Natural Hazards
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ORIGINAL PAPER

An upscaling multi-level and multi-hazard risk assessment for heat and other natural hazards concerning vulnerable groups in Žilina, Slovakia

Alexander Fekete[1] · Steffen Neuner[1] · Christopher Munschauer[1] · Lubos Buzna[2,3] · Daniel Chovanec[4] · Katarina Holla[4] · Samuel Kockar[4] · Ulrich Leopold[5] · Stefania Stellacci[6] · Derya Yilmaz[5] · Catarina Ferreira da Silva[6]

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Abstract

Climate change, natural hazards and heat stress increasingly affect everyone, with particularly severe impacts on vulnerable populations and individuals with special needs. However, there is a research gap in integrating peoples' needs with different levels of the built environment and spatial planning frameworks. This study analyses Žilina city, a major hub in North-Western Slovakia that is exposed to multiple natural hazards. A spatial assessment is conducted in this study, showing heat, earthquake, fire, flood, and landslide risks for the city, using Geographic Information Systems (GIS). Critical infrastructure exposure is mapped, and a built environment typology is developed to provide additional detail. Building exterior and interior information for the vulnerability analysis of the building and its current occupants is gathered through site visits, orthophotography, and street view photography. The results reveal hotspots of risk and special needs groups, as well as how this information can be scaled up to improve evacuation and reduce heat stress. This risk transect analysis, encompassing the individual, building, built environment, and city levels, can support more integrated and effective multi-risk assessment and management.

Keywords Climate change adaptation · Vulnerable groups · Critical infrastructure · Geographic information systems · Building information modelling · Žilina

1 Introduction

Europe has become a hotspot for Climate Change, with temperatures rising along with an increase in heat waves, wildfires and floods, as highlighted in recent reports and information services (e.g., IPCC 2023; Copernicus Climate Change Service (C3S) and World Meteorological Organization (WMO) 2025). In areas exposed to multiple natural hazards and other risks simultaneously, multi-risk assessments are gaining importance (Kappes et al. 2012a,

Extended author information available on the last page of the article

b). At the same time, multi-local and multi-modal studies are crucial for better connecting findings at the city or regional overview level with the needs of individual persons affected (Taubenböck et al. 2011; Zuccaro and Leone 2018; Pelizari et al. 2023). However, most hazard vulnerability information at geo-platforms or within risk indices is still available at a broader overview level. The European Union, for example, has a wide collection of open data sets available within the Copernicus programme, at the DRMKC Risk Data Hub (Joint Research Centre 2025), or is utilising the INFORM index at the national and regional levels (INFORM 2021). Despite these efforts and advances, the use of multi-risk assessments by public authorities in Europe remains limited, particularly due to siloed institutional structures and plans (Šakić Trogrlić et al. 2024). Cities, social organisations and the people themselves need more detailed information at higher spatial and temporal resolution. It is therefore important to conduct further research on integrating and combining such information at different regional, local, and household levels.

Research on a regional scale utilises open-access geoinformation and Geographic Information Systems (GIS) to integrate these levels. Another research area focuses on individual buildings or groups of buildings. Digital twins are three-dimensional geographic representations, but they have not yet been widely explored or made available for disaster risk assessments (Ugliotti et al. 2023; Zio and Miqueles 2024). Individual buildings can be digitally modelled and thoroughly analysed using Building Information Modelling (BIM). BIM enables simulation and analysis of building responses to hazards, identifying structural and occupational vulnerabilities, but its application to disaster risk assessment remains limited compared to broader regional-scale overview studies (Khanmohammadi et al. 2020; Baarimah et al. 2021; Perera et al. 2022). It is therefore important to analyse how the different levels, thematic areas and tools can be better combined. Ultimately, it is not only about tools and data, but also about individuals, social organisations and public authorities who require quality information to make informed decisions and respond effectively in the event of natural disasters. Vulnerability and resilience research is an important stream of analysis not only of hazards but also of factors influencing their impacts, and specifics of people (Wisner et al. 2004; Fuchs and Thaler 2018). Special needs groups, such as disabled persons, need assistance, especially as do elderly citizens or children (Cuny 1983; Cutter 2005). For a more comprehensive assessment of their risks, qualitative methods, such as interviews, have been already employed (Ward et al. 2022; Šakić Trogrlić et al. 2024). However, this level of data is difficult to integrate with quantitative data and to represent on broader scales. Upscaling data and models have been a research demand over the past decade, but it remains inadequately addressed (De Moel et al. 2015; Izumi et al. 2019).

This study, therefore, analyses how different levels (individual, building, and city) can be better integrated into multi-risk assessments. This is conducted by showcasing it at a concrete case study site prone to multiple hazards with special living groups. The objective is to analyse how multi-hazard and multilevel risk assessments can be conducted and combined. And how upscaling can be conducted. It is applied to the concrete example of the city of Žilina in Slovakia, to analyse its risk profile for selected high-risk groups of disabled persons.

The paper approach begins with a regional overview of hazards, then focuses on risks at the city level, and subsequently zooms in on individual building typologies. This study integrates multi-source spatial data, including orthophotos, open geoinformation platforms, and street-level imagery, into a layered GIS-based framework. This data is enriched by site visits. The findings of risks then inform the upscaling of actions along a storyline of selected indicators across the different levels of analysis. The main research gap addressed is how multiple hazards are affecting cities and how different levels of risk can be identified and utilised to scale up the information and integrate it. While studies exist that address this at the individual level, a main gap is how data-informed approaches can be conducted for multi-risk assessments at each spatial level, regional, urban, building and individual scale.

As a novelty to existing approaches, it illustrates how all the information at different levels of analysis can be retrieved, combined, and how a better upscaling and preserving of the vulnerability information at the local level of people or households in a building can be visualised, identified, and combined with the higher levels of risks in the building, in the neighbourhood and in the whole city. Special emphasis is placed on the spatial configuration of vulnerability, using typologies of the built environment to identify heat exposure, structural accessibility barriers, and service availability. The innovation involves upscaling actions resulting from a multi-level risk assessment. Another innovation is the study of these multiple risks in combination with critical infrastructure and special needs groups in Žilina. The spatial analytics applied here aim to bridge the gap between static hazard maps and dynamic, place-based vulnerability, contributing to a more operational understanding of multi-risk urban resilience.

The remainder of the paper is organised as follows: Sect. 2 presents the state of the art reviewing key concepts; Sect. 3 introduces the methodological approach, while Sect. 4 delineates the results; Sect. 5 discusses the findings, limitations and future directions. The paper concludes with the outline of the authors' contributions.

2 State of the art review on key concepts

2.1 Risk and vulnerability

In the context of disaster, risk is defined as "[t]he potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity" (UNDRR 2017). However, in the application of disaster risk assessments, not only probabilistic, but also other forms, and both qualitative and quantitative approaches, are used to combine the conceptual dimensions (Birkmann 2013; Fuchs and Thaler 2018). Especially for natural hazards, a paradigm shift has occurred, emphasising the vulnerability or impact side as equally important, if not more so, than the hazard or triggering side of risk (Wisner et al. 2004). This means that humans often are architects of disaster risk themselves, and even hazard adjustments can lead towards human behaviour aggravating the risk (White 1945). Heat, floods, urban fires, landslides and other hazards, therefore, are natural hazards with a major human component. Another aspect of the definition above that is often emphasised is the context-specific and environmental factors that need to be considered, including spatial, place-based, cultural, or other aspects (Baird et al. 1975; Cutter 1996). A key dimension to differentiate (and reduce) risk is exposure, but also vulnerability. "[v]ulnerability is generated by social, economic and political processes that influence how hazards affect people in varying ways and with differing intensities" (Wisner et al. 2004: 7). Similarly, this is addressed in the definitions of the United Nations (UNDRR 2017). Vulnerability to a hazard can lead to an impact when the vulnerable asset is exposed to that hazard (Šakić Trogrlić et al. 2022).

2.2 Multi-hazard research

The latest evidence indicates that multi-hazards and their interrelationships, such as triggering, compound, and consecutive hazards, are becoming more frequent across Europe Šakić Trogrlić et al. 2024). This highlights the need for resilience building by shifting from single-hazard-focused approaches to multi-hazard risk assessment and management (Šakić Trogrlić et al. 2024). Also, the shift from physical components of hazards to policy, adaptation, and social and technological aspects reveals a responsive and adaptive field (Huynh and Stringer 2018). The analysis of case studies, inclusive of multi-hazard interrelationships, is necessary not only for conducting but also for generalising findings into more inclusive frameworks applicable to a broad range of hazards and locations (Tilloy et al. 2019). In recent years, several European-funded projects have addressed multi-hazard assessment (e.g., ARMONIA, ENSURE, MATRIX, MEDIATE, MYRIAD, PARATUS, RETIME) using qualitative, semi-quantitative, or quantitative approaches (Boni et al. 2025).

2.3 Multi-risk research

The governance of multi-risk scenarios remains an area that is insufficiently studied. While most crisis management actors express a strong interest in tools capable of addressing multiple hazards, relatively few studies consider the population, environment, and agriculture as elements at risk (Curt 2021). Adopting a multi-risk approach is a fundamental priority at the international level. Accordingly, tools for multi-risk assessment should be further developed and strengthened (Scolobig et al. 2017). A methodology approach for civil protection uses the combination of multi-hazard and exposure levels, through a multi-risk levels matrix. In a flowchart, various cases of hazard relations are highlighted by considering different conditions of temporal, spatial overlapping, and interactions of hazards (Boni et al. 2025).

2.4 Vulnerable and special needs groups

Vulnerable groups, in the context of human rights, refer to specific populations that often face unequal treatment or require special attention to prevent potential exploitation (Reichert 2006). According to Humanitarian Global (2025), vulnerable groups are those "at risk of poor physical, psychological, or social health" following a disaster. Certain characteristics, such as disability, gender, age, race, religion, sexual identity, culture, socio-economic status, geographical location, or migration status, can increase a population group's vulnerability to disasters (WHO 2025). A reflection on vulnerability in hazard scenarios and the challenges of homogeneity, as well as other aspects of vulnerable groups, is provided by Kuran et al. (2020). Drakes and Tate (2022) identify disabilities or special needs as an indicator of social vulnerability. They note that current studies emphasise the interactions among natural hazards before addressing how social vulnerability arises from, or affects, outcomes of multiple hazard events. The majority of disaster management systems are often designed for individuals without disabilities who can see, walk, run, hear or quickly respond to instructions" (Raja and Narasimhan 2013). Crawford et al. (2023) focus on the preparedness, capabilities, and support needs of informal caregivers during disasters in Australia. Chen et al. (2022) explore the challenges faced by primary school students with varying degrees of disabilities during an earthquake in Taipei. a et al. (2022) examine the impacts of flooding on individuals with disabilities and their caregivers in Australia. Cavus et al. (2021) review studies on the use of augmented reality to assist people with special needs in their skill development process.

2.5 Built environment vulnerability

Heat island effects on the built environment are a stress factor in Slovakia, as in many other countries (Murtinová et al. 2022). Certain building types, such as apartment blocks, are commonly found in many European and former Soviet Union countries, and their characteristics can be compared. Heat stress is higher for higher floors in apartment buildings in many European contexts, particularly within industrial prefabricated concrete slab construction types with 7 floors (Ortlepp et al. 2021). West and south exposures to the sun exhibit higher ratios of overheating, with the highest floors most affected in German apartment blocks (Westermann et al. 2021). However, for attics, this is more significant than for underlying floors, and eastern exposition can also lead to overheating of attics (Ortlepp et al. 2021). Building access research examines design elements such as ramps, stairs, main entrances, lifts, handrails, and parking spaces (Yakob et al. 2022).

The interrelationship between home environments and individuals with functional limitations has been reviewed in terms of its health and social effects by Cho et al. (2016). The vulnerability of the built environment to various natural hazards has been assessed in several studies (Papathoma et al. 2003; Kappes et al. 2012b; de Ruiter et al. 2017) and depends on various building features, such as windows, materials, and building height.

Accessibility of buildings for persons with disabilities is a common research topic in this field (Froehlich-Grobe et al. 2008; Danso et al. 2019; Yakob et al. 2022). The use of spatial assessments using GIS is also commonly applied to assess accessibility, and it has been expanded from residential buildings and health/social infrastructure access to routing (Paez et al. 2010; Naruse et al. 2017; Yhee et al. 2021; Guida et al. 2022).

2.6 Critical infrastructure

Critical infrastructure encompasses multiple sectors, assets, processes, contexts, and interdependencies, and originates from a national security background (Rinaldi et al. 2001; US Government 1996). It is increasingly applied in other contexts, such as Disaster Risk Reduction, or under similar terms, including basic infrastructure, in urban resilience or built environment contexts (UN 2015; UN-Habitat 2016). In the built environment, these elements include, in particular, engineering structures, services, and information systems within the critical infrastructure sectors that fulfil functions of public interest. Their disruption or destruction could significantly impair the state's economic and social functions (Kubas et al. 2024). It is crucial to achieve and sustain an appropriate level of resilience in critical entities and their supporting infrastructures, allowing them not only to prevent disasters and natural hazards but also to respond effectively when such events arise. This requires that critical entities have a clear understanding of their risk exposure to these threats (Rehak et al. 2024).

2.7 Upscaling vulnerability

Upscaling is defined in the context of global change as "the process of extrapolating from the site-specific scale at which observations are usually made or at which theoretical relationships apply, to the smallest scale that is resolved in global-scale models" (Harvey 2000: 225).

Upscaling vulnerability is used in research concerning the upscaling of risk indices from local-level indicators (Birkmann 2007), climate mitigation and adaptation strategies Kern et al. 2023), or community-based adaptation (Reid and Schipper 2014). In this context, up- or downscaling is mostly used in either technical terms, in more quantitative approaches, or in relation to solutions and intervention measures, in more qualitative approaches. Studies on upscaling can be found in institutional, geographical/spatial, technological, temporal and economic contexts (Gillespie 2004).

Different upscaling challenges exist, including technical problems in data representation and the inheritance of information (King 1991), contextualisation at the respective level (Birkmann 2006), and the handling of various spatio-temporal scales and concepts (Kienberger et al. 2013).

3 Methodology

3.1 Methodological approach and steps

The methodology involves a spatial assessment utilising various open-source vector and raster data sources, including satellite imagery and orthophotos. The data is integrated and analysed, using an open-source GIS software (QGIS). In addition, openly available data, such as Google Street View or maps have been added. Maps not available in GIS format are georeferenced, and vector boundaries are extracted. Figure 1 and Table 1 provides an overview of the various steps and levels of assessment, including the respective analysis focus, method steps, and data used (Table 1).

The research design employs a downscaling approach, starting with a broader regional overview and then zooming in to the level of individual buildings and specific needs groups. After that, the findings from all those levels of the risk assessment are integrated into a risk assessment. In the final step, the information is organised into selected variables that can be combined to form a clear storyline of how individual needs of people with disabilities can be addressed or improved through specific actions. This information is then upscaled to the other levels, showing which action can support and complement the needs of people with special needs, and, even more importantly, those responsible for decision-making at those levels.

In addition to standard GIS visualisation, this study employed advanced spatial analytics using open-source tools such as QGIS and PostGIS software. Beyond basic mapping, the analysis applied layered spatial reasoning to structure the city into geosemantic typolo-

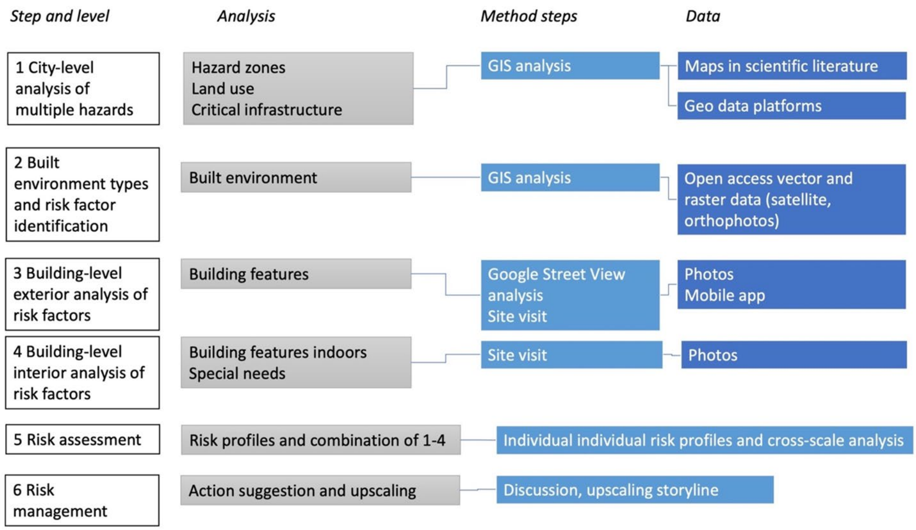


Fig. 1 Method steps flow-chart describing the multiple steps and levels that linke the levels (city to building-level) to the variables analysed and methods used

Table 1 Data sources used in this study

Level and contents	Data format	Data sources
Regional: city embedded within the surrounding environment	Vector GIS data	OpenStreetMap (OSM) contributors Flood and heat maps: https://geoikp.operandum-project.eu/data/map Geological maps, hazards, supply infrastructure lines: https://geoportal.gov.sk Landslide data: https://app.geology.sk/geofond/zosuvy/ Point of interest (POI): https://zilina.gisplan.sk/ Urban growth: Orthophotos: Historická ortofotomapa SR. Laboratórium geoinformatiky, TU Zvolen, https://mapy.tuzvo.sk/HOFM/
City: types of land use/built environment	Vector GIS data, Orthophotos (satellite images)	OpenStreetMap contributors Orthophotos: Historická ortofotomapa SR. Laboratórium geoinformatiky, TU Zvolen, https://mapy.tuzvo.sk/HOFM/
Building exteriors: individual buildings	Vector GIS data, Street View photography (aerial images)	OpenStreetMap contributors Google maps/Google Street View
Building interiors: individual buildings	Photos	Taken by the first author
Household: special needs groups	Photos	Taken by the first author

gies derived from orthophotos, volunteered geographic information (VGI, through OpenStreetMap), and digitised features. These typologies enabled hazard-specific vulnerability scoring by integrating physical parameters, such as sun orientation, building geometry, and tree cover, with social dimensions, including infrastructure access and population density. Furthermore, several building features, such as access restrictions, proximity to roads, and entrance locations, were systematically extracted and encoded into spatial models to inform the vulnerability classification of each typology. This approach demonstrates how GIS is used not only for data visualisation but also as a reasoning platform for multi-level risk attribution.

3.2 Natural hazards and societal needs in Slovakia

The Slovak Republic, centrally located in the European Union, lies in a temperate climate zone with distinct seasonal changes. Its inland position results in a transitional climate between oceanic and continental, making it a suitable case for studying climate change in a landlocked country. The structure and nature of emergencies related to climate change have recently changed. Floods have persisted for a considerable amount of time. In second place are snow calamities, followed by spills of hazardous substances. In fourth place is the lack of drinking water caused by climate change and the associated droughts that we are facing nowadays, which are also affecting the resilience of buildings. In these years, Žilina district has been on the 1st or 2nd place among 8 districts in Slovakia with the highest number of emergency events. Demographic trends in the region indicate an increasing proportion of more vulnerable populations in the post-productive age. The co-occurrence of multiple risks in the region gives a good basis for cascading effect scenarios. The older and lower-income population is highly exposed to the secondary impacts of climate stressors, including higher demand for water purification after floods, increased energy demand during cold spells and heatwaves, as well as higher medication costs, which can push lower-income households into poverty. Slovakia is also among the EU Member States that are seriously affected by energy poverty. Half of Slovaks could struggle to pay energy bills in 2022. According to the European Energy Poverty Index (EPI), Slovakia ranks 24th out of 28 European countries.

Žilina in Slovakia is selected as a case study for this research, as it is a major regional city and centre for the larger region of the Lower Tatra in north-western Slovakia. It is also a major transportation, logistics and industrial hub. Based on data from the Ministry of the Interior of the Slovak Republic's Crisis Management Section[1], extraordinary events such as floods, landslides, and fires were recorded in the Žilina Region from 2013 to 2022. The data show significant fluctuations in the occurrence of floods, with 2017 being an extreme year (73 cases) and, conversely, the lowest number of floods in 2015 (4 cases). Landslides had the highest occurrence in 2020 (10 cases), which may be related to intense rainfall. Fires occurred sporadically, with the highest number of cases in 2014, 2021, and 2022 (3–6 cases), and none in 2020. The graph visually (Fig. 2) depicts these trends, helping to identify risk years and potential links to climate extremes. This data complements the qualitative

[1] Central Monitoring and Control Center, Department of Operational Management, Crisis Management Section, Ministry of the Interior of the Slovak Republic. Statistical summaries of emergencies in the Slovak Republic, 2013–2022. Unpublished data, Bratislava. Obtained via email correspondence on [03/11, 2025].

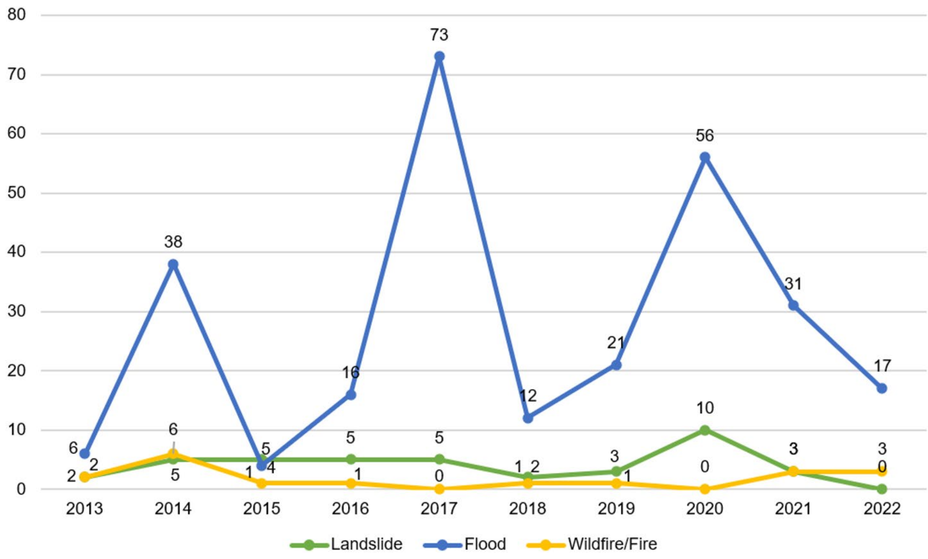


Fig. 2 Number of cases of landslides, floods, and wildfires/fires in Žilina Region in 2013–2022 (Ministry of the Interior SR, 2013–2022, see footnote [1])

observations and serves as a basis for a multi-level analysis of environmental risks in the Žilina region[1].

What is also becoming increasingly typical is the change in daytime temperatures from hot to cold in spring and autumn. A major earthquake destroyed most dwellings in the city in 1858, marking one of the first instances of scientific research and seismic mapping worldwide (Vaněk and Kozák 2007). Unprecedentedly, three wild forest fires kept firefighters busy in the Žilina region during the second week of May 2025, due to exceptionally dry weather and low soil moisture (Koscelník 2025). In July 2022, due to extreme heatwaves and drought, the Rajčianka River completely dried up along a stretch of approximately 1.5 km, endangering the local populations of crayfish, brown trout, and other species, with only a few individuals able to be relocated (Holešová 2022; TASR 2022).

The Žilina and Prešov regions have been identified as the most vulnerable in Slovakia to extreme rainfall, which can potentially lead to floods and landslides (Nánásiová et al. 2023). For example, in June 2020, extreme rainfall caused flooding on many streets in Žilina, resulting in a major transportation collapse (Webnoviny.sk 2020). Or early in 2024 strong rainfall led to landslides damaging local roads in Žilina city districts Bytčica (Mesto 2024), Budatín (Čapeková 2024), and the nearby village Hričovské Podhradie (TASR 2024).

4 Results

The results section is organised following the stages of the methodology presented in Fig. 1, and starts with an overview of multiple risks for the city of Žilina and its surroundings.

4.1 City-level overview of multiple risks

The map (Fig. 3, *top*) shows that heat island effects exist in the city centre and the west, along a long stretch of the Rajčanka River. This area has been developed into an industrial and commercial zone, contributing to the heat effect through soil sealing. Floods, riverine or flash floods, cover the outer rims of the city in the west and from east to west. We have derived the riverine flood zones from the geoportals (see Table 1) and have added former river beds visible in the 1950 orthophotos. Flash flood areas and smaller rivers are also visible, running from south to north, in the city centre. Forest fire areas are pervasive all around

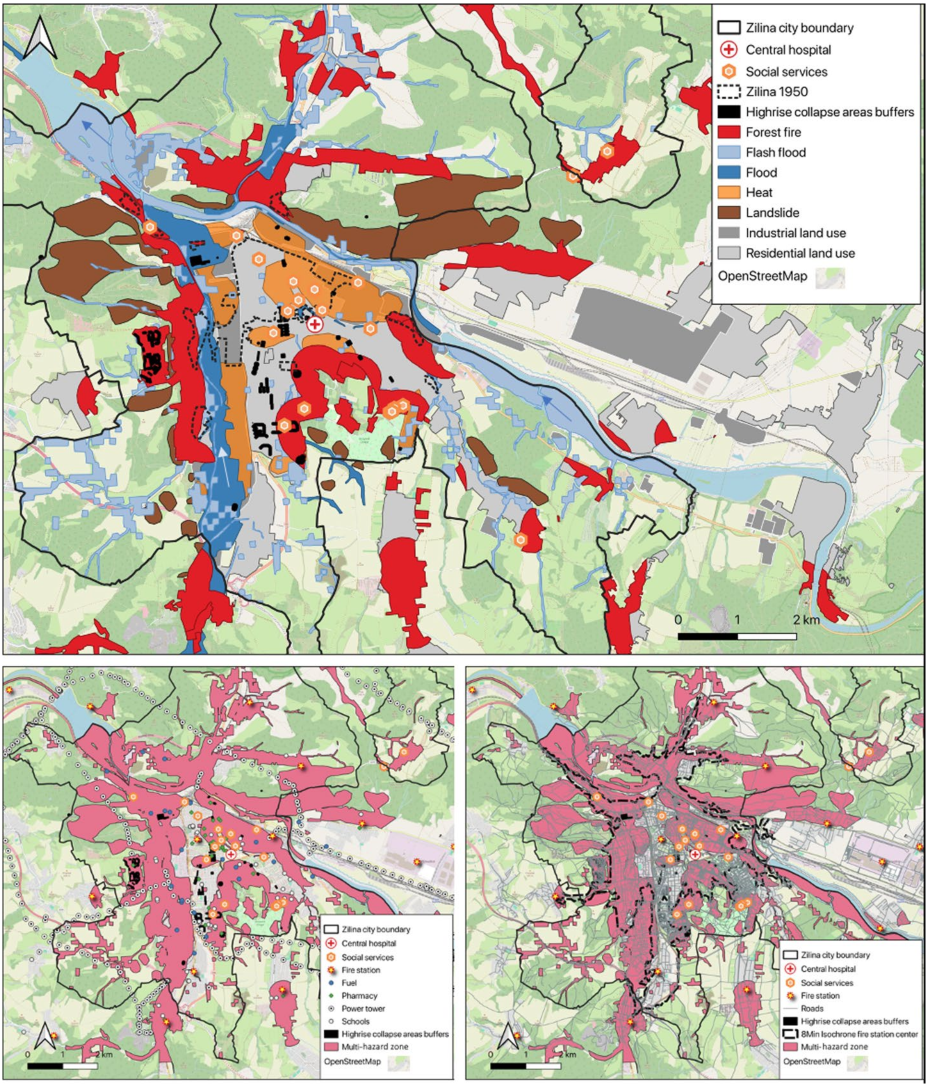


Fig. 3 Multi-hazard map of the city of Žilina (*top*) and distribution of selected critical infrastructure within the hazard zones combined (*lower left*) and area covered by the main fire station within eight minutes' car driving time (*lower right*)

the city, but also especially in the southern central part (named Lesopark). The mapping of the forest fire zone has been generated by the authors using forest data from OSM and adding a 400 m buffer, according to literature (Fekete and Nehren 2023). Landslides are distributed throughout the city, but especially in the western and northern parts. Earthquake risk is not visualised since detailed earthquake maps could not be identified. However, the 1858 earthquake affected the entire city area (Schmidt 1858; Kozák 2015), and a similar impact can also be expected for a next earthquake. We have used the height of buildings as a proxy for collapse width in the event of an earthquake, specifically around high-rises between 10 and 78 m in the city.

As critical infrastructure key examples, the map in Fig. 3 *(lower left*) shows the location of social service centres, with special needs groups such as the elderly or those with mental disabilities, which are at the centre of the study. They are exposed in the city centre and also on the outskirts, especially to wildfires, floods, heat islands, and earthquake risks. Fire stations are distributed throughout the city and its surrounding areas, and in these areas, they are particularly vulnerable to wildfires and occasionally to floods. The riverine flood areas are concentrated in the western part of the city, since the eastern part has been controlled by a dam since 1998. However, flash floods, earthquakes, and landslides also impact urban areas.

The maps in Fig. 3 (*lower left* and *lower right*) show the distribution of critical infrastructure over the city area and within the combined hazard zones. The lower left map shows that most infrastructure is concentrated in the grey residential area within the city centre. Power lines and fuel stations are especially exposed within the hazard zones. Schools and pharmacies are also exposed, which we have analysed in more detail according to each hazard type (Annex, Table A1). The lower right image shows the eight-minute service area from the main fire brigade station in the city centre. The map shows that this eight-minute area would be vulnerable to several hazards, including floods, landslides, earthquakes, and collapsing high-rises, which could affect roads and block them in the event of an earthquake, potentially hindering emergency vehicles such as fire trucks.

Using orthophotos from the 1950s and 2020–2022, we have mapped the city area and the urban growth into selected hazard zones. The oldest residential area, Hliny, was built in 1955, followed by Vlcince in 1972, Solinky in 1981, and Hajik in 1987. Table 2 compares the flood and heat areas of the river with the residential and industrial areas of Žilina. Residential areas experience high urban growth, and 45% are located in areas exposed to wildfires in 2023.

Table 2 Analysis of urban areas and hazard zones in Žilina

	City area in km^2	Flood area in km^2	%	Heat area in km^2	%	Wildfire area in km^2	%
Residential area 2025	30,291	1,947	6.4	3,012	9.9	13,502	44.6
Industrial area 2025	8,870	1,320	14.9	1,893	21.3	0,436	4.9
Urban area 2025	39,161	3,267	8.3	4,905	12.5	13,939	35.6
Urban area 1950	2769	0,164	5.9	0,882	31.9	0,436	15.8

4.2 Findings at built-up area type level

A typological analysis of the city's built environment has been developed using orthophotography and GIS data. The building roof types and geometry, derived from the orthophotos, helped classify the land use into eight major categories (Fig. 4).

1. **Farmhouse** At the urban rim, former farmhouses, now family homes along roads, typically have a long and narrow layout, covering green areas used as gardens or agricultural land. More and more buildings are being attached in 'farmhouses', especially on the front side of the main road, which is becoming densely built over time (Fig. 4, 1).
2. **Detached** The 'detached houses' (Fig. 4, 2) are organised around a linear road axis, which are similar to the first type but are of a more modern architecture, with square rather than rectangular building shapes. The green area is less than in the farmhouse class. The roads in both types are rather narrow, and street parking of cars is common. The parked cars can pose a problem when larger fire trucks must access the area. In a flood, the cars can float and block the road. This can also be the case for trees, which are quite common in these areas. However, trees are not so common along the streets, but rather in the gardens. Therefore, they pose an additional fire risk; however, in the event of a flood, it must be individually checked to see if the respective road would be affected.
3. **Old city** It is characterised by many attached buildings, which increases the risk of fire spreading from one house to the next. Due to the long and narrow shapes of the attached buildings, evacuation exits are also limited. The area has a distinct heat island profile since there are very few trees and a lot of soil sealing and roofs.
4. **Apartment blocks** These are typical building types found in many Eastern and former Soviet countries. This class can be identified by using additional information, such as side views of the buildings from photos on Google Street View. From the view above, long, narrow buildings with larger shaded areas, indicating the heights of the buildings, can be identified. Many green areas characterise this environment compared to other urban residential areas. Since these apartment blocks were built in the 1950–1970 s, trees have grown, providing a positive benefit by offering shade and a cooling effect.

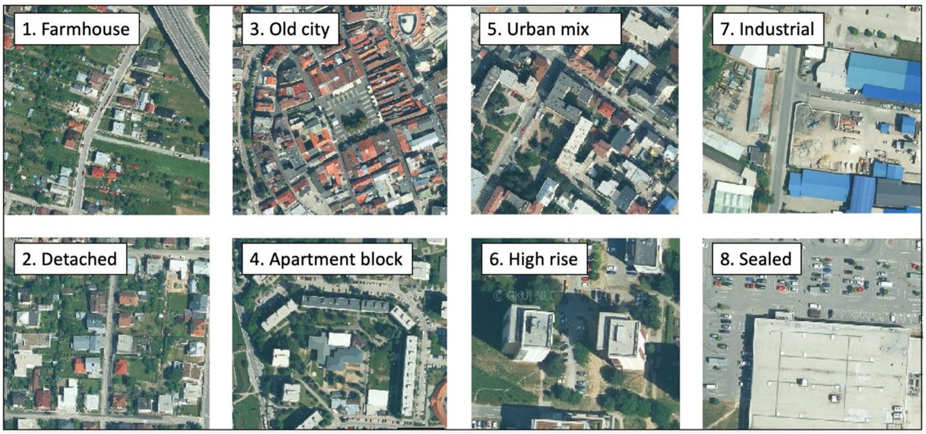


Fig. 4 Orthophotos of the city area of Žilina 2020–2022: https://mapy.tuzvo.sk/HOFM/

On the other hand, they pose a fire risk and can hinder access for fire trucks. Building density is influenced by the long shape of some buildings, which can also contribute to the spread of fire from one housing unit to another. Population density is rather high, even when land coverage is limited compared to the old city centre. Roads do not lead to every side of the apartments, and a more detailed analysis is needed to check access in case of a fire.

5. **Urban mix** This category is found in the area around the city centre and sometimes in between other land use areas. It is characterised by different architecture and many buildings attached next to each other. By comparison, the road width can be wider than in the first, second, and third classes. However, it is also heavily trafficked.
6. **High rise** includes buildings, whose height range from 10 to 14 m, are prevalent in the city, up to 78 m. They are mostly used as apartments, hotels or office spaces, which means high population densities. However, similar to the apartment blocks, it features a similar land use cover with wide open and green spaces that improve ventilation and can help reduce the heat island effect. Trees are relatively common and can be both beneficial for cooling, but they can also hinder accessibility. For evacuation, the height of buildings poses a special challenge, with typical fire ladders reaching 23 m and spanning nine stories. Rescue by jumping into air cushions is designed for heights up to 16 m, typically around six storeys.
7. **Industrial** The industrial area includes large one-storey buildings also used for commercial purposes. Soil sealing is very common, and few trees can be found. The street layout and narrow roads are rather beneficial for access.
8. **Sealed** The sealed areas can be classified as an extra class, although the buildings are similar to the industrial and commercial classes. However, it has been noted that within the available heat island maps, these reflected the strongest signal of overheating. They are characterised by huge parking lots typically found for big supermarkets or other commercial areas. Large areas of flat roofs are also typical and especially problematic in hot weather.

Table 3 presents a detailed representation of factors that increase risk, as determined by the assessment of the authors. This assessment is based on the identification of the risk factors per building type by visual analysis of the orthophotos and GIS data, as shown in Fig. 4, and the classification in the text above. We mark a general increased presence of risk features in Table 3, compared to the other building type classes by +, and a strong presence of risk features by ++. Further validation of these visual observations of maps is carried out in the sections further below, by field visits. It is essential to note that each feature can indicate different risk directions, depending on the specific hazard context (de Ruiter et al. 2017). For example, trees are highly beneficial in reducing heat stress, but can also pose a problem in terms of fire risk. Additionally, trees, as well as cars or other items, can block roads during a flood, landslide, or earthquake. Narrow roads are a problem, especially when parked cars pose an additional problem, leaving a single lane for traffic. Population density can also be derived from statistics, but building shapes also serve as proxies when such statistics are unavailable at such a spatial detail. In Table 3, we only use a representation of increasing risk, indicated by the pluses, to ease readability.

The city map (Fig. 5) shows that the built environment types cover larger areas. The city exhibits a pattern of planned development, characterised by distinct building phases and

Table 3 Risk-increasing factors per built environment type

Building type	Earthquake	Fire	Flood	Heat	Land-slide
1. Farmhouse	Narrow road: +	Narrow road: +	Narrow road: +		Narrow road: +
2. Detached	Narrow road: +	Narrow road: + Trees: +	Narrow road.: + Sealed: + Trees: +	Sealed: +	Narrow road: +
3. Old city	Building density ++ Population density: + Narrow road: ++	Build dens. ++ Pop dens: + Narrow road: +	Pop dens: + Narrow road.: + Sealed: ++	Build dens. ++ Pop dens: + Sealed: ++	Pop. Dens.: + Narrow road: ++
4. Apartment blocks	Pop. dens. ++ Narrow road: +	Build dens. ++ Pop dens: ++ Narrow road: + Trees: ++	Pop dens: ++ Narrow road.: + Sealed: + Trees: ++	Build dens. ++ Pop dens: ++ Sealed: +	Pop. dens. ++ Narrow road: +
5. Urban mixed	Build. dens. ++ Pop. dens. + Narrow road: +	Build dens. ++ Pop dens: + Narrow road: + Trees: +	Pop dens: + Narrow road: + Sealed: + Trees: +	Build dens. ++ Pop dens: ++ Sealed: +	Pop. dens. + Narrow road: +
6. High rise	Pop. dens. ++	Pop dens: ++ Narrow road: + Trees: +	Pop dens: ++ Narrow road: + Sealed: + Trees: +	Pop dens: ++ Sealed: +	Pop. dens. ++
7. Industrial	Pop dens: + Narrow road: +	Pop dens: + Narrow road: +	Pop dens: + Narrow road: + Sealed: ++	Flat roofs ++ Pop dens: + Sealed: ++	
8. Sealed	Pop dens: + Narrow road: +	Pop dens: + Narrow road: +	Pop dens: + Narrow road: ++ Sealed: ++	Flat roofs ++ Pop dens: + Sealed: ++	

well-defined land use categories. Sealed or waterproof soil surfaces are mostly found in industrial and commercial zones.

The overlay with critical infrastructure Points of Interest shows that schools are prominent in the building sector, particularly in apartment blocks and the city centre, of the building type for urban mixed residential areas. Considering risks such as heat or evacuation, schools would need to plan for the special needs of children. Pharmacies are distributed throughout the city, but are mainly found in the city centre. It is interesting to note where pharmacies are not located, which would result in longer travel times for people, for example, in certain social service centres. Fuel stations are mainly located in industrial and commercial areas, which means that accessibility from residential areas could be a problem when a river flood, for example, affects the industrial area in the west. Power towers are located in both residential and industrial areas. These are a concern because the sagging lines can come into contact with vegetation and trigger fires in hot weather. It is interesting to note that certain residential areas on the outskirts and industrial areas nearby may be affected by this specific hazard, as identified in a 400 m buffer distance from residential areas to power grid transmission lines. In the event of an earthquake, a multi-floor building collapse (due to exceeding load capacity and other structural failures) would primarily affect the apartment block areas.

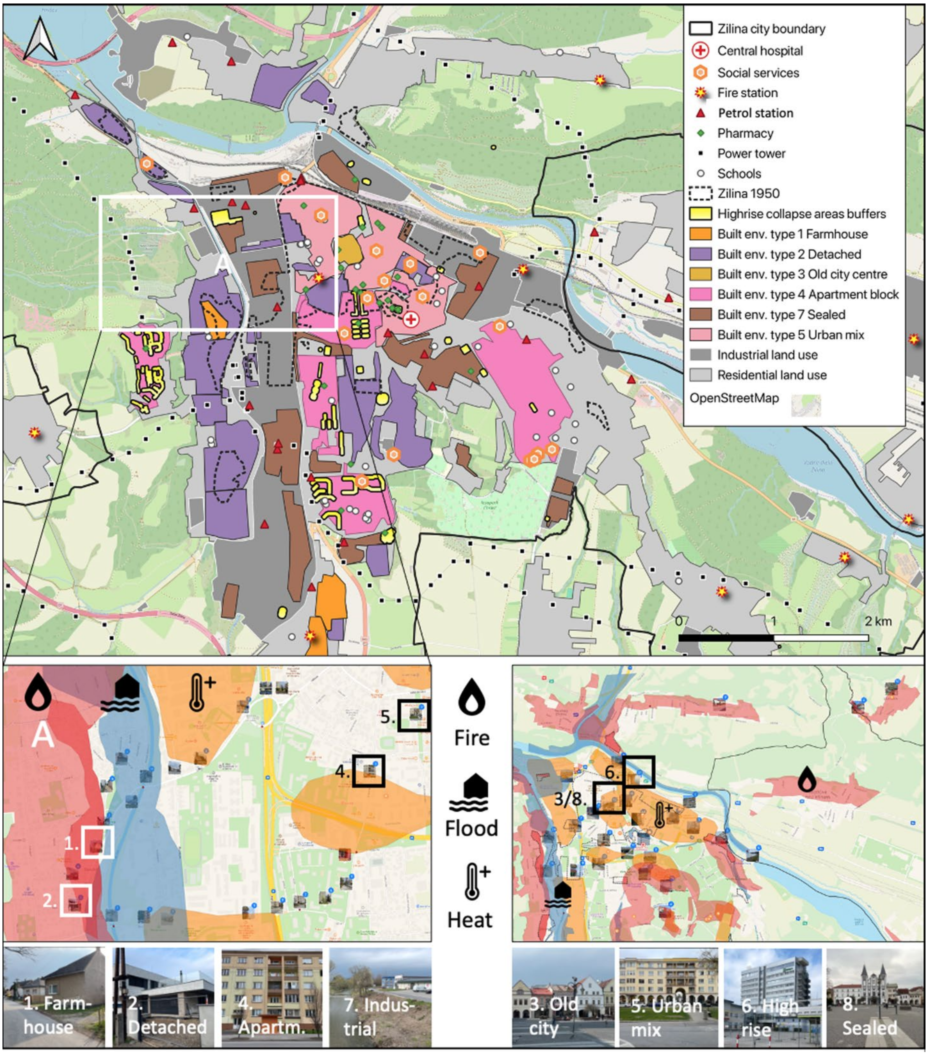


Fig. 5 Map of critical infrastructure within the built environment types of the city of Žilina

4.3 Findings at the building level

The next level analysed is individual buildings and their situation within the built environment types. Through a site visit, we could compare the assumptions from the classification and typology of built environment types with those of the real situation. The site visit brought additional information for clarification and additional criteria that aerial photography would not cover. For example, in the first building class of farmhouses, the first lines of photos in Fig. 6 illustrate the situation. The top row in Fig. 6 displays smaller houses with relatively small windows, narrow roads, and even narrower access ways that are not paved between the houses, which stand close to each other (Fig. 6, 1a–1c). This area is located

Fig. 6 Examples of features of buildings and street views in Žilina city (Photos: first author, April 10, 2025)

within the flood risk zone (Fig. 6, 1a–2c). One photo shows cellar windows (1c), and a door leading into a level below the ground surface.

The second class of detached houses includes modern houses that are recently built and still face mainly south and west sun exposures, featuring terraces and large windows (2a–2c). This could indicate that adaptation to increasing heat and prolonged summers has not occurred yet. The detached house class shows the typical parking situation for cars (2b, 2c), which leaves only a narrow line for fire trucks to enter the area. The height of overhanging power wires also has to be observed. Cellar windows and fences blocking access to the houses from behind are also visible.

The third class of the old city centre shows the situation of many houses attached next to each other (3a–3c). The access roads are almost completely blocked by car entry barriers, except for very few entry points (3b). The doors to the shops often have doorsteps that can hinder access for people with disabilities (3c).

The fourth class of apartment blocks illustrates the typical design of five-storey blocks from the Khrushchev era (4a), and the nine-storey type of the Brezhnev era from the 1970s (4b). Balconies exist, which can be used for fresh air in heat situations or for evacuation from smoke in case of a fire. The narrow roads adjacent to parking spaces can pose a challenge to the accessibility of fire trucks (4b). The photo on the right shows a typical entrance, and we found that most of them have doorsteps that hinder access for people with disabilities (4c). In many places, we also found ramps and handrails that help with access for wheelchairs, bicycles, or prams. However, an assistant is needed for such steep ramps.

The fifth class of urban mix shows different apartment blocks (from the 1900s to the 1960s) with an arched entry to the interior (5a). The street situation also features parked cars and occasionally trees that provide good summer cooling and shade (5b). However, in case of a fire, they can hinder accessibility by fire trucks and their ladders, for example. The main shopping street leads to the train station, and almost all of them, except for one shop, have steps, which may hinder access for persons with disabilities (5c).

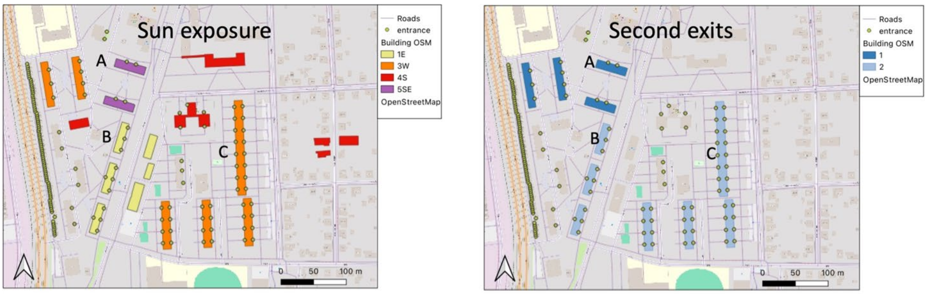
Class six (6) of high-rises shows the typical hotel environment. Most high-rises are apartments or office buildings, but some hotels also fall into this category. Some hotels, like this one, offer special accommodations for people with disabilities, including accessible rooms and facilities.

Class seven (7) shows one part of the commercial and industrial area bordering the river in the west. It is characterised by buildings with mainly one level that are highly exposed to flood damage, for example.

Class eight (8) shows a sealed or waterproof area, in this case not of the commercial areas but of the city centre. The city has two major squares in the city centre, which contribute to the heat island effect due to a lack of shade and vegetation.

During the site visit, we analysed the building classes by walking through the city in transit. We then explored how the analysis could be conducted for similar areas of the city that we had not visited. Figure 7 shows an area of apartment blocks bordering a class of detached houses on the right. The tables in Fig. 7 indicate how they might be assessed by experts in risk assessment, providing indications of relatively higher risk per feature (e.g., height) by using the symbols o for neutral, + for medium, or ++ for high risk.

The geospatial modelling applied here moved beyond static mapping by constructing detailed spatial attribution models at the building level. OSM building footprints were enriched with derived attributes, such as the number of storeys (approximated via building height shadows and façade analysis), façade orientation to estimate solar exposure, and entrance location points obtained from OSM tags and street-level imagery. These spatial enrichments enabled us to assess each building's risk profile based on a combination of structural features and contextual access constraints. For example, heat stress vulnerability



Additional information from street view, site visit or satellite data:

Heat stress risk

	A	B	C
Balconies	o	+	o
Height/storeys	9 +	5 o	8 +
Soil sealing	+	+	+
Trees	--	-	--

Evacuation risk

	A	B	C
Balconies	o	+	o
Door steps	No data	+	o
Height/ storeys	9 ++	5 +	8 ++
Trees	++	+	++

Fig. 7 Case study example of a risk assessment of apartment blocks in the southwest of the city of Žilina, Hliny V city quarter with mapped sun exposure orientations, and existence of a second exits of the buildings

was estimated by combining south-facing orientations with sealed surface indices and tree shading. At the same time, fire risk was scored based on the number of exits and the surrounding street width.

The apartment blocks can be analysed using GIS data from OSM for many features. For example, sun exposure can be mapped, and the buildings can be classified accordingly. Sun exposure to the south and west in this region and the northern hemisphere is a major factor in heating up buildings. OSM also offers a data class for the location and number of entrances/ exits of a building. These are not available for detached houses and many other types of buildings, but they are available for apartment blocks. Compared to the site visit and photo documentation, the results also seem plausible since the department block types are standardised in the city and the former Soviet region. Many apartment blocks we have visited have only a main door and an exit on one side of the building. In the example shown here, however, the class of buildings around the block marked with ‘C’ in Fig. 7 have better conditions for evacuation, also having a second exit.

Figure 7 illustrates a typical application of risk assessment conducted for both scenarios of heat stress and evacuation in the event of other hazards, such as fire, flood, earthquake, or landslide. The analysis revealed that many features important for identifying heat stress, as well as evacuation capability, need to be added from sources other than OSM data or aerial photos. For example, balconies, building heights, and tree heights can be better retrieved from Google Street View or through on-site visits. Trees and soil sealing can be mapped using satellite imagery or aerial photos. The height of buildings and the number of stories can sometimes be found already within the OSM data.

Not all building types include balconies. The height of the buildings might provide shade to other buildings, but since the buildings are set apart widely, there is no shading of one building by another. Higher buildings also have a larger area to heat up. Evacuation capability is especially hindered by the height of the buildings, which is relatively better for block ‘B’, as indicated in Fig. 7. Green corridors can also be a factor that hinders access for fire trucks or reduces the road’s width.

Table 4 summarises the features of buildings that are generally relevant for residents with special needs. Most of those features are not available by vertical view analysis or data, but need either photos with a side view or a site visit. As shown in Table 4, conducting a complementary analysis of all data types is crucial for acquiring the required information.

Many more features would be relevant for risk assessments specific to certain hazards. We focus here on concrete examples and, therefore, use only a reduced number of those features for the assessments shown.

4.4 Findings at the case study site of a social service centre

We visited a service centre in Žilina - Zástranie for people with mental disabilities, guided by the managers there on April 9, 2025. This exemplified that certain information about building interiors or individuals’ needs can be obtained through on-site visits only. Due to the sensitivity of the topic and the individuals involved, we only display an example here. Mentally impaired individuals require special guidance in the event of an evacuation and in daily situations involving heat stress, such as hydration reminders.

We found many more factors relevant to people living in those buildings. The results in Table 5 have been primarily informed by the previous steps and a combination of methods,

Table 4 Features of buildings relevant for residents and detectability by data type

Building feature	Orthophoto (vertical view)	Side view photo	Site visit necessary
Exterior access or evacuation system			
Backdoor			x
Balcony		x	
Distance to bus station	x		
Distance to car parking	x		
Entrance door type: swing door, sliding door, pivot door, motorised door		x	
Handrail		x	
Ramp for wheelchair or lift		x	
Rooftop window	x		
Fenced window		x	
Stairs		x	
External staircase/fire ladder		x	x
Storeys		x	
Indoor navigation and evacuation			
Elevator Floor width Stairs/lifts Guidance for blind persons			x
Health (indoors)			
Insulation Windows (sizes, ventilation corridors)		(x) partly	x
Hazard safety (indoors)			
Doors for fire safety Fire extinguishers Smoke sensors Sprinklers			x

including site visits and data retrieved from open-source platforms. Additional information in building information models or digital twins (DTs) could also be helpful; therefore, we have listed it on Table 4. However, we were unable to identify such data for the study areas. Table 5 is organised from the most local level to the smallest scale of the regional level to illustrate the upscaling opportunity provided by the findings.

Figure 8 shows how the information collected in all the steps can be identified for each level. As an overall risk assessment, it reveals that for each perspective and level, the risk profile of a selected social service centre can be identified. Starting with the regional risk profile, it is characterised by a high risk overall. There are many additional factors, but only the main ones are presented here to provide an easy overview that can also be useful for communicating with decision-makers or affected parties. The region's risk profile is high because the location of the social service centre is characterised by three hazard zones: landslide, flood, and forest fires (Fig. 8A). A forest fire or a landslide would block the road to the fire station. Another fire station to the east is not visible on the map, but can still be accessed.

The next level of built environment type is shown in Fig. 8, with the images on the upper right side marked with (B). The building is located in a residential area with a detached house class. The orthophotography helps to understand the situation with the narrow street

Table 5 Risk factors for the object of a social service centre for mentally impaired people in Žilina - Zástranie

Level of analysis	Heat stress	Evacuation risk aggravation	Information gathering method required
Household/persons	Need drinking reminders +	Mentally impaired: ++	On-site visit
Building interior	Limited window ventilation + Poor roof insulation +	No fire doors + Indoor steps and stairs +	On-site visit, BIM, DT
Building exterior	Sun exposition ++	Second exit missing ++	On-site visit, BIM, DT, GIS
Street/ built environment	Building density +	Access space only from one side and limited +	On-site visit, DT, GIS
Region	Hot summers +	Flash flood, forest fire and landslide hazard ++	GIS

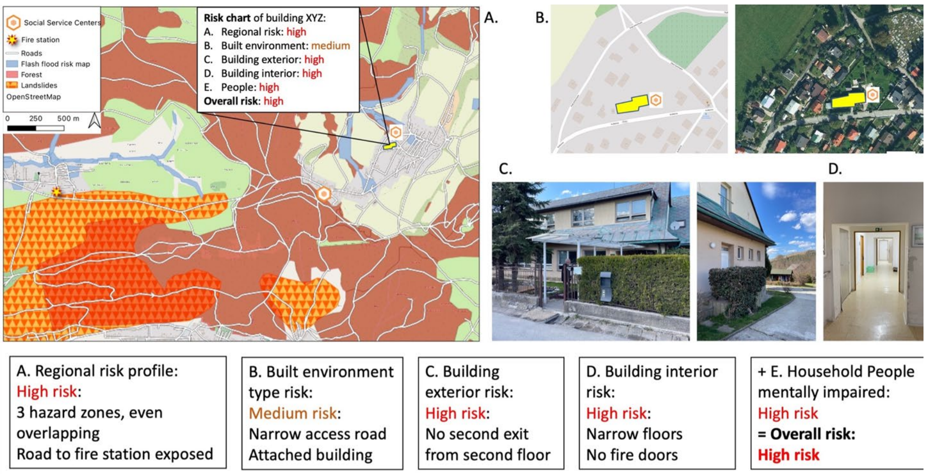


Fig. 8 Integrated risk assessment for multiple risks at multiple levels for the case of a social service centre on the northern part of the administrative area of the city of Žilina (Orthophoto from https://mapy.tuzvo.sk/HOFM/, photos by the first author, April 9, 2025)

and the building type itself, which is typically attached and of a longer shape. The risk is medium, considering some of the risk factors, but also because other building types in the city may have even higher risk factors.

Visiting the building, as shown in Fig. 8C, reveals that the main front door is rather narrow, and trees and fences block access. There is a second gate to access the building, located on the same narrow road. The photo in the middle shows the backside of the building, and there is no staircase to escape from the second level. The risk is, therefore, high overall due to the house construction, and accessibility.

The Fig. 8D, on the bottom right side, shows the building interior and it is also a high-risk area due to the narrow doors, narrow floors, and missing fire doors that would prevent fire and smoke from spreading throughout the building.

The final and most important level is that of the people affected by the potential risks (E). The risk for them is high because they have impaired capabilities to understand hazard information and are highly sensitive to stressful situations. It is also a high risk from the perspective of helpers, rescue personnel, management and staff, who would need additional than usual time and resources to deal with the mental disabilities' residents of this service centre in Zástranie in case of a hazard event occurrence.

The overall risk when combining all the levels and steps of analysis is high. This is because most steps and categories individually flag a high risk, except for step B (Fig. 8). The result can also be regarded through the lens of upscaling risk. At the centre are the mentally impaired people, and they already are at high risk, and this is scaling up and not ameliorated by either the interior building design, the exterior building design or situation in the street, and is also upscaled up to the city level because of the situation exposed to multiple hazards. However, from a city and regional perspective, such social service centres and special-needs groups are of special focus. Therefore, the higher risk emerges as a risk transect is upscaled through the levels.

Finally, all the individual levels of risk can be integrated into a visual representation, as outlined in the bottom right part of Fig. 8. This information could also be aggregated into a risk chart and attached to a risk map of the city area, or a photo of the building, or otherwise. This serves to illustrate the upscaling and preservation of information about risk at all levels analysed and that could support public authorities' decision-making.

5 Discussion

5.1 Upscaling using risk-impact chains and storylines

The information retrieved from the risk assessment can also inform risk management at different levels. Different types of measures are possible for each level, and they need to be designed according to the target group. Target groups include residents (U1), building owners and managers (U2), social services and authorities (U3). Authorities are either involved in disaster risk management, planning evacuation, or are responsible for operational actions. They are also involved in climate change mitigation and adaptation, as well as building renovation, building retrofitting, and spatial planning at the urban and regional scales.

Table 6 provides examples of information sources and risk information customised for user groups (U) that would require information for evacuation and health adaptation to heat stress. From the example above, we can create a storyline to illustrate the measures to be taken and the corresponding information related to the analysis steps outlined above.

The individuals exposed in a building, such as a social service centre, are the residents, their family members, building owners or managers, and staff. In case of a wildfire or kitchen fire, they must know how to evacuate the building. This information also needs to be context-specific. For example, in a flood, it would be crucial to determine whether the building or the city's roads would be blocked. Helpful information to be displayed on a totem (digital display) could include instructions on what to do, such as closing specific types of doors to hinder smoke from spreading. And an evacuation guide on where to go and where not to go. In the event of heat, a ventilation plan that specifies which type of windows to open or close, or which type of shading to use at specific times of the day, is helpful.

Such information can also be supplemented and informed by external equipment, such as sun blinds or other measures to reduce heat, including insulation, green areas, or corridors.

Table 6 Information sources and risk information examples relevant for evacuation and climate change actions (CCA) tailored to each user group (U1 residents, U2 Building managers, U3 authorities)

Topic	Building indoors	Building exteriors	Built environment	City
Evacuation	*U1: Display information*: Exit indoors and outdoors are blocked or impaired; Evacuation guidance	*U1: Exterior signs*: Evacuation guidance *U2*: Evacuation plans; Trainings; Updates; Renovations	*U3: Urban plan/alarm plan*: Safe zones	*U3: Urban plan/ alarm plan*: Risk zones; Evacuation centres
Health (CCA adaptation)	*U1: Totem information*: Ventilation plan; Shading suggestion	*U2*: Wall and roof insulation	*U3: Urban plan*: Sun exposition; Shades; Green corridors	*U3: Urban plan*: multi-hazard and risk hotspots

For an evacuation, it could also upscale and integrate the information displayed inside with signs of safe areas or exit directions. Such information would typically be in the hands of building owners and the respective responsible institutions. A guideline or certificate combined with training and updates could be provided.

At the built environment type level, this needs to be planned by those authorities responsible for integrating individual buildings within the whole setting. That could provide urban planners or those developing alarm plans for evacuation or heat stress with information on the needs of specific individuals and special needs groups, as well as the situation of specific buildings. In the case of standardised apartment blocks, this may be easier to conceive and upscale than for individual homes or detached house types. For heat waves, the renovation of buildings presents a window of opportunity to implement insulation, shading, and other energy-saving measures, if one considers the suitable material and adaptation building measures. Finally, at the city level, such urban planning or alarm planning could devise risk zones and evacuation centre locations. The locations of critical infrastructure, especially that of helpers and rescue personnel, should be identified in potential hazard zones. They should first avoid being placed in hazard zones, but they should also consider service areas and driving times. This information can be retrieved from GIS assessments of isochrones, for example.

The backbone of this risk storytelling approach was the integration of multi-scale geospatial data through a spatially indexed GIS architecture. By aligning regional hazards, building-level geometry, and individual-level vulnerability markers into a common geospatial reference, we developed interpretative risk storylines that are both scalable and actionable. This spatial structuring enabled targeted recommendations for stakeholders, ranging from emergency planners to social care providers, using location-specific indicators derived from GIS overlays.

5.2 Upscaling challenges from the local to the regional level

For the individual case of the social service centre special needs home, we found that it has a high risk due to its mentally disabled population, but also to limited staff numbers and challenges of the building's interior features for evacuation. Additionally, at the street and neighbourhood levels, accessibility is not ideal. In the regional overview, it is also at great risk due to blocked streets in the event of a landslide, wildfire, or flash flood. This building, however, serves as a case study example, and other buildings and vulnerable groups exist in the city, which have also been identified on the map. The approach is therefore transferable to other buildings and vulnerable groups within the city, and, as we have based the data retrieval mostly on open-source information, it can also be applied to some of the levels used in other cities and areas.

Several limitations of the study are related to data availability and the need for site visits and ground truthing. It is also a major challenge and an ethical demand to care for special needs groups, as well as address data and privacy sensitivity. While we have identified five natural hazards as a representative illustration of a multi-hazard risk approach, other hazards could be added to the analysis, both in terms of natural hazards and other technical hazards. The study is also limited to covering all possible dimensions of vulnerability, capacities, and resilience, as well as examining the multiple interrelations and interdependencies between individual and cumulative hazards and vulnerabilities, as well as cascading effects. The study also analyses critical infrastructure in a limited way, as there are multiple additional sectors and relevant assets, processes, and interrelations and dependencies between critical and infrastructure types that could, and should, also be analysed further in a city context. The aspect of upscaling is also illustrated only in an example. Certainly, much more advancement is needed here to integrate individual personal needs with the overall needs of a city's population, or to upscale individual variables and risk components.

However, the primary objective of this study was to demonstrate that it is possible to conduct a multi-level and multi-hazard risk assessment in a city and its surroundings, and to integrate it at various levels. This will be important for future research and policy work to address not only single hazards or single vulnerabilities, but also to leverage the advancement of open-source information to utilise it better and integrate spatial information using geographic information systems with building information modelling, digital twins, incorporating qualitative and personally specific information.

Most importantly, this will also help to better integrate the still differing research and perspectives on individuals and their needs, on building quality, health, and safety, versus the often-separate views on disaster, risk, and emergency management for more rapid-onset disaster types, such as extreme events of floods or similar. Given the ever-changing occurrence of individual hazard events, as well as political directions, a more comprehensive and long-term approach is needed, which is often currently flagged under the term resilience. Integrated disaster risk management should better combine the levels from individual needs of people to the needs of the whole city. A resulting strategy requires combining urban planning with emergency management, social needs and health services, infrastructure, and the built environment, as well as other urban planning sectors, including social organisations. However, it also longs for improving the integration of the daily safety aspects of living quality for populations in heat, particularly on exposed residential or office buildings, with the risk of extreme events such as heatwaves, fires, floods, or earthquakes. This integrative planning should create synergies to save costs, while also increasing awareness of a 360° vision encompassing both daily and extreme risks.

5.3 Other limitations and future perspectives

Some of the main limitations are the availability of more precise on-site data for the assessment. While the study has used on-site visits, indoor and outdoor, it is still limited and could be augmented by additional field visits and additional documentation. The spatial data used, especially from open data and aerial photos, could be more precise in spatial and temporal resolution. This has to be observed, especially when it is applied to other cities. We found that data availability is relatively good for this city, but for other cities in Europe that we have tested, it may not be at the same quality or availability or documentation, or in the same accessible type of language.

Compared to other existing studies, the contribution of this study is to identify useful data at respective levels of assessment. It is a mixed-method approach and also a mixed-data approach, which has the advantage of feasibility as demonstrated. However, another limitation is that it is not a consistent set of data types and methodology applied at every level. For example, aerial photography, even with the highest spatial resolution, will not be useful to capture vertical elements at buildings or to capture social vulnerability information. Therefore, all data and methods used are certainly compromises, but as compared to other studies, it has the benefit of matching existing approaches and open data. It does not replace individual empirical observation that is necessary at the street level, which can only partly be retrieved using uploaded street photography. Fieldwork and interviews with people are still indispensable for certain information to be retrieved.

The study's limitations include its dependency on the availability of open-source data and site visits, as well as the sensitivity of dealing with special needs groups. However, this is not a significant problem for the city area or even at the built environment level. The primary challenge is to expand the scope of data used in risk assessments to encompass more detailed information about exterior building designs, which can be obtained from street view photography, databases, or site visits. OpenStreetMap is a vibrant community that collects a vast amount of information, and the addition of three-dimensional information for digital twins could be a promising future area for expanding the concept of OpenStreetMap. Of course, there are limitations to using crowd-sourced, volunteered geographic information (Goodchild and Li 2012), particularly in areas with known data gaps. However, VGI and such data have several advantages, including free access and nearly worldwide availability.

There is a gap in research and application regarding the integration of household and personal perspectives with other levels (Lawrence 2015; Scolobig et al. 2017). Upscaling information could be enhanced by utilising storylines for selected indicators and variables (Kishita et al. 2017; Marciano et al. 2024). This approach is promising for generating a better understanding of the entire storyline, how to connect it, and why this is important, especially for decision-makers. It can also reduce the number of variables and data to be included, making it much more feasible. Because an indicator is only a proxy, adding more variables to such models does not necessarily improve them, but often dilutes the information, as has been shown by critiques in research (King 2001).

Other limitations of the study include the use of only an exemplary target group of special-needs individuals. The elderly and children, as well as all other targeted user segments, are to be affected. Future studies should be focused on the mid-age and elderly population, since according to the Statistics Slovakia (2024), the age pyramid is significantly skewed towards the mid age and elderly population, with the elderly-to-adult ratio equal to 27.6%.

Additionally, information on those in charge of vulnerable groups or caring for them would also need to be analysed, along with all types of building interiors and exteriors. This is hardly feasible given the traditional research approaches, which rely on open data or empirical data collection. It is therefore tempting to consider whether artificial intelligence could be of assistance here, also considering long-term demographic trends. An automated extraction of street view imagery could be one area to explore (Vo et al. 2023). However, data privacy in the personal environment of human beings and their living conditions is only one area that needs sensitive supervision.

Another promising direction for future works is the structured integration of GIS and BIM via interoperable standards, such as Industry Foundation Classes (IFC) (ISO 16739-1: 2024) and CityGML (Tan et al. 2023). While no BIM datasets were available for Žilina, our current building classification already reflects key attributes, such as number of floors, entry points, and material proxies, that could be linked to simplified BIM representations. Establishing a GIS-to-BIM pipeline using tools such as IfcOpenShell or FME would enable dynamic cross-referencing between spatial data and interior building models. This is particularly valuable for simulating evacuation routes, energy retrofits, and heat resilience interventions in facilities serving individuals with special needs.

Due to the limited empirical data, the current approach is based on expert judgment, which is valuable but is intrinsically subjective and can introduce biases. The expert-driven approach was used due to a lack of empirical data and to gather detailed on-the-ground verification. Another limitation of this study, and at the same time, a possible area for expansion in future studies is the dependency on critical infrastructure services, such as energy or information, on which each indicator may be dependent (Rinaldi et al. 2001). For example, we have excluded sliding doors, motor lifts, and air conditioning. In normal conditions, the air conditioning provides cooling but is also very dependent on electric power, which might not be available during a disaster. Therefore, providing services such as cooling or electronic information displays and heavy energy dependent-sensors creates a secondary risk that people become accustomed to them, and then, in the event of failure, are even more at risk than they would be without those devices. This 'vulnerability paradox' (NOTA-Rathenau-Instituut 1994) is similar to the 'dyke effect' (White et al. 2001), which occurs when protection features, such as a flood protection dam, increase the risk for individuals who are unaware of the flood situation. This enables more future research in the area, as Žilina has a large dam and several other flood dams upstream and downstream that manage the flooded area. However, in the event of a failure of such protective infrastructure, the impacts would also need to be analysed.

Future enhancements could also include geospatial machine learning to automate the detection of vulnerability hotspots and building feature extraction (Rezvani et al. 2024). Semantic segmentation of orthophotos could support identification of flat roofs, solar exposure zones, and accessibility barriers, while clustering algorithms might help prioritise interventions in high-risk urban sectors. Moreover, incorporating simulation-based methods such as isochrone analysis for fire response times or shadow casting models for solar load exposure would complement the current expert-driven scoring framework and move towards scenario-based predictive analytics. These tools, if implemented with appropriate privacy and data governance, could form the foundation of a spatial decision-support system for inclusive climate resilience planning.

6 Conclusion

As a main contribution, this study shows the multi-level integration of spatial, regional and building information with a focus on vulnerable groups. This study examined multiple hazards affecting cities and how different levels of risk can be identified and utilised to scale up the information and integrate it. We have identified multiple hazards in the city of Žilina (Slovakia), offering a scalable approach that can be applied to other European cities, both at the street and building levels. To better integrate different levels, from the household to the city level, we have tried to integrate building-related information, the spatial environment of the built environment, and spatial zonation of hazards. Additionally, we have considered factors for persons with disabilities and respective emergency services to enable evacuation as well as withstand daily risks.

Heat has been identified as a risk type that enables the illustration of daily health and safety risks, such as overheating. While this is a slow onset, and not a rapid hazard, such as floods or an earthquake, heat waves in Europe in 2003, but also increasingly in recent years, have shown the high death tolls of thousands of people dying in excess. The study has shown that this can be integrated with information from different layers and sources, such as open street map data, photos and views from above, as well as photos from street level and on-site visits, from public web-based sources. It is also identified which information needs to be added by ground truthing.

Other natural hazards have been added and analysed in the same line, including earthquakes, fires, floods, and landslides. At the city and regional levels, the results show that the city of Žilina is affected by all these hazards, and in some areas, there is an overlap of one or more of these hazards. Different types of critical infrastructure, such as health facilities and emergency management, as well as roads, are also exposed.

Within the impact side of risk, the study focused on vulnerable groups, with a specific example being disabled people. The analysis reveals that interrelations between the built environment and apartment building types, incorporating urban and social features, can be identified using this approach. For example, some buildings only have access and exit options in case of an emergency on one side of the building. Special features for people with disabilities, such as stairs or ramps, can be identified from street view imagery only when visibility is provided by the imagery. It is still necessary to conduct on-site visits to augment this information. The analysis of interior of buildings is often overlooked in most building information management studies, even globally. However, interior information is very important already for accessibility and evacuation, as the study found. The risk level of households or people is then identified at a selected social care home for individuals with mental disabilities. This is one of the extreme examples of special needs groups because those people are at high risk due to communication challenges and related risk prevention, as well as risk response and evacuation challenges.

The contributions are summarised in three points:

A. This paper proposes a multi-level and multi-hazard risk assessment framework for natural hazards that integrates considerations of vulnerable and special-needs populations, built environment characteristics, and critical infrastructure vulnerabilities, that can support public authority decision-making.
B. Considering the complexity of the analysis that encompasses a multitude of interdependent aspects, the proposed framework relies on easily accessible data and information. The proposed approach can be quickly reproduced in other geographical contexts.
C. To showcase the applicability of the proposed framework, we apply it to the city of Žilina, which is an example of a mid-sized city in Central Europe, that is lacking a comprehensive understanding of future risks to natural disasters.

Overall, this study demonstrates how open geospatial data and open-source tools can be effectively harnessed to conduct multi-hazard, multi-level risk assessments with high spatial detail, even in data-constrained urban contexts. By systematically combining orthophotos, VGI, and street-level observations within a GIS-based framework, we established a replicable approach to characterising the spatial distribution of vulnerability. This geospatial integration enabled the identification of built-environment typologies most at risk from heat and cascading natural hazards, and facilitated the development of structured vulnerability storylines centred on special needs groups. These findings contribute to bridging the gap between hazard modelling, spatial planning, and inclusive risk governance, particularly for vulnerable populations in Central and Eastern European cities.

Appendix

Table 7 Infrastructure exposure per hazard or built environment zone in the City of Žilina

Zone type	Infrastructure					
	Fuel station	Pharmacy	Power tower	School	Mental homes	Senior citizen home
Natural hazard zones						
Flood zone	2		10			1
Forest fire zone	3	3	3	11	1	3
Heat zone	9	11	3	6		1
Flash Flood	2	3	3	13	0	0
Built environment types						
Farmhouse						
Semi-detached			4	2		
Old city		1				
Apartment block		5		10		
High-rise						
Industrial	5		5			
Sealed	3	3	2			
Urban residential		10		6		

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Declarations

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Authors and Affiliations

Alexander Fekete[1] · Steffen Neuner[1] · Christopher Munschauer[1] · Lubos Buzna[2,3] · Daniel Chovanec[4] · Katarina Holla[4] · Samuel Kockar[4] · Ulrich Leopold[5] · Stefania Stellacci[6] · Derya Yilmaz[5] · Catarina Ferreira da Silva[6]

✉ Alexander Fekete
alexander.fekete@th-koeln.de

Steffen Neuner
steffen.neuner@th-koeln.de

Christopher Munschauer
christopher.munschauer@th-koeln.de

Lubos Buzna
lubos.buzna@fri.uniza.sk

Daniel Chovanec
daniel.chovanec@uniza.sk

Katarina Holla
katarina.holla@uniza.sk

Samuel Kockar
samuel.kockar@uniza.sk

Ulrich Leopold
ulrich.leopold@list.lu

Stefania Stellacci
Stefania_Stellacci@iscte-iul.pt

Derya Yilmaz
derya.yilmaz@list.lu

Catarina Ferreira da Silva
catarina.ferreira.silva@iscte-iul.pt

[1] Institute of Rescue Engineering and Civil Protection, TH Köln - University of Applied Sciences Cologne, Betzdorferstr. 2, 50679 Cologne, Germany

[2] Faculty of Management Science and Informatics, University of Žilina, Univerzitná 8215/1, 010 26 Žilina, Slovakia

[3] Department of International Research Projects - ERADIATE+, University of Žilina, Univerzitná 8215/1, 01026 Žilina, Slovakia

[4] University of Zilina, Univerzitna 1, 01026 Zilina, Slovakia

[5] Sustainable Built and Urban Environment, Luxembourg Institute of Science and Technology, 5 avenue des Hauts-Fourneaux, 4362 Esch-sur-Alzette, Luxembourg

[6] Instituto Universitário de Lisboa (ISCTE-IUL), ISTAR, Lisbon, Portugal