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Application of a fuzzy, indicator-based methodology for investigating the functional vulnerability of critical infrastructures to flood hazards

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Abstract

Hazard vulnerability assessment of critical infrastructures (CIs) is crucial for ranking infrastructures based on their level of criticality, enabling the urban managers to prioritize CIs for allocating funds in the hazard mitigation/recovery process. This study aims to provide a framework for ranking CIs based on a rapid and preliminary flood vulnerability assessment by introducing a methodology for classifying CIs according to their vulnerability to riverine flooding. An indicator-based vulnerability curve is calculated both quantitatively (using Fuzzy Logic Toolbox in MATLAB) and qualitatively (using susceptibility–exposure matrix), based on which CIs prioritization is accomplished with a focus on functional flood vulnerability considering structural/nonstructural damages. Besides, this study addresses the consequences that a damaged infrastructure may have on the rest of CIs and estimates their vulnerability given the additive impact of the surrounding failed infrastructures considering their interdependence. The methodology was applied to Berat (Albania) and Sarajevo (Bosnia-Herzegovina) with findings compared to those of a multi-criteria decision-making-based approach commonly used in CI ranking literature. The obtained results from both methods represent that roads are the most vulnerable studied infrastructure in the case of Berat, while regarding the city of Sarajevo, road infrastructures are considered the least vulnerable to riverine floods compared to bridges and schools.

KEYWORDS

Albania, Bosnia-Herzegovina, critical infrastructure, flood hazard, FLORIS project, MCDM, vulnerability curves

1 | INTRODUCTION

Infrastructures, depending on their types and function, are composed of technical assets, human staff (for planning, management, maintenance, and repair), their organizational functionality, and environmental services. Damage to each of these components due to natural hazards may result in a significant impact on various aspects of society, including economic security, health and safety, social well-being, and may have business impacts, environmental consequences, and influence on the other urban infrastructures, as the cascading effect, due to the interdependency of such important facilities (Grosse, 2023; Organisation for Economic Co-operation and Development [OECD], 2018; Pederson et al., 2006).

Investigating the vulnerability of critical infrastructures (CIs) to flood hazard is a relatively new field of study. This is while it is widely agreed that critical infrastructure failure can lead to serious consequences, including severe economic damage, social disruption, or even large-scale loss of life (Cabinet Office, 2010; OBrien et al., 2015; Pant et al., 2018). Eliminating the secondary impacts, including socio-economic consequences of infrastructure disruptions, can lead to underinvestment in disaster mitigation (Chang, 2016).

Before addressing vulnerability assessment and critical ranking of infrastructures, it is first necessary to clarify what is aimed at by the so-called "*critical infrastructures*" (*hereinafter referred to as CI*). A literature review reveals a series of definitions for CIs, of which the most are based on the concept that CI are vital to the security and welfare of a society and their disruption may cause serious consequences and cascade across borders of the primarily affected society (Biskupovic, 2021; Curt & Tacnet, 2018; Fisher & Gamper, 2017; Gheorghe et al., 2007; Heino et al., 2019; Katina & Hester, 2012; Organisation for Economic Co-operation and Development [OECD], 2022; Pescaroli & Alexander, 2016; United Nations Office for Disaster Risk Reduction [UNDRR], 2020). In this study, the term *critical infrastructures* includes the essential networks for providing the basic needs and functioning of a society both in normal situation and in case of disaster occurrence (Heilemann, 2013; Wijngaarden, 2013).

Disaster risk is often said to be a product of hazard and vulnerability (Birkmann, 2013a, 2013b; United Nations International Strategy for Disaster Reduction [UNISDR], 2004; Wisner, 2004). Vulnerability assessment of CIs is of great importance since an outage of such facilities due to flooding may have a serious, long-term impact on the affected society. There is a difference between "general vulnerability assessment" and "vulnerability assessment of CIs." General vulnerability assessments primarily focus on direct physical and economic damage, with some consideration of indirect effects. In contrast, criticality assessments mainly address the secondary effects of operational interruptions in CIs. Such a difference is because of the critical role of such infrastructures for the community and their necessary services both in the daily functioning of society and at the time of disaster occurrence. Thus, maybe it can be said that the direct damage to the CIs is of minor importance compared to the indirect effects of the CIs operational interruption and lack of services to the affected community (Ebbwater Consulting, 2018; Jafari-Shahdani et al., 2020; Ma et al., 2021; Pregnolato et al., 2020; Rose, 2004; Uckan & Akbas, 2015). A CIs lack of functionality may have both direct and indirect impacts on the rest of CIs. Past studies and experiences show that even infrastructures unaffected by flooding should be considered in flood analysis as their functionality may be indirectly impacted by the flooding of other infrastructure related to them (Arrighi et al., 2021; Assaad et al., 2024; United Nations Economic Commission for Europe [UNECE] & United Nations Human Settlements Programme [UN-Habitat], 2019). An example of this could be a hospital that is not flooded itself (exposure = 0); however, the road leading to the hospital has been inundated, which can affect the level of functionality of the hospital. In this context, redundancy, as well as increased robustness and restoration, play an important role in enhancing the CI resilience to flooding.

In the literature, vulnerability mostly has been defined as a function of susceptibility and exposure (Intergovernmental Panel for Climate Change [IPCC], 2014) to disasters (herein, riverine flooding) and at the same time, can be viewed as the inverse ratio to resilience. IPCC defines vulnerability as a function of exposure, sensitivity, and coping/adaptive capacity (Intergovernmental Panel for Climate Change [IPCC], 2012; UNESCO-IHE, 2012). Coping and adaptive capacities are derived from the resilience concept, as past studies have utilized resilience as a balancing factor to modify the obtained values for vulnerability (Karamouz et al., 2016). As a result, it could be said that vulnerability has a direct relationship with exposure and susceptibility and an inverse ratio to resilience.

Exposure generally refers to the extent to which a unit or system of the assessment (i.e., people, livelihoods, environmental services, resources or infrastructures, or other valuable items) falls within the geographical range of a hazard event (IPCC, 2012). Susceptibility (sometimes called sensitivity or fragility) characterizes the tendency to suffer harm when a hazard strikes an exposed system, which can be discussed from physical, social, environmental, cultural, and institutional perspectives (Birkmann, 2013a, 2013b). In the current study, we believe that a susceptible system exposed to a hazard is called vulnerable since the two elements of susceptibility and exposure form the hazard consequences. This definition is in agreement with the ideas of many researchers (Babcicky & Seebauer, 2021; Drakes & Tate, 2022; Hamidi et al., 2020; Mason et al., 2021; Ramalho Alves et al., 2021; Thomas et al., 2019; Tingsanchali & Promping, 2022; Vancouver Coastal Health [VCH], 2021; Yu et al., 2021). The risk value would be zero when an insusceptible system is exposed to a certain hazard. Vice versa, a fully susceptible system not in the exposure range of a given hazard would not be at risk, and both the hazard consequences and risk value would be zero for that system.

After clarification about the meaning of CI and the criticality assessment for the study at hand, attention can be turned to the CI ranking regarding their vulnerability to floods. The CIs' prioritization could be recognized as a significant gap in the literature. Prioritizing infrastructures is essential for allocating funds for their hazard mitigation and recovery. Even though the studies found in the literature are showing an increase in number starting from the past decade, there is still a need to work on various methodologies for more reliable ranking of the urban infrastructures especially from the hazard vulnerability viewpoint, for which few studies can be found in the literature.

Such studies have used various criticality criteria for identifying the criticality of infrastructure systems and prioritizing them, including likelihood and magnitude of failure, impact on system users (Koonce et al., 2008), environmental, and physical damage to properties and impact level on human beings (Patterson & Apostolakis, 2007), mortality, economic damage and consequences (Fekete, 2011), time to repair and rehabilitation costs (Gokey et al., 2009; Myers & Sorrentino Jr., 2011; Weil & Apostolakis, 2001).

Regarding the purposes of the current study, that is, CIs ranking based on vulnerability to floods, the literature review can be categorized into three main groups: (1) studies that have examined the CIs vulnerability to the same hazard, that is, flooding; (2) studies which have utilized the vulnerability curves for criticality evaluation of CIs; and (3) studies neither worked on flood hazard nor used vulnerability curves in the methodology, but investigated the CIs prioritization to a different hazard with a different method. A glance at such a literature review reveals the lack of research on developing vulnerability curves for criticality assessment of the CIs and prioritizing the infrastructures exposed to flooding hazard, at the same time.

Various methods have been utilized to characterize the criticality of CI and prioritization. Stergiopoulos et al. (2016) explain that all classification methods of CI go under "Purpose-Based" or "Technical Approach-Based" methods. In purpose-based classification of CIs, goals such as "Risk Identification," "Risk Impact Assessment," "Risk Prioritization," "Risk Mitigation Planning and Implementation," and "Effectiveness Evaluation" are included. This is while in Approach-Based ranking of CIs, various modeling and simulation approaches can be used, including "Empirical Approaches," "System Dynamics Approaches," "Agent-Based Approaches," "Network-Based Approaches."

In recent years, a large amount of research has been undertaken on the theoretical and application aspects of fuzzy multi-criteria decision making (MCDM) (Jahan et al., 2016). Smith et al. (1998) utilized fuzzy control system methods for characterizing the uncertainty distributions of the expert judgment. Akgun et al. (2010) suggest the use of fuzzy set theory to determine critical components and functions of a transport system, quantitatively. Merad (2016) ranked five CIs according to the resilience domains. Papathoma-Köhle (2016) compares the two methodologies based on vulnerability curve and vulnerability indicators for debris-flow hazards and concludes that there is a need for a "holistic framework for physical vulnerability assessment" by combining the existing methods to create synergy and use the additive power of the methods.

In the current study, a combination of vulnerability curves and vulnerability indicators has been provided, and an indicator-based vulnerability curve has been introduced. As hazard vulnerability of infrastructure networks is highly dependent on the level of vulnerability of their structural and nonstructural components, the proposed methodology considers this alongside the indicator-driven strategy. Vulnerability assessment is usually of three types: structural, nonstructural and functional vulnerability; the latter means the reduction in CI efficiency due to hazards. Past studies often concentrate on one of these vulnerability aspects, which mostly includes structural and sometimes nonstructural damage to such facilities. The current study attempts to introduce a framework to consider all three vulnerability types and present an integrated CI prioritization that emphasizes functional vulnerability to riverine floods with an eye to structural/nonstructural damages.

Usually, for ranking the criticality of infrastructures, MCDM-based methods are used. MCDM refers to the process of identifying the best feasible solution based on established criteria as well as decision makers' preferences and priorities to address common issues encountered in daily life (Jahan et al., 2016; Zakeri et al., 2023). Almeida (2008) proposed a multi-criteria methodology for the identification and ranking of CIs to modify the available Canadian model, using their original assumptions. Izuakor (2016) conducted research for identifying the most CI asset that requires additional risk assessment using a MCDM system. In the current work, an attempt has been made to compare the results of the proposed methodology with the results from a MCDM method. Study of cascade effects (both direct and indirect impacts) that a failed CI can have on the rest of infrastructures and on the whole society is very important to be included in infrastructure vulnerability analysis, this is while few studies have been conducted on that. Heilemann (2013) proposed a framework to identify and analyse the most vulnerable infrastructure with respect to floods. They investigated the generation of breakdowns to the whole infrastructures' network due to the failure of one single CI and the cascade effects. Pant et al. (2018) represent an integrated framework for CI flood impact assessment and quantify direct and indirect disruptions due to the interdependency of CI.

This paper aims at defining the discrete damage states for functionality of the flooded infrastructures and, finally, classify and prioritize the strategic infrastructures subjected to flooding from the hazard vulnerability point of view. In addition, this research attempts to briefly study the domino effects that various damaged infrastructures may have on the rest of CI and attempts to estimate the CI vulnerability curves after being impacted by the functionality reduction of the other flooded infrastructure.

The proposed methodology was developed as part of the FLORIS project (Innovative tools for improving FLood risk reductiOn stRategIeS) that has received funding from the European Commission—under the 2018 Call Prevention and Preparedness in Civil Protection (www.floris.unime.it). FLORIS project aimed at studying innovative approaches for the development of integrated flood risk scenarios, taking into consideration critical specific issues of areas at risk and the consequences of high frequency/low damage events that affect them. High-frequency floods still involve and require mitigation actions on the part of civil protection and citizens before floodwaters inundate the land and directly impact assets, which can benefit from enhanced protocol development based on realistic scenarios. The main idea of the project was to develop a supporting decision tool for the comparative analysis of disaster reduction strategies in flood risk management, with a specific interest in studying the functional vulnerability of CIs to preserve their efficiency during and after hazardous events.

2 | MATERIALS AND METHODS

2.1 | Introduction to the case studies

The proposed methodology has been applied in two flood-prone case studies affected by urban rivers. Distance from the river is, in fact, a major factor in the vulnerability of CI to river flooding (Al Baky et al., 2020). The literature shows that the highest probability of flooding is usually found in areas close to river channel network and low-lying areas (Gumindoga et al., 2014).

The first case study under analysis is in the city of Sarajevo (in Bosnia), a part of the Zujevina River basin (Figure 1). This catchment is the first left tributary of the Bosna River, with a length of about 40 km and a catchment area of 172 km^2. For a range of 3600 m from the river confluence into the Bosna River, usually frequent floods occur due to the insufficient capacity of the river at this part (Hadžić et al., 2020). The required data for this site were provided by the University of Sarajevo and by the Bosnia Civil Protection (under the IPA DRAM regional program[1]).

One of the significant flood events within the Bosna River basin occurred in May 2014, with an estimated return period exceeding 100 years. The flow discharge peaked at approximately 5000 m^3/s in certain areas of the basin (Vidmar et al., 2016), resulting in extensive damages and consequential effects. Further details regarding this severe flood and its impact on CIs are provided in Table 1.

The other case study is located in the city of Berat, a historical city located in the southern part of Albania and is a part of Osum *river basin* (Figure 2). *This area has experienced significant fluvial flooding during the past years, mostly due to the* large flows and the outflow of the river out of its bed. The data have been gathered through the MyDEWETRA World Platform, supported by the PRONEWS program in Albania.[2] The maps show both countries positions, and the FLORIS implementation activities target areas.

The target area for Albania has been the prefecture of BERAT, which is traversed by the Osum River basin, as one of the tributary rivers of the Semani River in the center of the country. The Albanian Rivers map in the following shows the Osumi river basin (orange color).

Over the past century, Osum river (flowing through Berat) has been flooded several times. Following the floods in Berat, there is a potential risk of a secondary hazard, that is, a landslide, due to the city's positioning around the foothills of a substantial elevation (Palermo et al., 2017). Table 1 presents the consequences of one significant riverine flood in Berat that prompted a critical situation in the areas adjoining the river floodplain.

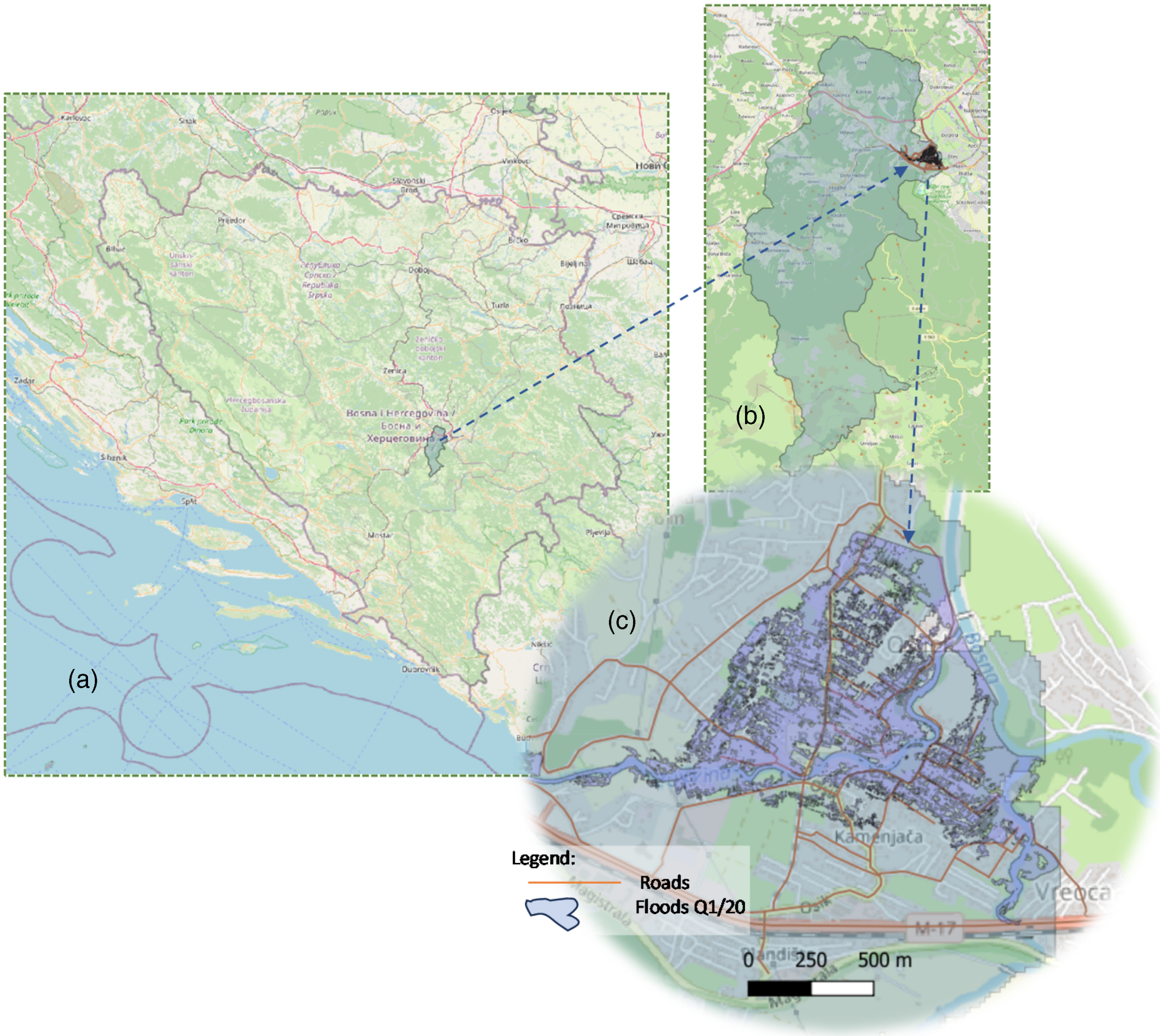

FIGURE 1 Zujevina River basin in Sarajevo, Bosnia: (a) location of the Zujevina River basin in Bosnia and Herzegovina, (b) location of the pilot zone within the Zujevina River basin, (c) flood map for *Q*1/20 and map of main roads for pilot zone. *Q* represents the flood flow rate.

2.2 | Proposed CI ranking framework

The proposed framework for CI ranking and categorization based on vulnerability to floods has been represented in Figure 3. The core tool in utilizing the proposed approach is developing some questionnaire surveys, taking into account various vulnerability indicators for structural and nonstructural elements of urban CI. The next step includes calculating the relative susceptibility and exposure levels of each element of the given infrastructure. Finally, the relative vulnerability level of each infrastructure was obtained qualitatively and quantitatively using an exposure–susceptibility matrix and the MATLAB Fuzzy Logic Toolbox, respectively.

2.2.1 | Developing the questionnaires

According to the proposed methodology, there is a need to develop a kind of, questionnaire (i.e., survey form) to gather the experts' ideas on the discrete damage to each structural/nonstructural element of flooded infrastructures with a focus on their functionality and the impacts on the function of other infrastructures. The expert group consisted of a multidisciplinary team of physical and social sciences, including local civil protection organization.

The self-completion questionnaire, whose results allow to develop a synthetic vulnerability curve for each structural and nonstructural element of the selected infrastructures on an indicator-driven basis, is reported

TABLE 1 Some examples of major past floods in the study sites and their impacts on critical infrastructures (CIs).

River Basin	Date of occurrence	Flood severity and consequences	Flood impacts on CI
Bosna River Basin	May 2014	Affecting more than a quarter of Bosnia's population (At least) 40 losses of lives Tens of thousands of people were displaced Damaging the markers at some leftover minefields Submerged lands and destroyed vehicles Secondary hazards such as land slides Concerns of a health hazard due to tons of drowned livestock	Inundating a bridge located 20 km north of Sarajevo Inundated roads Damage to railways School closure Impact on electricity infrastructure (at least 5000 households without electricity)
Osum River Basin	February 2015	Displaced people Loss of property and farmlands Loss of livestock Damage to residential buildings	Endangered some major highways Damage to electricity and power stations Damage to water supply systems Damage to bridges

in Appendix A, Supporting Information. The questionnaire consists of several sections representing the factors related to susceptibility, exposure, and resilience of infrastructures to flood events. In the developed questionnaire, susceptibility indicators have the same meaning as flood damages and consequences that disrupt the functional serviceability of the infrastructure. Exposure criteria involve both those items causing more inundation in the region and the measures that lead to exacerbating the flood consequences. While resilience measures include factors acting on both resistance and flexibility against flooding. In such a questionnaire, all direct, indirect, tangible, and intangible impacts of floods should be considered. It should be noted that the indicators considered herein as the sub-measures of exposure, susceptibility, and resilience were chosen in a way that represents the "functional" aspect of flood damages and consequences; therefore, the final results would be calculated as functional flood vulnerability values. This means that the mere structural/nonstructural damages by flooding are not intended. Only those damages to structural/nonstructural components are important, for the purpose of this study, that impact the functionality of the infrastructure, that is, reduction in its predefined or expected performance (or level of service) due to being inundated or affected by flooding. An example could be disrupted traffic and people's health as a result of inundated roads or disrupted water supply systems, respectively.

In total, the survey form includes three types of questions:

1. Estimating the reduction in functionality of the infrastructures with respect to each given indicator (related to susceptibility, exposure, and resilience) when there is significant damage to some structural and nonstructural components.
2. Determining the weights of the structural/nonstructural components and functionality indicators for each single infrastructure by asking about their level of importance in comparison to each other.
3. Determination of functional interdependency of different infrastructures during and after flood occurrence. The latter, in fact, investigates the impact degree of failure of each infrastructure on the functionality of the rest of CIs, seeking to obtain the functionality reduction for those groups of infrastructures that are not even flooded; however, may be impacted by the other types of flooded infrastructure in the region.

Based on the above-mentioned criteria, a questionnaire was developed focusing on two main types of infrastructures, that is, transportation systems and educational facilities. These two important infrastructures were selected considering the high number of infrastructures in cities and the available information for the two case studies. As the transportation infrastructure, roads and bridges were chosen to be investigated in detail, and among educational facilities, schools were considered as the main focus of this study. This means that the sample vulnerability curves were going to be achieved for roads, bridges, and schools, while the degree of impact that various infrastructures might have had on each other would still be discussed based on analyzing the experts' knowledge (Figure 4).

For roads and bridges, only questions regarding structural elements were analyzed, whereas for the schools,

FIGURE 2 The Albania map with Berati Region, and the position of roads and bridges alongside the Osumi River in Berat, Albania.

both structural and nonstructural components were considered. The experts were asked to answer the questions, especially while responding to exposure and resilience sections, based on their personal knowledge and expertise with an eye to real characteristics and equipment available in the case studies.

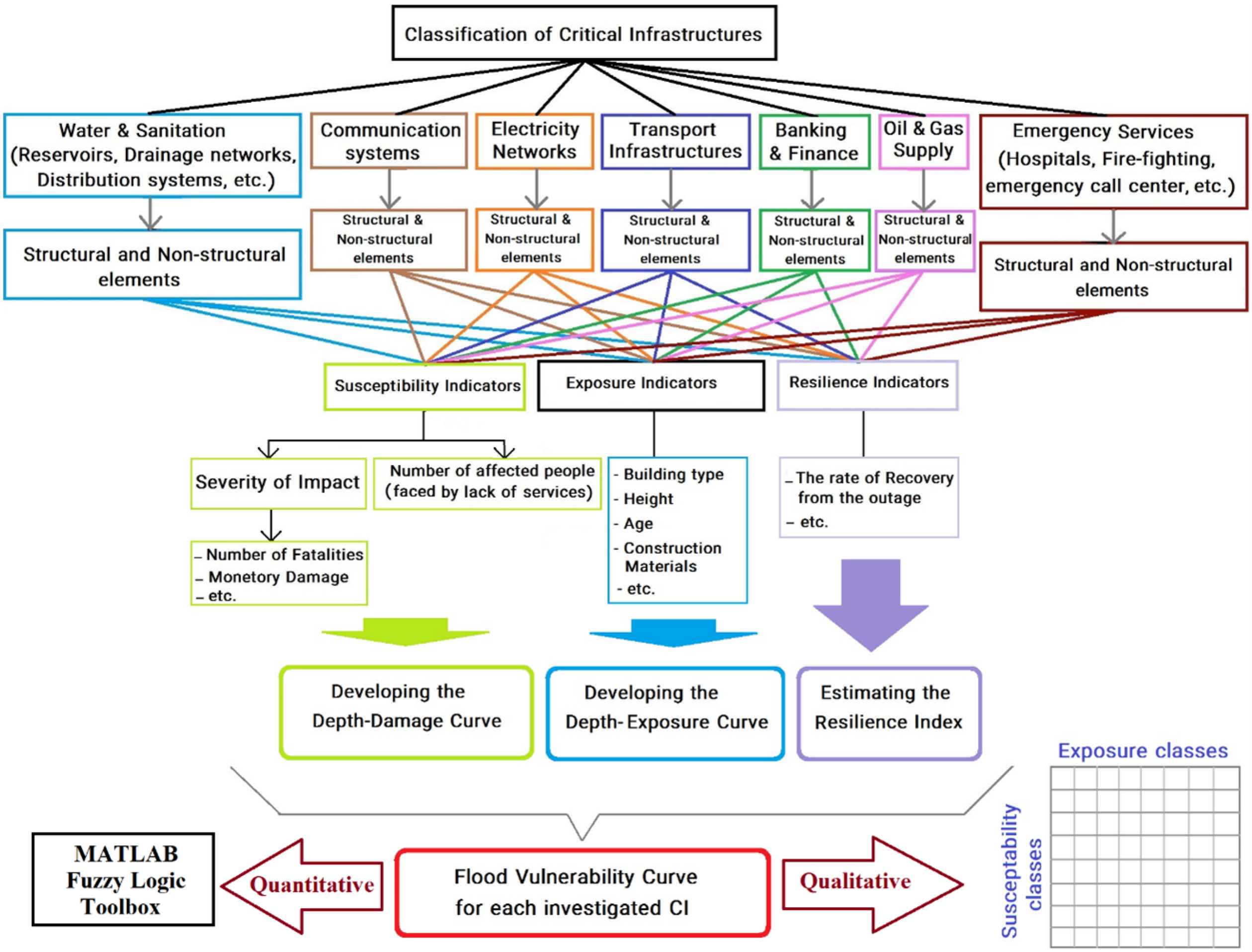

FIGURE 3 The proposed framework for classifying the Most Vulnerable Urban Infrastructures to flooding. CI, critical infrastructures.

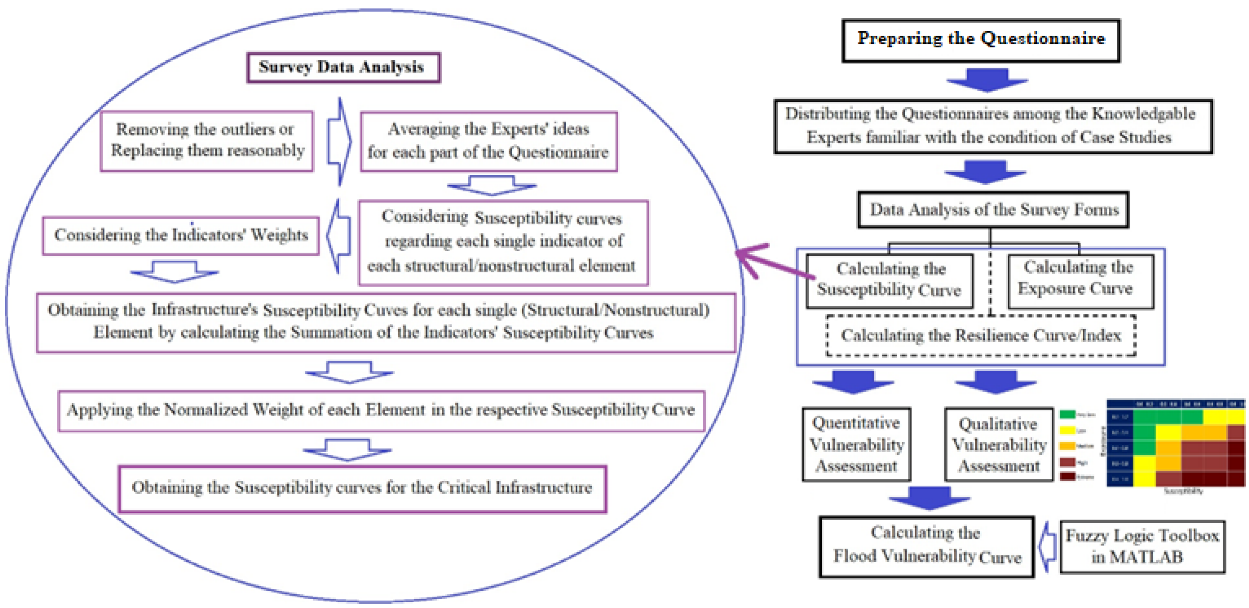

FIGURE 4 Flowchart shows the analysis of the questionnaire to obtain critical infrastructures flood vulnerability curves.

It is important to highlight that distinct questionnaires have been meticulously prepared for the three different infrastructure types, each tailored with specific details. Each questionnaire is designed to focus on a particular infrastructure type, accentuating its distinctive functional aspects and addressing the nuances of its individual components. The questions within each survey are dedicated to exploring the unique structural and nonstructural damages that may be encountered by that specific infrastructure, which could vary significantly among the investigated infrastructures.

In developing the questionnaires, an effort was made to consider the most important measures that best describe the criticality of infrastructures such as the severity of impact, the number of affected people faced by lack of services, the facility's replacement cost, relocation difficulties, and the infrastructure's role in responding to emergency situations. For example, infrastructures such as emergency operation centers, health care facilities, transportation system, police and fire stations, etc. have a major role in emergency responses after disasters, and at the same time, their probable relocations would be very difficult and complicated. Herein, we are not going to calculate how much damages may be applied to each flooded structural/nonstructural element of the infrastructures while most designed questionnaires in previous research aim at gathering information about a flood event that has already occurred and evaluating "structural" or "nonstructural" vulnerability to flooding. Consequently, this is a totally different use of questionnaires compared to those aiming at gathering information about the status of CIs and data related to the past flood events.

2.2.2 | Calculating the susceptibility and exposure curves

For different depths of flood water, the depth-damage curves, depth-exposure curves, and depth-resilience curves are developed for each single indicator and each single structural/nonstructural element. This is achieved by calculating the average scores assigned by the experts to each individual indicator/component at every floodwater level. Such detailed exposure and susceptibility curves hold significant value for infrastructure planners and practitioners as they enable a thorough examination of each infrastructure component individually, helping identify the root cause of reduced service. As in certain instances, the entire infrastructure may not be responsible for the service disruption. Therefore, understanding the percentage of failure originating from each infrastructure component becomes crucial for effective analysis and remedial action.

Resilience (R) can be represented either as a discrete depth-resilience curve or as an index. In both scenarios, this factor serves as a modulator to adjust the susceptibility and exposure curves. This modification is performed by incorporating a reduction rate of susceptibility (S) and exposure (E) originated from applying an adaptive capacity (i.e., resilience) (see Equations 1 and 2). The results return the Modified Exposure (Z) and the Modified Susceptibility (W):

$$Z = E - \left(\frac{E \times R}{100}\right), \tag{1}$$

$$W = S - \left(\frac{S \times R}{100}\right). \tag{2}$$

Eventually, a summation of the estimated curves for the structural/nonstructural components of a certain CI develops the final susceptibility and exposure curves for the whole infrastructure (Equations 3 and 4). Then, vulnerability curves can be calculated through a logical combination of susceptibility and exposure values at each water depth.

$$\sum_{i=1}^{n} \sum_{j=1}^{m} W_{ij} = S_{\mathrm{CI}}, \tag{3}$$

$$\sum_{i=1}^{n} \sum_{k=1}^{p} Z_{ip} = E_{\mathrm{CI}}, \tag{4}$$

where n is the number of CI components, m is the number of susceptibility indicators, and p is the number of exposure indicators. S_{CI} and E_{CI} represent the total susceptibility and exposure of the given infrastructure, and i, j, and k are the counters.

Alternatively, an exposure–susceptibility matrix can be developed as indicated in Figure 5, which includes some bands instead of the absolute values, which is applicable for covering the uncertainties associated with the vulnerability quantification.

It is similar to the exposure–vulnerability matrix utilized by Naso et al. (2016), even though with a different definition and usage. In such a crisscross analysis, there is an estimated range of values for susceptibility and an estimated range for exposure. Five different colors of the table cells represent various degrees of vulnerability, from low severity to extreme level. For each CI or each single element of it with a specific value of exposure and susceptibility to flooding, the location of the intersection point can be determined, and therefore, the class of vulnerability for that certain element or infrastructure is obtained. This way, various infrastructures falling in

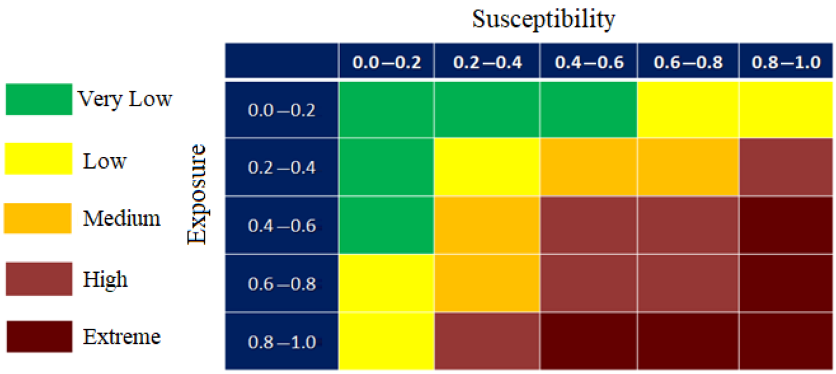

FIGURE 5 Estimating the critical infrastructures vulnerability class based on an exposure–susceptibility matrix.

one special band (with a specific color) have the same level of vulnerability to flooding.

Table 2 represents some of the structural/nonstructural components of the CIs for which the susceptibility curves have been obtained. For each case, various indicators regarding the CI susceptibility were considered.

2.2.3 | Calculating flood vulnerability curves

Decision-making often involves inaccuracies and ambiguities that can be effectively managed through fuzzy sets and fuzzy decision-making techniques (Jahan et al., 2016). Managing the uncertainty is an inherently important issue in the design of expert systems since much of the information in a typical expert system is inaccurate, incomplete, or partially unreliable (Zadeh, 1983).

The fuzzy logic and fuzzy set theory were proposed by mathematician Lotfi A. Zadeh in 1965. This theory can easily incorporate information described in linguistic terms and is used a lot in the field of risk management. Therefore, fuzzy rule-based models are considered the most convenient ones for integrating different expert opinions and of the most beneficial for uncertainty quantification when having insufficient or inaccurate data (Fakhravar, 2020; Janssen et al., 2010; Laner et al., 2015).

For the current study, for which the data are mostly collected through questionnaire based on the human experts' opinions, using fuzzy-based methods could be helpful to cover the uncertainties (Tahami & Fakhravar, 2020). Fuzzy Logic Toolbox in MATLAB was utilized to model the susceptibility–exposure matrix (Figure 5), which has two inputs (i.e., susceptibility and exposure values) and one output (i.e., vulnerability) (see Figure 6). The calculations were based on the Mamdani system, meaning that both inputs and output are in fuzzy form and not as an accurate number. First, the membership functions for each input and output are defined.

TABLE 2 Critical infrastructures components considered for the derivation of the vulnerability curves.

Infrastructure	Structural/nonstructural components	Type of damage due to flooding
Roads	Road pavement	Deteriorated and washed-out
	Road's shoulders and embankment	Significantly eroded
	Road's drains and culvert	Cut back, drainage problems, etc.
Bridges	Bridge piers/abutments	Washed-out by large debris
	Bridge road-bed asphalt	Torn out
	Connectors anchoring the bridge in place/the bridge bracing system	Broken apart
	Bridge structure	Lifted off its supports or collapsed due to salt/debris
	Bridge foundation	Extreme scour
Schools	School building structure (i.e., walls and foundation)	Significantly damaged/collapsed
	Components such as ceiling, lighting, doors, and windows	Significantly damaged/destroyed
	Teaching material, bookshelves, and desks	Significantly damaged/unusable
	Mechanical, and electrical items, potable water systems and wastewater collection lines, plumbing and piping systems, wiring, computers, and gas system	Significantly damaged/unusable

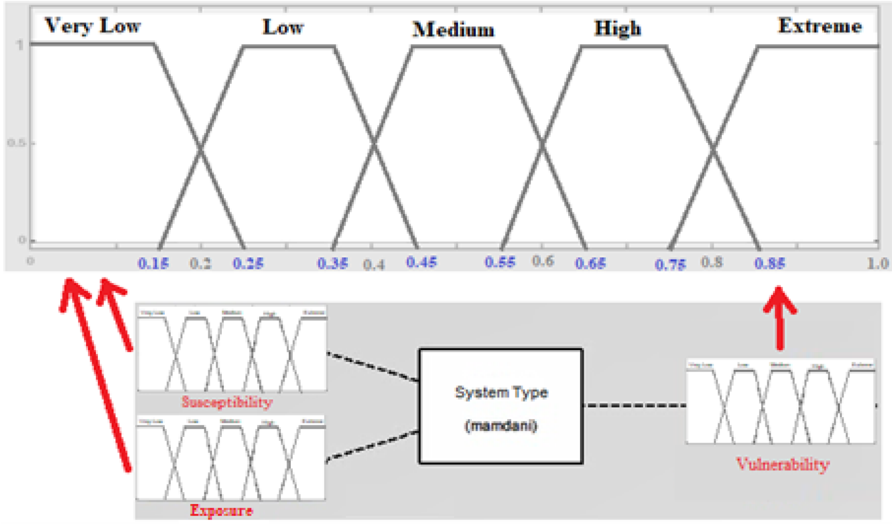

FIGURE 6 Definition of inputs, outputs, and their membership functions.

There is no unique rule about defining the fuzzy sets' membership functions, as both the mathematical form of the function and the parameters depend on the inputs from the experts (Shang & Hossen, 2013). In the current study, the intervals range from very low to extreme were defined for susceptibility, exposure, and vulnerability, which means considering five membership functions of trapezoidal type for each input/output (Figure 6). Special form of the trapezoidal membership function curve ($\Pi(u)$) can be seen in Equation (5) and Figure 7 (Fechera et al., 2012; Setiawan et al., 2020).

$$\Pi(u) = \begin{cases} 0, if\ (x<a) \text{ or } (x>d) \\ \dfrac{x-a}{b-a},\ if\ a \le u \le b \\ 1,\ if\ b \le x \le c \\ \dfrac{d-x}{d-c},\ if\ c \le x \le d \end{cases}. \quad (5)$$

Afterwards, the rules are defined, which determines how the vulnerability class changes with different combination (i.e., multiplication) of susceptibility and exposure interval ranges. Twenty-five rules were developed for various modes, based on which the values of vulnerability are obtained, having two values for susceptibility and exposure. An overview of the 3D susceptibility–exposure–vulnerability graph would be something similar to the primary matrix in Figure 5.

Figure 8 represents the better behavior of the selected system. It is obvious from the figure that vulnerability values increase with an increase in susceptibility values. In fact, a fuzzy model changes the defined rules to a continuous and spectral system.

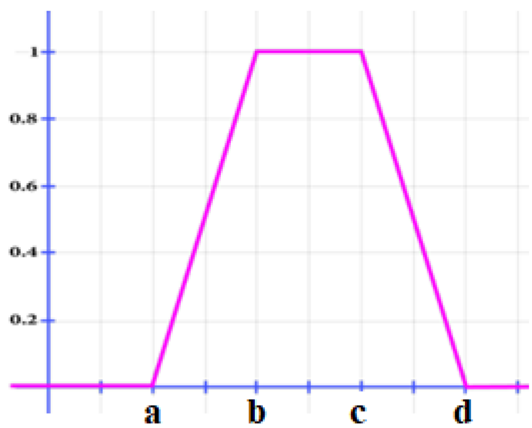

FIGURE 7 Trapezoidal membership function curve (Setiawan et al., 2020).

2.2.4 | Resilience measure as a modulator in calculating flood vulnerability

In the proposed methodology, it is intended to investigate the effect of using some adaptive measures from various types on reducing the flood vulnerability of the CIs. These adaptive actions can include a wide range of measures, from structural ones (e.g., using low impact development strategies, replacing or reinforcing structural components) to nonstructural ones (e.g., anchoring bookshelves at schools) and functional measures (e.g., training students to be prepared for surviving flood situations). For this purpose, some measures were inserted into the questionnaire to have the experts' ideas on their level of functionality and ability to reduce flood consequences for various water depths. Some of the

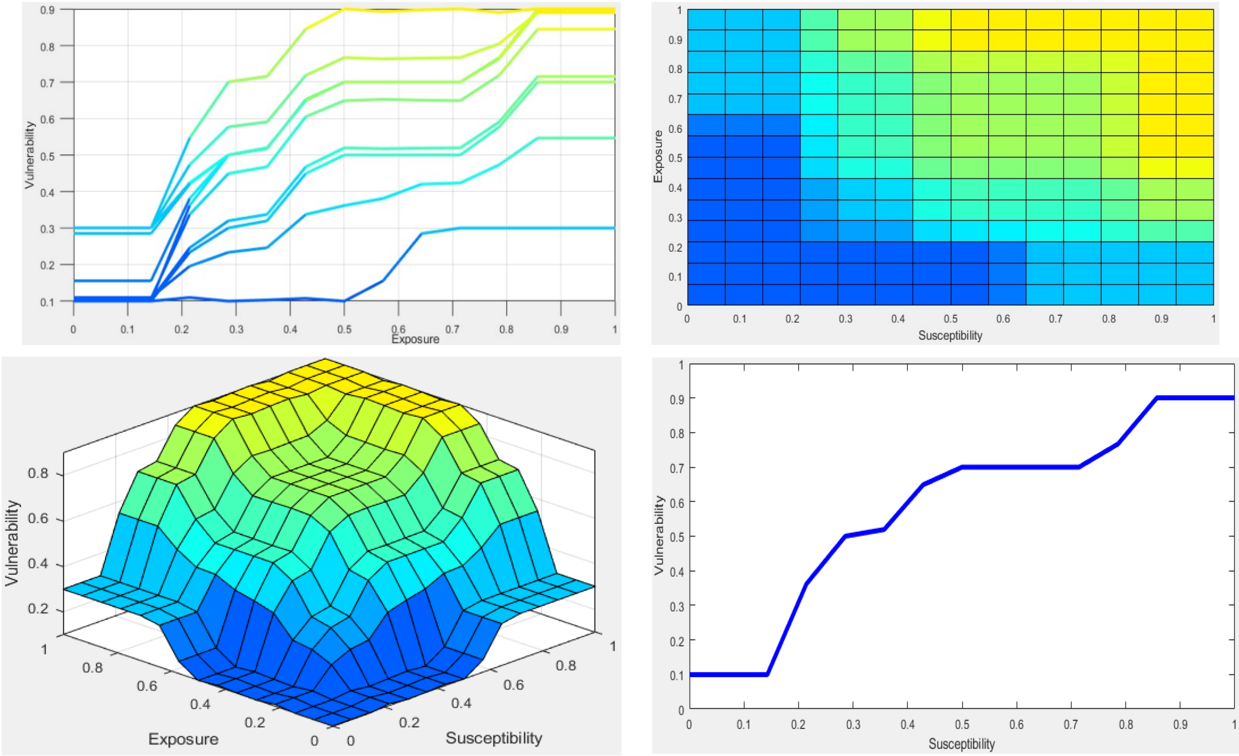

FIGURE 8 Fuzzy rules defined using Fuzzy Logic Toolbox in MATLAB.

considered resilience measures have been presented in Table 3 as an example.

For resilience, the rate of recovery from the outage seems to be a determinative factor and describes the level of criticality the best.

2.2.5 | Secondary impacts of flooded CIs on the other infrastructures

As mentioned earlier, in the survey forms, an investigation has been made into the level of impact that each flooded infrastructure may have on the rest of CIs and reducing their functionality, even if they have not been flooded directly. The aim was to both gain an insight into the impact level of each urban CI on the rest of CIs, and use the data for further analysis, that is, calculating the CI flood vulnerability curve while some other CIs connected to it have been flooded as well. Similar to the previous sections, the analysis is mainly based on the scores provided by experts in the questionnaire, which are then averaged and normalized for each infrastructure. Based on these initial calculations, more valuable results can be obtained by having the vulnerability curve of each infrastructure and its estimated impact on other CIs that have not been directly flooded but are affected by the hazard's consequences (as explained in Figure 17).

2.2.6 | Comparison with the MCDM method

To make a comparison and verify the results, the findings were compared to the results with a self-tailored version of the MCDM method. The flowchart of the proposed MCDM is provided in Figure 9.

To calculate the final value of criticality for each infrastructure in the MCDM method, first the averaged-weighted values of susceptibility assigned to each sub-indicator regarding each CIs component is multiplied by the normalize values of relative importance of the studied infrastructures to each other (all based on the experts' comments). Then the summation is calculated for each single infrastructure. The same procedure is performed for the CIs exposure and resilience. At the end, the CIs vulnerability value is calculated based on the well-known equation representing that flood vulnerability has a direct relationship with susceptibility and exposure and an inverse ratio to resilience to floods.

3 | RESULTS AND DISCUSSION

The following sections present the results of the application of both methodologies based on synthetic vulnerability curves and MCDM. It should be noted that resilience was introduced to provide a comprehensive methodology

TABLE 3 Some examples of investigated resilience measures in flood vulnerability reduction.

Roads	Bridges	Schools
Using adaptation measures regarding the design codes of road infrastructure	*Renovating* bridges with an eye to surviving 200-year flood levels	Locating/designing the sewer collection lines in a way that avoids infiltration and back-up due to rising floodwaters (i.e., designing a back-flow prevention device)
Considering alternate routes (i.e., redundancy) and increasing the roads density	Designing structures with decks that rise high above flood levels (in order to have dense and impenetrable parts of a bridge not hit by debris)	Preparing and training students/teachers regarding flood situations through running flood rehearsals (drills)
Improved drainage system in the vicinity of the roads' network	Placing boulders around the base of bridge piers (to keep the riverbed in place and prevent the effects of scour).	Flood-proofing of the school building (e.g., water-tight doors and special seals)
Utilizing *pervious* pavement systems wherever possible	Reducing the depth of the bridge roadway (so water can more easily flow around it), and adding structural elements (to let water pass through the road-bed)	Adequately anchoring structural/nonstructural elements (i.e., blackboards, bookshelves, etc.) to prevent flotation or lateral movement resulting from hydrodynamic and hydrostatic loads, including the effects of buoyancy
Available Green spaces in the surrounding areas of the roads	Replacing bridges having wood decks (which are weaker than other types) or metal decks (that can be lifted by powerful aquatic forces) with concrete decks supported by steel (to enhance both strength and flexibility as well as resistance to the shearing forces that can twist a bridge off its foundation)	Considering alternate roads/routes reaching to the school site (i.e., redundancy) as well as availability of back-up equipment

(Continues)

TABLE 3 (Continued)

that can be used in similar study sites. However, resilience was not included in the calculations herein, as the case studies are not equipped with significant adaptive measures. Therefore, the initially calculated exposure and susceptibility did not require modification. It is anticipated that, by implementing adaptive measures in the region and incorporating a resilience modulator, the rate of susceptibility and exposure will be mitigated to some extent.

3.1 | Application of the methodology based on synthetic vulnerability curves

Figure 10 depicts the percentage of experts who participated in providing the vulnerability ratings for each CI component. The participants' selection process was in a way that the experts belong to diverse knowledge fields and are acquainted with both infrastructure systems and the flooding situation in the study sites, that is, Berat and Sarajevo. As observed in the figure, a nearly equal distribution of expertise is evident in both case studies. The main expertise categories of respondents to the questionnaire primarily belong to the field of Civil Protection staff/engineers, followed by experts in hydro-technics and traffic management who are actively engaged in flood protection issues in the study sites. Considering the participants' expertise for responding to the questionnaire, it could be expected that they have enough knowledge of CIs performance and vulnerabilities in the given study site.

Figure 11 indicates an example of susceptibility curves (weighted according to the experts' ideas through multiplying each susceptibility indicator by the weight, i.e., level of importance of that indicator) for each indicator following the road pavement's deterioration and wash-out. According to this figure, in case of deterioration and wash-out occurrence due to flooding, delay in emergency relief and rescue process would be of the most critical functional consequences for Sarajevo's roads, while social consequences would be the least impacted by flooding.

Accordingly, for the rest of the road infrastructure's components, susceptibility curves were obtained, and the final susceptibility curve was calculated as represented in

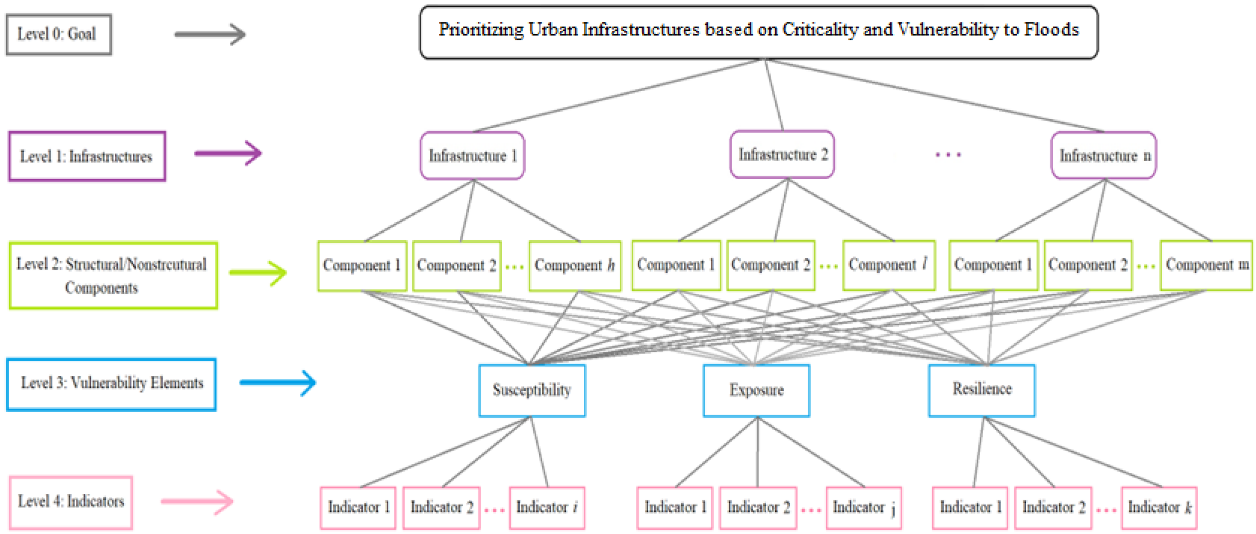

FIGURE 9 The proposed MCDM framework for calculating the criticality values (based on vulnerability to floods).

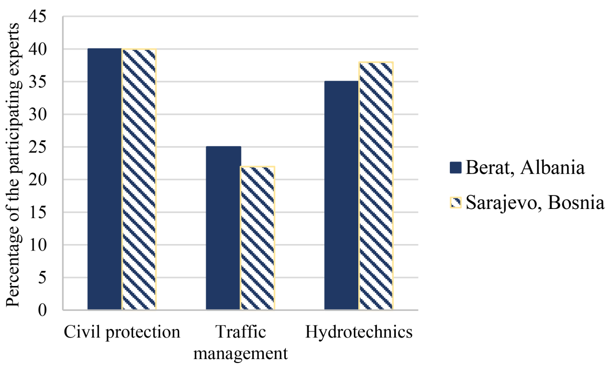

FIGURE 10 Statistics regarding participating experts who filled out the questionnaires, including their primary fields of expertise.

Figure 12 (top). It is obvious from the figure that the total susceptibility curve has been obtained by the summation of three flood-sensitive road components, including road pavement, shoulders/embankment, culverts, and drains. The same procedure was applied to calculating the susceptibility and exposure of the other infrastructures, that is, bridges and schools. Figure 12 (bottom) shows an example of exposure curves for bridges in Sarajevo, Bosnia obtained by the summation of exposure curves calculated considering the bridge functional sub-factors.

Figure 13 represents the fuzzy vulnerability curves calculated for the three studied types of infrastructure, that is, roads, bridges, and schools, in Sarajevo, Bosnia. As shown by the figure, the overall experts' ideas have been almost the same regarding the flood vulnerability of

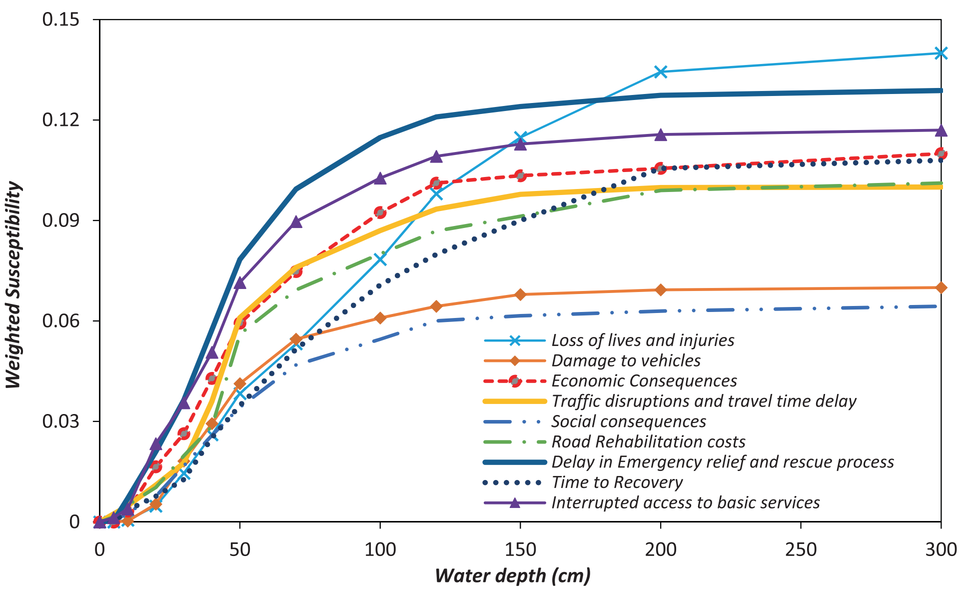

FIGURE 11 Weighted susceptibility curves for each indicator for one single component of the road infrastructure in Sarajevo, Bosnia.

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FIGURE 12 The indicator-based roads susceptibility (above) and bridge exposure (below) curves for Sarajevo, Bosnia.

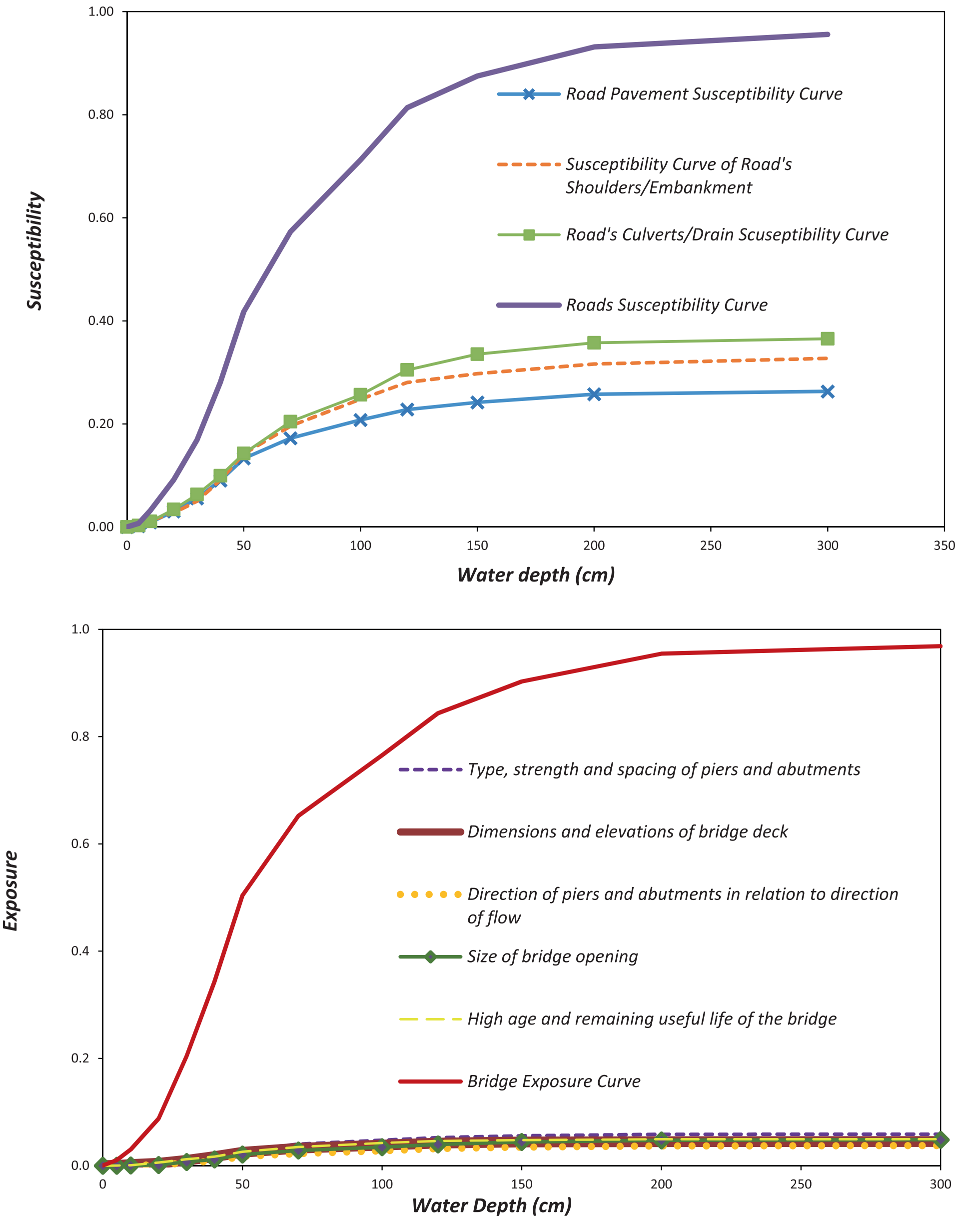

FIGURE 13 Vulnerability curves for roads, bridges (top), and schools (bottom) in Sarajevo, Bosnia.

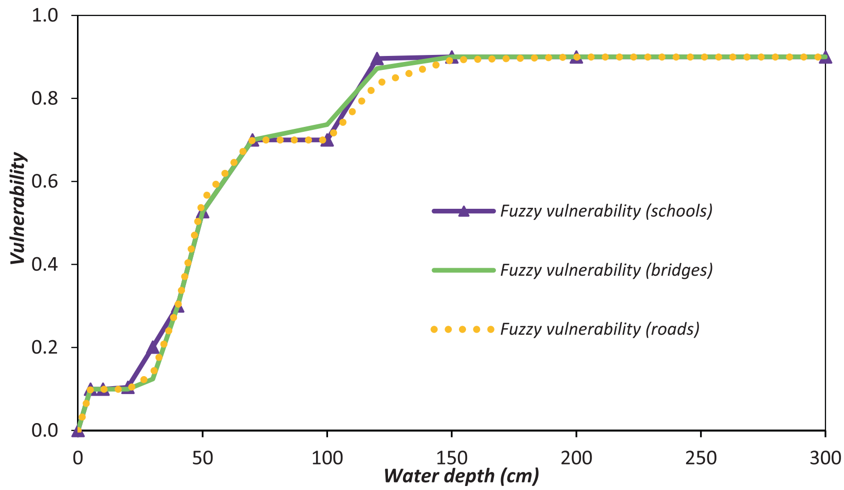

TABLE 4 Qualitative assessment of flood vulnerability for Sarajevo case study.

CI	Water depth (cm) 5	10	20	30	40	50	70	100	120	150	200	300
Schools	Very low	Very low	Very low	Very low	Low	Medium	High	High	Extreme	Extreme	Extreme	Extreme
Bridge	Very low	Very low	Very low	Very low	Low	Medium	High	High	Extreme	Extreme	Extreme	Extreme
Roads	Very low	Very low	Very low	Very low	Low	High	High	High	Extreme	Extreme	Extreme	Extreme

Note: The color shading represents varying levels of velnerability of the CIs to floods at different water depths. Green represents very low vulnerbility, yellow highlights low vulnerbility, orange indicates high vulnerability, and red signifies extreme vulnerability to flooding.
Abbreviation: CI, critical infrastructures.

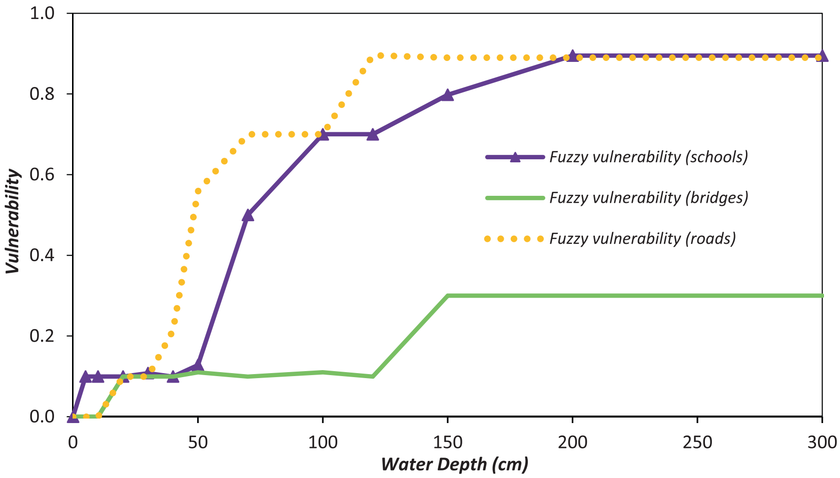

FIGURE 14 Fuzzy vulnerability curves for roads, bridges, and schools in Berat, Albania.

all the three infrastructures. Accordingly, Table 4 shows the qualitative interpretation of the vulnerability curves for roads, bridges, and schools in Sarajevo. According to this table, flood depths up to 30 cm are not a threat to these three infrastructures since they pose a "*very low*" vulnerability to such CIs. This is while flood depths equal and greater than 120 cm, would bring an "*extreme*" vulnerability to these infrastructures according to the vulnerability of each structural/nonstructural element and indicators related to their exposure and susceptibility. While such findings from the current study and similar ones can provide valuable insight for city planners and emergency responders in managing urban infrastructures based on varying floodwater depths, it is crucial to conduct investigation from a detailed technical, hydrological, and hydraulic perspective at each specific site where individual infrastructure are situated to ensure accurate and tailored infrastructure planning. For instance, the vulnerability level may vary between different bridges, this is while the result of the current study is a combination of the findings for several bridges located in the study site.

For flood depths equal to 50 cm, bridges and schools experience a "medium" vulnerability, while the same water depth is considered a serious threat for road infrastructure since it implies a "high" vulnerability. One possible reason for this could be attributed to the fact that a school requires a higher inundation level to collapse in comparison to a road, where a mere 50 cm of water height can lead to the overturning of vehicles. It should be noted that these findings stem from considering a wide range of susceptibility and exposure factors evaluated based on the experts' opinions according to their knowledge of the study site and the distinctions in the infrastructure conditions in that specific area (as can be seen in the subsequent sections discussion, the results for the first study site (i.e., Sarajevo) diverge from the case of Berta, Albania).

The same procedure was applied for the other case study, that is, the city of Berat in Albania, and the vulnerability curves were obtained for the three investigated infrastructures (as shown in Figure 14). As can be seen in the picture, according to the experts' knowledge and ideas, among the three given infrastructures, the highest level of vulnerability to floods in Berta is dedicated to roads, while bridges are evaluated to have the lowest level of flood vulnerability. Besides, the qualitative assessment of flood vulnerability (Table 5) indicates that the roads vulnerability to floods in Berat is so similar to Sarajevo in Bosnia. However, for bridges, the flood vulnerability has been assessed to be either "low" or "very low." For schools, up to a water level equal to 50 cm, the flood

TABLE 5 Qualitative assessment of flood vulnerability for the Berat case study.

CI	Water depth (cm)											
	5	10	20	30	40	50	70	100	120	150	200	300
Schools	Very low	Very low	Very low	Very low	Very low	Very low	Medium	High	High	Extreme	Extreme	Extreme
Bridge	0	0	Very low	Very low	Very low	Very low	Very low	Very low	Very low	Low	Low	Low
Roads	0	0	Very low	Very low	Low	High	High	High	Extreme	Extreme	Extreme	Extreme

Note: The color shading represents varying levels of velnerability of the CIs to floods at different water depths. Green represents very low vulnerbility, yellow highlights low vulnerbility, orange indicates high vulnerability, and red signifies extreme vulnerbility to flooding.
Abbreviation: CI, critical infrastructures.

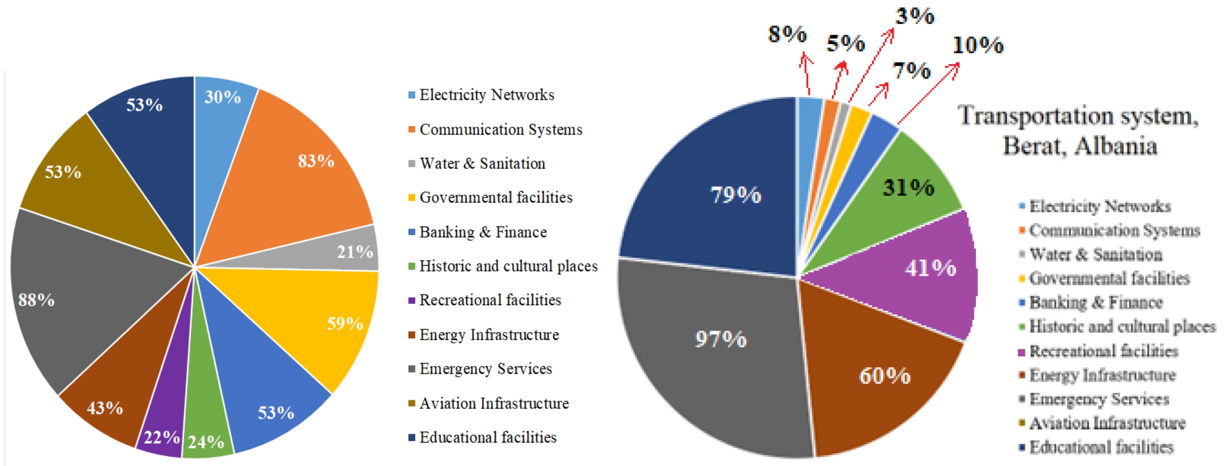

FIGURE 15 The fraction of impact level of transportation system on the rest of critical infrastructures.

vulnerability is negligible, but starting from the depth of 70 cm the schools' vulnerability would be significant and considerable.

According to the final obtained vulnerability curves for the Sarajevo case study and some additional calculations, it turned out that all three investigated infrastructures have nearly the same level of vulnerability to floods. However, it can be said that "schools" have the highest rate of flood vulnerability compared to the transportation system in Sarajevo, even though the difference in criticality of the three CIs is not that significant. This finding generally suggests the need for the same level of preparedness, prevention, and mitigation measures for the three infrastructures in this site, however, as emphasized previously, such results are an overview of the entire region, including all schools, bridges, and road segments within the area, whose vulnerability levels could be different from each other. Thus, each one needs to be examined individually from a hydraulic, structural, and geotechnical perspective in the next studies with similar concerns to be able to develop a tailored plan specific to each single infrastructure in the region.

Figure 15 indicates the level of impact that the transportation system (while inundated or damaged due to flooding) may have on the functionality of the rest of CIs, even if they are not flooded directly. The results were obtained by averaging all the experts' ideas for both Sarajevo and Berat case studies. According to the results, it is estimated that a failure in transportation system due to flooding may result in the functionality reduction of emergency services the most and have the least impact on the functionality of water and sanitation systems.

Considering the normalized impact values of each infrastructure on the other of CIs and the relative importance of each CIs for the daily functioning of the whole community (based on the experts' ideas), the severity of CI failure was calculated through multiplying the impact value by the assigned weight (i.e., relative importance). The results are represented in Table 6. According to the table, energy infrastructure failure could have the most severe impact on the whole society in the case of Sarajevo, Bosnia, as an example, while the impact severity of the failure of some infrastructures, such as recreational facilities, are considered the lowest of all. Similar

TABLE 6 The overall impact degree of each flooded infrastructure on the whole society (for Sarajevo, Bosnia).

Flooded infrastructure	Normalized impact on the other CIs	Normalized weight (i.e., relative importance)	Severity of impact and consequences on the society
Electricity networks	0.1500	0.0840	0.0130
Transportation system	0.1200	0.0800	0.0100
Communication systems	0.1400	0.0840	0.0120
Water and sanitation	0.1100	0.0910	0.0100
Governmental facilities	0.0700	0.0870	0.0061
Banking and finance	0.0400	0.0750	0.0030
Historic and cultural places	0.0200	0.0790	0.0020
Recreational facilities	0.0100	0.0540	0.0005
Energy infrastructure	0.1800	0.0910	0.0164
Emergency services	0.1000	0.0940	0.0094
Aviation infrastructure	0.0400	0.0930	0.0037
Educational facilities	0.0400	0.0870	0.0035

Abbreviation: CI, critical infrastructures.

calculations and results are applicable to the case of Berat, Albania.

Figure 16 shows the overall impact value (normalized) for each flooded infrastructure may have on the remaining CIs. It is obvious from the figure that, according to the experts' ideas, CIs such as energy infrastructure, electricity networks, and communication systems have the highest impact on the other CIs if damaged due to flooding. On the other hand, damage to recreational facilities and historic and cultural places has been believed to have the lowest effect on the functionality reduction of the other infrastructures.

For the Berat case study, the results are a bit different. As can be seen in Figure 16 (bottom), the experts believe that in Berat, emergency services have the highest impact on the other CIs if being disrupted due to flooding. This is while damage to aviation infrastructure is believed to have the lowest effect on the functionality reduction of the other infrastructures in the region.

From Figure 15 it is obvious that, based on the experts' opinions for the case of Sarajevo, the flooded transportation system can have an impact equivalent to 53% on the educational facilities. On this basis, it could be said that if both schools and roads were flooded in the Sarajevo case study, there would be a relationship similar to the graph represented in Figure 17 (left) between the functional vulnerability of the two infrastructures (considering the increased flood vulnerability of the school due to the flooded roads leading to it). This means that by having the vulnerability curves of one of the CIs, herein the roads in Sarajevo, one can have the vulnerability curve for schools in the same area. An estimated relationship between the vulnerability values of the two infrastructures would be according to Equation (6). This equation was derived by fitting a trendline to the graph in Figure 17 (left graph).

$$\mathrm{Vul}_{\mathrm{S},i\mathrm{R}} = -1.1454(\mathrm{Vul}_{i\mathrm{R}})^2 + 2.1956(\mathrm{Vul}_{i\mathrm{R}}) - 0.0319, \quad (6)$$

where $\mathrm{Vul}_{i\mathrm{R}}$ is the vulnerability of inundated road at the flood depth i and $\mathrm{Vul}_{\mathrm{S},i\mathrm{R}}$ is the vulnerability value of the flooded school while the road leading to it is inundated (with the same flood depth: i). Similar equations are derivable for all connected infrastructures in the studied region.

Figure 17 (right) shows the vulnerability curves for inundated roads, flooded schools, as well as vulnerability

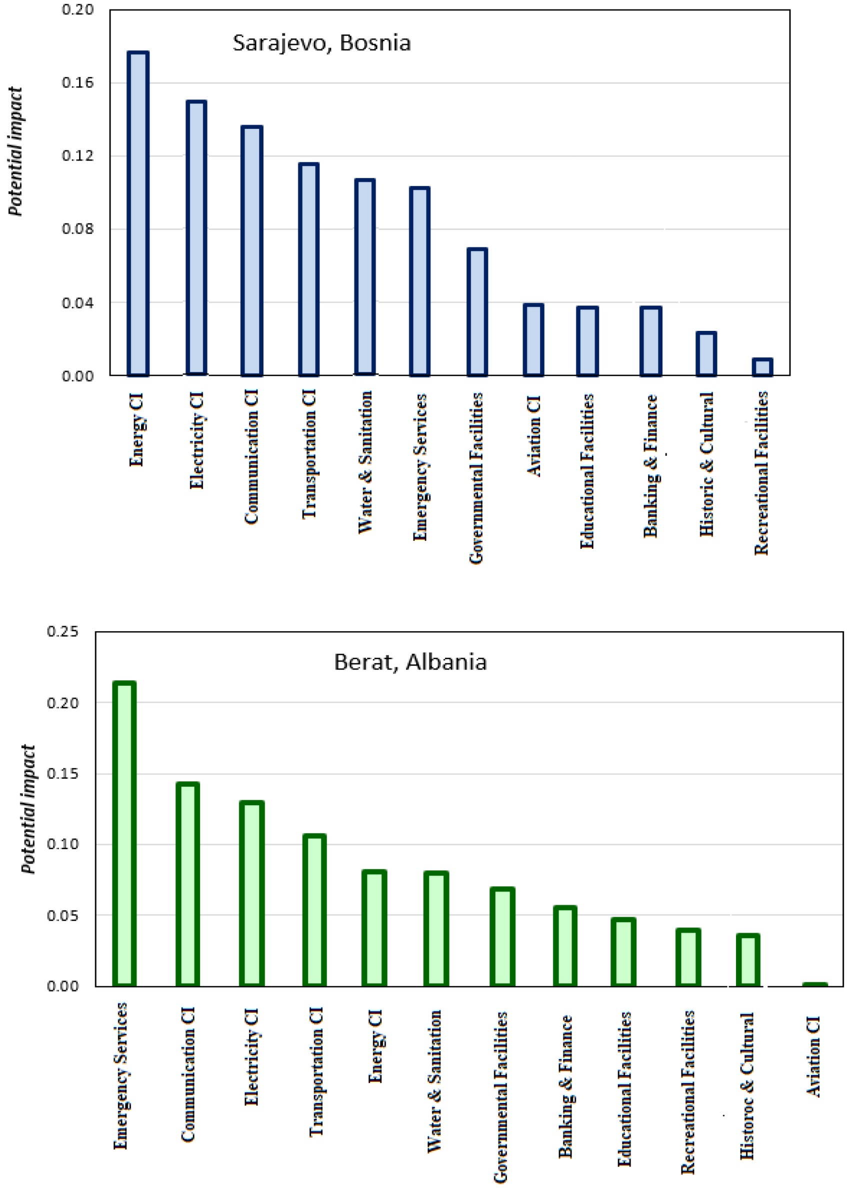

FIGURE 16 Potential impact of each infrastructure on the other critical infrastructures (CIs) for the two case studies.

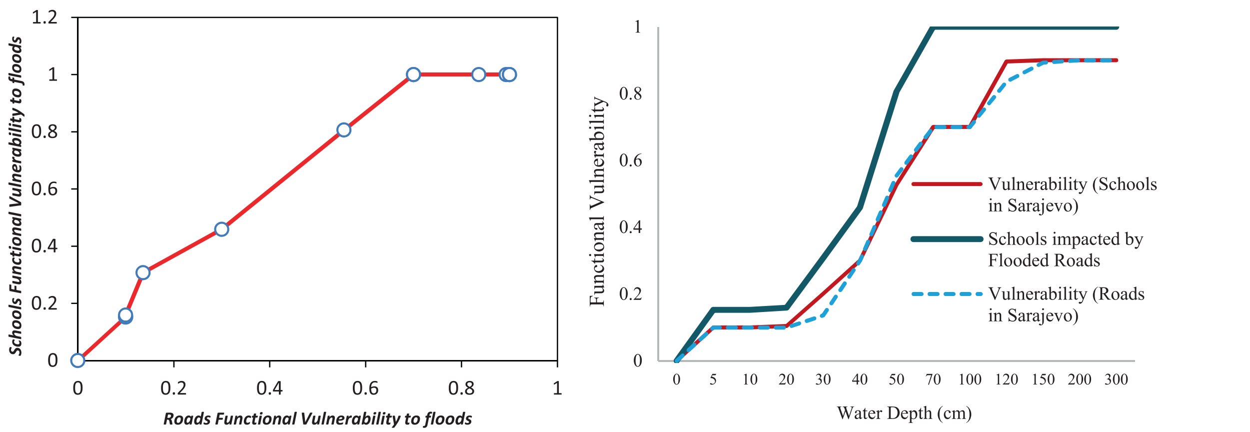

FIGURE 17 Relationship between the functional vulnerability of two exposed infrastructures and the impact on each other (Sarajevo case study).

curves for schools when the roads leading to them are inundated.

3.2 | Prioritizing the CIs based on criticality and vulnerability to floods: Comparison of the two methods

Table 7 represents the averaged normalized vulnerability values for the three studied infrastructures in Barat and Sarajevo using the methodology based on synthetic vulnerability curves. According to the table, it is possible to conclude that, for the Sarajevo case study, the most vulnerable CIs—among the studied ones—are firstly schools, then bridges, and finally roads. Regarding the Berat case study, roads are the most critical ones, followed by schools and finally bridges. It is observed that the estimated prioritized infrastructures with respect to flood hazard are different for the two case studies using the first proposed method, even though their vulnerability values are approximating each other.

Table 8 represents the CI rankings based on the MCDM methodology, based on which bridges and roads are the most and least vulnerable infrastructures (among the studied ones) for the case of Sarajevo, and roads and schools are estimated to be ranked the highest and lowest for the case of Berat, respectively.

By comparing the results represented in Tables 7 and 8, it is possible to understand how the findings by the two methods (MCDM and vulnerability curves) are not identical, even though there are similarities. Both methods introduced the "roads" as the most critical infrastructure of all in Berat case study, while the second and third rank infrastructures are represented differently by the two methods. For the case of Sarajevo, "roads" are estimated to be the least vulnerable of all considered CIs by both methods; however, the first and second ranks are differently estimated. For both methods, the final flood vulnerability values of the three CIs are very close to each other, and thus, the difference in the results by the two methods is justified this way. In addition, not a big difference can be emphasized for the flood vulnerability of the three studied CIs.

The slight disparity in results arises from the fundamental differences between the two methods. The first method employs a fuzzy approach, whereas the second method predominantly relies on MCDM, calculating results through a linear combination of indicators and their weights. Despite these methodological distinctions, the variation in results between the two methods is not substantial, even though prioritizations could differ when accounting for the minor differences in calculated scores. In addition, the slight difference in the results by the two methods may be due to the fact that in the current study, only three types of infrastructures were investigated (of which two are considered of the same type, which is transportation system); this is while the prioritization and ranking order may be more precise and reliable if more CIs are included in the analysis. The other reason may be the fact that there could be various ways to calculate the final vulnerability values in the methodologies based on MCDM. Herein, the final vulnerability was obtained through averaging the assigned values (of exposure and susceptibility) for various water depths regarding each sub-indicator, while in the other MCDM-based methods, a linear combination of factors through assigning one specific value to each factor may be considered. All in all, this comparison can give an insight for future studies and developing more detailed methodologies in this regard, considering more infrastructures to be prioritized from a flood vulnerability point of view.

TABLE 7 The infrastructures ranking using the fuzzy vulnerability curve method based on the experts' ideas.

Case study	Sarajevo			Berat		
CI	**Roads**	**Bridges**	**Schools**	**Roads**	**Bridges**	**Schools**
Normalized vulnerability	0.518	0.522	0.527	0.495	0.135	0.427
CI criticality ranking	Third	Second	First	First	Third	Second

Abbreviation: CI, critical infrastructures.

TABLE 8 The infrastructures ranking using MCDM method based on the experts' ideas.

Case study	Sarajevo			Berat		
CI	**Roads**	**Bridges**	**Schools**	**Roads**	**Bridges**	**Schools**
Normalized vulnerability	0.306	0.359	0.336	0.469	0.281	0.250
CI criticality ranking	Third	First	Second	First	Second	Third

Abbreviation: CI, critical infrastructures.

4 | CONCLUSIONS

The main contribution of this study is in terms of quantifying the vulnerability of CIs and investigating how functionality reductions in one may impact others. In this work, two methodologies (including a crisscross analysis using MATLAB Fuzzy Logic Toolbox and a MCDM-based approach) were introduced and compared to each other for infrastructures' criticality ranking against riverine flooding. The methods are based on the study, which provides a thorough assessment of flood vulnerability across three types of infrastructures (i.e., schools, roads, and bridges) in the two case studies and concludes that almost all three infrastructures could be vulnerable to flooding when water depths reach 50 cm or more. As various infrastructures can have secondary impacts and profound interdependencies, even with an exposure equal to zero for a specific CI, urban managers should still consider a level of vulnerability for that infrastructure (based on the vulnerability level of other influencing infrastructures, as detailed in Figure 17) and devise anticipated investment and mitigation strategies.

The results outlined in this paper provide a framework for the classification of CIs from the perspective of functional vulnerability to flooding. Despite many limitations in gathering reliable data and finding the knowledgeable experts who are familiar with both the flood risk of CIs and the studied region, the final results can provide the urban managers with some predictions on the level of vulnerability that each CI may suffer during various depths of flooding. Besides, the outputs of this study can be used to develop scenarios for planning and exercises in flood risk management strategies in the studied region. Based on the findings of this study, in the city of Sarajevo, Bosnia, all three investigated infrastructures require attention for the implementation of mitigation strategies. However, schools and bridges hold a higher priority, to some extent. In the city of Berat, Albania, roads take precedence, followed by schools, as areas of focus for vulnerability reduction strategies. However, as emphasized in the results section, it is essential to note that the findings of this study are based on the expert opinions considering a combination of all available infrastructures of each type in the region, rather than individual examinations. Further studies need to address geological, hydrological, and hydraulic aspects of these two sites to obtain more accurate results before practical implementation. For instance, even a 20–30 cm floodwater level can pose significant issues in certain cases, justifying specific attention for some schools, bridges, or road segments.

The crisscross analysis (i.e., the analysis using exposure–susceptibility matrix) for vulnerability classification alongside using fuzzy methods for evaluating the data allows for covering the possible uncertainty involved, especially in gathering information through running the survey forms in the region using the experts' ideas and estimations.

Although there are similarities in the determination of the most CIs by the two methods, the highest ranked CIs are not exactly the same. For the present study, such differences lack substantial significance given that the final calculated indicators frequently approximate each other closely. Furthermore, the study examined only a limited set of infrastructure types as examples. Nevertheless, variations in the results in certain cases emphasize the need for additional comparative studies that employ diverse methodologies for prioritizing criticality across various infrastructure types and in the face of different natural hazards. This helps invest more professionally and give priority to those infrastructures that are not only the most important ones for serving society, both in normal situation and in the recovery process after disasters, but also have the potential to influence the functionality of other infrastructures connecting to them in some way.

While the results of this study are customized to the specific conditions of the study sites and their infrastructure, the proposed methodology is applicable to all regions with flowing rivers. This adaptability enables it to serve as a swift and primary assessment tool for targeted investments in infrastructure assets within the region, particularly in the context of fluvial flood risk.

Even though this study considered the resilience-related factors within the questionnaire and gathered the experts' estimations on that, the final vulnerability curves were derived without factoring in the resilience modulator, as adaptive measures were not significantly implemented at the study sites. However, the data collected by the experts effectively represents the impact of incorporating adaptive measures in reducing flood vulnerability in the studied areas, underscoring the significance of resilience-oriented approach in flood risk reduction strategies. Hence, the inclusion of such adaptive approaches is strongly recommended for the study sites.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Most data analyzed during this study are included in this article; and the rest of data (regarding the experts' ideas collected by questionnaire) and the performed analysis that support the findings of this study are available from the corresponding author upon request.

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ENDNOTES

[1] One IPA DRAM PRogramme—The program for Disaster Risk Assessment and Mapping in Western Balkans and Turkey (http://www.ipadram.eu/).

[2] PRONEWS—Program for Improving National Early Warning System and Flood Prevention in Albania (http://www.pronewsprogramme.eu/).

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