, such as first aid, search and rescue, and emergency evacuation, in order to better protect lives and property during a disaster. Communities can also be supported in diversifying their livelihoods and economic activities in order to reduce their dependence on a single industry or sector that may be vulnerable to hazards, such as agriculture or tourism.

Enhancing the economic resilience of a city is also critically important. This can involve, for example, supporting the development of a diverse and robust economy with a mix of industries and sectors that are less vulnerable to hazards. It can also involve supporting the development of small and medium enterprises, which are often more resilient to hazards than larger enterprises, as they are more flexible and adaptable. In addition, it can involve supporting the development of a strong and well-functioning financial system, with access to credit and insurance, in order to enable businesses and households to recover from the impacts of hazards. Some of these aspects will be treated in more detail in the next chapters of this book.

6 Future Directions for Research and Practice in Multi-hazard Risk for Resilient and Sustainable Cities

As the impacts of climate change and other natural hazards continue to increase, the need for effective multi-hazard risk management for resilient and sustainable cities becomes more pressing. There are many areas where further research and practice are needed in order to better understand and address the risks that cities are exposed to. Some key directions for future research and practice in this field include the following:

1. Improved understanding of multi-hazard risk interactions: In order to develop effective risk management strategies for cities, it is critical to better understand the ways in which different hazards interact with one another, as well as the combined impacts of these hazards. Further research is needed to identify the key factors that contribute to multi-hazard risk interactions, and to develop methods for quantifying and predicting these interactions.
2. Development of more comprehensive risk assessment and management approaches: Current risk assessment and management approaches tend to focus on individual hazards, rather than on the combined risks of multiple hazards. In order to more effectively reduce the risks posed by multi-hazard risks, it is necessary to develop more comprehensive approaches that consider the interdependent nature of hazards and the combined impacts of these hazards. This may involve developing new methods for analyzing and quantifying multi-hazard risks or adapting existing methods to better account for multi-hazard risks.
3. Integration of risk assessment and management into planning and decision-making processes: In order to effectively reduce the risks posed by natural hazards, it is important to integrate risk assessment and management considerations into the planning and decision-making processes of cities. This may involve the development of new planning and decision-making tools and methodologies that explicitly consider risk or the integration of risk considerations into existing planning and decision-making processes.
4. Improved communication and engagement with stakeholders: Effective risk management for cities requires the participation and engagement of a wide range of stakeholders, including government officials, community leaders, businesses, and the general public. In order to effectively engage these stakeholders, it is important to develop improved communication and engagement strategies that effectively convey the risks that cities are exposed to, and the steps that can be taken to reduce these risks.
5. Research on the effectiveness of risk management strategies: In order to better understand which risk management strategies are most effective in reducing the risks posed by natural hazards, it is important to conduct research on the effectiveness of these strategies. This may involve evaluating the effectiveness of different risk management approaches in different contexts or comparing the effectiveness of different risk management strategies for specific hazards. This

research can help to inform the development of more effective risk management strategies for cities, and can help to identify best practices for risk management.

By focusing on these key areas, researchers and practitioners can help to create more resilient and sustainable cities and contribute to the development of a more secure and sustainable future for our communities.

7 Final Remarks

In this chapter, we have examined the concept of multi-hazard risk and its importance in urban planning and development. We have also listed and briefly reviewed some of the natural hazards that affect cities the most and discussed the importance of risk assessment and management in reducing the risks posed by these hazards. Finally, we have discussed a few strategies for building resilience in cities and pointed out some future directions for research and practice in multi-hazard risk management for resilient and sustainable cities.

Through this discussion, we have seen that multi-hazard risk is a complex and multifaceted issue, and that effective risk management requires a comprehensive approach that considers the interdependent nature of hazards and the multiple impacts of these hazards. After briefly discussing the concept of "urban resilience", we have also seen that enhancing urban resilience is a crucial step in reducing the risks posed by natural hazards and creating more sustainable and livable communities.

As the impacts of climate change and other natural hazards continue to increase, it is more important than ever to better understand and address the risks that cities are exposed to. We hope that the contents of this book will help researchers, practitioners, and decision-makers to better understand this complex topic and, in this way, contribute to the development of more resilient, secure, and sustainable cities and communities.

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