



District based flood risk assessment in Istanbul using fuzzy analytical hierarchy process

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Abstract

Floods, among the most frequent and severe hazards in the world, threaten the sustainability of the built environment by causing immense damage to infrastructures, buildings, economies, social activities and beyond all, cause loss of lives. Istanbul is the most densely populated industrial, commercial and cultural center of Turkey. Besides, the population of Istanbul has increased over the last decade since the city attracts immigrants from all over Turkey, along with other countries. Therefore, it is vital to prioritize the districts of Istanbul by determining flood risk mitigation strategies since flood risk management is carried out at district level units in local municipalities in Istanbul. In this study, a new hierarchical procedure that consists of thirteen flood vulnerability and hazard criteria is proposed for the generation of Istanbul's district-based flood risk map. To obtain the criteria weights the fuzzy analytical hierarchy process (AHP) was adopted. The sensitivity analysis conducted in this study reveals the stability and robustness of the proposed fuzzy AHP model. Among all the criteria, land use and the return period of a storm event were found as the most significant criteria for vulnerability and hazard clusters, respectively. Criteria weights calculated through the fuzzy AHP method were integrated with the data taken from various institutions with respect to each district to calculate risk scores of the districts. Consequently, district risk scores were used to generate a flood risk map of Istanbul. The findings show that high-risk districts are mainly at the center and highly populated areas of the city. Moreover, the accuracy of the proposed approach was validated through observations of the significant flood events experienced in the last two decades. Thus, the fuzzy AHP method can be considered as advantageous to make a quick and regional flood risk assessment. In addition, the proposed approach is useful to mitigate flood risk along with allocating a fair budget to the local municipalities for flood risk mitigation measures. The findings of this research could also provide useful procedures for professionals of the water resources and local authorities.

Keywords Flood risk mapping · Fuzzy analytical hierarchy process · Istanbul · District prioritization · Vulnerability and hazard · Sensitivity analysis

1 Introduction

Floods cause massive economic losses, failures in infrastructures, disruption in social activities, and beyond all, they result in serious casualties. The increase is estimated in the frequency of floods with the adverse impacts of

climate and land-use changes (Salman and Li 2018). Despite numerous studies in flood prevention and risk mitigation from various locations and perspectives, extreme flooding still damages cities, thus threatening the sustainability of the built environment (Felsenstein and Lichter 2014).

In a general sense, natural and meteorological factors are considered to be effective in flood hazards; however, the effects of anthropogenic factors on the occurrence and the severity of floods are non-negligible. In other words, although floods are natural hazards, they can be prevented from becoming disasters (Bertilsson et al. 2019) by resilient social, economic and political infrastructures. In

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addition, many geomorphological parameters such as the total drainage area, average slope, shape of the basin, soil structure and infiltration capacity could play a vital role in the formation of floods. Therefore, it is of paramount significance to evaluate potential damages of floods (Ozger 2015), by considering both qualitative (Perrone et al. 2020; De et al. 2020) and quantitative (Tariq 2013; Tehrany et al. 2015; Stoleriu et al. 2020) manners. Hence, the research society commonly use the multi-criteria decision-making (MCDM) tools to deal with not only the qualitative but also the quantitative data sources (Hammond et al. 2015). The AHP has been presented as a combination of qualitative and quantitative approaches, and it is based on the principle of melting tangible and intangible attributes in the same pot (Wedley 1990). The fuzzy AHP method was particularly adopted in this study since (i) hierarchical representation of the problem could aid decision-makers to understand the context of the problem easily (Tehrany et al. 2015), (ii) reliability of the experts could be controlled through consistency analysis (Yang et al. 2013), (iii) integration of the fuzzy set theory could be useful to consider inherent fuzziness in the flood risk management (FRM) applications (Büyüközkan and Feyzioğlu 2004), (iv) it is suitable for group decision-making analysis with a small sample size and it could provide meaningful and reliable results (Darko et al. 2019). These features of the fuzzy AHP approach highlight the significance of the method compared to other MCDM tools.

In Turkey, 1209 floods have taken place in total between 1975 and 2015, resulting in a death toll of 720 people and 900,000 ha submerged areas. In addition, floods have caused an average of \$100 million economic losses yearly (Ministry of Agriculture and Forestry 2017). Istanbul is the most densely populated city in Turkey with nearly 16 million residents (2986 people/km²), and it is at serious risk of flooding (Turkish Statistical Institute 2019). The flood event in the Marmara region in 2009 led to serious casualties (at least 31 people) and economic losses, particularly in Istanbul, Ayamama basin, and as a result intensified studies were conducted in the region (Gülbaz et al. 2019; Altunkaynak and Bizimana 2020). Thus, these devastating natural events brought forth the pre-flood studies such as flood mapping to be carried out in the region.

Studies about flood risk maps have been generated in almost every country; however, most of them are still limited to a spatial basis. In Europe, only 14 countries have flood risk maps covering all areas within their borders, while other countries have maps of limited territories (Moel et al. 2009). Even so, studies over the previous decades have provided significant information on flood mapping and contributed to the flood risk management literature. Also, several researchers have attempted to integrate the GIS tools with the AHP and fuzzy AHP

methods to produce flood risk maps (Wang et al. 2011; Aher et al. 2013; Stefanidis and Stathis 2013; Papaioannou et al. 2015; Dahri and Abida 2017; Hammami et al. 2019; Meshram et al. 2019; Souissi et al. 2019; Sepehri et al. 2020). However, in the past literature: (i) the criteria included for flood risk maps did not cover some of the critical vulnerability indicators, (ii) clarification of the expert demographics has been overlooked even though generated maps highly relied on the judgments of the experts, (iii) consistency ratio (CR) to ensure the survey instrument reliability, which has been considered as one of the most powerful attributes of the AHP (Darko et al. 2019), remained to be addressed, and iv) sensitivity analysis based on the fuzziness degree has not been considered, yet it can be used to ensure the stability of the developed models (Ishizaka and Labib 2011). Therefore, to fill these gaps, the cornerstone of this research is to prioritize districts of Istanbul in the sense of flood risk, by considering both vulnerability and hazard clusters, and covering all the requirements of the fuzzy AHP method. The specific objectives of this study can be summarised as follows:

- Determination of vulnerability and hazard criteria that are appropriate to develop a district-based flood risk map in Istanbul,
- Collection of data related to the criteria on a district basis from either external sources or related institutions,
- Performing the fuzzy AHP method to calculate weights of criteria,
- Developing a flood risk map of Istanbul through integrating collected data with the results of the fuzzy AHP analysis,
- Validating the proposed approach by comparing the risk scores of each district with the past flood events.

Since there has been no comprehensive assessment made for Istanbul yet, the findings of this research can be used by the water resource authorities, disaster management institutions and governmental authorities to mitigate the flood risk along with allocating a fair budget to the local municipalities for flood risk mitigation measures.

2 Studies on flood risk mapping

Recently, different perspectives have gained significance for making preliminary plans for floods and the predictability of floods has become increasingly difficult because of the alteration on atmospheric processes that are related to climate change. One of these preliminary approaches, which has increased the interest of researchers in recent years, is flood mapping. There are a variety of maps generated regarding floods such as flood depth maps, flood propagation maps, flood hazard maps, flood duration

maps, the rate of rising of the water, flood vulnerability, and eventually flood risk maps. The flood risk maps differ from others with their non-homogeneous features since they are obtained by combining vulnerability and hazard clusters. Therefore, such research direction received attention from a variety of researchers by adopting different approaches such as hydro-geomorphological (Bourenane et al. 2019), statistical (Liu et al. 2016; Pham et al. 2020), statistical-hydrological (Le et al. 2019), numerical (Li et al. 2017) and hydraulic-hydrological (Papaioannou et al. 2016). However, since some of the abovementioned methods mainly based on meteorological factors or hydraulic-hydrological calculations, MCDM approaches have been adopted in recent years to further expand the practical implications of the studies to evaluate the flood risk in various research areas such as transportation systems (Lyu et al. 2019), protected areas (Wang 2015; Hategekimana et al. 2018), urban areas (Li et al. 2013) and watersheds (Zou et al. 2013), which became the greatest research focus.

A few of the similar studies using MCDM methods for flood mapping are provided in Table 1. Wang et al. (2011) integrated the GIS tools and the fuzzy AHP method through the spatial MCDM approach. They determined flood risk criteria using the Delphi method for the Dongting Lake region and assessed the flood risk with a stepwise questionnaire by reducing the criteria to a practicable number. As a result, by categorizing the study area into five risk categories, they found the extent of flood risk for each zone. In another study, in which the weights of flood vulnerability and hazard criteria were also specified by using the fuzzy AHP method, Zou et al. (2013) obtained the grades by means of the combination of the set pair analysis (SPA) and the variable pair fuzzy sets (VFS). They have developed a comprehensive method as an alternative to the conventional VFS, which can be used not only for flood hazards but also for other natural hazards. Yang et al. (2013) performed a fuzzy AHP analysis and found that rainstorm and population density were the most significant sub-criteria according to the triggering and vulnerability main criteria, respectively. Papaioannou et al. (2015) compared the two MCDM approaches, i.e. the AHP and the fuzzy AHP, for the flood risk assessment of Xerios Basin, Greece, which was an inundation area. They aimed to find potential flood-prone areas, and the established model has been validated with the flood occurred in 2006. Wu et al. (2017) determined the criteria weights with the AHP and investigated the flood risk variations. By integrating GIS data sources with MCDM algorithms, Das (2018) used the AHP to evaluate criteria weights and categorized flood-prone areas. They found that nearly 20% of the Vaitarna basin, India, is highly prone to the floods. Hategekimana et al. (2018) created a flood hazard index map with the

fuzzy AHP technique for a data-limited region in Kenya and highlighted the high flood risk of the UNESCO World Heritage. Tang et al. (2018) proposed a local MCDM method to evaluate flood susceptibility by incorporating the uncertainty into a local weighted linear combination. Meshram et al. (2019) used remote sensing integrated AHP/ fuzzy AHP tools to identify the most critical sub-basins of two watersheds in India. 14 morphometric parameters were considered and a comprehensive matrix has been presented regarding these parameters. They determined the priority weights by using both the AHP and fuzzy AHP and conducted the evaluations by dividing potentially vulnerable zones into five different priority types.

Furthermore, there were also the official attempts to prepare flood risk maps for Istanbul and flood hazard maps were produced for both the European and Asian sides by Istanbul Metropolitan Municipality (IBB) as a part of the microzonation studies. In the generation of these maps, extreme precipitation, topography, drainage system, dam reservoir volumes and past flooding data were utilized (IBB 2009). A possible dam failure was considered as a cause of earthquakes and tsunamis. Analyses were performed for the 10m×10m grids. The Water and Energy transfer Process (WEP) model developed by Japan Public Works Research Institute was used to conduct numerical calculations (Jia et al. 2001). Thus, potential flood risk zones were determined by calculating the excessive water flooding amount for each grid. Another attempt for developing a flood hazard map of Istanbul was performed by Yalçın (2012). The researcher used the AHP method to calculate relative weights of six criteria as flow, elevation, slope, drainage density, aspect, and basin size, and then developed a flood hazard map of the European side of Istanbul. We generated the flood risk map of the entire Istanbul considering both vulnerability and hazard criteria as an initial attempt in this study. All the past efforts, either related to Istanbul or other parts of the world, provided valuable information for further development of flood risk maps of Istanbul city.

3 Study area and data

In this study, the Istanbul metropolitan city located in the northwest part of Turkey, was focused. The city ascends between the Black Sea and the Marmara Sea, with the Bosphorus in the middle dividing two continents, Europe and Asia (Fig. 1). The surface area of the Istanbul is 5461 km² in total and the city consists of 39 districts, 14 of which are located on the Asian and 25 on the European parts. Besides, 65% and 35% of the residents live in the European and Asian sides, respectively.

Table 1 Summary of the similar multi-criteria decision making (MCDM) studies

Reference	Study Area	Country	Area (km ²)	Main clusters	N of criteria	Adopted method(s)	Number of experts	Expert profile	Consistency
Wang et al. (2011)	The Dongting Lake Region	China	N/A	Hazard and vulnerability	10	FAHP	10	From universities	N/A
Aher et al. (2013)	Pimpalgaon Ujjaini Watershed	India	30.1	Morphometric	9	FAHP	N/A	N/A	N/A
Stefanidis and Stathis (2013)	Kassandra Peninsula	Greece	365	Hazard and anthropogenic	10	AHP	N/A	N/A	Consistent
Yang et al. (2013)	Yangtze River section	China	N/A	Hazard and vulnerability	16	AHP/FAHP	N/A	N/A	N/A
Zou et al. (2013)	Jingjiang district	China	921	Hazard and vulnerability	13	FAHP	6	All familiar to the area	All consistent
Papaioannou (2015)	Xerias basin	Greece	120	Hazard	10	AHP/FAHP	9	All from hydrology	Consistent
Dahri and Abida (2017)	Gabes basin	Tunisia	95	Hazard	6	AHP/MCAHP	8	N/A	Consistent
Gigović et al. (2017)	Palilula Municipality	Serbia	71	Hazard	6	AHP/FAHP/IRAHP	10	Experienced	All consistent
Das (2018)	Vaitarna basin	India	3795	Hazard	9	AHP	N/A	N/A	Consistent
Hategekimana et al. (2018)	Mombasa county	Kenya	219	Hazard	6	FAHP	N/A	N/A	Consistent
Hammami et al. (2019)	North-east of Tunisia	Tunisia	524.4	Hazard	8	AHP	N/A	N/A	Consistent
Meshram et al. (2019)	Manot and Mohgaon watersheds	India	8862	Morphometric	14	AHP/FAHP	N/A	N/A	N/A
Souissi et al. (2019)	Gabes region	Tunisia	N/A	Hazard	8	AHP	N/A	N/A	Consistent
Meshram et al. (2020)	Bamhani and Mohgaon watersheds	India	6520	Morphometric	14	SAW and TOPSIS	N/A	N/A	Not required
Sepehri et al. (2020)	The Ilanlu Watershed	Iran	15	Hazard	6	IRAHP	6	N/A	All consistent
This study	Istanbul city	Turkey	5461	Hazard and vulnerability	13	FAHP	14	Diverse stakeholders	All consistent

AHP Analytical hierarchy process, *FAHP* Fuzzy analytical hierarchy process, *IRAHP* Interval rough analytical hierarchy process, *MCAHP* Monte carlo aided analytical hierarchy process, *SAW* Simple additive weighting, *TOPSIS* Technique for order of preference by similarity to ideal solution

N/A indicates that the data was not found in the corresponding studies

The highest point of the city is Aydos Hill with a height of 537 m, located on the Asian part. The surface area of forest lands in Istanbul is 535,250 ha. However, the distribution of the forests in the city is irregular since the city has the feature of being a metropolitan area. As the city grows, the forests have remained as urban groves. The climate of Istanbul is mild, while the summers are hot and winters are cold and rainy (Nefeslioglu et al. 2010). The city's annual average temperature is 13.7 °C (MGM 2010). Furthermore, the precipitation occurs in almost each month and annual precipitation of Istanbul is 845 mm in total. In

Istanbul, 38%, 18%, 13%, and 31% of the precipitation take place in winters, springs, summers, and autumns, respectively.

Istanbul is one of the richest cities in Turkey in terms of water resources with nearly 20 dams and regulators, such as the Ömerli, Terkos and Büyükçekmece Dams, located on both sides of the city. An annual yield of 1.6 billion cubic meters is obtained from these dams (ISKI 2020). Besides, related institutions and organizations are in quest for not only the new water resources but also flood

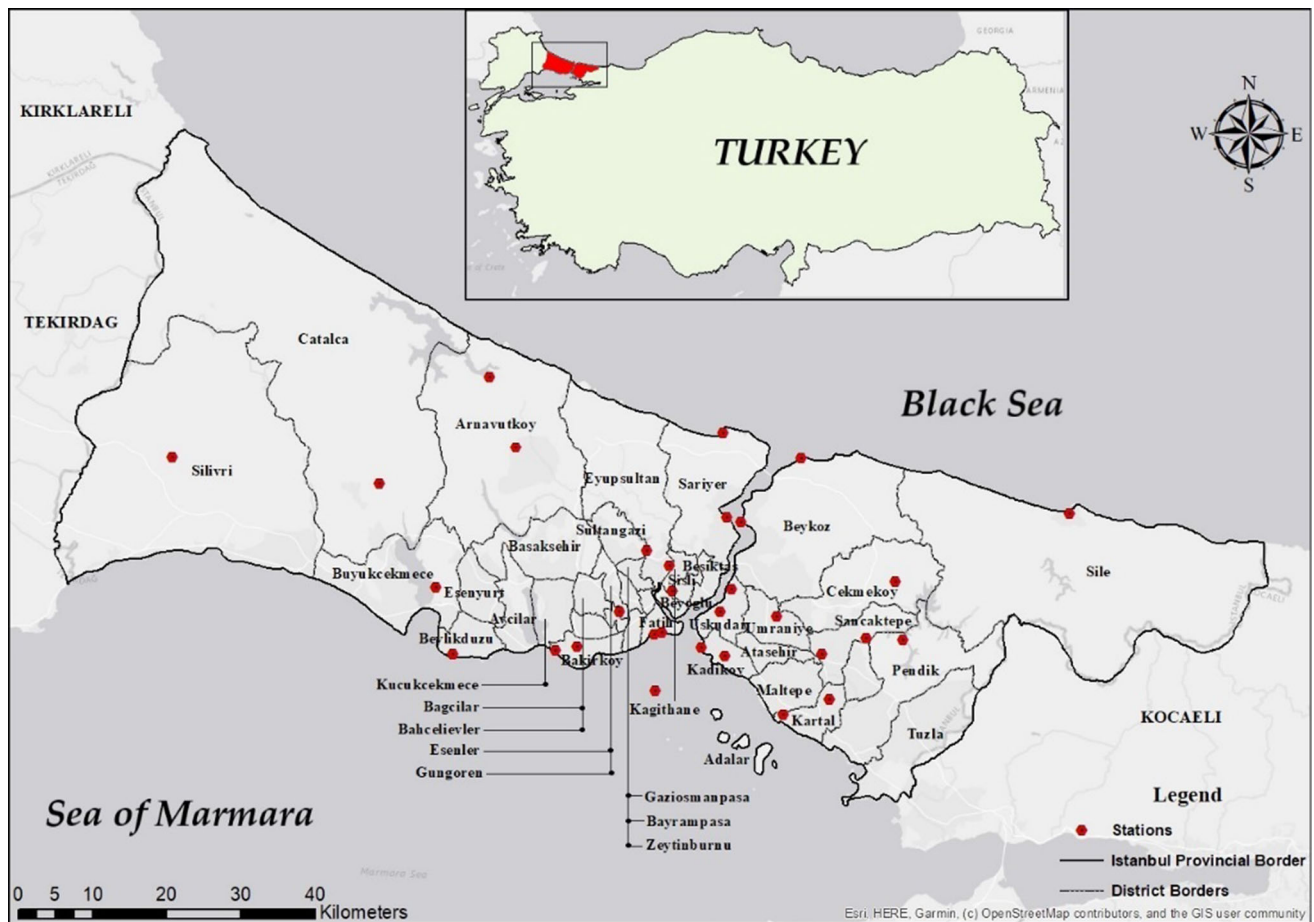


Fig. 1 Study area

prevention strategies due to the increasing population and inevitable urbanization.

As stated in the previous sections, a wide range of criteria including both vulnerability and hazard indicators are required to find the extent of flood risk since the flood risk is a function of both of these elements. In this context, the required criteria have been determined through a literature survey based on the necessities and FRM problems in Istanbul. Then, data availability and accessibility were also taken into account to develop a decision framework. 13 criteria were considered with varying perspectives according to the recommendations of the experts attended to the pilot study. The criteria required to generate a district-based flood risk map of Istanbul are provided in Table 2, with corresponding references, explanations and data sources.

In this study, some significant vulnerability criteria that had been rarely investigated in the past studies were also included. In this context, the structural vulnerability of buildings, education level of residents with respect to flood risk awareness, and the number of households in terms of emergency aid and occupancy were also included in the

proposed model based on recommendations of the pilot study participants (Table 2). The built year of the structures is of critical importance in the assessment of the vulnerability of buildings in the districts since occupants of older buildings could be affected more severely by flood events in terms of economic and social vulnerability (Fedeski and Gwilliam 2007). This criterion becomes even more crucial with respect to a flood risk map of Istanbul as there are significant numbers of old and historical buildings in Istanbul, in addition to the ongoing new construction projects. Also, the inclusion of the level of education criterion enabled the calculation of risk awareness of the people more precisely since it can be considered as a tangible criterion. Moreover, the average number of households could be related to the occupancy of buildings, which is also important in terms of emergency aid for the family members and dwellers inhabit in the same building.

It should also be noted that the way some of the criteria had been planned to be handled was changed by pilot study participants (Table 2). For instance, the return period of a storm event (RP) was recommended by pilot study participants instead of average rain to provide better results. In

Table 2 Flood risk criteria and related data sources

Clusters	Criteria	ID	Reference	Explanation	Data source
Vulnerability (V)	Vulnerable structures (Built year)	VS	Pilot Study	Vulnerability of the structures was included based on the year buildings were built	Konukcu et al. (2017), Ekonomist (2019)
	Population density (N/km ²)	PD	Wang et al. (2011)	Increase in the population density could increase the possible exposed individuals during flood	HGM (2014), Trakyanet (2019)
	Vulnerable population (Age)	VP	Binh et al. (2019)	This criterion considers the vulnerability of the population according to their ages	Trakyanet (2019)
	Education level	EL	Pilot Study	The criterion was included to highlight the level of awareness of the population	Endeksa (2020)
	Income level	IL	Dang et al. (2011)	People with low income could become more vulnerable for post disaster mitigation measures	Endeksa (2020)
	Transportation network (Number of bus stop)	*TN	Zou et al. (2013)	The number of bus stop can refer to the main transportation network so that the emergency aid can access to the exposed area	E-sehir (2020)
	Number of household (Average)	NH	Pilot Study	Increase in the number of households can increase the emergency aid within family	Endeksa (2020)
	Land use	*LU	Dahri and Abida (2017)	Different use of land and properties can be damaged differently during floods	BIMTAS
Hazard (H)	Storm water pipe network (km/built km ²)	*SP	Meshram et al. (2019)	As the length of rainwater pipeline per kilometer increases, the rate of drainage will increase	ISKI
	Slope (%)	SL	Darabi et al. (2019)	Depending on the topography, the increase in the slope will cause an increase in the extent of flooding	USGS (2020)
	Imperviousness (Curve number)	*IM	Papaioannou et al. (2015)	Increase in the curve number is associated with increase in the imperviousness	Jaafar et al. (2019)
	Return period of a storm event (year)	*RP	Wang et al. (2011)	Return periods can be obtained from the intensity-duration curves, and increase in the return period increases the severity of floods	MGM
	Number of rainy days in a year (Average)	NR	Risi et al. (2020)	Increasing the number of rainy days will increase the saturation of the soil moisture, and thus the imperviousness	MGM

ISKI Istanbul Water and Sewerage Administration, MGM Turkish State Meteorological Service, BIMTAS Private company, USGS United States Geological Survey, HGM Turkish General Directorate of Mapping

*The way the corresponding criteria is handled was changed according to the recommendations during pilot studies

addition, the transportation network was also discussed during the pilot study and the participants recommended to use the number of bus stops in each district of Istanbul to estimate the transportation network since the locations of bus stops can be regarded as one of the mobility parameters during floods (Freire et al. 2016).

4 Methodology

In this study, we followed three main steps (Fig. 2). In the preliminary step, flood risk criteria were identified through a literature survey and finessed with pilot studies. The

structure was organized based on two fundamental sources of flood risk, i.e. flood hazard and flood vulnerability. Four groups of experts were selected as target groups: (i) academicians from universities, (ii) professionals from local and metropolitan municipalities, (iii) experts from water and sewerage administrations, and (iv) representatives from disaster management and coordination centers. Pilot studies with four experts, including one expert from each target group, were performed to finesse the predetermined criteria with respect to flood problems in Istanbul. The hierarchic representation of the finessed framework is illustrated in Fig. 3. The AHP hierarchy was structured due to its several advantages in making critical decisions (Yang

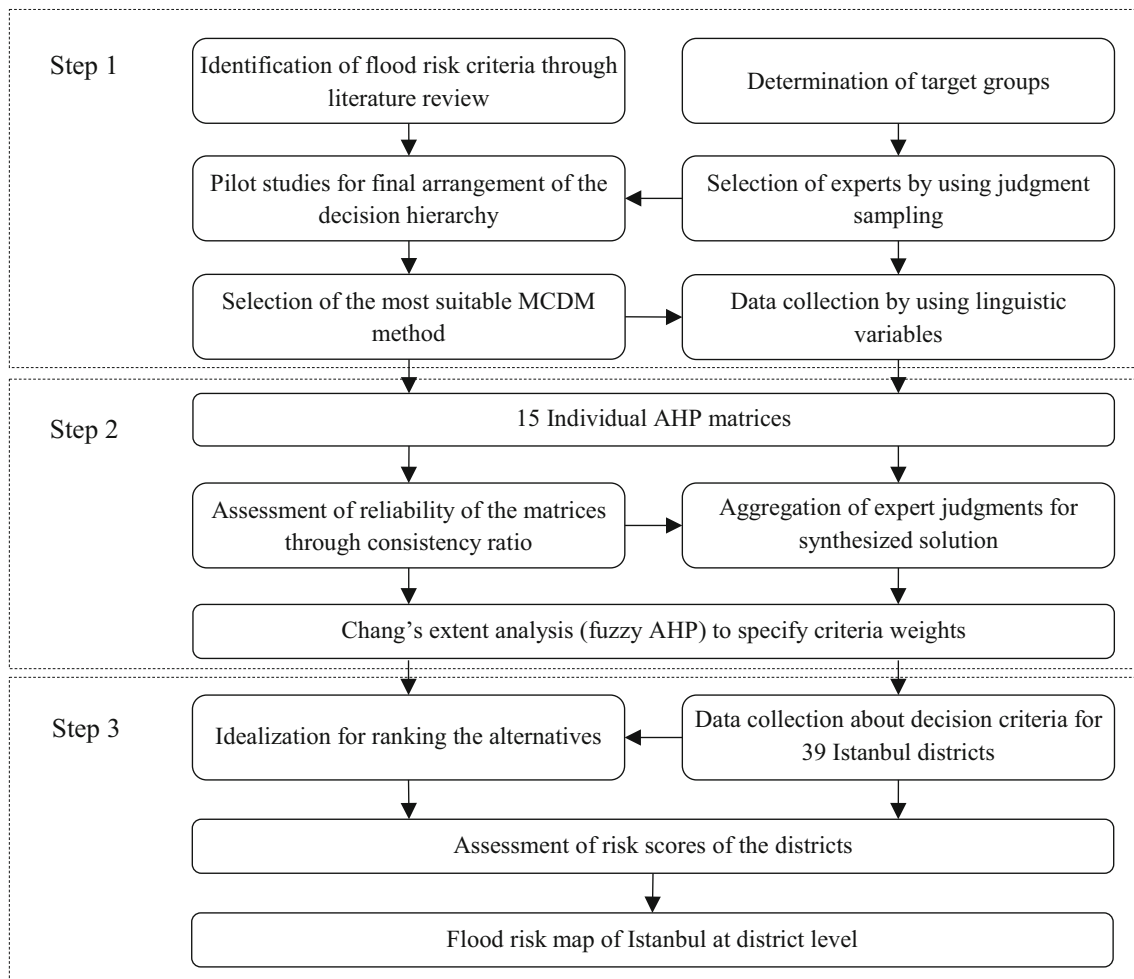


Fig. 2 Flowchart of the study

et al. 2013; Budayan 2019; Darko et al. 2019; Gurgun and Koc 2020). In addition, the AHP is one of the most commonly used MCDM tools in the FRM literature.

Profiles, experiences and professional qualities of the experts attended to the AHP survey are of crucial significance (Darko et al. 2019) since created maps directly related to the data provided by them. Thus, 15 experts, including those who attended to pilot studies, were selected to attend the AHP survey based on purposive sampling technique (Budayan 2019). Past experience of each respondent was deeply examined, and their positions in the FRM practices were taken into account to ensure that their judgments would represent the dynamics of flood risk. Underlying causes of each criterion were explained to the experts during interviews to confirm that the problem at all points was comprehended.

In the second step, the reliability of the experts was checked and 14 of them were found consistent since CR was calculated as less than 0.1 for each of them (Saaty 1990). However, the CR value of one expert was calculated

as significantly higher than 0.1 for nearly half of the criteria groups, for both initial and revised judgments. Thus, the judgments of inconsistent expert was not considered in the following calculations. The profile of the experts attended to the questionnaire survey for consistent judgments is provided in Table 3.

Despite numerous advantages of the AHP method, it does not consider fuzziness and uncertainty; yet judgments of subjective experts obtained by using precise values may result in less reliable outcomes. Thus, various authors criticized traditional AHP method due to its failure to deal with the uncertain nature of the problems precisely (Vahidnia et al. 2009; Yang et al. 2013). Zadeh (1965) has proposed the fuzzy set theory and different fuzzy AHP approaches were developed based on this theory. However, extent analysis (Chang 1996) is one of the most frequently adopted approaches. Therefore, this study employed the fuzzy AHP method to specify the criteria weights. AHP and fuzzy AHP techniques have commonly been adopted for similar purposes to map flood risk zones in the literature

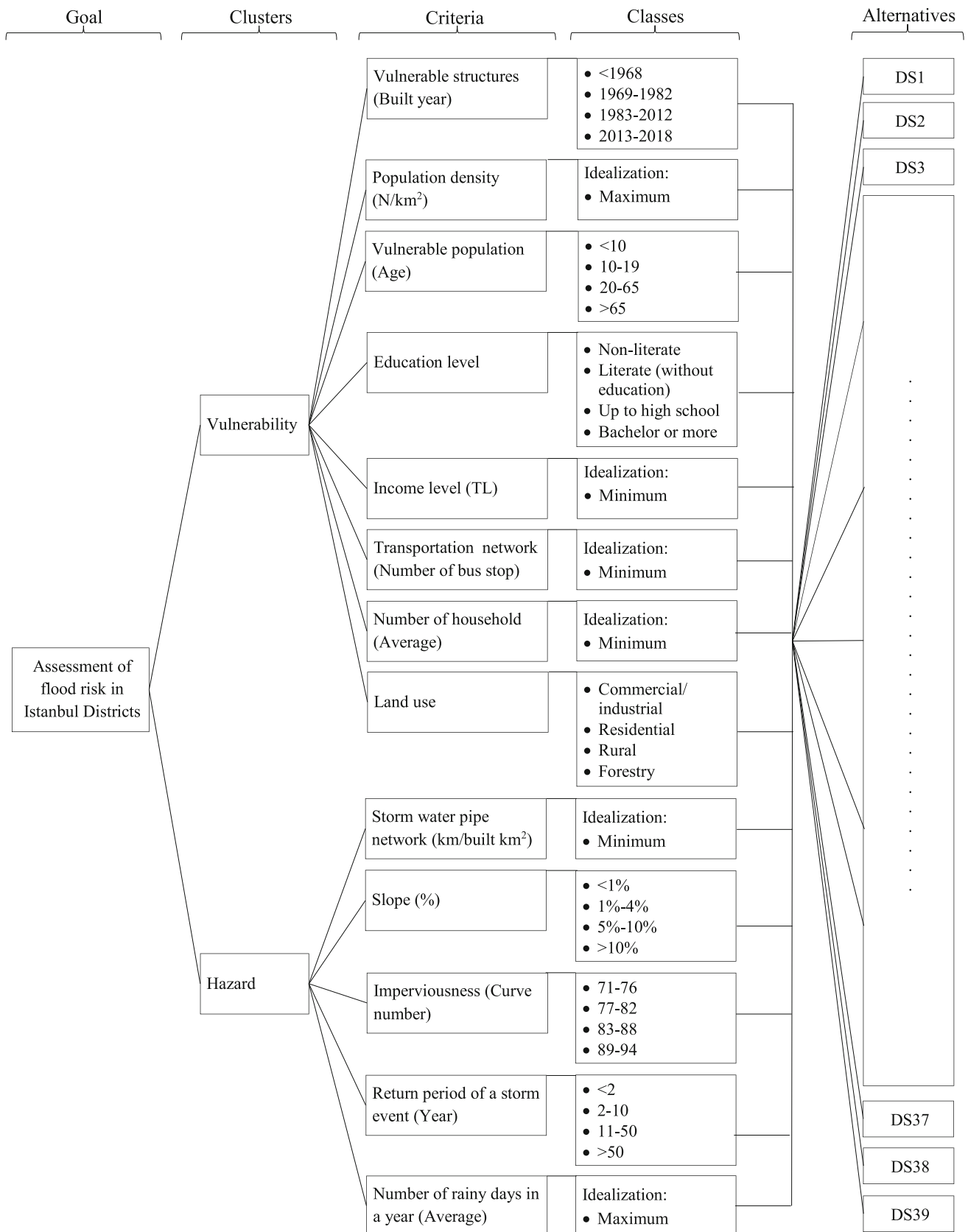


Fig. 3 Hierarchical framework of the study

Table 3 Profile of the experts attended to AHP survey

ID	Role	Sector of the firm	Division	Proficiency	Experience
E1	Auditor	Municipality	Structural engineering	Civil engineer	11
*E2	Professor	University	Hydraulics	Civil engineer	17
*E3	Board advisor	Disaster management and coordination	Meteorology	Meteorological engineer	26
E4	Planning manager	Disaster management and coordination	Planning	Civil engineer	18
E5	Meteorological Engineer	Disaster management and coordination	Meteorology	Meteorological engineer	10
E6	Associate Professor	University	Construction management	Civil engineer	12
E7	Associate Professor	University	Environment	Environmental engineer	13
*E8	Infrastructure manager	Water and sewerage administration	Infrastructure works	Civil engineer	18
E9	Planning engineer	Disaster management and coordination	Planning	Civil engineer	9
E10	Technical office engineer	Water and sewerage administration	Planning	Civil engineer	13
E11	Technical office engineer	Water and sewerage administration	Infrastructure works	Civil engineer	16
E12	Associate Professor	University	Hydraulics	Civil engineer	16
*E13	Project coordinator	Municipality	Infrastructure works	Civil engineer	28
E14	Control engineer	Municipality	Infrastructure works	Civil engineer	17

*Expert attended to pilot study

(Table 1). Therefore, the judgments of 14 consistent experts, who attended to AHP survey in face-to-face interviews, were used to obtain the triangular fuzzy numbers and aggregated to achieve a synthesized solution. Chang’s (1996) extent analysis technique was used to determine criteria weights by considering fuzziness and subjectivity in the judgments of the participants.

In the last step, data about all decision criteria for each district were collected from related institutions (Table 2). Then, idealized weights of the districts for each criterion, and criteria weights calculated from the aggregated fuzzy AHP matrix were integrated to calculate risk scores of the districts. Finally, the risk scores were used to develop a district-based flood risk map of Istanbul. The idealized weights were obtained for each criterion with respect to data for all the districts. It should be noted that the data whose references are expressed in Table 2 are open access and available on the corresponding websites. On the other hand, non-referenced data (BIMTAS, ISKI, and MGM) is confidential and obtained as a result of inter-institutional correspondence.

4.1 Fuzzy analytical hierarchy process (FAHP)

The FAHP technique is adopted for the calculation of criteria weights. There are five main steps in the application of the FAHP method.

4.1.1 Step 1 data collection using linguistic variables

Based on the hierarchical structure of the study, experts were asked to perform pairwise comparisons among decision criteria by using linguistic variables. Triangular fuzzy scales used in this study for the FAHP method are provided in Table 4, along with the importance values used in the AHP method (Vahidnia et al. 2009; Papaioannou et al. 2015). l_{ij}, m_{ij} and u_{ij} are lower width, mean, and upper width of the pairwise comparisons provided by experts attended for criterion i , with respect to criterion j , respectively.

4.1.2 Step 2 Consistency check

The procedures used in the traditional AHP were used prior to the FAHP analysis to calculate the CR values in order to validate the reliability of the experts (Vahidnia et al. 2009; Suganthi 2018). The CR values should be calculated for each expert to ensure the reliability of the aggregated judgments (Suganthi 2018). If the value of CR is found lower than 0.1, the assessments can be considered as consistent (Saaty 1990), otherwise, the corresponding expert should be asked to rearrange the judgments. CR can be calculated as:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

$$CR = \frac{CI}{RI} \tag{2}$$

Table 4 AHP and FAHP linguistic scales

Linguistic variables	AHP		Fuzzy AHP	
	Importance	Value for reciprocals	Triangular fuzzy numbers (l_{ij}, m_{ij}, u_{ij})	Triangular fuzzy reciprocals $(1/u_{ij}, 1/m_{ij}, 1/l_{ij})$
Equally important	1	(1/1)	(1,1,1)	(1,1,1)
Intermediate value	2	(1/2)	(1,2,3)	(1/3,1/2,1)
Moderately important	3	(1/3)	(2,3,4)	(1/4,1/3,1/2)
Intermediate value	4	(1/4)	(3,4,5)	(1/5,1/4,1/3)
Important	5	(1/5)	(4,5,6)	(1/6,1/5,1/4)
Intermediate value	6	(1/6)	(5,6,7)	(1/7,1/6,1/5)
Very important	7	(1/7)	(6,7,8)	(1/8,1/7,1/6)
Intermediate value	8	(1/8)	(7,8,9)	(1/9,1/8,1/7)
Extremely important	9	(1/9)	(9,9,9)	(1/9,1/9,1/9)

Table 5 Consistency ratios (CR) of experts

Experts	V (%)	H (%)	VS (%)	VP (%)	EL (%)	LU (%)	SL (%)	IM (%)	RP (%)
E1	5.01	9.86	1.29	9.89	6.85	6.24	7.73	6.44	6.70
E2	5.11	7.84	1.05	9.73	5.44	6.39	3.04	3.04	3.04
E3	7.94	3.34	0.38	6.61	4.39	7.23	9.10	4.39	5.80
E4	1.94	0.74	1.15	2.23	1.90	5.12	0.38	0.38	0.38
E5	9.76	9.40	2.85	7.30	2.85	6.01	4.77	5.11	3.50
E6	5.47	4.15	0.75	0.00	0.38	1.36	0.38	0.38	1.15
E7	9.81	3.86	3.70	6.44	0.00	6.62	3.04	4.39	3.70
E8	4.19	1.31	0.15	8.24	1.15	4.15	4.39	0.38	0.46
E9	9.40	8.63	7.22	0.77	5.34	9.10	8.94	6.99	8.94
E10	5.85	7.99	9.67	6.64	7.81	9.72	7.95	7.82	8.86
E11	7.34	2.96	8.02	8.85	7.91	5.12	3.04	3.04	3.04
E12	6.43	9.30	1.15	2.06	3.70	8.91	9.25	9.25	9.25
E13	9.89	8.75	8.83	9.15	8.83	9.06	9.58	6.83	6.83
E14	8.94	4.07	9.46	6.06	5.01	8.99	9.10	5.65	8.84

in which λ_{max} is the highest eigenvalue of a decision matrix, n denoted as the number of criteria. The CI and RI are the consistency index and the random index defined for each n value, respectively. Table 5 illustrates CR values of expert decisions, excluding the ones with high CR values. All of the CR values are less than the threshold value which is 10%. CR values were calculated only for the criteria consisting of more than two sub-criteria and classes since the RI is 0 for 1×1 and 2×2 matrices, and therefore CR values are not calculated (Saaty 2004).

4.1.3 Step 3 Aggregation of group decisions

Linguistic variables assigned by the expert k for each pairwise comparison were converted to their triangular fuzzy equivalences as $(l_{ijk}, m_{ijk}, u_{ijk})$, representing lower

width, mean, and upper width, respectively. Then, the judgments of consistent experts were aggregated by computing the minimum of l_{ijk} , of u_{ijk} , resulting in the aggregated triangular fuzzy numbers (l_{ij}, m_{ij}, u_{ij}) as (Büyüközkan and Feyzioğlu 2004; Chang et al. 2009):

$$l_{ij} = \min(l_{ijk}), m_{ij} = \left(\prod_{k=1}^K m_{ijk} \right)^{1/K}, u_{ij} = \max(u_{ijk}) \quad (3)$$

in which K is the total respondent number.

4.1.4 Step 4 Chang's extent analysis

After the individual judgments were aggregated, Chang's (1996) extent analysis (EA) approach was utilized to tackle the human decision-making process's inherent uncertainty. This method uses crisp mathematical notations to indicate

fuzzy amounts. Let $X = \{x_1, x_2, x_3, \dots, x_n\}$ an object set, and $U = \{u_1, u_2, u_3, \dots, u_m\}$ a goal set. To conduct the EA for each goal, all objects are taken into account. Thus, the outcomes of the EA, called m values, can be acquired for all objects. To obtain the fuzzy synthetic extent value for object i , we utilized the Eq. 4:

$$S_i = \sum_{j=1}^m M_{gi}^j \times \left[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j \right]^{-1} \tag{4}$$

in which M_{gi}^j denoted as a triangular fuzzy number. To obtain $\sum_{j=1}^m M_{gi}^j$, we utilized Eq. 5 as follows:

$$\sum_{j=1}^m M_{gi}^j = \left(\sum_{j=1}^m l_j, \sum_{j=1}^m m_j, \sum_{j=1}^m u_j \right) \tag{5}$$

and to calculate $\left[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j \right]^{-1}$, the fuzzy addition process of the values $M_{gi}^j (j = 1, 2, \dots, m)$ is conducted:

$$\left[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j \right] = \left(\sum_{j=1}^m l_j, \sum_{j=1}^m m_j, \sum_{j=1}^m u_j \right) \tag{6}$$

Then, the inverse of this vector can be obtained by using:

$$\left[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j \right]^{-1} = \left(\frac{1}{\sum_{j=1}^m u_j}, \frac{1}{\sum_{j=1}^m m_j}, \frac{1}{\sum_{j=1}^m l_j} \right) \tag{6}$$

The possibility degree (PD) can be obtained by using the fuzzy synthetic extent value. As $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are triangular fuzzy numbers, the PD of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is expressed as:

$$V(M_2 \geq M_1) = \sup_{y \geq x} [\min(\mu_{M_1}(x), \mu_{M_2}(y))] \tag{8}$$

This can also be indicated as:

$$V(M_2 \geq M_1) = \text{htg}(M_1 \cap M_2) = \begin{cases} 1 & \text{if } m_2 \geq m_1 \\ 0 & \text{if } l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \tag{9}$$

For comparing M_2 and M_1 , both $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$ are required.

The PD for a convex fuzzy number to be higher than k convex fuzzy $M_i (i = 1, 2, \dots, k)$ numbers is expressed as:

$$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_1) \text{ and } (M \geq M_2), \dots \text{ and } (M \geq M_k)] = \min V(M \geq M_i) \tag{10}$$

where $i = 1, 2, 3, \dots, k$.

Considering that, $d'(A_i) = \min V(S_i \geq S_k)$ for $k = 1, 2, \dots, n; k \neq i$, then the weigh vector (W') is computed by:

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T \tag{11}$$

where $A_i (i = 1, 2, 3, \dots, n)$ are n elements.

Via normalization, using the formula given below the following formula given below is used to obtained the normalized weight vectors:

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T \tag{12}$$

4.1.5 Step 5 Sensitivity analysis

In the fuzzy AHP technique, the sensitivity analysis with respect to the degree of fuzziness is essential to indicate the stability of the proposed frameworks. Therefore, the sensitivity analysis can be performed to explore how the criteria weights and rankings vary as a result of the changes in the degree of fuzziness. The initial value of the degree of fuzziness in the adopted FAHP method was 1, as the distance between l , m and u values (Table 4). If the ranking orders do not change, the results attained from the analysis can be regarded to be robust and stable, otherwise, criteria can be regarded as sensitive to the degree of fuzziness values (Ishizaka and Labib 2011).

4.2 Idealization

In this study, the idealization technique was adopted to assign the overall criteria weights to the most risky districts. This idealized solution makes the value of the most risky district as 1 with respect to corresponding criterion, while the value is proportionally less for the other districts (Saaty 2004).

4.2.1 Criteria without classes

As to the positive criteria, in which higher values indicate more flood risk, the maximum approach was adopted (Eq. 13). Besides, the minimum approach was applied to the negative criteria, in which lower values indicate more flood risk (Eq. 14).

$$v_{id} = \frac{x_i}{x_{imax}} \tag{13}$$

$$v_{id} = \frac{x_{imin}}{x_i} \tag{14}$$

where v_{id} is an idealized weight for criterion i , x_i is an initial data of criterion i for district x , x_{imax} and x_{imin} are the maximum and minimum values that criterion i was applied to, among all districts, respectively.

4.2.2 Criteria with classes

Since more risky classes were given more extreme points in FAHP matrices, only maximum method is required for the idealization of criteria consisting of classes. Prior to the idealization, the idealized weight of each class was multiplied with corresponding values of the criteria.

$$v_{id} = \sum_{j=1}^k x_{ij} \cdot c_j \times \left[\left(\sum_{j=1}^k x_{ij} \cdot c_j \right)_{max} \right]^{-1} \quad (15)$$

in which k is the total class number. x_{ij} and c_j are the initial data of districts with respect to class j in criterion i and the idealized weight of class j , respectively.

4.3 Risk scores of the districts

Overall criteria and idealized weights were used to obtain the risk score of districts by Eq. (16) (Hajkowicz and Collins 2007).

$$R_x = \sum_{i=1}^n w_i \times v_{id} \quad (16)$$

where R_x is the risk score of district x , n is the number of criteria, and w_i is the overall weight of criterion i . Overall weights were obtained by adopting the fuzzy AHP technique.

5 Results and discussions

This study aims to evaluate the districts of Istanbul in terms of flood risk by considering both vulnerability and hazard criteria. Based on the data collected from 14 experts in step 1, criteria weights are computed via the fuzzy AHP approach in step 2. Then, criteria weights are used to evaluate the flood risk of Istanbul at the district level.

5.1 Weights of decision criteria

In the fuzzy AHP, criteria weights and classes are identified based on expert judgments, therefore the method highly relies on the assessment of experts. This highlights the significance of finding highly qualified and experienced professionals from a diversity of institutions. In addition, the reliability of the experts is verified via CR, which can be considered as one of the most significant aspects of the AHP technique (Darko et al. 2019). By using purposive sampling, 15 experts were invited to participate in one-to-one questionnaire surveys and all of them agreed to take part. However, since one of them was found highly inconsistent, only judgments of 14 experts were used to calculate flood vulnerability and hazard criteria weights

(Table 6). The findings indicate that land use (LU), population density (PD), and vulnerable structures (VS) were the most significant vulnerability criteria, while the return period of a storm event (RP), imperviousness (IM), and stormwater pipe network (SP) were the most crucial hazard criteria. Besides, there was a minor difference between the weights of vulnerability and hazard clusters, showing the equal importance of both in flood risk evaluation.

All decision frameworks present results by adopting different approaches. However, it is required to obtain similar results under different scenarios, since decision processes could be inherently unstable for some complex problems. For instance, this study adopted the 1–9 triangular fuzzy scale (Vahidnia et al. 2009; Papaioannou et al. 2015), while some others adopted the 1–6 scale to calculate criteria weights in the FAHP (Aladağ and Işık 2019). Decision frameworks should give similar results by using different degrees of fuzziness in the adopted scale. Thus, at the last step, the decision process should be terminated with a sensitivity analysis to ensure not only the stability but also the robustness of the results (Ishizaka and Labib 2011). A sensitivity analysis was used to explore how the rankings may change as a result of a change in the degree of fuzziness used in the fuzzy AHP method. If the rankings do not change based on the degree of fuzziness, then the criteria weights can be accepted as robust; otherwise, the importance of the criteria is sensitive to the fuzziness degree (Ishizaka and Labib 2011; Aladağ and Işık 2019). The degree of fuzziness of the adopted triangular fuzzy scale was equal to 1 (Table 4). The same fuzzy AHP calculations (Step 3 and 4) were conducted by taking the degree of fuzziness as 0, 0.4, 0.8, 1.2, 1.6, and 2. The findings presented in Fig. 4 show that the proposed AHP model is stable and robust since no change was observed in the rankings of criteria for both vulnerability (Fig. 4a) and hazard clusters (Fig. 4b).

5.2 District prioritization

39 districts of Istanbul have been prioritized in terms of flood risk based on the criteria weights that were calculated through the fuzzy AHP analysis, robustness and stability of which was proven by the sensitivity analysis. Flood risk grades of districts were calculated by summing the grades achieved from each criterion (Table 7). Then the maps are generated from the most risky to the safest districts based on vulnerability criteria (Fig. 5a), hazard criteria (Fig. 5b), and by considering both vulnerability and hazard criteria (Fig. 5c).

According to the analysis results, Bayrampasa, Bagcilar, and Esenler were found to be the top three districts in terms of flood risk. All three districts have gained the highest risk scores from the return period for precipitation (RP),

Table 6 Evaluation criteria with their corresponding weights

Clusters	Weights	Criteria	Weights	Classes	Weights			
Vulnerability	0.507	VS	0.137	< 1968	0.389			
				1969–1982	0.333			
				1983–2012	0.232			
				2013–2018	0.045			
		PD	0.144	–	1.000			
				VP	0.127	< 10	0.361	
						10–19	0.251	
						20–64	0.051	
		> 64	0.337					
		EL	0.124	Non-literate	0.320			
				Literate (without education)	0.296			
				Up to high school	0.246			
				Bachelor or more	0.138			
		IL	0.119	–	1.000			
				TN	0.092			
		NH	0.097	–	1.000			
				LU	0.158	Commercial/ Industrial	0.439	
Residential	0.425							
Rural	0.136							
Forestry	0.000							
Hazard	0.493	SP	0.200			–	1.000	
						SL	0.193	< 1%
		1%–4%						0.196
		5%–10%		0.346				
> 10%	0.458							
IM	0.200	71–76	0.000					
		77–82	0.198					
		83–88	0.340					
		89–94	0.462					
RP	0.217	< 2	0.048					
		2–10	0.211					
		11–50	0.329					
		> 50	0.412					
NR	0.189	–	1.000					

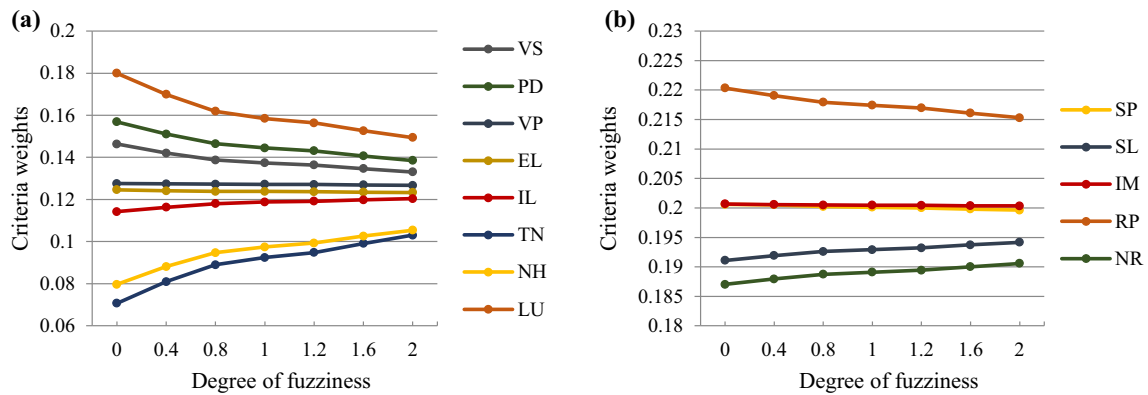


Fig. 4 Sensitivity analysis based on the degree of fuzziness. **a** Vulnerability, **b** Hazard clusters

imperviousness (IM), and land use (LU); which were the most significant hazard criterion, the second most significant hazard criterion, and the most significant vulnerability criterion, respectively. The standard deviation (SD) of IM

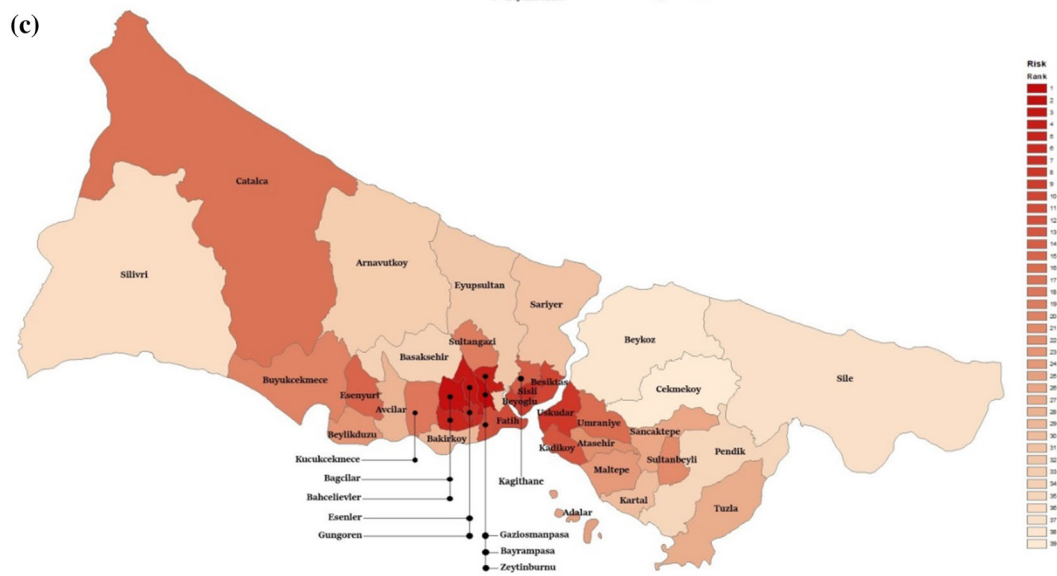
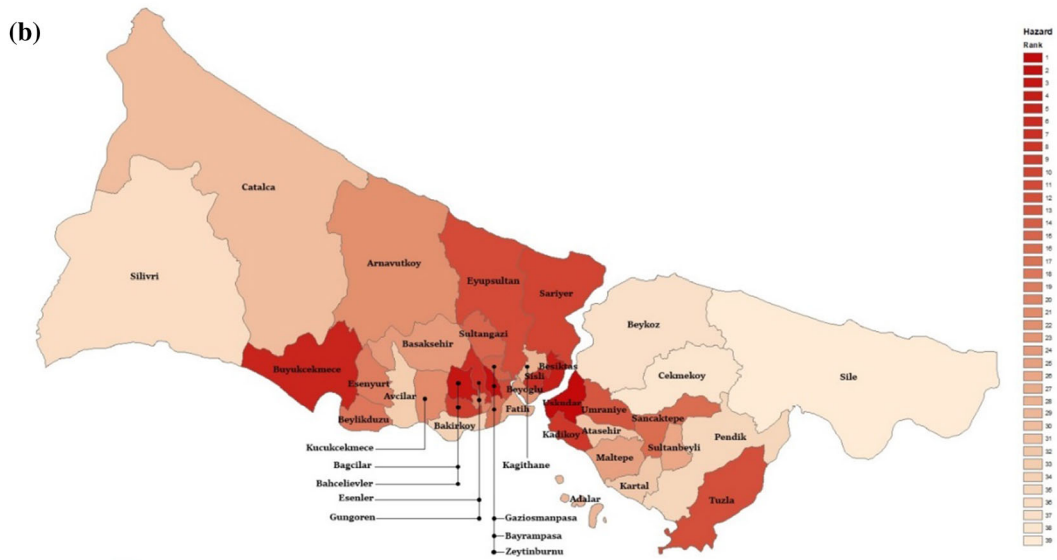
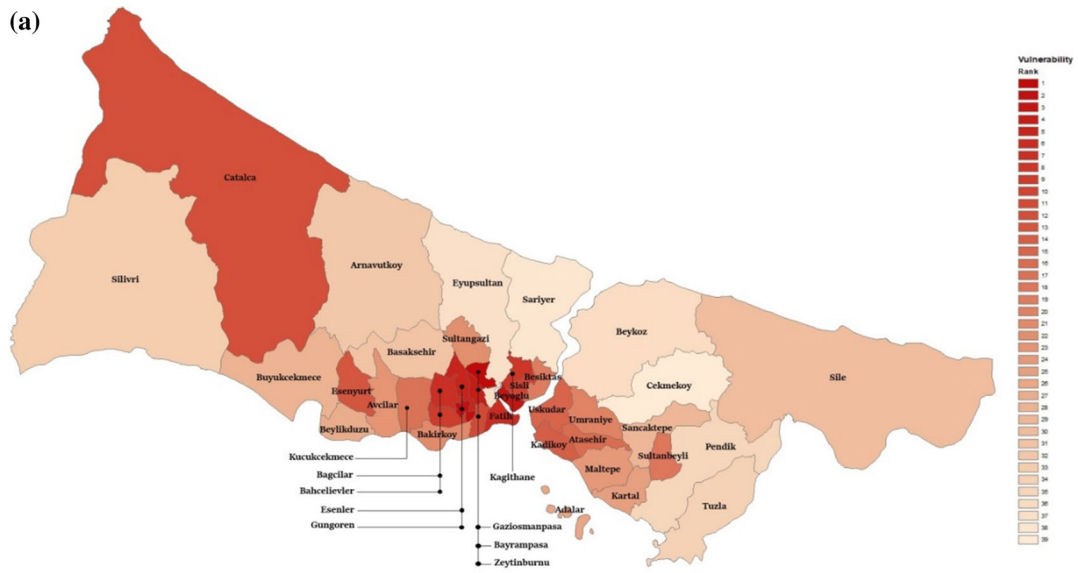
Fig. 5 Istanbul area generated. **a** Vulnerability map, **b** Hazard map, and **c** Flood risk map

Table 7 District based flood risk scores of Istanbul for each criterion

Districts	VS	PD	VP	EL	IL	TN	NH	LU	SP	SL	IM	RP	NR	Total	Rank
Adalar	0.070	0.002	0.059	0.056	0.042	0.047	0.047	0.015	0.014	0.095	0.040	0.078	0.038	0.605	25
Arnavutkoy	0.048	0.001	0.064	0.063	0.060	0.011	0.030	0.023	0.072	0.025	0.030	0.081	0.071	0.580	33
Atasehir	0.051	0.030	0.056	0.057	0.044	0.010	0.039	0.077	0.008	0.049	0.083	0.086	0.037	0.625	22
Avcilar	0.044	0.016	0.058	0.059	0.049	0.018	0.036	0.065	0.027	0.060	0.069	0.052	0.044	0.596	28
Bagcilar	0.052	0.057	0.060	0.062	0.053	0.013	0.031	0.079	0.006	0.058	0.097	0.102	0.068	0.739	2
Bahcelievler	0.045	0.064	0.057	0.059	0.048	0.015	0.036	0.080	0.008	0.052	0.099	0.094	0.055	0.709	5
Bakirkoy	0.049	0.014	0.058	0.053	0.037	0.017	0.042	0.078	0.012	0.044	0.097	0.049	0.045	0.595	29
Basaksehir	0.030	0.008	0.062	0.059	0.047	0.009	0.033	0.063	0.012	0.046	0.054	0.088	0.071	0.580	34
Bayrampasa	0.059	0.054	0.057	0.060	0.049	0.025	0.036	0.077	0.010	0.055	0.095	0.100	0.074	0.751	1
Besiktas	0.062	0.018	0.055	0.050	0.033	0.015	0.049	0.078	0.012	0.067	0.088	0.107	0.048	0.681	10
Beykoz	0.067	0.001	0.057	0.059	0.045	0.006	0.037	0.014	0.027	0.048	0.016	0.075	0.039	0.491	38
Beylikduzu	0.027	0.016	0.059	0.057	0.045	0.015	0.037	0.079	0.014	0.063	0.078	0.070	0.055	0.616	23
Beyoglu	0.068	0.046	0.055	0.060	0.047	0.022	0.039	0.079	0.010	0.055	0.095	0.056	0.063	0.695	9
Buyukcekmece	0.045	0.003	0.059	0.058	0.049	0.010	0.038	0.054	0.083	0.043	0.043	0.083	0.069	0.636	20
Catalca	0.056	0.000	0.058	0.060	0.057	0.033	0.045	0.070	0.099	0.015	0.016	0.071	0.064	0.644	17
Cekmekoy	0.040	0.003	0.059	0.058	0.049	0.019	0.036	0.018	0.021	0.049	0.020	0.074	0.039	0.485	39
Esenler	0.053	0.042	0.059	0.062	0.055	0.031	0.033	0.080	0.007	0.057	0.089	0.085	0.077	0.729	3
Esenyurt	0.026	0.039	0.061	0.061	0.055	0.013	0.034	0.080	0.011	0.049	0.080	0.074	0.066	0.650	15
Eyup	0.052	0.003	0.057	0.059	0.048	0.009	0.037	0.019	0.065	0.030	0.045	0.070	0.093	0.587	32
Fatih	0.064	0.052	0.056	0.059	0.047	0.017	0.038	0.080	0.016	0.058	0.095	0.063	0.036	0.681	11
Gaziosmanpasa	0.057	0.073	0.059	0.060	0.052	0.020	0.035	0.078	0.008	0.060	0.094	0.043	0.088	0.728	4
Gungoren	0.048	0.073	0.057	0.060	0.049	0.021	0.036	0.080	0.009	0.030	0.097	0.072	0.072	0.706	6
Kadikoy	0.052	0.034	0.052	0.050	0.036	0.011	0.049	0.079	0.010	0.061	0.097	0.058	0.082	0.672	13
Kagithane	0.055	0.053	0.055	0.059	0.048	0.016	0.037	0.080	0.005	0.042	0.086	0.074	0.059	0.670	14
Kartal	0.049	0.022	0.057	0.057	0.045	0.009	0.039	0.063	0.015	0.054	0.064	0.065	0.056	0.595	30
Kucukcekmece	0.044	0.032	0.058	0.059	0.049	0.009	0.036	0.074	0.010	0.054	0.093	0.077	0.045	0.641	18
Maltepe	0.046	0.017	0.055	0.056	0.044	0.010	0.040	0.073	0.025	0.068	0.067	0.058	0.051	0.611	24
Pendik	0.045	0.007	0.059	0.059	0.050	0.005	0.036	0.033	0.047	0.054	0.034	0.068	0.044	0.541	35
Sancaktepe	0.037	0.012	0.061	0.061	0.054	0.014	0.033	0.041	0.038	0.059	0.040	0.059	0.089	0.598	26
Sariyer	0.063	0.003	0.055	0.057	0.038	0.007	0.039	0.019	0.079	0.045	0.034	0.062	0.086	0.588	31
Silivri	0.056	0.000	0.055	0.060	0.053	0.036	0.035	0.003	0.033	0.023	0.016	0.089	0.070	0.530	36
Sultanbeyli	0.051	0.021	0.064	0.063	0.059	0.015	0.029	0.059	0.029	0.070	0.052	0.082	0.036	0.630	21
Sultangazi	0.050	0.026	0.062	0.063	0.059	0.020	0.031	0.038	0.015	0.069	0.052	0.074	0.082	0.640	19
Sile	0.038	0.000	0.062	0.060	0.056	0.047	0.046	0.003	0.077	0.024	0.008	0.043	0.039	0.503	37
Sisli	0.057	0.050	0.053	0.055	0.040	0.015	0.045	0.079	0.010	0.078	0.094	0.046	0.080	0.703	7
Tuzla	0.040	0.003	0.058	0.058	0.049	0.009	0.037	0.042	0.042	0.074	0.049	0.058	0.077	0.596	27
Umraniye	0.049	0.027	0.057	0.058	0.047	0.007	0.036	0.069	0.007	0.063	0.069	0.072	0.082	0.644	16
Uskudar	0.060	0.027	0.056	0.056	0.041	0.007	0.040	0.077	0.009	0.073	0.090	0.082	0.083	0.701	8
Zeytinburnu	0.042	0.043	0.058	0.061	0.048	0.027	0.033	0.079	0.007	0.033	0.097	0.061	0.086	0.674	12
<i>Average</i>	<i>0.050</i>	<i>0.025</i>	<i>0.058</i>	<i>0.059</i>	<i>0.048</i>	<i>0.017</i>	<i>0.038</i>	<i>0.058</i>	<i>0.026</i>	<i>0.053</i>	<i>0.066</i>	<i>0.072</i>	<i>0.063</i>	<i>0.632</i>	–
<i>SD</i>	<i>0.010</i>	<i>0.022</i>	<i>0.003</i>	<i>0.003</i>	<i>0.006</i>	<i>0.010</i>	<i>0.005</i>	<i>0.026</i>	<i>0.025</i>	<i>0.016</i>	<i>0.029</i>	<i>0.015</i>	<i>0.018</i>	<i>0.187</i>	–

Bold values indicate the highest risk scores of each column (criterion)

Italic values refer the statistical features, i.e. average and standard deviation (SD), of the risk scores of each column (criterion)



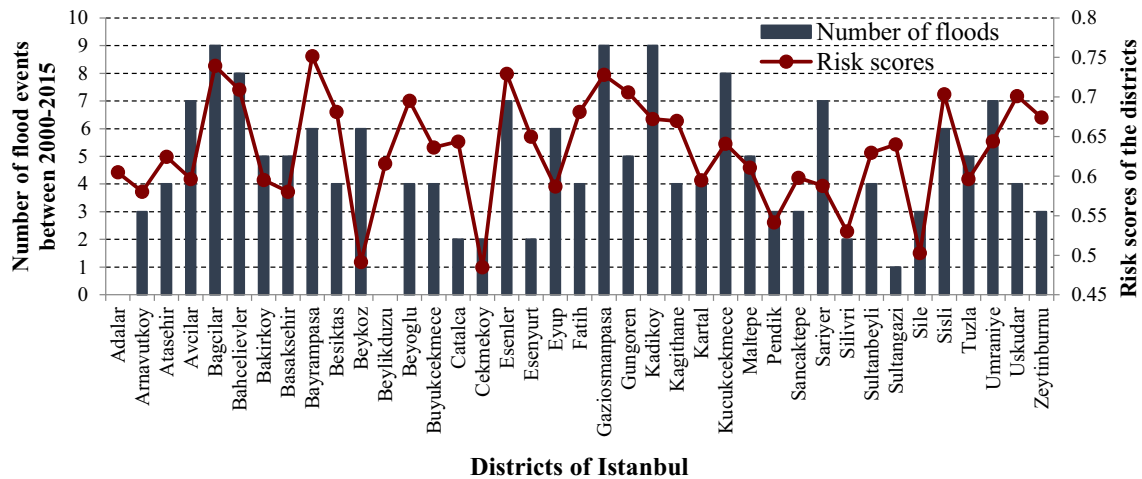


Fig. 6 Historical flood events occurred between 2000 and 2015 and calculated risk scores at the district level

and LU was the highest among all criteria, having a direct impact on the flood risks of districts.

Gaziosmanpasa, Gungoren, and Beyoglu were the top three flood-prone districts in terms of the vulnerability cluster (Fig. 5a). Land use criterion was the main reason for the high vulnerability of the top three districts due to a variety of commercial and residential activities in the districts. In addition, population density contributes to risk score in Gaziosmanpasa and Gungoren considerably, while vulnerable structures highly determine the risk score in Beyoglu. In terms of the hazard cluster, the most flood-prone districts are found to be Uskudar, Bayrampasa, and Bagcilar which are densely urbanized areas and the imperviousness criterion is the reason for their high-risk scores (Fig. 5b). Uskudar, which was regarded as one of the ten most risky regions according to the report prepared by the IBB (2009), known for its hilly topography, gained considerable risk scores from the slope criterion.

Criteria based analysis results show that Adalar (Prince Islands) was the most vulnerable district in terms of aging stormwater system and transportation network and also the most hazardous district with respect to the slope. The reasons for these are that Adalar is one of the oldest districts in Istanbul, consisting of nine separated and bus-restricted islands. Arnavutkoy becomes the most vulnerable district when education level, income level, and population by age are taken into consideration. However, the low population density of the district prevented it from being ranked among the top vulnerable districts (Table 7). It should be noted that New Istanbul Airport is located in Arnavutkoy, therefore, the population density of the district is expected to increase. This is of paramount significance since increasing population could make Arnavutkoy as one of the most risky districts in terms of flood risk.

Validation of the obtained results with real-time observations is an essential step in flood risk map studies. Although generating flood maps using sophisticated algorithms is guiding the way, the validation of the produced maps with the findings of the previous studies and historical flood events could support the findings of the proposed models. Figure 6 illustrates the comparison of the number of flood events that occurred between 2000 and 2015 (Özeyranlı Ergenç 2016), and the calculated risk scores of each district in this study. There was a significant similarity between observed events and calculated risk scores in most of the districts such as Bagcilar, Esenler and Arnavutkoy. However, the findings showed relatively poor performance in some districts such as Adalar, Beylikduzu, Esenyurt, Sultangazi, Zeytinburnu. It should be noted that Adalar is a district of islands and this fact highlights that the results for districts with divergent attributes could be different than others. Therefore, the proposed approach could work well in districts with similar geological attributes, while more complex approaches should be developed when some significant diversified attributes exist such as consisting of islands, bordering some significant rivers or Bosphorus. As for the other districts, a noteworthy land-use change was observed over the last decade in districts such as Beylikduzu, Esenyurt, Sultangazi, and Zeytinburnu, which could be one of the reasons for higher risk scores compared to the number of floods events. Furthermore, calculated risk scores are based on the data provided in 2020, while compared floods were between 2000 and 2015. Consequently, this study shows that the use of up-to-date data is significantly important to adopt the proposed fuzzy AHP approach in flood risk mapping.

The results obtained from the analysis show strong agreement with the pertinent literature in the study area. According to the Üstün and Anagün (2016) and Ergenç and

Table 8 The historical event-based risk scores

Flood Events	VS	PD	VP*	EL*	IL	TN	NH	LU	SP	SL*	IM*	RP	NR	Total	District Risk score
Kadikoy–2008	0.068	0.035	0.052	0.050	0.014	0.017	0.041	0.079	0.003	0.061	0.097	0.068	0.075	0.6605	0.672
Ayamama 2009–Bagcilar	0.059	0.052	0.060	0.062	0.038	0.036	0.029	0.071	0.003	0.058	0.097	0.106	0.078	0.7492	0.739
Ayamama 2009– Bahcelievler	0.062	0.056	0.057	0.059	0.026	0.030	0.035	0.078	0.003	0.052	0.099	0.104	0.077	0.736	0.709
Esenler–2014	0.062	0.004	0.059	0.062	0.043	0.047	0.029	0.076	0.003	0.057	0.089	0.094	0.070	0.6943	0.729

*The data is not available or the same used in this study, therefore the same district risk scores were used

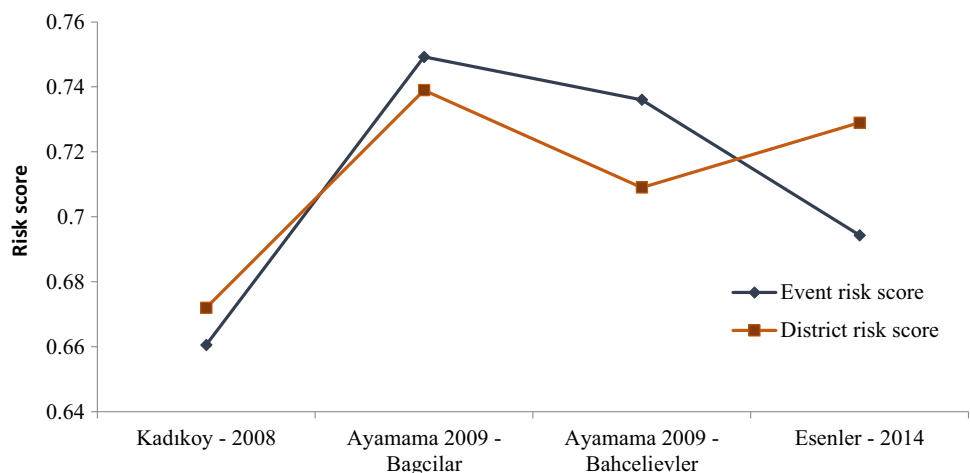
Bariş (2018), Bayrampasa, Esenler, Bagcilar and Gaziosmanpasa were the districts with the highest weights with respect to both vulnerable structures and population density criteria, while Bagcilar and Bahcelievler contained the most risky zones in European side according to the IBB report (IBB 2009). Bagcilar, Bayrampasa, Esenler and Gaziosmanpasa were also found to be the most risky districts by 0.052, 0.059, 0.053 and 0.057 grades in terms of vulnerable structures, while by 0.057, 0.054, 0.042 and 0.073 with respect to population density in this study.

100 and 300 years return period of storm events occurred in 2007 in the Tavukcu stream located in Bahcelievler, and then in 2009 in the Ayamama stream, which passed through Bagcilar, respectively (Güçlü and Şen 2016). Bagcilar and Bahcelievler received the second and fourth highest scores with respect to the return period of a storm event criterion by 0.102 and 0.094, respectively (Table 7). It is worth to mention that even though some of the other districts, i.e. Besiktas and Bayrampasa, received higher scores based on the return period criterion, the rapid change in land use due to the urbanization caused a serious increase in surface water runoff, and so these unfortunate

events (Gülbaz et al. 2019; Nigussie and Altunkaynak 2019).

Moreover, the Kadikoy flood that occurred in 2008, and the year 2014 flood that occurred in Esenler, in which the largest bus terminal of Istanbul is located, may provide the validation of the calculated results. Kadikoy was found as the second most risky district in the Asian part, while Esenler was the third most risky district in the European part. Therefore, the flood events in these regions were examined according to the criteria used in this study, and risk scores of the stated events were obtained. Accordingly, the data of these events were gathered with respect to the vulnerability and hazard clusters, and criteria that did not change or unavailable were considered as the same with the up to date data. As a consequence, the risk scores of Kadikoy (2008), Esenler (2014), Bagcilar and Bahcelievler districts, which were affected by the Ayamama (2009) flood event were obtained as 0.6605, 0.7492, 0.736 and 0.6943, respectively (Table 8). Figure 7 illustrates that the risk scores calculated in this study show a strong relationship with the event-based risk scores in the districts at the time these events occurred. Compared to the general risk scores at the district level, there is an increase in the

Fig. 7 Comparison of historical flood event scores with the calculated risk scores at the district level



risk scores of Kadikoy and Esenler, albeit slightly, while the decrease in the risk scores of Bagcilar and Bahcelievler was also observed. The reason for the decrement in Bagcilar and Bahcelievler risk scores can be explained by the rehabilitated infrastructure and superstructure system after the disaster occurred in the Ayamama basin. In addition, the increase in the risk score of Esenler can be related to the decrease in surface perviousness due to the increasing urbanization compared to 2014, when the flood disaster was experienced; such that imperviousness and land use were found to be the highest risk criteria for Esenler. Thus, it can be said that the calculated risk scores are consistent with the risk scores of the historical flood events.

6 Conclusions

Floods threaten the built environment in all three pillars of sustainability i.e. economic, social and environmental, as supported by many flood events in the world. Flood risk analysis is a problem that requires the inclusion of multiple vulnerability and hazard criteria. However, since the solution made by multi-criteria analysis depends on the subjective judgments of the experts; fuzziness of the human decision process need to be integrated with an adequate multi-criteria decision-making tool. Hence, this study aimed at prioritizing the districts of Istanbul with respect to flood risk by using the fuzzy analytical hierarchy process. Prioritization of districts is of paramount significance in flood risk management since the administration is carried out by district-level units and local municipalities in Istanbul. The following conclusions can be made according to the results of the analysis:

- Land use, population density and vulnerable structures are the most significant vulnerability criteria, while the return period of a storm event, imperviousness and stormwater pipe network are the most crucial hazard criteria for flood risk assessment for Istanbul districts. A minor difference between the weights of vulnerability and hazard clusters indicates that both of them are important in flood risk evaluation, equally.
- The findings of sensitivity analysis showed the stability and robustness of the proposed fuzzy AHP model since there was no change in the rankings of both vulnerability and hazard criteria as the degree of fuzziness value of the triangular fuzzy scale changes.
- The flood risk of Bayrampasa, Bagcilar, and Esenler districts were found to be the highest among 39 districts of Istanbul owing to their dense population. The most flood-prone districts were Uskudar, Bayrampasa, and Bagcilar in terms of their hazard cluster, while Gaziosmanpasa, Gungoren, and Beyoglu were the most flood-

prone areas in terms of vulnerability cluster. Therefore, urgent risk mitigation strategies should be developed to reduce the flood risk of these districts since they were among the most populated regions in Istanbul.

- The findings of this study coincide with the district-based records in terms of the number of floods occurred in the last two decades in Istanbul. Furthermore, the outcomes of this study support not only the result of previous studies but also event-based risk scores of the previous flood events at a district level.

These findings are useful for water resource professionals, urban planners, and particularly local authorities to improve flood risk mitigation plans based on the criteria that the districts are prone at most. Resources of Istanbul for flood risk mitigation program can be allocated to the districts based on the prioritization of them by means of flood hazard and vulnerability criteria. In addition, insurance companies could also use the outcomes of the research to identify the risk scores of the districts with respect to flood risk.

It is worth mentioning that, more attempts need to be undertaken for improving the flood risk assessment in order to enhance the validity of the proposed approaches. Since four different target groups were selected in the fuzzy AHP analysis to specify criteria weights, the perception difference of these stakeholders can be investigated to reveal the dynamics of flood risk evaluation based on the respondents' profiles. Besides, other vulnerability criteria such as historical sites and public awareness, and hazard criteria such as distance from the river and flood frequency can also be included in the model for future attempts, based on the available data of the Istanbul. At last, the same procedures can be applied to all cities in Turkey to generate a country-wide flood risk map.

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