ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

COMPREHENSIVE FLOOD RISK ASSESSMENT AND IDENTIFICATION OF THE POTENTIAL FLOOD MITIGATION STRATEGIES

Ph.D. THESIS

Ömer EKMEKCİOĞLU

Department of Civil Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

KAPSAMLI BİR TAŞKIN RİSK DEĞERLENDİRMESİ VE OLASI RİSK AZALTMA STRATEJİLERİNİN BELİRLENMESİ

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HAZİRAN 2022

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To my country,

FOREWORD

Floods pose a plethora of challenges having detrimental impacts on human and environment across the world. Turkey is among the countries mostly encountered the flood phenomena. In this vein, comprehensive flood risk assessments and identification of the potential mitigation strategies are essential to combat unintented consequences of floods by early diaganosis of the preliminary actions. Hence, this study was designed to be remedy to potential disruptions encompassing casualties, property losses and many other straight-forward adversities.

I would like to thank Prof. Dr. Mehmet ÖZGER, my advisor, who shared his knowledge, supported me throughout my thesis.

I would also express my graditutes to Kerim KOÇ, my friend and colleague, for his valuable contributions and supporting me in every stage of my thesis.

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Finally, I hope that this thesis will not only make significant contribution to the body of literature but also be a valuable source to solve one of the most important problems of our country, floods.

June 2022 Ömer EKMEKCİOĞLU
(Civil Engineer)

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ABBREVIATIONS

AHP	: Analytic Hierarchy Process
ANP	: Analytic Network Process
BWM	: Best-Worst Method
CORINE	: Coordination of Information on the Environment
CR	: Consistency Ratio
CRD	: Causal Relationship Diagram
DEMATEL	: Decision-Making Trial and Evaluation Laboratory
EEA	: European Environment Agency
FAHP	: Fuzzy Analytic Hierarchy Process
FGD	: Focus Group Discussion
FRM	: Flood Risk Management
GIS	: Geographic Information System
HGM	: Turkish General Directorate of Mapping
IBB	: Istanbul Metropolitan Municipality
IRAHP	: Interval Rough Analytical Hierarchy Process
ISKI	: Istanbul Water and Sewerage Administration
MCAHP	: Monte Carlo Aided Analytical Hierarchy Process
MCDM	: Multi-Criteria Decision-Making
MGM	: Turkish State Meteorological Service
SAW	: Simple Additive Weighting
SPA	: Set Pair Analysis
SWAT	: Soil and Water Assessment Tool
TFN	: Triangular Fuzzy Number
TOPSIS	: Technique for Order of Preference by Similarity to Ideal Solution
USGS	: United States Geological Survey
VFS	: Variable Pair Fuzzy Sets
VIKOR	: VIse KriterijumsaOptimiz acija I Kompromisno Resenje
WEP	: Water and Energy transfer Process
WHO	: World Health Organization

SYMBOLS

A^-	: Negative Ideal Solution
A^*	: Positive Ideal Solution
A_{ij}	: Evaluation Matrix
CC_i	: Closeness Coefficient
CI	: Consistency Index
$l_{ijk}, m_{ijk}, u_{ijk}$	: Triangular Fuzzy Equivalences
M_{gi}^j	: Triangular Fuzzy Number
$\tilde{Q}_i$	: VIKOR İndex
$\tilde{R}_i$	: Regret Measure
RI	: Random İndex
r_{ij}	: Normalized Evaluation Matrix
r_s	: Spearman’s Rank Correlation Coefficient
$\tilde{S}_i$	: Utility Measure
W'	: Weigh Vector

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COMPREHENSIVE FLOOD RISK ASSESSMENT AND IDENTIFICATION OF THE POTENTIAL FLOOD MITIGATION STRATEGIES

SUMMARY

Floods are among the natural disasters frequently encountered in our country, i.e. Turkey, and across the globe. Considering some of the conditioning factors, such as geographical location, geological and hydrological structure and even demographic characteristics, that characterize the formation of natural disasters, the most common natural disasters in Turkey are described as floods. A total of 1209 floods occurred in Turkey between 1975 and 2015, resulting in 720 deaths and the inundation of 900,000 hectares. In addition, floods cause an annual average of 100 million dollars of economic loss. The constitution of floods may vary in different types; scuh that coastal floods are frequent in coastal areas, while river floods mostly occur in rural and/or urban areas, and urban flooding poses significant challenges in densely populated regions. In this context, especially in cities with high population densities, urban flood events not only cost human lives but also cause serious property damage.

Istanbul is also among the cities that frequently face urban floods across Turkey. The city is the most populated city in Turkey with a population of approximately 16 million (2986 people/km²) and is at serious risk of flooding. Therefore, within the scope of this thesis, it is aimed to determine the regions that may be affected as a result of the floods potentially occur in Istanbul and to reveal the factors that trigger the vulnerability of these regions. In order to ensure the functionality of both data collection procedures and the early diagnosis actions to be determined on an administrative basis, analyzes were carried out on a district basis in this thesis. Through district-based analyzes, both hazard and vulnerability factors, which are the two most critical pillars of the risk concept, were carried taken into account. In line with the hazard cluster, stormwater pipe network, slope, imperviousness (in terms of curve number), number of rainy days and return period of storm event criteria were taken into the consideration. Within the scope of vulnerability cluster, vulnerable structures, population density, vulnerable population, education level, income level, transportation network, number of households and land use criteria were considered. Thus, this thesis not only tried to determine the regions having high susceptibility of flooding but also sought to designate the social environments, i.e., residents and/or buildings, that have the potential to be damaged as a result of floods.

In the research articles included in this thesis, multi-criteria decision-making algorithms were used to perform the district-based flood risk mapping of Istanbul. In the first research article published within the scope of the thesis, district-based flood risk maps were generated using the fuzzy analytic hierarchy process, and risky districts and the criteria to be taken into account specific to these districts were identified. In the second research article published within the scope of the thesis, the perception differences on the flood risk of four different stakeholders (i.e., Istanbul Water and Sewerage Administration, Disaster Coordination Center, Istanbul Metropolitan Municipality and Universities) at Istanbul scale were analyzed. For these purpose, the

technique for order of preference by the similarity-to-ideal-solution (TOPSIS) method was integrated along with the fuzzy analytical hierarchy process method utilized in the first study. As a result of the model configurations on the basis of expert judgments pertaining to abovementioned four institutions, flood risk, flood hazard and flood vulnerability maps were separately generated. The third research article published within the scope of the thesis focused on the interrelationships of the criteria that were not examined in the previous two studies. On the other hand, for the first time in the literature, analyzes were carried out using two distintictive criteria weighting methods (analytical hierarchy process for the hazard cluster and analytical network process for the vulnerability cluster) together. At this point, another innovation that has been methodically accomplished is the integration of the decision-making trial and evaluation laboratory (DEMATEL) method which was used in the refinement of the analytical network process framework. Visekriterijumska optimizacija i compromisno resenje (VIKOR) method, which is accepted as an improved version of the TOPSIS method, was performed to prioritize the districts in terms of flood risk by combining the outputs obtained from the two different criteria weighting methods and the numerical values of the corresponding criteria.

According to the findings obtained in the first of the articles published within the scope of the thesis, land use, population density and the vulnerable structures were determined as the most important vulnerability criteria, while the return period of a storm event, imperviousness and stormwater pipe networks were obtained as the most significant hazard criteria. On the other hand, the comparison between the main clusters, i.e., vulnerability and hazard, indicates that these two classes have almost equal importance in terms of the flood risk concept in Istanbul. In addition, sensitivity analyzes were implemented in order to illustrate the stability and robustness of the fuzzy analytic hierarchy process applications. According to the district-based analyzes, Bayrampasa, Bagcilar and Esenler were found to be the three most risky districts with the significant effect of their dense populations. While Uskudar, Bayrampasa and Bagcilar districts stand out according to the hazard cluster representing the probability of flood events, it was concluded that special precautions should be taken for Gaziosmanpasa, Gungoren and Beyoglu districts according to the analyzes made within the generic of vulnerability cluster.

According to the findings obtained in the second of the articles published within the scope of the thesis, disaster management and coordination authorities and local municipalities have point out that hazard and vulnerability clusters have almost similar importance in terms of flood risk. On the other hand, water and sewerage administrations take the hazard class into consideration, while universities consider vulnerability more important than the other. Once the produced flood risk maps and correlation analyzes are examined, one can conclude that there are high perception differences between the judgments of the experts from universities and water and sewerage administration, while perception similarities can be seen among other stakeholders. Therefore, this study highlighted that the inclusion of only one type of stakeholder in the flood risk management system is not sufficient to evaluate the overall flood risk criteria. Instead, it was concluded that the participation of various stakeholders from different disciplines is required to make more reliable flood risk analyzes. Hence, the results of this study not only provide a flood risk maps showing the most flood-prone districts of Istanbul, but also reveal the perception differences among various stakeholders who are responsible for taking the necessary measures to reduce, prevent and manage the flood risk.

According to the findings obtained in the third of the articles published within the scope of the thesis, the income level, which is one of the criteria evaluated in the vulnerability class, not only affects all the vulnerability criteria, but also has been affected by the others (vulnerable structures, population density, vulnerable population, and education level). In addition, although the education level criterion affects all other criteria, it is only affected by the income level. Also, the population density criterion is almost as important as the education level according to the results of the study. The insight gained from the DEMATEL analysis has indicated that the population density is highly correlated with the education level and income level. Furthermore, the analyzes performed for the hazard cluster showed that the return period of a storm event is the most important criterion. Hence, especially considering extreme rainfall events where climate change has a great impact, district management authorities should take special measures such as flood-retardant structures and rainwater harvesting on their agenda to deal with the floods. In addition, storm water pipe networks and imperviousness criteria, which are among the other hazard related criteria, have been found to have very close importance to each other. At this point, the fact that districts with old or insufficient storm water drainage systems focus on these investments, increase the amount of green areas in districts where the land use includes urbanization intensively, or implement sustainable measures such as green roofs on existing buildings will make significant contributions to reducing the flood risk in the relevant regions and/or districts.

In general, within the scope of this thesis, comprehensive flood risk analyzes were carried out for Istanbul. In addition, not only flood risk mapping, but also the ways to be followed for strategies to reduce the flood risk in risky areas are pointed out. In this context, it is believed that the publications contained in this thesis will be useful for not only Istanbul but also entire country and will play a guiding role in taking the necessary actions.

KAPSAMLI BİR TAŞKIN RİSK DEĞERLENDİRMESİ VE OLASI RİSK AZALTMA STRATEJİLERİNİN BELİRLENMESİ

ÖZET

Taşkınlar ülkemizde ve Dünyada sıklıkla karşılaşılan doğal afetler arasında yer almaktadır. Her bölgenin bulunduğu coğrafi konum, jeolojik ve hidrolojik yapısı ve dahi demografik özellikleri farklı doğal afetlerin karakterize olmasını etkilediği düşünüldüğünde, Türkiye'de bu değişkenlerin ışığı altında en yaygın karşılaşılan doğal afetler taşkınlar olarak nitelendirilmektedir. Türkiye'de 1975-2015 yılları arasında toplam 1209 sel meydana gelmiş olup 720 kişinin ölümüne ve 900,000 hektarın su altında kalmasına neden olmuştur. Ayrıca taşkınlar yıllık ortalama 100 milyon dolarlık ekonomik kayba neden olmaktadır. Kıyısı olan bölgelerde gerçekleşen kıyı taşkınları, kırsal kesimlerde akarsu taşkınları ve yoğun yerleşim bölgelerinde ise kentsel sel olayları sıklıkla meydana gelmektedir. Bu bağlamda, özellikle popülasyon yoğunluklarının fazla olduğu kentlerde kentsel sel olayları sadece insan hayatlarına mal olmakla kalmayıp, aynı zamanda maddi açıdan ciddi hasarlara da neden olmaktadır.

İstanbul ili de kentsel taşkınlar ile sıklıkla yüzleşen iller arasında yer almaktadır. İstanbul, yaklaşık 16 milyon nüfusuyla (2986 kişi/km²) Türkiye'nin en yoğun nüfuslu şehridir ve ciddi sel riski altındadır. 2009 yılında Marmara bölgesinde meydana gelen sel olayı, özellikle İstanbul, Ayamama havzasında ciddi can kayıplarına ve ekonomik kayıplara yol açmış ve bunun sonucunda bölgede yoğunlaştırılmış çalışmalar yapılmıştır. Bu nedenle, bu tez kapsamında İstanbul ilinde meydana gelebilecek taşkınlar neticesinde etkilenebilecek bölgelerin belirlenmesi ve bu bölgelerin etkilenebilirliğini tetikleyen unsurların ortaya koyulması amaçlanmıştır. Gerek veri toplama prosedürleri gerekse de belirlenecek erken müdahale aksiyonlarının yönetimsel bazda etkinliğinin sağlanabilmesi adına analizler ilçe bazlı olarak gerçekleştirilmiştir. İlçe bazlı analizler kapsamında ise risk kavramının en kritik iki sac ayağı olan hem tehlike hem de hasar görebilirlik analizleri gerçekleştirilmiştir. Tehlike analizleri doğrultusunda, yağmursuyu alt yapı boru sistemleri, eğim, geçirimlilik durumu (eğri numarası cinsinden), yağışlı gün sayısı ve yağışların tekerrür periyotları değişkenleri ilçe bazlı olarak göz önünde bulundurulmuştur. Hasar görebilirlik analizleri kapsamında ise, hasar görebilir bina oranları, nufüs yoğunluğu, hasar görebilir nüfus oranı, eğitim seviyesi, gelir seviyesi, ulaşım ağı, hane halkı nüfusu ve arazi kullanımı kriterleri hesaba katılmıştır. Böylelikle, sadece taşkınların gerçekleşme ihtimali olan bölgeler değil, ayrıca taşkınlar neticesinde zarar görme potansiyeli olan sosyal çevreler de belirlenmeye çalışılmıştır.

Taşkın olaylarının tetiklenmesini sağlayan unsurların birçoğunun sayısal olarak ifade edilebildiği literatürce ortaya konulmuş bir gerçektir. Öte yandan, faktörlerin önem derecelerinin özellikle bölgesel olarak değişkenlik gösterebileceği de yadsınamaz bir gerçektir. Örneğin, ciddi yağış alan iki bölge karşılaştırıldığında kentsel yerleşimlerin yaygın olduğu bir bölge taşkın olaylarından ciddi anlamda etkilenebilecekken, görece daha kırsal kesimler aynı yağış olaylarından daha az etkilenebilmektedir. Benzer

şekilde, hemen hemen aynı iklim koşullarına sahip yerleşim bölgelerinde gelir seviyesi yüksek olan bölgelerde taşkın olaylarına karşı alınacak önlemler düşük olduğu bölgelerde farklılık gösterebilmektedir. Ayrıca, ulaşım ağının güçlü olduğu yerlerde herhangi bir afet anında afetzedelere kolaylıkla yardım götürme imkanı olduğu söz konusu iken, aynı şiddete sahip taşkın afetinde ulaşım yolları açısından daha az gelişmiş bölgelere yardım götürmenin zorlaştığı ve dolayısıyla, afet sonrası müdahalenin gecikmesi dolayısıyla daha büyük sonuçların doğacağı başka bir gerçektir. Tüm bu değişkenlikler hesaba katıldığında bu tez kapsamında gerçekleştirilen kapsamlı analizlerin yapılması bir gereklilik olarak karşımıza çıkmaktadır.

Taşkın riskine doğrudan etkisi olacak kriterlerin aralarındaki önem derecelerinin belirlenmesinde ise bölgeyi bilen ve konularında uzman profesyonellerden bilgiler alınması analizlerin sağlam temellere dayandırılmasını sağlamaktadır. Bu bağlamda, çok kriterli karar verme algoritmaları uzman bilgilerini önemli ölçüde sayısal sonuçlara dönüştürerek ilgilenilen bölgelere ait kriter bazlı verileri ile de entegre biçimde çalışmak suretiyle araştırmacılara yerinde tespitlerin gerçekleştirilmesinde olanaklar tanımaktadır. Dolayısıyla, bu tez çalışmasında yer alan araştırma makalelerinde İstanbul ili ilçe bazlı taşkın risk haritalaması gerçekleştirilirken çok kriterli karar verme algoritmalarından yararlanılmıştır. Tez kapsamında yayınlanan ilk araştırma makalesinde bulanık analitik hiyerarşi süreci kullanılarak ilçe bazlı taşkın risk haritalaması gerçekleştirilerek riskli ilçeler ve bu ilçelere yönelik için önlem alınması gereken kriterler belirlenmiştir. Tez kapsamında yayınlanan ikinci araştırma makalesinde ise İstanbul ili ölçeğinde taşkın risk kavramı üzerinde paydaş görevi gören dört farklı kurumun (İstanbul Su ve Kanalizasyon İdaresi, Afet Koordinasyon Merkezi, İstanbul Büyükşehir Belediyesi ve Üniversiteler) taşkın riski üzerine algı farklarının ortaya koyulması gerçekleştirilmiştir. Bu işlemler için ise yöntemsel açıdan ilk çalışmada kullanılan bulanık analitik hiyerarşi süreci metoduna ilaveten technique for order of preference by the similarity-to-ideal-solution (TOPSIS) metodu entegre edilmiştir. Yapılan analizler neticesinde önerilen melez çok kriterli karar verme çerçevesinde genel bir risk haritası üretilmiş olup hem de her bir paydaşın görüşleri neticesinde ayrı ayrı risk haritaları oluşturulmuştur. Tez kapsamında yayınlanan üçüncü araştırma makalesinde ise, daha önceki iki çalışmada incelenmeyen kriterlerin kendi aralarındaki etkileşimlerine odaklanılmıştır. Öte yandan yöntemsel olarak literatürde ilk kez olacak şekilde bir çerçeve içerisinde iki ayrı (analitik hiyerarşi süreci tehlike sınıfı için ve analitik bağlantı süreci hasar görebilirlik sınıfı için) kriter ağırlıklandırma yöntemleri bir arada kullanılarak analizler gerçekleştirilmiştir. Bu noktada ilgili literatüre yöntemsel olarak katılan bir diğer yenilik ise analitik bağlantı süreci çerçevesinin oluşturulmasında kullanılan Decision-making trial and evaluation laboratory (DEMATEL) yönteminin entegre edilmesidir. TOPSIS metodunun geliştirilmiş versiyonu olarak kabul edilen visekriterijumska optimizacija i kompromisno resenje (VIKOR) yöntemi ise ifade edilen iki farklı kriter ağırlıklandırma yönteminden elde edilen çıktıları girdi olarak kullanarak ve bu ağırlık değerlerine kriterlerin sayısal değerlerini entegre ederek ilçeler arası bir önceliklendirme gerçekleştirmiştir.

Tez kapsamında yayınlanan makalelerin birincisinde elde edilen bulgulara göre arazi kullanımı, nüfus yoğunluğu ve hasar görebilir bina oranı en önemli hasar görebilirlik kriterleri olarak belirlenirken, yağış tekerrür periyodu, geçirimlilik ve yağmur suyu altyapı sistemleri en önemli tehlike kriterleri olarak elde edilmiştir. Öte yandan, ana sınıflar olan hasar görebilirlik ve tehlike sınıfları arasındaki karşılaştırma ise bu iki sınıfın taşkın risk kavramı açısından hemen hemen birbirine eşit önem derecelerine işaret etmiştir. Ayrıca, bulanık analitik hiyerarşi süreci yönteminin stabilizasyonunun sağlanması adına gerçekleştirilen hassasiyet analizleri de yöntemin sağlamlığını ve doğrulanmasını önemli ölçüde desteklemiştir. İlçe bazlı yapılan analizlere göre ise, Bayrampaşa, Bağcılar ve Esenler nüfus yoğunluklarının da önemli etkisi ile en riskli üç ilçe olarak bulunmuştur. Taşkın olaylarının gerçekleşme ihtimallerini temsil eden tehlike kriterlerine göre ise Üsküdar, Bayrampaşa ve Bağcılar bölgeleri ön plana çıkarken, taşkınlardan hasar görebilirlik çerçevesinde yapılan analizlere göre Gaziosmanpaşa, Güngören ve Beyoğlu bölgelerine özel önlemlerin alınması gerektiği sonucuna varılmıştır.

Tez kapsamında yayınlanan makalelerin ikincisinde elde edilen bulgulara göre afet yönetimi ve koordinasyon yetkililerinin ve yerel belediyelerin taşkın tehlikesi ve hasar görebilirlik sınıfları bakımından neredeyse benzer bir öneme sahip olarak değerlendirdiğini göstermektedir. Öte yandan, su ve kanalizasyon idareleri tehlike sınıfını önemli ölçüde dikkate alırken, üniversiteler hasar görebilirliği diğerinden daha önemli görmektedir. Oluşturulan sel risk haritaları ve korelasyon analizleri dikkate alındığında, üniversiteler ve su ve kanalizasyon idareleri uzmanları arasında yüksek algı farklılıklarının olduğu, diğer paydaşlar arasında ise büyük oranda algı benzerliklerinin görülebildiğine işaret edilmiştir. Bu nedenle, bu çalışma, yalnızca tek tip paydaşın taşkın risk yönetimi sistemine dahil edilmesinin taşkın risk kriterlerini değerlendirmek için yeterli olmadığının göstergesi olmuştur. Bunun yerine, daha güvenilir taşkın risk analizleri yapmak ve bu analizler neticesinde haritalar oluşturmak için farklı disiplinlerden çeşitli paydaşların katılımı gerekli olduğu sonucuna ulaşılmıştır. Dolayısıyla, bu çalışmanın sonuçları sadece İstanbul'un sel afetine en yatkın ilçeleri gösteren bir sel risk haritası sunmakla kalmayıp, aynı zamanda sel riskini azaltmak, önlemek ve yönetmek için gerekli önlemleri almaktan sorumlu olan çeşitli paydaşlar arasındaki algı farklılıklarını da ortaya koymuştur. Bu durum ise taşkın riskiyle başa çıkmak için stratejiler geliştiren ve yapılacak yatırımları organize eden karar vericilerin algılarına ilişkin bulgulardan yararlanılabilmesi açısından oldukça önemlidir.

Tez kapsamında yayınlanan makalelerin üçüncüsünde elde edilen bulgulara göre hasar görebilirlik sınıfı içerisinde değerlendirilen kriterlerden biri olan gelir seviyesi sadece tüm hasar görebilirlik kriterlerini etkilemekle kalmayıp, aynı zamanda diğerlerinden (hasar görebilir bina oranı, nufüs yoğunluğu, hasar görebilir nufüs oranı, eğitim seviyesi) de etkilenmiştir. Ayrıca, eğitim seviyesi kriteri ise diğer tüm kriterleri etkilemekle birlikte sadece gelir seviyesinden etkilenmiştir. Nüfus yoğunluğu kriterinin de neredeyse eğitim seviyesi kadar önemli çıktığı çalışma sonuçlarına göre, DEMATEL analizi neticesinde elde edilen bilgiler nufüs yoğunluğunun eğitim seviyesi ve gelir seviyesi ile oldukça ilişkili olduğu sonucuna varılmıştır. Tehlike sınıfını içeren analizler ise yağış tekerrür periyodunun en önemli kriter olarak bulunduğuna işaret etmiştir. Özellikle iklim değişikliğinin büyük etkisi olduğu yağış olayları hususunda ilçelerin taşkın geciktirici yapılar ve yağmur suyu hasadı gibi özel önlemleri gündemlerine almaları gerekmektedir. Ayrıca, diğer tehlike sınıfı kriterlerinden olan yağmur suyu altyapı sistemleri ve geçirimlilik kriterleri de birbirlerine oldukça yakın öneme sahip olacak şekilde bulunmuştur. Bu noktada, yağmur suyu alt yapı sistemleri eski veya yetersiz olan ilçelerin bu yatırımlara odaklanması, arazi kullanım yapısının kentleşmeyi yoğun olarak içerdiği ilçelerin ise yeşil alan miktarlarını artırması veya mevcut binalara yeşil çatılar gibi sürdürülebilir önlemleri hayata geçirmesi ilgili bölge ve ilçelerde taşkın riskinin azaltılmasına oldukça önemli katkılar yapacaktır.

Genel olarak bakıldığında, bu tez kapsamında İstanbul ili için kapsamlı taşkın risk analizleri gerçekleştirilmiştir. Ayrıca, sadece taşkın risk haritalama ile kalınmayıp, riskli olarak bulunan bölgelerde taşkın riskini azaltıcı stratejiler için de izlenebilecek yollara işaret edilmiştir. Bu bağlamda, İstanbul ili özelinde hazırlanan bu tezin içerdiği yayınların ve bu yayınlar neticesinde edinilen bulguların tüm ülkemize faydalı olabileceği ve gerekli aksiyonların alınması için bir yol gösterici rol oynacağına inanılmaktadır.

1. INTRODUCTION

Floods, among the most frequent and severe hazards in the world, threatens the sustainability of built environment with a massive loss by means of infrastructures, buildings, economies, social activities, and beyond all, lives. As an initial exploration, preliminary studies which are conducted for the identification of key points to be addressed in flood risk management (FRM) processes are crucial to mitigate potential impacts of floods. In addition, multi-dimensional risk assessment strategies aided by the active participation of stakeholders are essential to combat flood events for metropolitan cities. Thus, generating the flood risk maps with the participation of diverse stakeholders at each level of administration is essential to develop effective FRM strategies.

The pertinent literature has recognized the importance of preliminary studies to combat flood incidents (Shahabi et al, 2021). Thus, flood risk maps are produced and the strategies are determined in this regard. Identification of pre-flood strategies and early-diagnosis of most triggering factors became prominent especially in the last decade (Chapi et al, 2017; Khosravi et al, 2018). To accomplish these goals, advanced techniques have been used proposed. The relevant literature suggests applying a wide spectrum of methodologies, such as statistical methods, machine learning algorithms, numerical techniques, and modern modeling tools (Costache et al, 2020). Moreover, with the introduction of multi-criteria decision-making algorithms, combining the qualitative and quantitative aspects of flood phenomena has been performed by the research community (Ekmekcioğlu et al, 2021a). Thus, the application of multi-criteria decision-making techniques has gained much momentum to deal with the hard-to-repair effects of flood-related problems during recent years (Souissi et al, 2020; Tella and Balogun, 2020). Accordingly, there have been countless efforts regarding the utilization of multi-criteria decision-making algorithms to determine flood-prone areas.

Scholars have broadly implemented various multi-criteria decision-making (MCDM) techniques in flood mapping, in which those techniques are commonly comprised of the factors with regards to two main pillars of flood risk concept, i.e., hazard and vulnerability. On the one hand, taking flood hazard factors into consideration is relatively more practical as the criteria required to obtain hazardous consequences are easy-to-find and mostly related to the topographical and hydrological characteristics of the focalized regions (Abedi et al, 2021). On the other hand, a minority of the research society has focalized the examination of vulnerability criteria as gathering adequate information regarding human-related variables is a challenging task (De Brito et al, 2018). Furthermore, the records of flood inventories could be acquired from the relevant authorities especially in developed countries, or the researchers widely applied up-to-date sources which can be regarded as satellite-derived remote sensing data as the validation of produced flood maps is essential (Costache et al, 2020). Here, plenty of criteria regarding hazard cluster (i.e., elevation, slope, aspect, curvature, topographic wetness index, sediment transport index, temperature, rainfall, storm frequency, evapotranspiration, curve number, soil group, soil moisture, lithology, land use/land cover, distance to road, etc.) and vulnerability cluster (i.e., vulnerable structures, population density, vulnerable population, education level, income level, transportation network, number of households) are considered to generate flood mapping in addition to the flood inventories in MCDM studies (Ekmekcioğlu et al, 2022). It is worth to note that the first attempts have begun with the adoption of classical methods such as pairwise comparisons, weighted overlay method, entropy weight method, while the more complex algorithms such as analytic hierarchy process (AHP), fuzzy AHP, analytic network process (ANP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and VIse KriterijumsaOptimiz acija I Kompromisno Resenje (VIKOR), have been integrated recently within the scope of MCDM applications in flood mapping domain.

Overall, the major purpose of this thesis is to generate the flood risk map of Istanbul which is the most densely populated industrial, commercial and cultural center of Turkey. Especially considering the fact that the population of Istanbul has been increasing over the last decades since the city attracts ongoing migration from all over Turkey along with other countries, it is of paramount significance to prioritize districts of Istanbul in terms of flood risk. Furthermore, this thesis also presents several mitigation strategies to combat flooding incidents.

The second chapter of the thesis contains the prioritization of the districts of Istanbul with respect to flood risk by using fuzzy analytical hierarchy process and generation of the corresponding flood risk maps. In addition, evaluation of the criteria importance affecting the flood risk in Istanbul was performed and specific recommendations were made for the district that have found as risky in terms of flood risk.

The third chapter comprised the application of hybrid fuzzy AHP and TOPSIS methodology to identify the perceptions of different stakeholders that have significant responsibilities in the assessment of flood risk in Istanbul. Besides, district-based vulnerability, hazard, and flood risk maps for Istanbul were produced to prioritize the districts of Istanbul with respect to the judgments of each stakeholder.

The fourth chapter of the thesis containing further investigations regarding different MCDM techniques mainly aimed to illustrate the interrelationship among the criteria through a multi-tiered comprehensive decision-making procedure. In this chapter, a neoretic approach covering the separate implementation of AHP and ANP has been proposed, in which the first applied to the hazard cluster, while the latter was considered in evaluating the vulnerability cluster.

Finally, concluding remarks are summarized in the last chapter along with the implications to the flood risk practitioners and the recommendations to the researchers for the follow up attempts.

2. DISTRICT BASED FLOOD RISK ASSESSMENT IN ISTANBUL USING FUZZY ANALYTICAL HIERARCHY PROCESS[1]

2.1 Introduction

Floods are among the most frequent and severe hazards in the world, causing massive economic losses, failure in infrastructures, disruption in social activities, and beyond all, serious number of losses of life. In addition to the increasing trend of the flood frequencies over the last decades, it is estimated to increase in the future due to 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 remains to damage 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 to become a disaster (Bertilsson et al, 2019) by resilient social, economic and political infrastructures. In addition, many geomorphological parameters such as total drainage area, average slope, shape of the basin, soil structure and infiltration capacity could also play a crucial 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; Risi et al, 2020, Yusmah et al, 2020) and quantitative (Darabi et al, 2019; Stoleriu et al, 2020; Tariq, 2013; Tehrany et al, 2015; Zaharia et al, 2017) manner. In this respect, multi-criteria decision making (MCDM) tools are commonly used approaches to deal with both qualitative and quantitative data sources (Hammond et al, 2015). One of the most widely used MCDM tools, analytical hierarchy process (AHP), has been proposed as a combination of qualitative and quantitative approaches, and is based on the principle

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[1] This chapter is based on the paper "Ekmekcioğlu, Ö., Koc, K. and Özger, M. (2021). District based flood risk assessment in Istanbul using fuzzy analytical hierarchy process. Stochastic Environmental Research and Risk Assessment, 35(3), 617–637. 10.1007/s00477-020-01924-8".

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 fuzzy set theory could be useful to consider inherent fuzziness in the FRM applications (Büyüközkan and Feyzioğlu, 2004; Evers et al, 2016), iv) it is suitable with group decision making (Darko et al, 2019), v) analysis with small sample size could provide meaningful and reliable results (Darko et al, 2019). These features of fuzzy AHP approach highlight the significance of the method compared to other MCDM tools.

In Turkey, a total number of 1209 floods have taken place between 1975 and 2015, resulting in 720 death tolls and 900,000 ha submerged areas. In addition, floods have caused an average of $100 million economic losses yearly according to the Ministry of Agriculture and Forestry of Turkey. Istanbul is the most densely populated city in Turkey (2986 people/km^2), and is under serious flood risk with nearly 16 million residents (Url-10). The flood event in Marmara region in 2009 left serious casualties (at least 31 people) and economic losses, particularly in Istanbul, Ayamama basin, which resulted with the intensified studies in the region (Altunkaynak and Bizimana, 2020; Gülbaz et al, 2019; Kömüşcü and Çelik, 2013; Nigussie and Altunkaynak, 2016). Thus, such 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 on 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. Particularly with the integration of GIS, AHP and fuzzy AHP methods have been regarded as alternative approaches to produce flood risk maps by several authors (Aher et al, 2013; Dahri and Abida, 2017; Hammami et al, 2019; Meshram et al, 2019; Papaioannou et al, 2015; Sepehri et al, 2020; Stefanidis and Stathis, 2013; Wang et al, 2011a). However, in the past literature: i) the criteria included for flood risk map 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) used in the AHP method to ensure the reliability of the survey instrument, 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 degree of fuzziness 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 lacks, the cornerstone of this research is to prioritize districts of Istanbul in the sense of flood risk, by considering both vulnerability and hazard clusters, covering all the requirements of fuzzy AHP method. The specific objectives of this study can be summarised as follows:

- Determination of vulnerability and hazard criteria that is appropriate to develop 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 fuzzy AHP method to calculate weights of criteria,
- Developing flood risk map of Istanbul through integrating collected data with the results of 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 such a comprehensive assessment made for Istanbul yet, the findings of this research can be used by water resource authorities, disaster management institutions and governmental authorities to mitigate flood risk along with allocating fair budget to the local municipalities for flood risk mitigation measures.

2.2 Studies on Flood Risk Mapping

Recently, different perspectives have gained significance for making preliminary planning for floods, whose predictability has become increasingly difficult due to the impact of global climate change on atmospheric processes. One of these preliminary approaches, which increased the interest of researchers in recent years, is flood mapping. There are a variety of maps generated in the sense of flood such as flood depth maps, flood propagation maps, flood hazard maps, flood duration maps, rate of rising of the water, flood vulnerability, and eventually flood risk maps. In this context, 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 variety of researchers by adopting different approaches such as hydro-geomorphological (Bourenane et al, 2019), statistical (Giovannettone et al, 2018; Liu et al, 2016; Pham et al, 2020; Tehrany et al, 2014), statistical-hydrological (Binh et al, 2019), numerical (Li et al, 2017; Motevalli and Vafakhah, 2016) 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 assess flood risk in various research areas such as transportation systems (Lyu et al, 2019), protected areas (Hategekimana et al, 2018a; Wang, 2015), urban areas (Li et al, 2013) and watersheds (Zou et al, 2013), which received the greatest research focus.

A few of the similar studies using MCDM methods for flood mapping are provided in Table 2.1. Wang et al. (2011a) integrated fuzzy AHP method with GIS through the spatial multi criteria analysis approach. They determined flood risk criteria using the Delphi method, and assessed flood risk of Dongting Lake region with the stepwise questionnaire by reducing the criteria to a practicable number. As a result, by categorising the study area into 5 risk categories, they found the extent of flood risk for each zone. In another study, where the weights of flood vulnerability and hazard criteria were also specified by using fuzzy AHP method, Zou et al. (2013) obtained grades with an approach, in which set pair analysis (SPA) and variable pair fuzzy sets (VFS) were combined. 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 fuzzy AHP analysis and found that rainstorm and population density were the most significant sub-criteria with respect to triggering and vulnerability main criteria, respectively. Papaioannou et al. (2015) compared AHP and fuzzy AHP methods for flood risk assessment of Xerios Basin, Greece, which was the historical inundation area. They aimed to find potential flood prone areas for particularly ungauged watersheds, and the established model has been validated with the flood occurred in 2006. Wu et al. (2017) determined the criteria weights using the AHP method and investigated the flood risk variations due to climate change. By integrating GIS data sources with MCDM algorithms, Das (2018) used AHP to evaluate criteria weights and categorized flood prone areas. They found that nearly 20% of the total study area, Vaitarna basin, India, had very high flood potential. Hategekimana et al. (2018a) created flood hazard index map by using 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 with regards to these parameters. They determined the priority weights by using both AHP and fuzzy AHP, and conducted the evaluations by dividing potential vulnerable zones into 5 different priority types.

Furthermore, the official attempts were also conducted to prepare flood risk maps for Istanbul; such that flood hazard maps were produced for both the European and Asian sides by Istanbul Metropolitan Municipality (IBB), as 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. A possible dam failure as cause of earthquake and tsunami were considered. Analyses were performed for the 10mx10m 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 obtained by calculating the excessive water flooding amount for each grid. Another attempt for the development of flood hazard map in Istanbul was performed by Yalçın (Yalçın, 2012). The researcher used 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 European side of Istanbul. Flood risk map of Istanbul was generated by 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 map of Istanbul city.

Table 2.1 : 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. (2011a)	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
Gigovic 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. (2018a)	Mombasa county	Kenya	219	Hazard	6	FAHP	N/A	N/A	Consistent
Hammami et al. (2019)	North-east of Tunusia	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. (2020)	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**

Note: 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.

2.3 Study Area and Data

The focus of this study is the Istanbul city located in northwest part of Turkey. With a surface area of 5461 km², the city ascends between the Black Sea in the north, and the Marmara Sea in the south, with the Bosphorus in the middle dividing two continents, Europe and Asia (Figure 2.1). Istanbul 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.

The highest point of the city is Aydos Hill with a height of 537 meters, 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 with urban groves. The climate of Istanbul is mild due to its transition features between the Black Sea climate and the Mediterranean climate. While the summers of Istanbul are hot and humid, the winters are often cold, rainy and sometimes snowy (Nefeslioglu et al, 2010). The average temperature in winters is around 2°C to 9°C, while it is about 18°C and 28°C in summers. The hottest months are July and August with the average temperature of 23°C, while the coldest months are January and February with that of 5°C. The city' annual average temperature is 13.7°C (URL-1). Furthermore, total annual precipitation of Istanbul is 843.9 mm and it occurs year around. 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, especially Ömerli, Terkos and Büyükçekmece Dams, located both sides of the city. An annual yield of 1.6 billion cubic meters is obtained from these dams (URL-2). Besides, related institutions and organizations are in quest for not only the new water resources, but also flood prevention strategies due to the increasing population and inevitable urbanization.

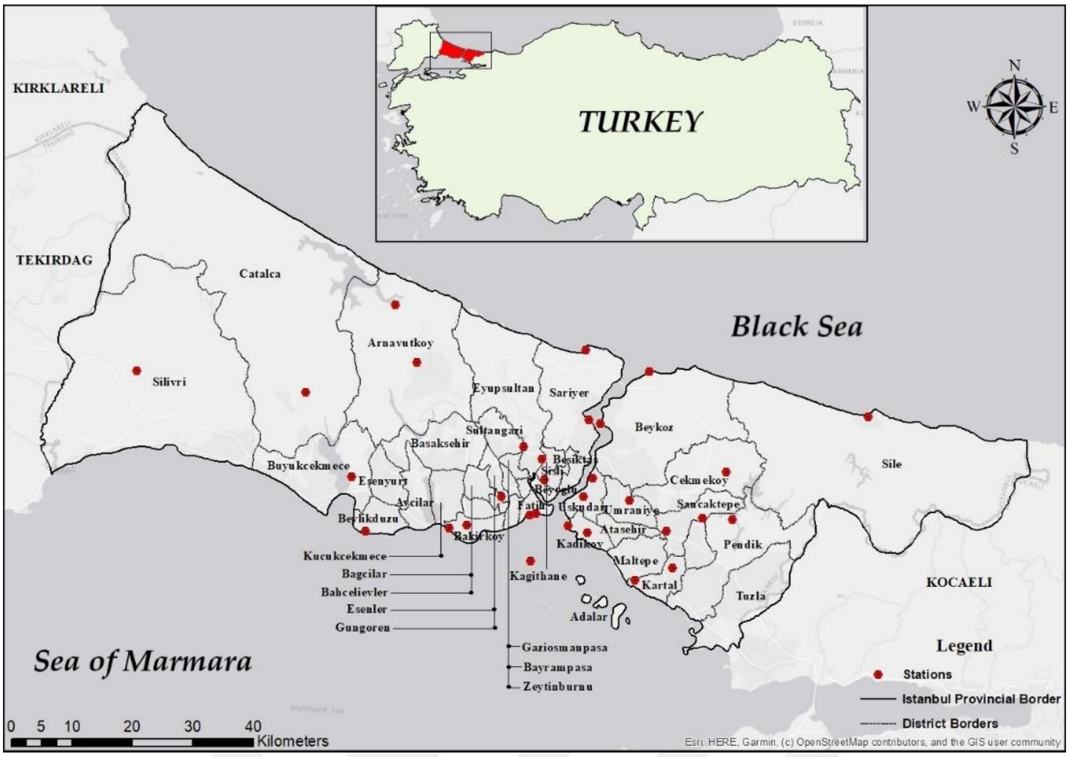

Figure 2.1 : Study area.

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 vulnerability and hazard elements. In this context, required criteria has been determined through literature survey based on the necessities and FRM problems in Istanbul. Then, data availability and accessibility were also taken into account to develop decision framework. A number of 13 criteria were considered with varying perspectives according to the recommendations of the experts attended to the pilot study. The criteria required to generate the district basis flood risk map of Istanbul is provided in Table 2.2, with corresponding references, explanations and data sources. In this study, some significant vulnerability criteria that have rarely investigated in the past studies were also included. In this context, structural vulnerability of buildings, education level of residents with respect to flood risk awareness, and number of households with respect to emergency aid and occupancy was also included in the proposed model based on recommendations of the pilot study participants (Table 2.2). Built year of the structures is of critical importance in the assessment of 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 number of old and historical buildings in Istanbul, in addition to the ongoing new construction projects. Also, inclusion of 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, average number of households could be related to the occupancy of buildings as well as considering emergency aid within the family members, and dwellers inhabit in the same building.

Table 2.2 : 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), URL-3
	Population density (N/km2)	PD	Wang et al. (2011a)	Increase in the population density could increase the possible exposed individuals during flood.	URL-4, URL-5
	Vulnerable population (Age)	VP	Binh et al. (2019)	This criterion considers the vulnerability of the population according to their ages.	URL-5
	Education level	EL	Pilot Study	The criterion was included to highlight the level of awareness of the population.	URL-6
	Income level	IL	Dang et al. (2011)	People with low income could become more vulnerable for post disaster mitigation measures.	URL-6
	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.	URL-7
	Number of household (Average)	NH	Pilot Study	Increase in the number of households can increase the emergency aid within family.	URL-6
	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 km2)	*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.	URL-8
	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 storm event (year)	*RP	Wang et al. (2011a)	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

Note: 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

It should also be noted the way some of the criteria are handled were changed by pilot study participants (Table 2.2). For instance, return period of storm event (RP) was recommended by pilot study participants instead of average rain to provide better results. In addition, transportation network was also discussed during pilot and pilot study participants recommended to use the number of bus stops in each districts of

Istanbul to estimate transportation network since the locations of bus stops can be regarded as one of the mobility parameters during floods (Freire et al, 2016).

2.4 Methodology

The research methodology followed in this study involves three main steps (Figure 2.2). In the preliminary step, flood risk criteria were identified through literature survey and finessed with pilot studies. Since flood risk is a function of flood hazard and flood vulnerability (Dang et al, 2011), the structure was organized based on these two fundamental sources of flood risk. Four group 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 centres. Pilot studies with four experts, including one expert from each target group, were performed to fines the predetermined criteria with respect to flood problems in Istanbul. The hierarchic representation of the finessed framework is illustrated in Figure 2.3. AHP hierarchy was structured due to its several advantages in making critical decisions (Budayan, 2019; Darko et al, 2019; Gurgun and Koc, 2020; Yang et al, 2013). In addition, AHP is one of the most widely used MCDM tools in flood risk management literature (De Brito and Evers, 2016).

Profile, experience and quality of the experts attended to AHP survey is of crucial significance (Darko et al, 2019) since created maps directly related to the data provided by them. Thus,15 experts were selected to attend the AHP survey, including those attended to pilot studies, by using judgment sampling (Budayan, 2019). Therefore, the background and experience of each professional was deeply investigated, and they were selected according to their positions in flood risk management practices 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.

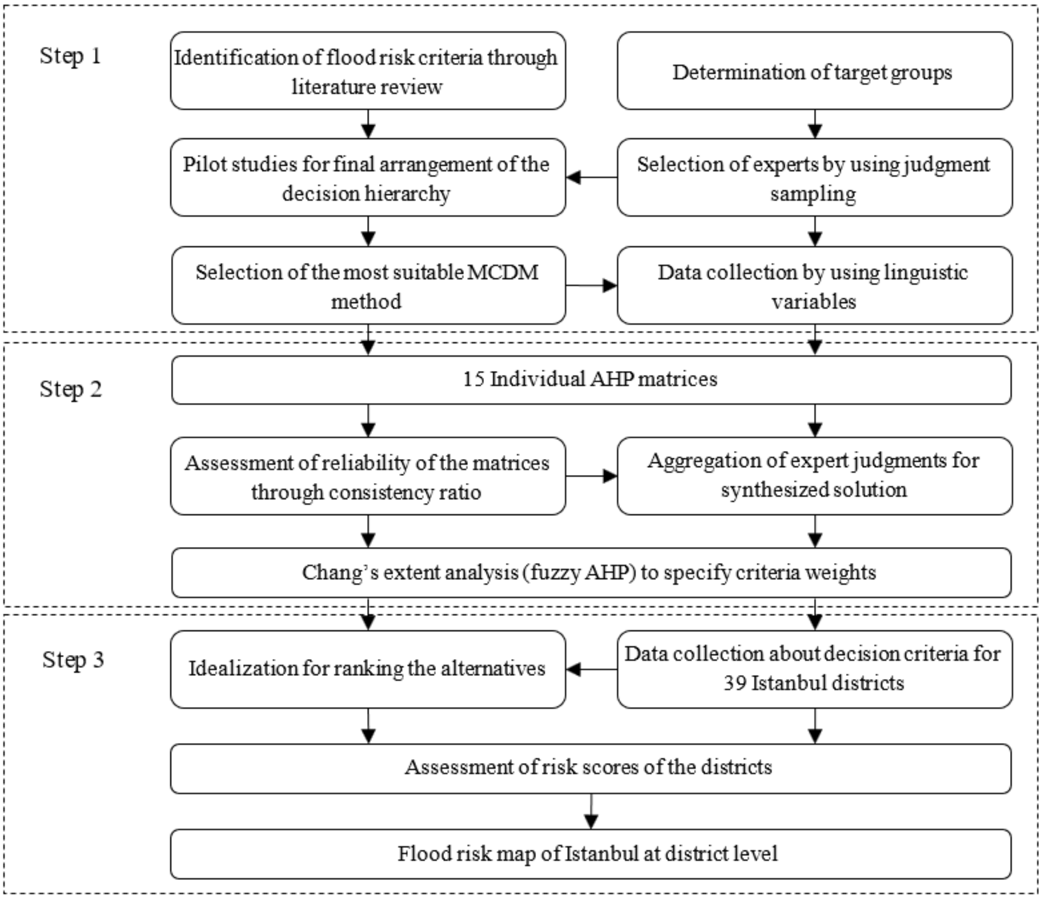

Figure 2.2 : Flowchart of the study.

In the second step, the reliability of the experts were 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 1 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 were not considered in the following calculations. The profile of the experts attended to the questionnaire survey for consistent judgments is provided in Table 2.3. Despite numerous advantageous of AHP method, it does not consider fuzziness and uncertainty; yet judgments of subjective experts by using precise values may result in less reliable outcomes. Thus, traditional AHP has widely been criticized for its failure to precisely handle the uncertain nature of the problems (Vahidnia et al, 2009; Yang et al, 2013). Based on the fuzzy set theory introduced by Zadeh (Zadeh, 1965), different fuzzy AHP approaches were developed and Chang's extent analysis (Chang, 1996) is one of the most widely adopted approaches. Therefore, fuzzy AHP method was employed to determine criteria weights in this study. AHP and fuzzy AHP methods have commonly been adopted for similar purposes to map flood risk zones in the literature (Table 2.1). Therefore, the judgments of 14 consistent experts, who provided pairwise comparisons of AHP matrices in face-to-face interviews, were converted to the triangular fuzzy numbers and aggregated to achieve synthetized solution. Chang's (1996) extent analysis method was applied to determine criteria weights by considering fuzziness and subjectivity in the judgments of the participants.

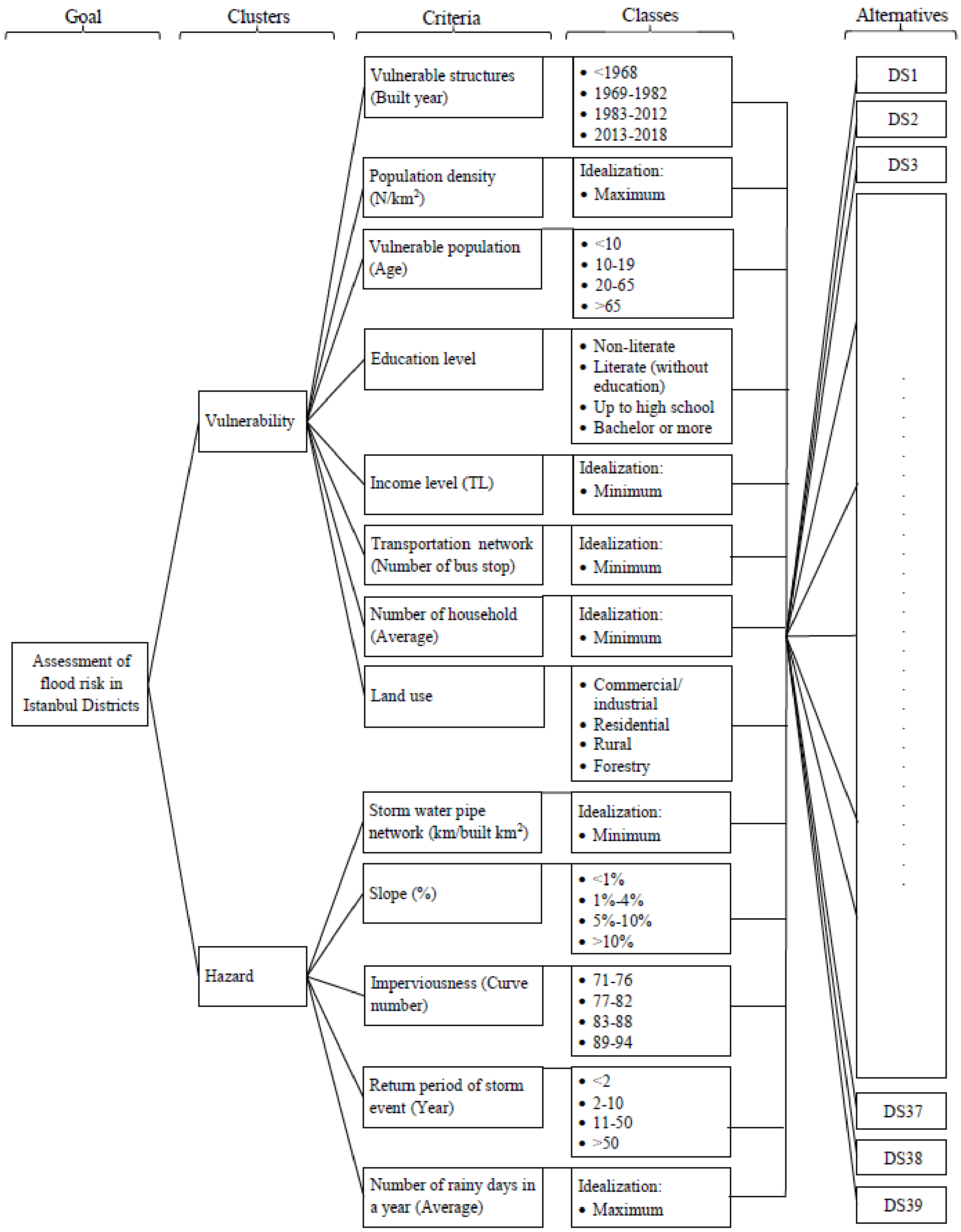

Figure 2.3 : Hierarchical framework of the study.

Table 2.3 : 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	Meteorologica l engineer	26
E4	Planning manager	Disaster management and coordination	Planning	Civil engineer	18
E5	Meteorological Engineer	Disaster management and coordination	Meteorology	Meteorologica l 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.

In the last step, data about all decision criteria for each district were collected from related institutions (Table 2.2). 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 generate 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 2.2 are open access and available in 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.

2.4.1 Fuzzy Analytical Hierarchy Process

To obtain the weight of each thirteen criteria the FAHP method was employed. There are five main steps in the application of FAHP method.

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 FAHP method is provided in Table 2.4, along with the importance values used in AHP method (Papaioannou et al, 2015; Vahidnia et al, 2009). l_{ij}, m_{ij} and u_{ij} are lower width, mean, and upper width of the pairwise comparison of experts for criterion i, with respect to criterion j, respectively.

Table 2.4 : AHP and FAHP linguistic scales.

	AHP		Fuzzy AHP	
Linguistic variables	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)
İntermediate 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)
İntermediate 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)
İntermediate 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)
İntermediate 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)

Step 2. Consistency check:

The procedures used in traditional AHP was used prior to the FAHP analysis to calculate the CR values, thus validating the reliability of the experts (Suganthi, 2018; Vahidnia et al, 2009). The CR values should be calculated for each individual expert to ensure the reliability of the aggregated judgments (Suganthi, 2018). If the value of CR is found less than 0.1, the judgments can be considered as consistent (Saaty, 1990), otherwise the corresponding expert should be asked to rearrange the judgments. CR can be calculated by equation (2.1) and equation (2.2):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2.1}$$

$$CR = \frac{CI}{RI} \qquad (2.2)$$

where λ_{max} is the largest eigenvalue of a pairwise comparison matrix, n is the dimension of the matrix, CI is the consistency index, and RI is the random index defined for each n value in Saaty (Saaty, 2004). Table 2.5 illustrates CR values attained from the first rounds of expert decisions, excluding the one 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).

Table 2.5 : 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%

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}, geometric mean of m_{ijk}, and maximum of u_{ijk}, resulting in the aggregated triangular fuzzy numbers (l_{ij}, m_{ij}, u_{ij}) by equation (2.3) (Büyüközkan and Feyzioğlu, 2004; Chang et al, 2009):

$$l_{ij} = min(l_{ijk}), \qquad m_{ij} = \left(\prod_{k=1}^{K} m_{ijk}\right)^{1/K}, \qquad u_{ij} = max(l_{ijk}) \qquad (2.3)$$

where K is the total number of respondents.

Step 4. Chang's extent analysis:

After the individual judgments were aggregated, Chang's (1996) extent analysis method was applied to tackle the inherent uncertainty of human decision making process. This method uses crisp mathematical concepts to indicate fuzzy quantities. Let $X = \{x_1, x_2, x_3, \dots \dots \dots, x_n\}$ an object set, and $U = \{u_1, u_2, u_3, \dots \dots \dots u_m\}$ a goal set. Each object is taken and extent analysis for each goal is conducted respectively. Thus, m extent analysis values can be acquired for each object. The value of the fuzzy synthetic extent, with respect to object i can be calculated by using equation (2.4):

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \times \left[\sum_{j=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \tag{2.4}$$

where M_{gi}^{j} is a triangular fuzzy number. To obtain $\sum_{j=1}^{m} M_{gi}^{j}$, the operational laws of two triangular fuzzy numbers are performed by equation (2.5):

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j \, , \sum_{j=1}^{m} m_j \, , \sum_{j=1}^{m} u_j \right) \tag{2.5}$$

and to calculate $\left[\sum_{j=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1}$, the fuzzy addition operation of $M_{gi}^{j}(j = 1, 2, \dots \dots \dots, m)$ values is conducted through equation (2.6):

$$\left[\sum_{j=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right] = \left(\sum_{j=1}^{m} l_j \, , \sum_{j=1}^{m} m_j \, , \sum_{j=1}^{m} u_j \right) \tag{2.6}$$

Then, the inverse of the vector above is calculated by using equation (2.7):

$$\left[\sum_{j=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} = \left(\frac{1}{\sum_{j=1}^{n} u_i}, \frac{1}{\sum_{j=1}^{n} um_i}, \frac{1}{\sum_{j=1}^{n} l_i} \right) \tag{2.7}$$

The degree of possibility can be calculated 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 two triangular fuzzy numbers, the degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined through equation (2.8):

$$V(M_2 \geq M_1) = \sup_{y \geq x}\left[\min\left(\mu_{M1}(x), \mu_{M2}(y)\right)\right] \tag{2.8}$$

which can be expressed by equation (2.9):

$$V(M_2 \geq M_1) = htg(M_1 \cap M_2) \\ = \begin{Bmatrix} 1 & if\ m_2 \geq m_1 \\ 0 & if\ l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{Bmatrix} \tag{2.9}$$

In order to compare M_2 and M_1, both $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$ is required.

The degree of possibility for a convex fuzzy number to be higher than k convex fuzzy M_i $(i = 1,2, \dots, k)$ numbers is defined by equation (2.10):

$$V(M \geq M_1, M_2, \dots\dots, M_k) = V[(M \geq M_1) \text{ and } (M \geq M_2), \dots, \text{ and } (M \geq M_k)] = minV(M \geq M_i) \tag{2.10}$$

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

Assume that, $d'(A_i) = \min V(S_i \geq S_k)$ for k =1, 2, …, n; k ≠ i, then the weigh vector (W') can be computed by equation (2.11):

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T \tag{2.11}$$

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

Via normalization, the normalized weight vectors are calculated using equation (2.12):

$$W = \left(d(A_1), d(A_2), \dots, d(A_n)\right)^T \tag{2.12}$$

Step 5. Sensitivity analysis:

Sensitivity analysis based on degree of fuzziness used in fuzzy AHP method is essential to indicate stability of the proposed frameworks. Therefore, in the final step of FAHP analysis, the sensitivity analysis can be performed to explore how the criteria weights and rankings vary as a result of changes in the degree of fuzziness. Initial value of the degree of fuzziness in the adopted FAHP method was 1, as the distance between l, m and u values (Table 2.4). 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).

2.4.2 Idealization

Idealized weights are obtained by dividing each element of the relative weight array by its largest element (Rao, 2007). In this study, idealization technique was adopted to assign the overall criteria weights to the most risky districts. This idealized solution makes the value of most risky district as 1 with respect to corresponding criterion, while proportionally less for the other districts (Saaty, 2004).

As to the positive criteria, in which higher values indicate more flood risk, the maximum approach was adopted using equation (2.13). Besides, the minimum approach was applied to the negative criteria by using equation (2.14), in which lower values indicate more flood risk.

$$v_{id} = \frac{x_i}{x_{imax}} \tag{2.13}$$

$$v_{id} = \frac{x_{imin}}{x_i} \tag{2.14}$$

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.

Since more risky classes were given more extreme points in FAHP matrices, only maximum method is required for idealization of criteria consisting of classes. Prior to the idealization, idealized weight of each class was multiplied with corresponding values of the criteria through equation (2.15):

$$v_{id} = \sum_{j=1}^{k} x_{ij}.c_j \times \left[\left(\sum_{j=1}^{k} x_{ij}.c_j\right)_{max}\right]^{-1} \tag{2.15}$$

Where k is the number of classes, x_{ij} is an initial data of districts with respect to class j in criterion i, and c_j is the idealized weight of class j.

2.4.3 Risk scores of the districts

Overall criteria and idealized weights were used to calculate risk score of each district by using equation (2.16) (Hajkowicz and Collins, 2007).

$$R_x = \sum_{i=1}^{n} w_i \times v_{id} \tag{2.16}$$

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 calculated through fuzzy AHP method.

2.5 Results and Discussions

The main goal of this study is 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 calculated by using fuzzy AHP method in step 2. Then, criteria weights are used to asses flood risk of Istanbul at district level.

2.5.1 Weights of decision criteria

In fuzzy AHP method, weights of criteria and classes are calculated based on expert judgments, therefore highly rely on the assessment of experts. This highlights the significance of finding adequate and experienced professionals from diversity of institutions. In addition, reliability of the experts can be validated by calculating consistency ratio, which is also regarded as one of the most powerful attributes of AHP method (Darko et al, 2019). By using purposive sampling, 15 experts were invited to one-to-one questionnaire survey and all accepted. 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 2.6). The findings indicate that land use (LU), population density (PD), and vulnerable structures (VS) were the most significant vulnerability criteria, while return period storm event (RP), imperviousness (IM), and storm water 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.

Table 2.6 : 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	—	1.000
		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%	0.000
				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

All decision frameworks present some results by adopting different approaches. However, it is required to adopt similar results under different scenarios, since decision processes could be inherently unstable for some complex problems. For instance, this study adopted 1-9 triangular fuzzy scale (Papaioannou et al, 2015; Vahidnia et al, 2009), while some others adopted 1-6 scale to calculate criteria weights in FAHP (Aladağ and Işık, 2019). Decision framework should give similar results by using different degree of fuzziness in the adopted scale. Thus, at the last step, the decision process should be terminated with a sensitivity analysis to ensure the stability and robustness of the proposed results (Ishizaka and Labib, 2011). In line, a sensitivity analysis was performed to explore how the rankings may change as a result of 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 are sensitive to fuzziness degree (Aladağ and Işık, 2019; Ishizaka and Labib, 2011). In the fuzzy AHP analysis, degree of fuzziness of the adopted triangular fuzzy scale was equal to 1 (Table 2.4). 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 results presented in Figure 2.4 indicate that the proposed AHP model is stable and robust since no change was observed in the rankings of criteria for both vulnerability (Figure 2.4a) and hazard clusters (Figure 2.4b).

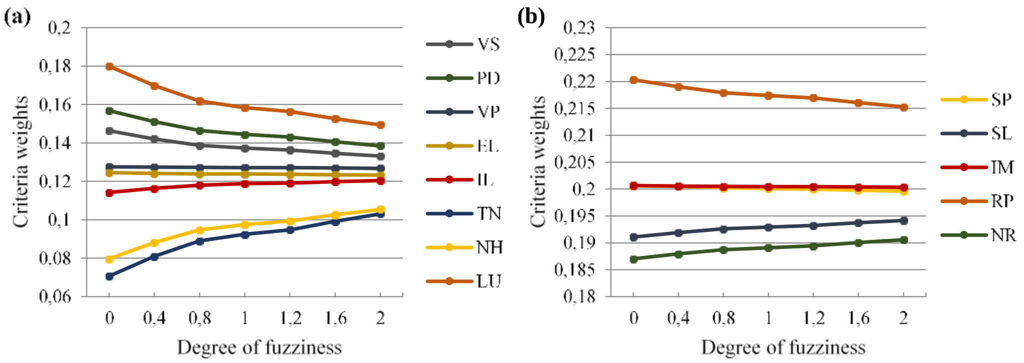

Figure 2.4 : Sensitivity analysis based on degree of fuzziness. a Vulnerability, b Hazard clusters.

2.5.2 District prioritization

A number of 39 districts of Istanbul have been prioritized in terms of flood risk, based on the criteria weights calculated through fuzzy AHP analysis, robustness and stability of which was proven by sensitivity analysis. Flood risk grades of districts were calculated by summing the grades achieved from each criterion (Table 2.7). Then the maps are generated from the most risky to the safest districts based on vulnerability criteria (Figure 2.5a), hazard criteria (Figure 2.5b), and by considering both vulnerability and hazard criteria (Figure 2.5c). According to the analysis results, Bayrampasa, Bagcilar, and Esenler were found to be top three districts in terms of flood risk. All three districts have gained the highest risk scores from return period for precipitation (RP), 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. Standard deviation (SD) of IM and LU was the highest among all criteria, having direct impact on the flood risks of districts.

Gaziosmanpasa, Gungoren, and Beyoglu were the top three flood prone districts in terms of vulnerability cluster (Figure 2.5a). Land use criterion was the main reason for high vulnerability of top three districts due to the high 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.

Table 2.7 : 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	#
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	26
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	34
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	23
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	29
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	30
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	35
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	39
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	24
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	40
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	33
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	31
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	25
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	36
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	27
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	32
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	37
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	22
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	38
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	28
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
Average	*0.050*	*0.025*	*0.058*	*0.059*	*0.048*	*0.017*	*0.038*	*0.058*	*0.026*	*0.053*	*0.066*	*0.072*	*0.063*	*0.632*	−
SD	*0.010*	*0.022*	*0.003*	*0.003*	*0.006*	*0.010*	*0.005*	*0.026*	*0.025*	*0.016*	*0.029*	*0.015*	*0.018*	*0.187*	−

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

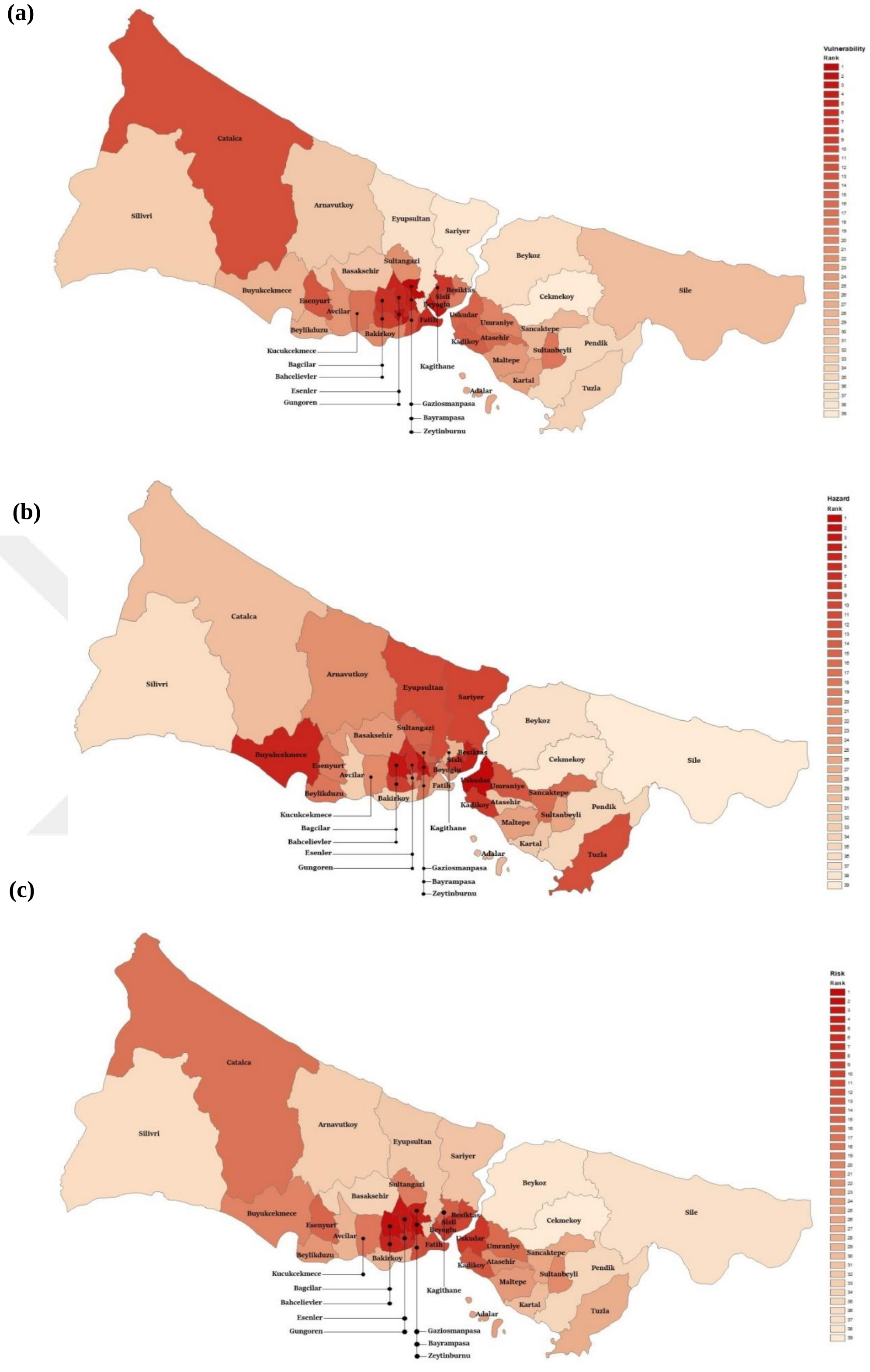

Figure 2.5 : Istanbul area generated. a. Vulnerability map, b. Hazard map, and c. Flood risk map.

On the other hand, with respect to hazard cluster, the most flood prone districts are found to be Uskudar, Bayrampasa, and Bagcilar which are densely urbanized areas and imperviousness criterion is responsible for their high risk scores (Figure 2.5b). Uskudar, which was regarded as one of the ten most risky regions according to the report prepared by the IBB (URL-9), known with its hilly topography, gained considerable risk scores from slope criterion.

Criteria basis analysis results show that Adalar (Prince Islands) was the most vulnerable district in terms of ageing storm water system and transportation network, while the most hazardous district with respect to slope. The reasons of 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, low population density of the district prevented it from being ranked among top vulnerable districts (Table 2.7). 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 flood-prone districts in Istanbul.

Validation of the obtained results with real time observations is an essential step in flood risk map studies. Although the generating flood maps using sophisticated algorithms is guiding, the validation of those maps with the findings of the previous studies and historical flood events could support the accuracy of the proposed models. Figure 2.6 shows the comparison of the number of flood events occurred between 2000 and 2015 (Özeyranlı Ergenç, 2016), and the calculated risk scores of each districts in this study. There is a good agreement 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, which highlights that the results for districts with divergent attributes could be different than others. Therefore, proposed approach could work well in districts with similar geological attributes, while more complex approaches should be developed when some significant diversified attributes exists such as consisting of islands, bordering some significant rivers or Bosporus. As for the other districts, there has been significant land use change observed over the last decade in districts such as Beylikduzu, Esenyurt, Sultangazi, and Zeytinburnu, which could be one of the reasons of higher risk scores compared to the number of floods events.

Furthermore, calculated risk scores are based on data provided in 2020, while compared number of floods were between 2000-2015. Consequently, this study shows that use of up-to-date data is significantly important to adopt proposed fuzzy AHP approach in flood risk mapping.

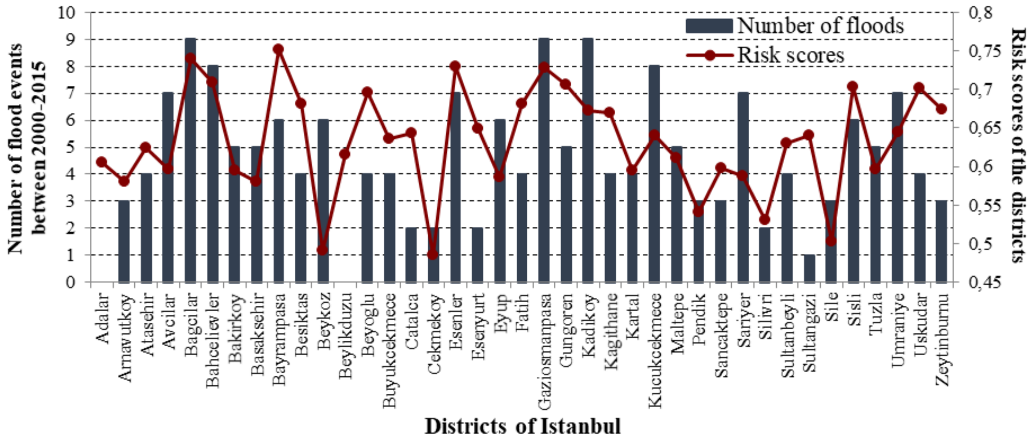

Figure 2.6 : Historical flood events occurred between 2000-2015 and calculated risk scores at district level.

The results obtained from the analysis shows strong agreement with the pertinent literature in the study area. According to the Üstün and Anagün (2016) and Ergenç and Barış (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 (URL-9). Bagcilar, Bayrampasa, Esenler and Gaziosmanpasa were also found as the most risky districts by 0.052, 0.059, 0.053 and 0.057 in terms of vulnerable structures, while by 0.057, 0.054, 0.042 and 0.073 with respect to population density in this study.

The rapid change in land use caused a serious increase in surface water runoff (Gülbaz et al, 2019). 100 and 300 years return period storm events occurred in 2007 in the Tavukcu stream located in Bahcelievler, and then in 2009 in the Ayamama stream, which passes through Bagcilar, respectively (Güçlü and Şen, 2016). Bagcilar and Bahcelievler received the second and fourth highest scores with respect to the return period of storm event criterion by 0.102 and 0.094, respectively (Table 2.7). The reason of this could be related to the high urbanization rate of the districts over the last decade.

Moreover, Kadikoy flood occured in 2008, and year 2014 flood in Esenler, which hosts the largest bus terminal in Istanbul, 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 up to date data. As a consequence, the risk scores of Kadikoy (2008), Bagcilar and Bahcelievler, which are affected by the Ayamama (2009) flood event, and Esenler (2014) districts were obtained as 0.6605, 0.7492, 0.736 and 0.6943, respectively (Table 2.8). Figure 2.7 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 district level, there is an increase in the risk scores of Kadikoy and Esenler, albeit slightly, while the decrease in the risk scores of Bagcilar and Bahcelievler was also observed. The reason of decrement in Bagcilar and Bahcelievler risk score can be explained by the rehabilitated infrastructure and superstructure system after the disaster occurred in Ayamama basin. In addition, the increase in risk score in Esenler can be related with 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.

Table 2.8 : The historical event-based risk scores.

E	VS	PD	VP*	EL*	IL	TN	NH	LU	SP	SL*	IM*	RP	NR	S
I	0.06	0.03	0.05	0.05	0.01	0.01	0.04	0.079	0.003	0.061	0.097	0.068	0.075	0.672
II	0.05	0.05	0.06	0.06	0.03	0.03	0.02	0.071	0.003	0.058	0.097	0.106	0.078	0.739
III	0.06	0.05	0.05	0.05	0.02	0.03	0.03	0.078	0.003	0.052	0.099	0.104	0.077	0.709
IV	0.06	0.00	0.05	0.06	0.04	0.04	0.02	0.076	0.003	0.057	0.089	0.094	0.070	0.729

* The data is not available or the same used in this study, therefore the same district risk scores were used. I: Kadikoy – 2008; II: Ayamama 2009 – Bagcilar; III: Ayamama 2009 – Bahcelievler; IV: Esenler – 2014.

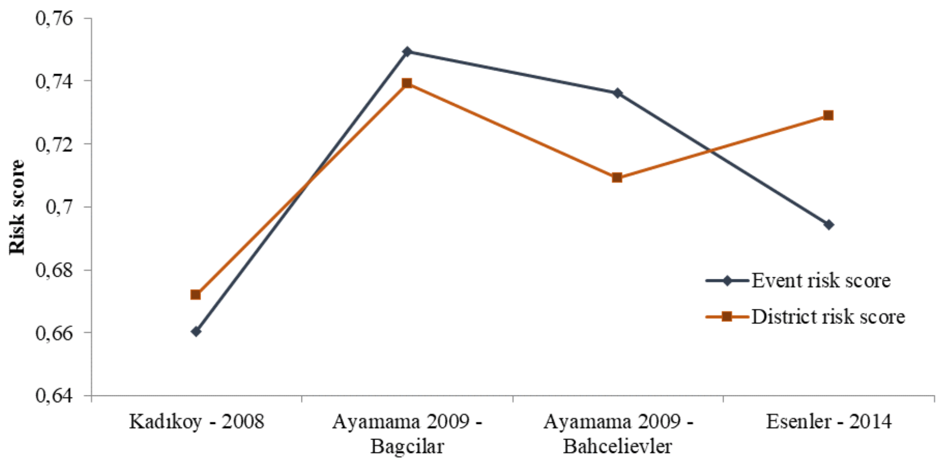

Figure 2.7 : Comparison of historical flood event scores with the calculated risk scores at district level.

2.6 Conclusions

Floods threaten the built environment in all three pillars of sustainability i.e. economic, social and environmental, as evidenced by many flood events in the world. Flood risk analysis is a multi-criteria problem that requires the consideration of both vulnerability and hazard criteria. However, since the solution made by multi-criteria analysis depends on subjective judgments of experts; fuzziness, uncertainty and imprecision of human decision-making process needs 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 fuzzy analytical hierarchy process. Prioritization of districts is of paramount significance in flood risk management since 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 analyses:

Land use, population density and vulnerable structures are the most significant vulnerability criteria, while return period of storm event, imperviousness and storm water pipe network are the most crucial hazard criteria for flood risk assessment of 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 results 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 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 for the number of floods occurred in the past two decades in Istanbul. Furthermore, the outcomes of this study not only support the result of previous studies, but also event-based risk scores of the previous flood events at a district level.

The results of this research can be useful for decision-makers in water resource professionals, urban planners, and particularly local authorities to develop flood risk mitigation strategies 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 findings of this study to identify the risk scores of the districts with respect to flood risk.

It is worth mention that, more efforts need to be made to improve the flood risk assessment to enhance the validity of the flood risk maps. Since four different target groups were selected in 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 respondent profile. 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 the all cities in Turkey to generate country-wide flood risk map.

3. STAKEHOLDER PERCEPTIONS IN FLOOD RISK ASSESSMENT: A HYBRID FUZZY AHP-TOPSIS APPROACH FOR ISTANBUL, TURKEY[2]

3.1 Introduction

As one of the most damaging disasters all around the world, floods occur as a result of the combined effects of natural and man-made stressors (Serre and Heinzlef, 2018). Rapid population growth and urbanization are sped up around the natural water resources in the world more than ever (Bao and Fang, 2012). Changes in land use because of urbanization, and the inevitable increase in the runoff coefficient indicate that the alarm bells ring for the metropolitan cities in terms of flood risk. In order to provide enhanced flood prevention and risk mitigation strategies, researchers have focused on different flood risk management (FRM) practices, starting with the identification of risk perceptions of both the public community and professional stakeholders (Ullah et al, 2020). The risk perception represents the subjective evaluations of individuals or groups regarding the likelihood of any hazard, as well as assessing the challenges resulting from this hazard (Eryılmaz Türkkan and Hırca, 2021; Kim and Madison, 2020). In this sense, factors such as psychological background, experience, and socio-cultural influences are the aspects covered by the risk perception concept (Hong and Chang, 2020). These factors have a pivotal role in understanding the consequences of floods (Ge et al, 2021), especially for individuals. Most surveys indicate a correlation existing between one’s flood experience and awareness of preparedness for the flood incident and consequently an increase in risk perception (Netzel et al, 2021). Meanwhile, the risk perception is relatively weak in communities that are not directly affected by floods or whose properties are far from the river bank (Mashi et al, 2020). Furthermore, it is an undeniable fact that the local authorities are the professional stakeholders and must leave subjectivity aside in the

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[2] This chapter is based on the paper “Ekmekcioğlu, Ö., Koc, K. and Özger, M. (2021). Stakeholder perceptions in flood risk assessment: A hybrid fuzzy AHP-TOPSIS approach for Istanbul, Turkey. International Journal of Disaster Risk Reduction, 60, 102327. 10.1016/j.ijdrr.2021.102327”.

evaluation of FRM practices. At this point, it is significant what stakeholders perceive and how they approach the potential risks of the flood phenomenon (Heitz et al, 2009). Besides, determining the relationship among stakeholders and the distribution of roles is essential not only to understand the risk perception in a region but also to designate the activities depending on the characteristics of the region (Heitz et al, 2009). Martinez et al. (2018) included eight different stakeholders, i.e. coastal manager, land use planner, disaster management agency, academicians, consultants, local residents, chairperson and local authorities, in the interviews to formulate the disaster risk reduction measures for coastal regions. Thus, potential conflicts between the stakeholders can be eliminated by providing an interdisciplinary collaboration (Santoro et al, 2019). In addition, the co-production of information is provided with the participation of versatile disciplines, ensuring the reliability of the output of the performed operation in line with the realization of specific goals and objectives (Hu et al, 2019). Considering these, effective FRM practices can be achieved only with the participation of various stakeholders from different disciplines, highlighting the requirements in this respect (Raadgever et al, 2008). Therefore, to develop a comprehensive FRM framework, it is vital to consider the contributions of many perspectives, such as pre and post-flood planning, public awareness, theoretical and technical analyses amplified with field studies, besides the regulations of local administrations (Minucci et al, 2020).

Istanbul is the most densely populated industrial, commercial and cultural centre of Turkey (Konukcu et al, 2017). The population of Istanbul has surged over the last decade since it attracts ongoing migration not only from all over Turkey but also from other countries (Biehl, 2019). Istanbul can also be regarded as one of the most flood-prone cities in Turkey, so much so that nearly 200 flood events were recorded over the last two decades (Özeyranlı Ergenç, 2016). To prevent extreme floods, several structural adjustments such as stream remediation and revision of the storm water pipe network have been carried out recently. After severe floods in Istanbul, municipalities have been assigned several tasks such as developing watershed protection plans and establishing flood prevention structures, while other institutions such as water and sewage administrations and disaster management and coordination centres officiated as the leading stakeholders under the administration of Istanbul metropolitan municipality. In addition, academic staff in universities consult both relevant public enterprises and citizens at every stage of FRM strategies. Ultimately, FRM practices in Istanbul are mainly held by four different organizations, such as i) local and metropolitan municipalities (LM), ii) disaster management and coordination centres (DM), iii) water and sewerage administrations (WS), and iv) universities (UN); thus, considered in this study.

Generation of flood risk maps is one of the most important means to perform adequate FRM practices, since required precautions, new settlement plans, effective water management, early warning improvements, and evacuation simulations can be aided significantly according to flood risk maps. Comprehensive flood risk maps can be produced by considering several factors regarding vulnerability and hazard criteria. Although there are many methods proposed by the research community, recently (Eini et al, 2020; Perrone et al, 2020; Shrestha and Kawasaki, 2020), multi-criteria decision-making (MCDM) algorithms have gained a significant place in the literature (Hammond et al, 2015). Few studies showing the application of several MCDM approach in various disciplines are provided in Table 3.1. As one of the most widely used MCDM tools, the analytical hierarchy process (AHP), and fuzzy AHP have long been adopted by researchers to generate flood risk maps or watershed prioritization (Das, 2018; Meshram et al, 2019; Papaioannou et al, 2015; Wang et al, 2011b; Yang et al, 2013). For instance, Wang et al. (2011b) evaluate several flood risk criteria to investigate the potential flood risks in Dongting Lake, China, by integrating GIS tools and fuzzy AHP method. Also, Papaioannou et al. (2015) compared the performance of AHP and fuzzy AHP to obtain flood prone zones in Xerios Basin, Greece. In addition, another MCDM tool, a technique for order of preference by the similarity-to-ideal-solution (TOPSIS), works well in prioritization problems, while AHP is effective in criteria assessment in the case of multi-tier hierarchies (Ertuğrul and Karakaşoğlu, 2008). Therefore, flood risk map studies have benefitted significantly from a hybrid MCDM approaches. Meshram et al. (2019) evaluated fourteen indicators that are effective in the determination of flood damage by utilizing hybrid simple additive weighting (SAW) and TOPSIS method; such that SAW was used for obtaining criteria weights, while latter was used for prioritizing the sub-watersheds. Nguyen et al. (2020) applied both fuzzy AHP and TOPSIS methods to produce flood hazard maps. They classified the study area (Phuoc Thang, Vietnam) into four different categories, i.e. low hazard, medium hazard, high hazard, very high hazard, according to their findings and concluded that nearly 50% of the selected area has very high flood hazard potential.

Table 3.1 : Few MCDM studies in various research areas.

Reference	Applied MCDM method(s)	Context of the study
Wood (2016)	Fuzzy TOPSIS, intuitionistic fuzzy TOPSIS	Supplier selection for petroleum industry facilities
Gigovic et al. (2017)	AHP, fuzzy AHP, interval rough AHP	Flood hazard mapping in urban areas
Gupta and Barua (2017)	Best worst method, fuzzy TOPSIS	Supplier selection among small and medium enterprises
Yaakob et al. (2017)	TOPSIS, fuzzy networks TOPSIS	Prioritization of traded equities in developing and developed markets
Hategekimana et al. (2018b)	Fuzzy AHP	Estimation of the degree of susceptibility for ranking of flood hazard index
Moktadir et al. (2018)	Fuzzy AHP	Assessment of drivers of corporate social responsibility in the footwear industry
Yazdi (2018)	Intuitionistic fuzzy TOPSIS	Prioritization of hazards a gas refinery for the welding and lamination task
Asl-Rousta and Mousavi (2019)	TOPSIS	Prioritization of the Soil and Water Assessment Tool (SWAT) hydrological model
Zhang et al. (2019)	Decision-making trial and evaluation laboratory (DEMATEL)	Determination of critical risks in public-private partnership projects
Gurgun and Koc (2020)	AHP	Contractor prequalification in green building projects
Meshram et al. (2020)	Simple additive weighting (SAW), TOPSIS	Watershed prioritization based on Morphometric factors
Nguyen et al. (2020)	Fuzzy AHP, TOPSIS	Flood hazard assessment and mapping
Sepehri et al. (2020)	Interval rough AHP	Regional scale flood prone area assessment
Yazdi et al. (2020)	Fuzzy AHP, fuzzy TOPSIS	Risk assessment of the spherical storage hydrocarbon tank in case of fire and explosion in the process industry

The novelty of this study comes from two primal objectives. The first objective is to generate a district-based flood risk mapping in Istanbul by adopting a hybrid fuzzy AHP-TOPSIS approach; such that the Fuzzy AHP and TOPSIS methods were used to evaluate criteria weights and prioritize districts, respectively. This preference is critical since fuzzy AHP and TOPSIS methods are among the most influential MCDM tools in criteria and alternative assessments, respectively (Ertuğrul and Karakaşoğlu, 2008). However, the literature is limited related to the hybrid use of fuzzy AHP and TOPSIS methods in flood risk mapping. The second objective of this study is to prioritize the 39 districts of Istanbul separately according to the responses of four main stakeholders through presenting the perception differences of stakeholders on the generated flood risk maps. In this respect, the criteria weights were calculated by aggregating the responses of corresponding stakeholders to illustrate perception differences. Pearson's correlation coefficient and Spearman's rank correlation coefficient tests were also used to examine the agreement levels among stakeholders statistically. The approach adopted in this study aid in determining which stakeholders consider vulnerability more crucial, while the hazard criteria are highlighted by which stakeholders. Overall, the outcomes of this study can be used by governmental, disaster management, and water resource authorities to mitigate flood risks properly. Besides, decision-making bodies developing risk management strategies and initializing investments to deal with flood risk can benefit from the findings related to the perceptions of other stakeholders.

3.2 Roles of Stakeholders in Flood Risk Management

Effective flood risk management (FRM) should involve a wide set of actions such as planning, mitigation, governance, protection, early warning, education, post-disaster relief, etc., considering both vulnerability and hazard aspects (Moel et al, 2009; Plate, 2002). Flood risk mapping is a widely used and proper technique to visualize potential impacts and threats with respect to performing effective FRM (Papaioannou et al, 2015). The information provided by flood risk mapping is essential since it significantly contributes to developing early warning systems and flood attenuation measures as FRM schemes (Binh et al, 2019). The perceptions of experts from different institutions might differ crucially based on varying perspectives, leading to unique flood risk maps according to each stakeholder (da Silva et al, 2020).

Studies related to stakeholders involved in FRM practices are limited in the literature. As an example of limited attempts, Raadgever et al. (2008) conducted flood management analysis for the Rhine basin to raise awareness amongst a wide range of stakeholders and reveal the differences in their perspectives. Nearly 50 participants responded to various questions and stated their FRM priorities. Three distinct groups were assigned as they approached FRM through different perspectives, such as climate change, taking structural measures and policymaking. Almoradie et al. (2015) conducted two case studies in the UK to establish web-based support tools through face-to-face workshops organized over 1.5 years, bringing together local government representatives, non-governmental authorities, emergency managers, larger business companies and notable FRM professionals. Maskrey et al. (2016) established a model to introduce a participatory local risk management strategy, in which the inclusion of diverse stakeholders in the system as a key element is required. However, the effects of each stakeholder on the generated flood risk maps have not been considered in the literature.

FRM practices in Istanbul are mainly held by four stakeholders: i) local and metropolitan municipalities (LM), ii) disaster management and coordination centres (DM), iii) water and sewerage administrations (WS), and iv) universities (UN) as consultancy. The role of these stakeholders to carry out effective FRM practices in Istanbul is illustrated in Figure 3.1. The contributions of each stakeholder are summarized in the following sub-sections.

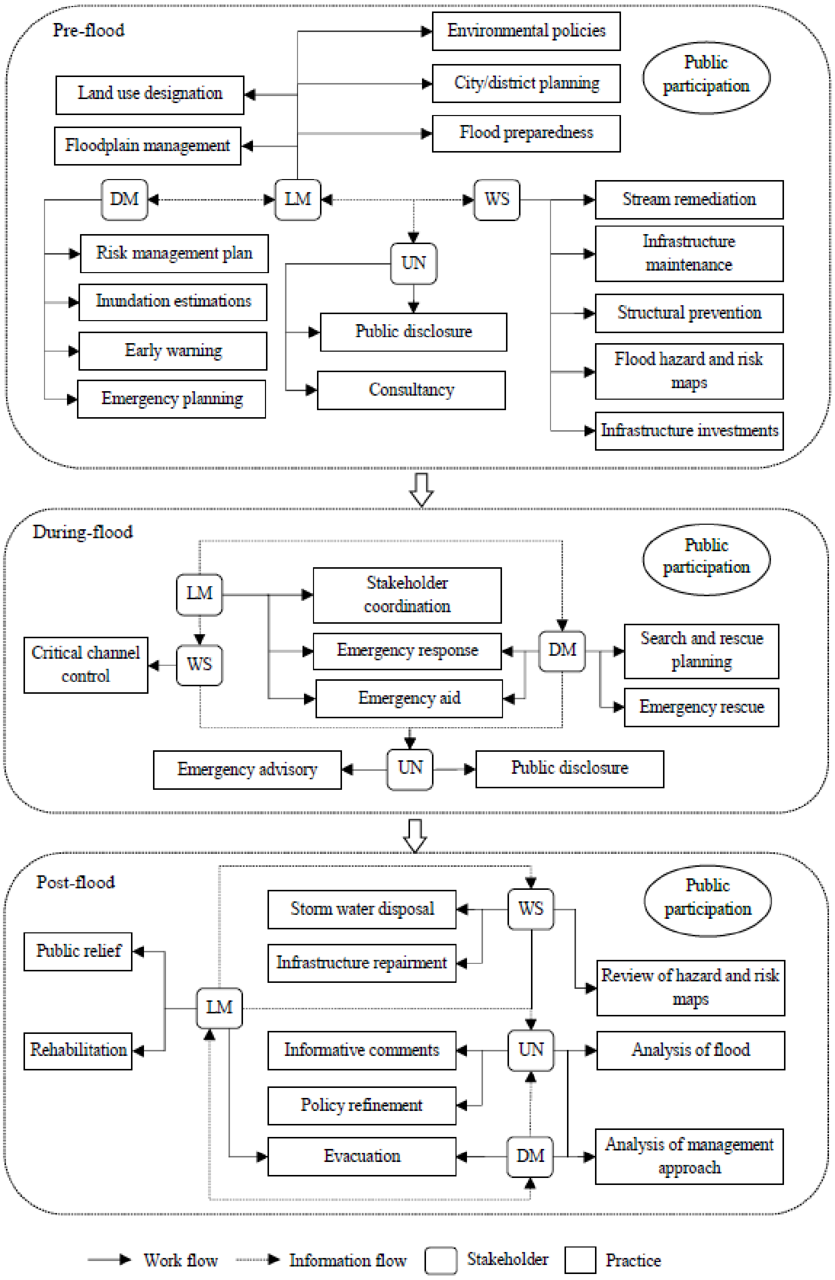

Figure 3.1 : Typical flood risk management practices in Istanbul city.

3.2.1 Local and metropolitan municipalities (LM)

FRM practices are usually oriented from national, provincial to local scale authorities that have a particular role to increase the resilience of the flood-prone areas. In this context, one of the major missions of local municipalities is to cooperate with not only county level but also national level institutions (Norén et al, 2016). Accordingly, local municipalities are responsible for both sustaining infrastructure investments and have the right of initiative in the organization of environmental management strategies, including afforestation and increasing green areas (Edelenbos et al, 2017). Thus, environmental protection practices, emergency planning, implementation of environmental policies, and local scale planning are major responsibilities of local municipalities (Næss et al, 2005). In addition, increasing public awareness is also one duty of local administration units(Correia et al, 1998).

In Istanbul, the metropolitan municipality provides comprehensive support to relevant institutions for emergency response and search and rescue facilities, along with undertaking the coordination of institutions such as WS and DM. In addition, local authorities in Istanbul assign the institutions to generate flood risk maps and regulate both floodplain management and land use planning. As a dense and rapidly urbanized city, it is expected in Istanbul that the infrastructure facilities will be provided to expedite the disaster response. In this context, LM could guarantee the protection of both natural resources and environmental values that may be damaged by floods, besides ensuring all manner of public disclosures as parts of the necessity of public participation, which is a key aspect of risk communication (Salman and Li, 2018).

3.2.2 Disaster management and coordination centres (DM)

Although local authorities have the utmost importance among major FRM stakeholders, regional basis DMs could also play a vital role in pre-disaster and post-disaster phases to reduce vulnerability and increase resilience (Madan and Routray, 2015). Particularly measurement and early warning activities in the pre-flood phase and evacuation activities in the post-flood phase are held by such organizations and committees (Khan and Rahman, 2007). While during floods by taking responsibility for planning, coordinating and supervising the search and rescue operations, they have a direct impact on the welfare of the flood victims and the number of casualties (Chan, 2012).

In case of an event-based consideration of Istanbul, DMs provide preliminary meetings with the relevant units when the unfavourable weather conditions are estimated that may lead to floods and take necessary precautions before emergencies. In this regard, one of the organizations considered as a unit of DMs provided the establishment of meteorological measurements and monitoring of early warning systems (TEUS). TEUS performs the flood calculations through various information related to meteorological, satellite and radar, weather forecast models and stream gauge, and transmits the relevant information regarding a potential flood to the authorities where a flood could occur, usually one to three hours before the event. Moreover, DMs contribute to the relevant researches and feasibility studies aimed at reducing meteorological risks in Istanbul. Thus, DMs determine and evaluate the meteorological risk factors that should be considered for future development plans and enable them to be shared with Istanbul metropolitan municipality.

3.2.3 Water and sewerage administrations (WS)

Effective interventions within the scope of FRM are required to be carried out on a watershed basis or local units such as districts and provinces (Douglas, 2017). Mitigation procedures should also be oriented with parallel or intertwined responsibilities to ensure continuous cooperation between institutions (Sayers et al, 2015). In this context, the participation of institutions such as WS could be useful for effective FRM applications (László, 2020). For instance, the Detroit Water and Sewerage Department regularly prepares temporary flood risk plans per annum and performs risk mitigation measures such as barriers, sandbags and berms to manage flood events that occurred in the region. Furthermore, flood water evacuations can be provided with large drainage systems such as surface swales, ditches and streams (HEC-22, 2013).

Within the scope of watershed protection in Istanbul, WS has critical responsibilities in stormwater handling and disposal from settlements (Bodur, 2018). WS puts the measures into practice to mitigate the runoff such as afforestation works in water basins (URL-2). Besides, damaged sewage infrastructure systems during floods are rebuilt by WS, which also carries out stream remediation works, particularly in risk-bearing streams of top priority. While taking structural measures during the operational process, WS performs periodic maintenance and cleaning activities, ensuring that the structures built as part of precautions will show the desired performance during floods.

3.2.4 Universities (UN)

Universities are not considered load-bearing columns to produce disaster preparedness and FRM planning. They have often been regarded as a source of solutions, which play a constructive role in creating analytical and critical methods. Alternative standpoints regarding the development of flood-prone areas within the scope of consultancy are usually required from universities (Edelenbos et al, 2017). Some particular suggestions to local authorities are also provided by universities to revise FRM policies in certain periods, such as 5 or 10 years (López-martínez et al, 2020). Universities supply land protection and urban planning strategies by providing technical support to the local authorities and institutions (Santoro et al, 2019), with respect to the vulnerability of the population. Based on these examples, universities and other institutions congregate to evaluate and develop flood mitigation strategies within a multidisciplinary framework. With strong management skills and existing assets, the academy can make great and lasting contributions to manage floods.

3.3 Study Area

Istanbul is located in the northwest part of Turkey; the city rises between the Black Sea in the north, and the Marmara Sea in the south, with the Bosporus in the middle dividing two continents, Europe, and Asia (Figure 3.2). Istanbul has a total area of 5,461 km², and it comprises 39 districts; 14 on the Asian side and 25 on the European side (Ekmekcioğlu et al, 2021a). Catalca is the largest district of Istanbul (1,142 km²) in terms of surface area, whereas Gungoren covers the smallest area with nearly 7 km². Istanbul, with approximately 15 million residents, is the most populated city in Turkey, and 65% and 35% of the residents live on the European and Asian sides, respectively. The most densely populated district is Sultangazi with nearly 54 thousand (person/km²), while the least populated district is Sile (44 person/km²) (URL-10).

Nearly 90% of the daily water requirement, which is 3 million m³, is supplied from the eight watersheds, i.e., Terkos, Buyukcekmece, Sazlidere, Kucukcekmece and Alibeykoy watersheds on the European side, and Elmali, Omerli and Darlik watersheds for the Asian side. On the other hand, while 67 streams on the European side cover 58% of Istanbul’s total stream length, 39 streams on the Asian side correspond to 42 %. Although Istanbul is one of the richest cities in Turkey in terms of water resources, institutions and authorities are in search of more water resources, and flood prevention strategies because of the increasing population and inevitable urbanization.

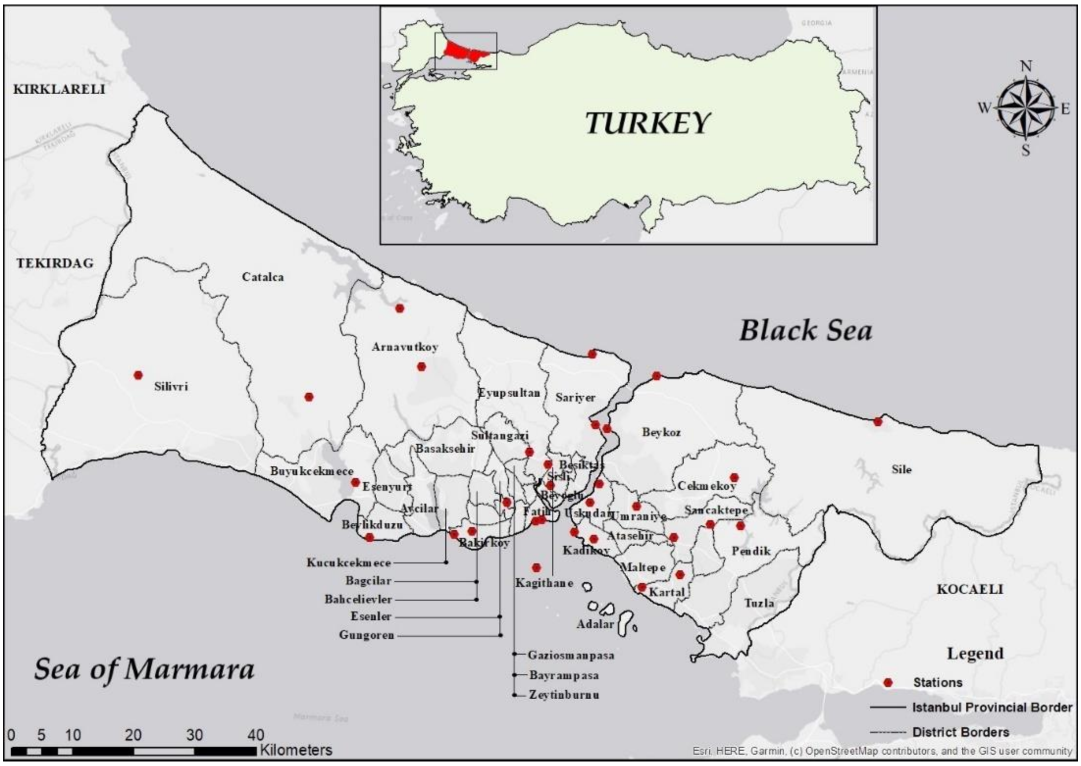

Figure 3.2 : Study area.

3.4 Methodology

The research methodology followed in this study comprises four primary stages, as illustrated in Figure 3.3. First, flood risk criteria were developed based on a literature survey accompanied by a pilot study. Then, a hybrid fuzzy AHP-TOPSIS approach was adopted to prioritize districts of Istanbul regarding flood risk. Fuzzy set theory (FST), proposed by Zadeh (1965), was adopted to the AHP method to find criteria weights since opinions of subjective experts by using discrete values could lead to less reliable criteria weights (Vahidnia et al, 2009). In addition, fuzzy AHP has widely been used by researchers to determine the criteria weights in flood risk mapping studies (Aher et al, 2013; Ekmekcioğlu et al, 2021a; Hategekimana et al, 2018b; Wang et al, 2011b). Despite fuzzy AHP being criticized by some scholars (Zhü, 2014), its frequent application showed the suitability of the method in FRM literature (Hategekimana et al, 2018b; Zyoud et al, 2016). Meshram et al. (2019) compared the application of AHP and fuzzy AHP methods in prioritizing watersheds and found that the fuzzy AHP method is a more practical and convenient technique to highlight potential areas prone to flood risk.

On the other hand, FST was not applied to the TOPSIS method since the district evaluation was performed based on the actual values collected from various institutions in this study. Therefore, fuzzy AHP was used to calculate the criteria weights, which were regarded as input weights in the TOPSIS application. Flood risk, hazard, and vulnerability maps of Istanbul were generated based on the judgments of different stakeholders to illustrate perception differences in FRM, besides the maps created regarding judgments of all experts. Finally, Pearson's correlation coefficient and Spearman's rank correlation coefficient tests were used in examining agreement levels among stakeholders.

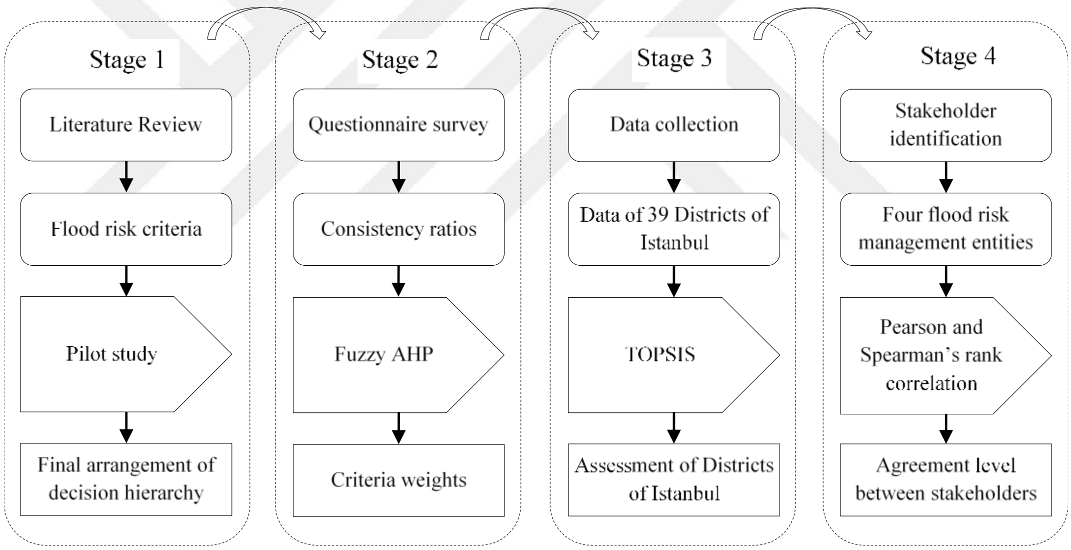

Figure 3.3 : Research flow.

3.4.1 Identification of flood risk criteria (Stage 1)

In the preliminary stage, flood risk criteria were identified by conducting a literature review and finessed through a pilot study with four professionals from various entities involved in flood risk decisions. The structure was first organized based on two fundamental flood risk sources as hazard and vulnerability (Kittipongvises et al, 2020), so that flood risk can be calculated by considering both vulnerability and hazard criteria. Professionals from four aforementioned stakeholders were selected as target groups: i) LM, ii) DM, iii) WS, and iv) UN.

Table 3.2 : Flood risk criteria and data sources.

Clusters	Criteria	ID	Sub-criteria	TOPSIS positive ideal	Reference	Data source
Vulnerability (V)	Vulnerable structures (Built year)	VS	• <1969 • 1969 - 1982 • 1983 - 2012 • 2013 - 2018	Max	Pilot Study	Konukcu et al. (2017), URL-3
	Population density (N/km2)	PD	–	Max	Wang et al. (2011b)	URL-4, URL-5
	Vulnerable population (Age)	VP	• <10 • 10 - 19 • 20 - 64 • >64	Max	Binh et al. (2019)	URL-5
	Education level	EL	• Non-literate • Literate (without education) • Up to high school • Bachelor or more	Max	Pilot Study	URL-6
	Income level	IL	–	Min	Dang et al. (2011)	URL-6
	Transportation network (Number of bus stop)	*TN	–	Min	Zou et al. (2013)	URL-7
	Number of household (Average)	NH	–	Min	Pilot Study	URL-6
	Land use	*LU	• Commercial/ Industrial • Residential • Rural • Forestry	Max	Dahri and Abida (2017)	BIMTAS
Hazard (H)	Storm water pipe network (km/built km2)	*SP	–	Min	Meshram et al. (2019)	ISKI
	Slope (%)	SL	• <1% • 1% - 4% • 5% - 10% • >10%	Max	Darabi et al. (2019)	URL-8
	Imperviousness (Curve number)	*IM	• 71 – 76 • 77 - 82 • 83 - 88 • 89 – 94	Max	Papaioannou et al. (2015)	Jaafar et al. (2019)
	Return period of storm event (year)	*RP	• < 2 • 2-10 • 11-50 • > 50	Max	Wang et al. (2011b)	MGM
	Number of rainy days in a year (Average)	NR	–	Max	Risi et al. (2020)	MGM

Note: 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

Therefore, a pilot study with four experts, including one expert from each target group, was carried out to finesse the predetermined flood risk criteria regarding the flood problems in Istanbul. The hierarchic representation of the finessed framework is shown in Table 3.2. Expressions such as max and min in the Table indicate whether criteria present the riskiest condition for districts when the value corresponding to the criteria is maximum or minimum, which were used in the TOPSIS method to calculate positive and negative ideal solutions.

3.4.2 Assessment of criteria weights (Stage 2)

To determine flood risk criteria weights, the AHP approach was adopted because i) both qualitative and quantitative data can be handled in the AHP method, ii) reliability of the respondents can be controlled with consistency ratio (CR), iii) it is one of the most widely adopted MCDM tools in flood risk assessment, and iv) experts may get better insight about the study objectives with a hierarchical representation (Darko et al, 2019; Yang et al, 2013).

However, despite its many advantages, because AHP cannot reflect the human's cast of mind by neither considering fuzziness nor subjectivity; assessments of subjective experts will yield less reliable outcomes (Wang et al, 2011b). Thus, traditional AHP is frequently criticized for its inability to accommodate the inherent uncertainty in the problems throughout the pairwise comparison process precisely (Yang et al, 2013). Chang (1996) introduced the fuzzy AHP approach by synthesizing the fundamentals of fuzzy set theory (Zadeh, 1965) and AHP, referred to as extent analysis, which was adopted in this study. A triangular fuzzy number (TFN) M is shown in Fig. 4, modified from (Moktadir et al., 2018). It is denoted as (p,q,r), such that r>q>p. Each TFN has linear portrayals to its left and right side, and its membership function can be expressed through equation (3.1):

$$\mu(z/\widetilde{M}) = htg(M_1 \cap M_2) = \begin{Bmatrix} 0 & z < 1 \\ (z-p)/(q-p), & p \le z \le q \\ (r-z)/(r-q) & q \le z \le r \\ 0 & z > r \end{Bmatrix} \tag{3.1}$$

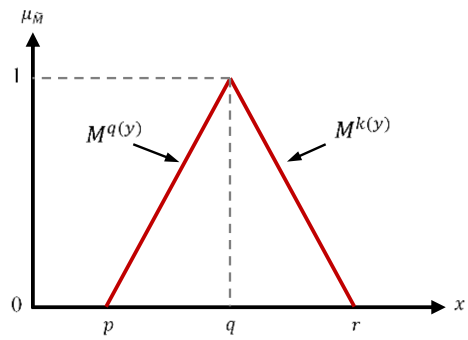

Figure 3.4 : Representation of TFN.

In this study, the professional knowledge of 14 experts was utilized. Each expert had been involved in FRM applications in Istanbul city as a part of one of the aforementioned four stakeholders. The profile of the experts who attended the questionnaire survey is shown in Table 3.3. Experts were selected by using purposive sampling (Koc and Gurgun, 2020) so that their judgments would represent the dynamics of flood risk. Each criterion was reviewed with the participants that took part in the pilot study to ensure that the problem was comprehended at all points.

Table 3.3 : Profile of the experts.

Stakeholder group	ID	Role	Division	Experience (year)
Local and metropolitan municipalities (LM)	E1	Auditor	Structural Engineering	11
	*E2	Project coordinator	Infrastructure works	28
	E3	Control engineer	Infrastructure works	17
Disaster management and coordination centres (DM)	*E4	Board advisor	Meteorology	26
	E5	Planning manager	Planning	18
	E6	Meteorological Engineer	Meteorology	10
	E7	Planning engineer	Planning	9
Water and sewerage administrations (WS)	*E8	Infrastructure manager	Infrastructure works	18
	E9	Technical office engineer	Planning	13
	E10	Technical office engineer	Infrastructure works	16
Universities (UN)	*E11	Professor	Hydraulics	17
	E12	Associate Professor	Construction Management	12
	E13	Associate Professor	Environment	13
	E14	Associate Professor	Hydraulics	16

* Expert attended to pilot study

After far-reaching expert interviews, the collected data was analysed by adopting a four-step fuzzy AHP approach:

Step 1. Data Collection: Experts were asked to show the importance of criteria compared to others by using linguistic variables through a 1-9 pairwise comparison scale (Table 3.4) (Papaioannou et al, 2015). Therefore, they were asked to make pairwise comparisons among elements in each matrix concerning cluster-based goals. A total of ten matrix utilized were as follows: i) risk matrix including two clusters such as vulnerability and hazard, ii) vulnerability matrix including eight criteria such as VS, PD, VP, EL, IL, TN, NH, and LU, iii) hazard matrix including five criteria such as SP, SL, IM, RP, and NR, and iv) seven individual matrices for criteria comprising sub-criteria such as VS, VP, EL, LU, SL, IM, and RP (Table 3.2). Cluster-based goals are related to their influence on the districts, making them more risky, vulnerable, or hazardous. For instance, when using linguistic variables presented in Table 3.4, experts compared vulnerability and hazards clusters in the risk matrix and provided higher values (from equally important to extremely important, importance values:1-9) for the one which they considered poses more risk than the other. Similarly, when performing pairwise comparisons in vulnerability and hazard matrices, they provided higher values for criteria that they considered it makes a district more vulnerable and hazardous compared to other criteria, respectively. In this respect, the degree of importance was also included by using linguistic variables. Reciprocals of linguistic variables were also used when necessary, by the participant experts. l_{ij}, m_{ij}, u_{ij} in Table 3.4 indicate lower width, mean, and upper width of the pairwise judgments of experts for criterion i, with respect to criterion j, respectively.

Table 3.4 : Fuzzy AHP linguistic scales.

Linguistic variables	Importance	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)
İntermediate value	2	(1,2,3)	(1/3,1/2,1)
Moderately important	3	(2,3,4)	(1/4,1/3,1/2)
İntermediate value	4	(3,4,5)	(1/5,1/4,1/3)
Important	5	(4,5,6)	(1/6,1/5,1/4)
İntermediate value	6	(5,6,7)	(1/7,1/6,1/5)
Very important	7	(6,7,8)	(1/8,1/7,1/6)
İntermediate value	8	(7,8,9)	(1/9,1/8,1/7)
Extremely important	9	(9,9,9)	(1/9,1/9,1/9)

Step 2. Reliability check: Calculation of consistency ratio (CR) is one of the strongest attributes of the AHP approach, which ensures the consistency of the experts. CR values need to be computed for each participant to ensure the reliability of the collected data (Suganthi, 2018). 0.1 is the threshold of CR in the AHP method, such that lower values indicate more consistent judgments (Saaty, 1990). CR values are calculated by using equation (3.2) and equation (3.3):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.2}$$

$$CR = \frac{CI}{RI} \tag{3.3}$$

where λ_{max} is the largest eigenvalue of a pairwise comparison matrix, n is the number of criteria, CI and RI are denoted as the consistency index and the random index, respectively (Saaty, 2004). The RI is calculated by Saaty (2004) through 50,000 simulations and provided in Table 3.5 for matrices of size 1, 2, …, 10.

Table 3.5 : Random index.

N	1	2	3	4	5	6	7	8	9	10
Random Index	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Step 3. Group decision making: Once the linguistic variables were assigned by expert k, they were converted into triangular fuzzy equivalences as $(l_{ijk}, m_{ijk}, u_{ijk})$. By using the judgments of all experts, the aggregated triangular fuzzy numbers (l_{ij}, m_{ij}, u_{ij}) were calculated by taking the minimum of l_{ijk}, the geometric mean of m_{ijk}, and the maximum of u_{ijk} as indicated in equation (3.4) (Büyüközkan and Feyzioğlu, 2004):

$$l_{ij} = min(l_{ijk}), \qquad m_{ij} = \left(\prod_{k=1}^{K} m_{ijk}\right)^{1/K}, \qquad u_{ij} = max(l_{ijk}) \tag{3.4}$$

where K is the total number of respondents.

Step 4. Chang's extent analysis: Aggregated group judgments are used in applying Chang's (1996) extent analysis approach to handle the inherent uncertainty of human decision-making process. Crisp mathematical concepts are used in this approach to address fuzzy quantities. Detailed description of the computational progress of the extent analysis can be found at (Chang, 1996).

3.4.3 District evaluation (Stage 3)

Owing to its many advantages regarding stability, mathematical calculations, and required computational time, the TOPSIS method was used in this study to evaluate the districts of Istanbul in terms of flood risk (Iç, 2012). The working principle of the TOPSIS method is similar to the human decision-making process. Besides, the TOPSIS method has been proven to be one of the most powerful MCDM tools in ranking problems (Ertuğrul and Karakaşoğlu, 2008). Also, it should be noted that the AHP method is effective in multi-level hierarchical decision problems, and the TOPSIS approach is favourable in one-tier decision frameworks. Therefore, the criteria weights were calculated by using the fuzzy AHP method in this study, while the district prioritization was handled through the TOPSIS method.

TOPSIS method relies on ranking the alternatives with respect to the shortest geometric distance from the positive ideal solution, and longest geometric distance from the negative ideal solution (Chen, 2000). The key steps of the adopted TOPSIS method are:

Step 1: Evaluation matrix is formed with respect to m alternatives and n criteria (including sub-criteria) as a matrix $(A_{ij})_{mn}$ as shown in equation (3.5)

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \tag{3.5}$$

where a_{ij} is the importance of alternative i with respect to criteria j.

It is important to note that while developing the evaluation matrix, sub-criteria were also included rather than criteria that consist of sub-criteria. Here, the weight of a criterion is distributed to its sub-criteria based on the fuzzy AHP analysis with respect to these clusters (VS, VP, EL, LU, SL, IM, RP). Then the importance of alternatives was considered as a percentage for criteria consisting of sub-criteria. For instance, the percentages of vulnerable population intervals or sub-criteria (<9, 10-19, 20-64, >65) were used to develop the VP part of the evaluation matrix. Here, the evaluation matrix consists of 39 alternatives (districts of Istanbul) and 34 criteria including sub-criteria (7x4=28 for criteria consisting of sub-criteria, 6 criteria with no sub-criteria PD, IL, TN, NH, SP, NR; forming a total of 28+6=34 criteria).

Step 2: The matrix $\left(A_{ij}\right)_{mn}$ is normalized and $R = \left(r_{ij}\right)_{m \times n}$ is obtained through equation (3.6):

$$r_{ij} = a_{ij} \Bigg/ \sqrt{\sum_{k=1}^{m} a_{kj}^2} \tag{3.6}$$

The normalization is performed for each criterion and sub-criterion individually. The percent values are used when normalizing sub-criteria, while numeric values corresponding to each district with respect to each criterion were used for normalizing criteria without sub-criteria.

Step 3: Weighted normalized matrix $V = \left(v_{ij}\right)_{m \times n}$ is calculated, $i = 1,2, \dots, m$ using equation (3.7), where w_j is the weight of criterion j. Weights of two main clusters (vulnerability and hazard), weights of criteria, and weights of sub-criteria used in this step were calculated through fuzzy AHP analysis.

$$V = \left(v_{ij}\right)_{m \times n} = \left(w_j\, r_{ij}\right)_{m \times n} \tag{3.7}$$

Step 4: Positive ideal solution (A^*) and negative ideal solution (A^-) are determined using equation (3.8) and equation (3.9). A^* is calculated by taking the maximum of each sub-criteria which corresponds to VS, VP, EL, LU, SL, IM, and RP criteria with respect to values belong to districts, in addition to PD and NR, while by taking the minimum of criteria such as IL, TN, NH, and SP. On the other hand, A^- is calculated through the opposite way round, by taking the minimum of VS, VP, EL, LU, SL, IM, RP, PD, and NR, and by taking the maximum of IL, TN, NH, and SP.

$$A^* = \left[\left(\max_i v_{ij} \,\middle|\, j \in J\right), \left(\min_i v_{ij} \,\middle|\, j \in J'\right)\right] = \{v_1^*, v_2^*, \dots, v_n^*\} \tag{3.8}$$

$$A^- = \left[\left(\min_i v_{ij} \,\middle|\, j \in J\right), \left(\max_i v_{ij} \,\middle|\, j \in J'\right)\right] = \{v_1^-, v_2^-, \dots, v_n^-\} \tag{3.9}$$

Step 5: Distance of each alternative from A^* and A^- are calculated by using equation (3.10) and equation (3.11)

$$d_i^* = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^*\right)^2} \tag{3.10}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2} \tag{3.11}$$

Step 6: Closeness coefficient (CC_i) of each alternative is calculated through equation (3.12), where $0 \leq CC_i \leq 1$,

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*} \tag{3.12}$$

Thus, the ranking of the alternatives is determined by comparing CC_i values. In this study, districts of Istanbul were ranked based on CC_i values, such that the higher the CC_i value is, the greater the magnitude of flood risk.

Finally, based on the prioritization, flood vulnerability, hazard, and risk maps of Istanbul were generated. Flood vulnerability and hazard maps were generated by considering only vulnerability and hazard criteria, respectively. In order to generate a flood risk map, all the criteria (Table 3.2) were used in the evaluation matrix. In addition, all the calculations were performed by aggregating the judgments of experts in a single stakeholder group based on criteria weights calculated through the fuzzy AHP method by aggregating only their judgments, and flood risk, vulnerability, and hazard maps were generated individually for the corresponding stakeholder.

3.4.4 Aggreement analysis between stakeholders (Stage 4)

There are mainly four responsible entities in FRM applications in Istanbul with their distinctive perspectives. Generated maps could provide insight into the differences in the perception of stakeholders. To analyse if these differences are statistically significant or not, the agreement levels were evaluated. Pearson's correlation coefficient and Spearman's rank correlation coefficient are commonly used approaches in terms of criteria weights and rankings, respectively in comparing perception differences among stakeholders (Budayan, 2019). Pearson's correlation coefficients can be calculated by using MS Excel via built-in function, while Spearman's rank correlation coefficients are calculated by using equation (3.13):

$$r_s = 1 - \frac{6\sum d^2}{n(n^2-1)} \tag{3.13}$$

where r_s is the Spearman's rank correlation coefficient, d is the difference in rankings between two stakeholders, and n is the number of criteria. CC_i values of the districts with respect to i) flood risk, ii) flood vulnerability, and iii) flood hazard were considered in the analyses to illustrate district-based perception differences. Besides, to examine underlying causes of divergent flood risk mappings, analyses were also conducted with respect to criteria weights assigned by different group of experts.

3.5 Results and Discussions

This study aims to evaluate Istanbul districts in terms of flood risk based on thirteen criteria, including both vulnerability and hazard and reveal the agreement level among major FRM stakeholders in Istanbul. Criteria weights were calculated through a fuzzy AHP questionnaire collected from 14 experts and used in the TOPSIS method to evaluate the districts of Istanbul for each stakeholder separately. The results were analysed by using Pearson's correlation coefficient for criteria weights and closeness coefficients, and Spearman's rank correlation coefficient for criteria and district rankings. The findings of fuzzy AHP analysis regarding criteria and sub-criteria weights are shown in Table 3.6 and Table 3.7, respectively.

Table 3.6 : Criteria weights based on different stakeholders.

Cluster	Criteria	Overall	LM	DM	WS	UN
Vulnerability	Vulnerable structures	0.070	0.096	0.080	0.038	0.105
	Population density	0.073	0.087	0.085	0.059	0.119
	Vulnerable population	0.064	0.054	0.074	0.033	0.085
	Education level	0.063	0.042	0.069	0.025	0.065
	Income level	0.060	0.057	0.055	0.030	0.079
	Transportation network	0.047	0.009	0.010	0.015	0.053
	Number of households	0.049	0.031	0.039	0.024	0.071
	Land use	0.080	0.120	0.100	0.069	0.132
Hazard	Storm water pipe network	0.099	0.120	0.118	0.146	0.057
	Slope	0.095	0.107	0.093	0.137	0.057
	Imperviousness	0.099	0.104	0.114	0.175	0.047
	Return period of storm event	0.107	0.142	0.127	0.177	0.072
	Number of rainy days in a year	0.093	0.032	0.036	0.071	0.058

The results show that the return period of the storm event was determined as the most significant factor contributing to the flood risk of Istanbul by 0.107, while land use was the most important criterion in terms of vulnerability cluster with a weight of 0.080. However, different stakeholders considered criteria weights in terms of their priorities, which could in return lead to a change in generated maps as well as preferred mitigation measures. LM determined the top three criteria as the return period of the storm event (0.142), storm water pipe network (0.120), and land use (0.120), similar to the judgments of DM, who also regarded the same two criteria at the top with weights of 0.127, 0.118; while assessing imperviousness instead of land use as the third most critical criterion. However, WS and UN had the most divergent opinions about criteria weights of hazard and vulnerability criteria. The professionals who are mostly responsible for the structural adjustments in the flood control strategies evaluated all-hazard criteria (minimum 0.071) more important than any vulnerability criteria (maximum 0.069). Similarly, academics regarded the top five vulnerability criteria (minimum 0.079) as more important than any hazard criteria (maximum 0.072), with exceptions of the number of households (0.071), education level (0.065), and transportation network (0.053) as the least significant vulnerability criteria. Besides, the participants from UNs mostly concentrated on the people-oriented factors, such as land use, population density and vulnerable structures. These results may come from the fact that academicians contemplate with the governance of risk in terms of institutional framework by making policy development considering social-related aspects. The results showed the three featured criteria, i.e., return period of the storm event, imperviousness, and storm water pipe network, which also pertains to the hazard cluster, determined as the most important criteria by WS. This can be expected as the principal focal point of WS is taking structural precautions to mitigate the impacts of floods (URL-2). Academicians, on the other hand, have a relatively more balanced perception of the flood risk with closer criteria weights among the 13 criteria. They consider every aspect of flood incident and regarded as the consultants more than being one of the main pillars (Ekmekcioğlu et al., 2021a).

Table 3.7 : Sub-criteria weights based on different stakeholders.

Criteria	Sub-criteria	Overall	LM	DM	WS	UN
Vulnerable structures	<1969	0.389	0.607	0.426	0.414	0.441
	1969 - 1982	0.333	0.393	0.352	0.360	0.343
	1983 - 2012	0.232	0.000	0.188	0.226	0.186
	2013 - 2018	0.045	0.000	0.034	0.000	0.030
Vulnerable population	<10	0.361	0.513	0.413	0.404	0.470
	10 - 19	0.251	0.075	0.239	0.180	0.149
	20 - 64	0.051	0.000	0.000	0.000	0.000
	>64	0.337	0.412	0.348	0.416	0.381
Education level	Non-literate	0.320	0.633	0.411	0.366	0.314
	Literate (without education)	0.296	0.367	0.326	0.336	0.303
	Up to high school	0.246	0.000	0.213	0.259	0.234
	Bachelor or more	0.138	0.000	0.050	0.038	0.150
Land use	Commercial/ Industrial	0.439	0.705	0.527	0.475	0.448
	Residential	0.425	0.295	0.473	0.503	0.465
	Rural	0.136	0.000	0.000	0.022	0.087
	Forestry	0.000	0.000	0.000	0.000	0.000
Slope	<1%	0.000	0.000	0.000	0.000	0.000
	1% - 4%	0.196	0.000	0.122	0.000	0.197
	5% - 10%	0.346	0.122	0.369	0.340	0.345
	>10%	0.458	0.878	0.509	0.660	0.458
Imperviousness	71 - 76	0.000	0.000	0.000	0.000	0.000
	77 - 82	0.198	0.000	0.157	0.117	0.200
	83 - 88	0.340	0.239	0.345	0.357	0.346
	89 - 94	0.462	0.761	0.498	0.526	0.455
Return period of storm event	< 2	0.048	0.000	0.000	0.000	0.037
	2 - 10	0.211	0.000	0.132	0.007	0.221
	11 - 50	0.329	0.280	0.351	0.386	0.332
	> 50	0.412	0.720	0.517	0.607	0.411

It is also important to note that values considered in the evaluation matrix correspond to the criteria consisting of sub-criteria that need to be minimized at all, since TOPSIS positive ideal of all of them were max, indicating maximizing them would result in maximum CC_i values in terms of flood vulnerability, hazard, and risk. Table 3.7 shows that i) buildings built before 1969 in VS criteria, ii) population aged less than 10 in VP criteria, iii) non-literate in EL criteria, iv) commercial/industrial area in LU criteria, v) area with higher than 10% slope in SL criteria, vi) area with curve number 89-94 in IM criteria, and vii) storm events with higher than 50 years in RP criteria are sub-criteria to be minimized in order to reduce flood vulnerability, flood hazard and inevitably flood risk. In addition, some other criteria without sub-criteria such as PD and NR need to be minimized for better flood response since the TOPSIS positive ideal of these criteria are max (Table 3.2). On the other hand, IL, TN, NH, and SP criteria are to be maximized in order to better deal with flood risk, as the TOPSIS positive ideal of them is min (Table 3.2). In this context, fuzzy AHP analyses could provide a valuable policy direction for decision-makers by highlighting which criteria to deal with first.

Based on the calculated criteria weights, 39 districts of Istanbul have been assessed via a hybrid fuzzy AHP-TOPSIS analysis. Then, the maps were generated regarding the closeness coefficient value determined through TOPSIS analysis for vulnerability (Figure 3.5a), hazard (Figure 3.5b), and combining both to evaluate flood risk of the districts (Figure 3.5c), by aggregating the judgments of all participants. Vulnerability and hazard maps were generated by considering only vulnerability (8 criteria) and hazard (5 criteria), respectively, while the risk map was generated by considering all vulnerability and hazard criteria (13 criteria).

The maps were also generated based on the judgments of different stakeholders (LM, DM, WS and UN) separately, considering not only vulnerability (Figure 3.6) and hazard (Figure 3.7), but also both to evaluate flood risk (Figure 3.8). This could make it easier to analyse the perception differences of stakeholders with a practical mapping approach. Table 3.8 shows the ranking differences based on the perceptions of different stakeholders with respect to flood vulnerability, hazard, and risk, along with the number of flood events that occurred between 2000 and 2015 in Istanbul (Özeyranlı Ergenç, 2016).

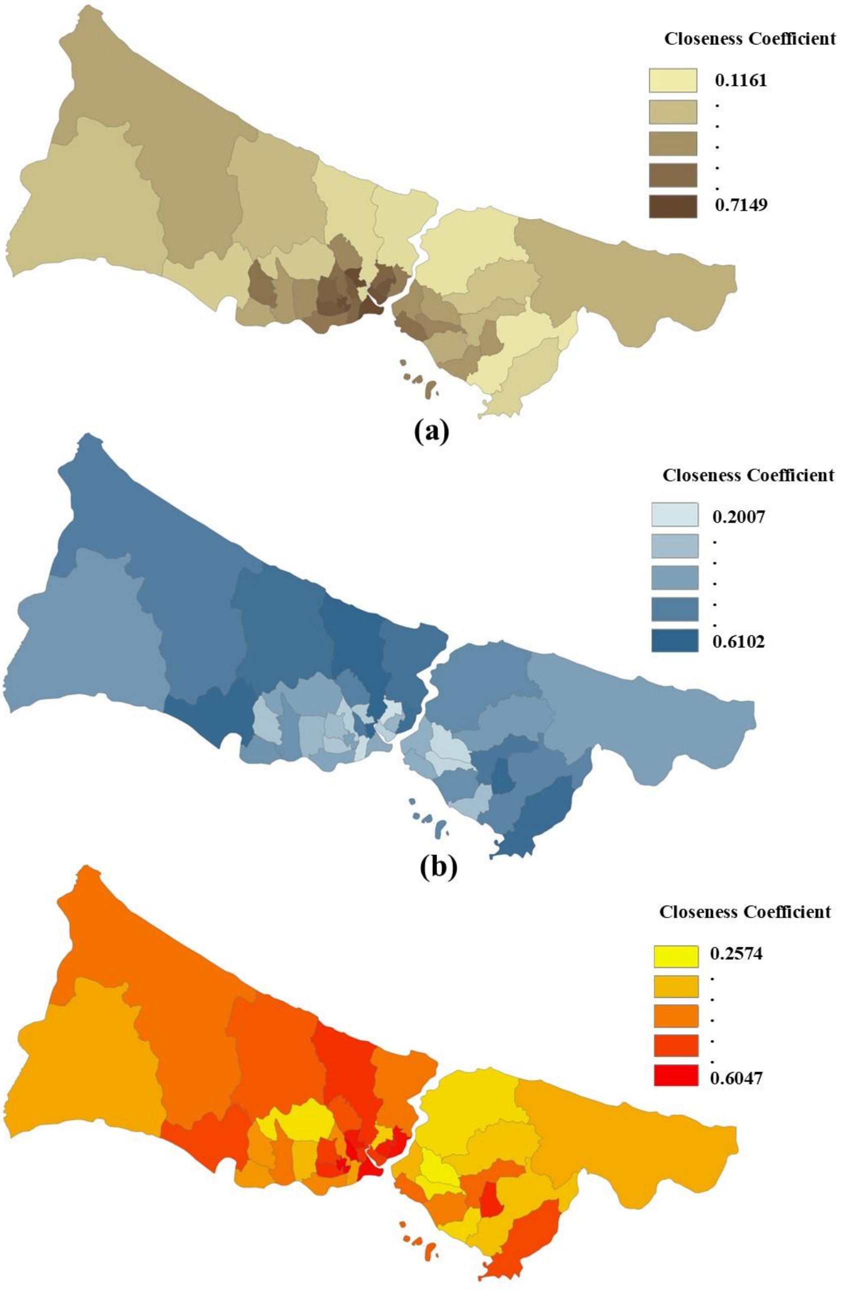

Figure 3.5 : District-based generated maps of Istanbul

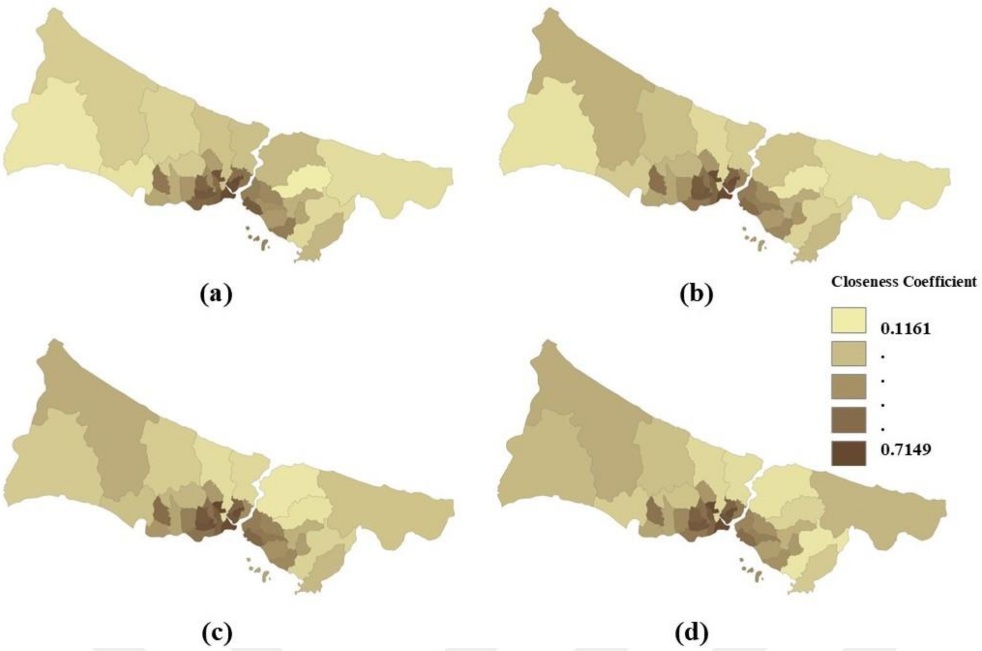

Figure 3.6 : District-based vulnerability maps of Istanbul

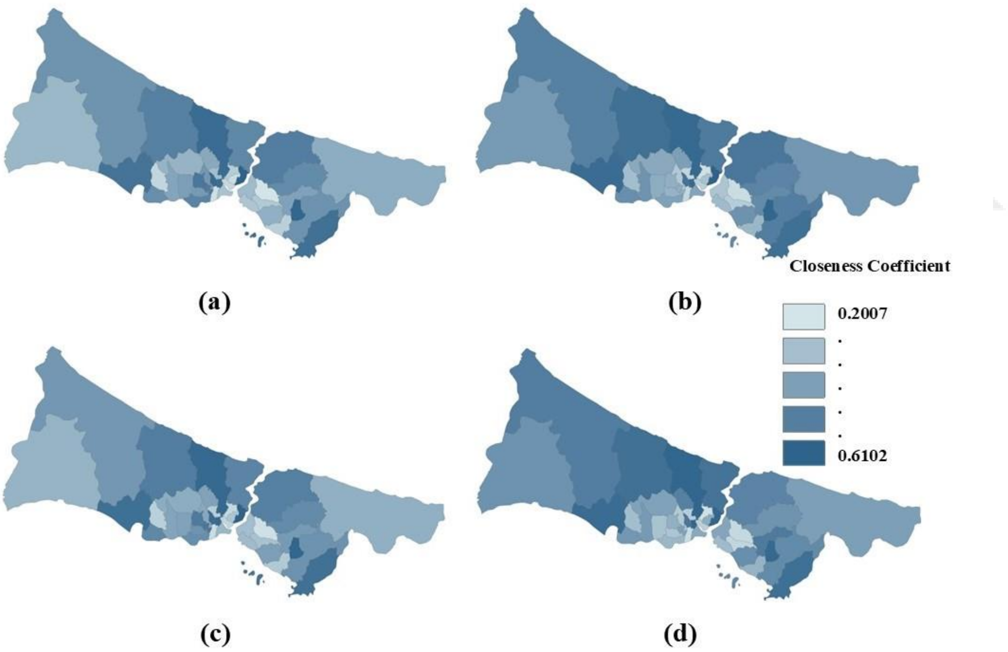

Figure 3.7 : District-based flood hazard maps of Istanbul

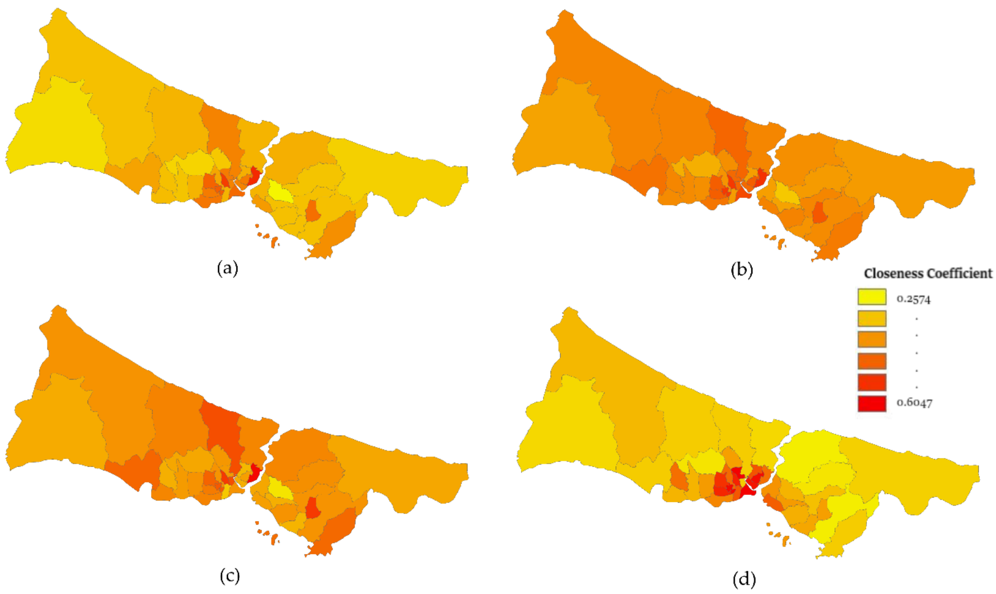

Figure 3.8 : District-based flood risk maps of Istanbul

Even though the overall aggregated framework could provide reliable results as it reflects the perceptions of all stakeholders, there is still a need to examine the impacts of different perceptions on the generated flood risk maps. Table 3.8 provides the details of CC_i values and corresponding ranks based on the districts according to four stakeholders. According to the Table, there is no significant change in the ranking of districts in terms of vulnerability or hazard clusters. However, due to the divergent opinions about the importance of vulnerability and hazard criteria, the overall ranking of districts differs crucially in terms of flood risk, enough to orient different FRM strategies. It can also be seen from Table 3.8 that Gaziosmanpasa, Fatih, Gungoren, Beyoglu, and Sisli were the most vulnerable districts of Istanbul, with CC_i values of 0.644, 0.639, 0.614, 0.614, and 0.613, respectively. The rest of the districts were evaluated with CC_i values significantly lower than the top five districts such that CC_i value of the sixth most vulnerable district Bahcelievler was 0.580, separating the top five from them. Eyup, Buyukcekmece, Sultanbeyli were assessed with 0.579, 0.555, and 0.553 CC_i values by considering only hazard criteria. With respect to both clusters, Bayrampasa (0.526), Gungoren (0.517), Fatih (0.499), Besiktas (0.498), and Gaziosmanpsa (0.491) were found to be the top flood-prone districts of Istanbul.

Table 3.8 : Ranking variations of Istanbul Districts according to the stakeholders.

	Vulnerability					Hazard					Risk				
	CC_i	Rank				CC_i	Rank				CC_i	Rank			
Districts	All	LM	DC	WS	UN	All	LM	DC	WS	UN	All	LM	DC	WS	UN
Adalar	0.405	17	24	26	19	0.477	5	13	7	13	0.446	7	18	9	17
Arnavutkoy	0.312	34	31	34	31	0.524	11	6	10	6	0.448	24	17	12	30
Atasehir	0.391	20	16	15	16	0.338	32	34	31	36	0.359	26	36	34	18
Avcilar	0.354	26	26	25	26	0.469	22	17	23	19	0.430	33	23	25	25
Bagcilar	0.553	9	7	7	8	0.406	8	26	9	26	0.466	4	7	6	8
Bahcelievler	0.580	6	6	5	6	0.399	19	27	17	32	0.472	11	6	10	7
Bakirkoy	0.423	10	14	14	14	0.428	12	22	15	28	0.426	8	13	11	15
Basaksehir	0.262	32	29	29	32	0.438	26	24	25	21	0.373	37	38	29	36
Bayrampasa	0.567	11	8	8	7	0.496	3	7	4	8	0.526	2	3	2	6
Besiktas	0.413	13	17	20	15	0.549	1	1	1	2	0.498	1	1	1	13
Beykoz	0.204	29	32	39	38	0.477	10	8	11	12	0.386	19	26	14	39
Beylikduzu	0.340	25	25	22	25	0.466	15	15	13	18	0.416	25	25	13	26
Beyoglu	0.614	3	4	6	4	0.372	36	35	36	35	0.466	12	11	33	5
Buyukcekmece	0.254	37	33	31	34	0.555	7	4	5	4	0.455	16	12	7	32
Catalca	0.342	33	28	27	27	0.489	17	11	18	10	0.437	31	20	20	27
Cekmekoy	0.281	39	39	38	35	0.458	14	12	14	17	0.391	34	31	16	37
Esenler	0.490	19	13	13	12	0.374	18	33	24	33	0.425	17	29	19	12
Esenyurt	0.458	14	12	12	13	0.400	35	30	35	30	0.423	32	22	35	14
Eyup	0.243	31	36	37	36	0.579	4	3	3	1	0.469	13	9	4	29
Fatih	0.639	2	1	2	1	0.422	30	23	28	24	0.499	5	4	21	1
Gaziosmanpasa	0.644	4	3	1	2	0.386	29	36	34	34	0.491	9	10	26	2
Gungoren	0.614	5	5	4	5	0.438	9	18	8	22	0.517	3	2	5	3
Kadikoy	0.472	7	11	11	11	0.420	31	29	29	29	0.439	15	16	27	11
Kagithane	0.531	12	10	10	9	0.290	33	39	37	39	0.390	18	35	37	9
Kartal	0.360	15	18	19	20	0.406	34	28	33	27	0.390	27	30	36	22
Kucukcekmece	0.384	21	20	17	18	0.413	20	25	22	31	0.402	23	27	22	19
Maltepe	0.330	22	23	21	24	0.474	25	16	20	15	0.428	29	15	17	23
Pendik	0.194	35	35	35	39	0.482	16	10	16	14	0.396	30	24	18	38
Sancaktepe	0.317	27	27	28	28	0.504	21	14	19	9	0.444	28	21	23	28
Sariyer	0.218	30	34	36	37	0.517	13	9	12	7	0.429	22	19	15	35
Silivri	0.309	38	38	33	30	0.466	27	20	27	16	0.409	38	37	32	34
Sultanbeyli	0.365	24	21	24	23	0.553	2	2	2	3	0.482	6	5	3	20
Sultangazi	0.389	23	22	23	22	0.488	23	21	21	11	0.449	35	28	24	21
Sile	0.326	36	37	32	29	0.448	24	19	26	20	0.406	36	33	30	33
Sisli	0.613	1	2	3	3	0.417	37	31	32	25	0.486	10	8	28	4
Tuzla	0.253	28	30	30	33	0.549	6	5	6	5	0.453	14	14	8	31
Umraniye	0.344	18	19	18	21	0.334	39	38	39	37	0.338	39	39	39	24
Uskudar	0.371	16	15	16	17	0.420	28	32	30	23	0.403	20	34	31	16
Zeytinburnu	0.527	8	9	9	10	0.330	38	37	38	38	0.410	21	32	38	10

The number of past flood events also shows that Bagcilar, Gaziosmanpasa, and Kadikoy have experienced flood events at most between 2000-2015, which were also assessed with CC_i values of 0.553, 0.644, and 0.472 in terms of vulnerability, 0.406, 0.386, and 0.420 in terms of hazard, and 0.466, 0.491, 0.439 in terms of flood risk, respectively. Bagcilar was among the riskiest districts, particularly when judgments of the experts from LM are considered. Gaziosmanpasa was admitted as the most vulnerable district (Table 3.8). In addition, Kadikoy was also among one of the most vulnerable districts in the Asian side of the city, particularly for LM experts. The reason for higher flood risk scores of districts such as Bayrampasa, Gungoren, and

Fatih than other districts compared to historical flood events is that these areas experienced significant urbanization and inevitable land-use change over the last couple of years, which were not covered in the past flood events. It should be noted that calculated risk scores were based on the data provided in 2020, while compared floods were between 2000-2015.

Furthermore, official initiatives have been carried out by the Istanbul Metropolitan Municipality within the scope of the micro zonation projects (Ekmekcioğlu et al, 2021a). The flood hazard maps were produced by considering a set of factors, such as extreme precipitations, topography, storm water drainage systems, dam reservoir volumes, and past flood records, which showed that the most hazardous districts coincide with the hazard ranks of LM calculated in this study. Besides, Yalçın (2012) developed the flood hazard map for the European side of Istanbul. The researcher also found that the riskiest districts in terms of urban floods were in the middle of the European side of Istanbul; such that the top three districts in terms of flood risk, Fatih, Gungoren and Gaziosmanpasa (Figure 3.1), as ranked by the UN, are located in the middle of the European side of Istanbul (Table 3.8). In addition, several researchers from various universities performed in-depth investigations for the Ayamama watershed (Altunkaynak and Bizimana, 2020; Gülbaz et al, 2019; Nigussie and Altunkaynak, 2019; Yucel, 2015), which was affected by one of the biggest flood disasters that took place in Istanbul. It is also worth mentioning that the Ayamama stream passes through the Bahcelievler and Bagcilar districts, in which these two districts were found as the sixth and seventh risky districts in terms of the assessments of the UN experts.

Academicians considered Fatih as the most flood-prone district, while other groups named Besiktas. It is important to note that even though none of the stakeholders assessed Bayrampasa at the top, the district is found to be the riskiest district after the combination of the different opinions obtained from the expert groups about other districts. Particularly, perception differences between WS and UN are of paramount significance because there are some opposite views. For instance, UN assessed Fatih, Gaziosmanpasa and Sisli as the first, second and fourth districts, while WS considered them as the twenty-first, twenty-sixth and twenty-eighth in terms of flood risk, respectively (Table 3.8). This can be further supported with the results of Pearson’s correlation coefficient test for criteria weights and closeness coefficients, and

Spearman's rank correlation coefficient test for the ranking of criteria and district prioritization, as provided in Table 3.9 and Table 3.10, respectively. The results show that a high agreement level exists between all stakeholders, apart from WS and UN. Even a negative correlation was observed between the perceptions of WS and UN about the criteria weights by -0.326 (Table 3.9) and rankings by -0.159 (Table 3.10), which is a clear reason for the low correlation coefficients in terms of CC_i value (Table 3.9: 0.080), and ranking order of districts (Table 3.10: -0.055) for flood risk.

Table 3.9 : Agreement level between stakeholders though Pearson's correlation.

Category	Stakeholders	LM	DM	WS	UN
Flood risk	LM		0.919**	0.764**	0.649**
	DM	–		0.790**	0.594**
	WS	–	–		0.080
	UN	–	–	–	
Flood vulnerability	LM		0.971**	0.940**	0.950**
	DM	–		0.992**	0.988**
	WS	–	–		0.987**
	UN	–	–	–	
Flood hazard	LM		0.860**	0.983**	0.784**
	DM	–		0.916**	0.959**
	WS	–	–		0.847**
	UN	–	–	–	
Criteria weights	LM		0.946**	0.775**	0.274
	DM	–		0.792**	0.163
	WS	–	–		-0.326
	UN	–	–	–	

** Correlation is significant at 0.05 level

Although the experts included in the current research are from different institutes and their perspectives on the flood risk concept differ from each other, their engineering backgrounds may lead to a similarity in the results, particularly for the experts attended from LM, DM, and WS. Nevertheless, the biggest difference expected between the perceptions of the experts comes from the universities which showed a more theoretic and analytical approach to the problems with a broader horizon (Table 3.9 and Table 3.10). It is also important to note that the results of the study can be reinforced with a more diverse range of participants by including versatile stakeholders in terms of their educational backgrounds in the surveys.

Table 3.10 : Agreement level between stakeholders though Spearman's rank correlation.

Category	Stakeholders	LM	DM	WS	UN
Flood risk	LM		0.810**	0.590**	0.654**
	DM	–		0.710**	0.474**
	WS	–	–		-0.055
	UN	–	–	–	
Flood vulnerability	LM		0.968**	0.938**	0.942**
	DM	–		0.982**	0.971**
	WS	–	–		0.979**
	UN	–	–	–	
Flood hazard	LM		0.846**	0.981**	0.754**
	DM	–		0.891**	0.952**
	WS	–	–		0.811**
	UN	–	–	–	
Criteria weights	LM		0.945**	0.808**	0.198
	DM	–		0.824**	0.066
	WS	–	–		-0.159
	UN	–	–	–	

** Correlation is significant at 0.05 level

High correlation between flood vulnerability and hazard maps can also be observed from Figure 3.6 and Figure 3.7. Besides, the disagreement between stakeholders, specifically between WS and UN, can be seen in Figure 3.8. It is important to note that high level of correlation does not mean that both stakeholders have the same ideas about the flood risk of districts. The correlation rather shows that the increase in the CC_i values of the districts assigned by a stakeholder is associated with the increase in the CC_i values of the districts assessed by another. Figure 3.8 reveals that even though maps generated by DM and UN show distinct differences in the extent of risk, they have a common ground (Table 3.9: 0.594). Meanwhile, there is a lack of agreement between WS and UN at most (Table 3.9: 0.080), which can be traced back to the contrast in Figure 3.8. Older districts surrounded by Bosphorus in the middle were assessed with significantly higher CC_i values by UN, while WS evaluated the new settled and old districts similarly in terms of flood risk. Furthermore, it is especially worth mentioning that these varieties in perception differences among stakeholders are quite important for investigating the main determinants of flood risks (Lechowska, 2018).

3.6 Conclusions

The purpose of this study is to assess the districts of Istanbul concerning flood risk by using a hybrid fuzzy AHP-TOPSIS approach to investigate the perception differences between four stakeholders. Hazard and vulnerability criteria weights for Istanbul were determined by using fuzzy AHP analysis based on the experts from four main stakeholders as i) local and metropolitan municipalities, ii) disaster management and coordination centres, iii) water and sewerage administrations, and iv) universities, thus considered in the study. The collected data were aggregated on a stakeholder basis to examine perception differences. TOPSIS method was then conducted for the calculation of closeness coefficients of each district, and a flood risk map of Istanbul was generated for each stakeholder group separately, along with the maps representing the synthesized perspective. Agreement levels between stakeholders were also examined by using Pearson's correlation coefficient and Spearman's rank correlation coefficient tests.

The findings show that disaster management and coordination authorities (DM) and local municipalities (LM) consider the flood hazard and vulnerability clusters with almost similar importance. On the other hand, water and sewerage administrations (WS) consider hazards, while universities (UN) consider vulnerability as more significant than the other. Generated flood risk maps and correlation analyses show that high perception differences exist between experts from universities (UN) and water and sewerage administrations (WS), while perception similarities can be observed between other stakeholders. Even negative correlations were observed for both criteria weights and district risk scores. Therefore, this study ensures that including solely one type of stakeholder is not enough to evaluate flood risk criteria. Rather, the involvement of a variety of stakeholders is required to generate more reliable flood risk maps.

The results of this study provide not only a flood risk map of Istanbul illustrating the most flood-prone districts but also reveal the perception differences among various stakeholders responsible for performing necessary measures to mitigate, avoid, and manage flood risk. This is significantly important since decision-makers, who develop strategies and initialize investments to deal with flood risk, can benefit from the findings related to the perceptions of the others. Even though this study presents an initial attempt to illustrate perception differences among stakeholders in flood risk management strategies, still it has some limitations that need to be considered in future studies. In this sense, including more experts from sectors other than the engineering sector could be considered in future attempts on flood risk mapping, since generated maps by adopting MCDM tools highly depend on the subjective data provided by a distinct group of participants. Further research could also be conducted by considering not only more criteria but also interrelationships between the criteria. It is especially worth mentioning that if criteria that cannot be expressed with certain values are included, then some other different methods, such as fuzzy network TOPSIS (FN-TOPSIS), could be used rather than the TOPSIS method. Besides, for determining the criteria weights, more novel methods such as the best-worst method (BWM) or fuzzy ANP can be considered in future studies. Probability-based approaches could also help in dealing with vagueness and uncertainty, along with fuzzy approaches. Therefore, a comparison of several methods such as AHP, fuzzy AHP, fuzzy ANP, and BWM could be a valuable research direction for future studies. Finally, although applicability and practical implications were considered in this study, a validation of the results can reasonably improve the reliability of the proposed approach in future studies.

4. TOWARDS FLOOD RISK MAPPING BASED ON MILTI-TIERED DECISION MAKING IN A DENSELY URBANIZED METROPOLITAN CITY OF ISTANBUL[3]

4.1 Introduction

Damages caused by floods affect community life in various ways. These damages include casualties, property losses, and deteriorating sanitation generated from waterborne diseases. Additionally, economic activities are disrupted because of the damage to transportation networks and interruption of communication infrastructure resulting from flood events (Lyu et al, 2019). A flood event defined as a "natural hazard" with atmospheric and meteorological factors in play can metamorphose into a "disaster" with anthropogenic factors. These factors may include erroneous land use, insufficient infrastructure, rapid population growth, and low socioeconomic status. As urbanization leads to irreversible changes in the hydrological characteristics of a region, albeit indirectly, the frequency of flood events and their negative effects increase incrementally (Handayani et al, 2020). With the escalation of imperviousness, especially in urbanized areas, heavy rains can turn into the surface flow, i.e., runoff, and inevitably floods, threatening the built and sustainable environment with great ease (Mohtar et al, 2020).

Worldwide, over 2 billion people have been affected by flood events in the last two decades. Besides, the damage to the economy accounts for 174 billion $ per annum according to the World Health Organization. In Europe alone, nearly a thousand serious events (i.e., natural disasters) have occurred over the last 20 years. Floods accounted for 41% of the total disasters, which resulted in over 2,000 casualties, and the floods contributed to half of the disaster-induced economic losses (URL-11). Regarding Turkey, the country experienced over 700 flood events in the last two

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[3] This chapter is based on the paper "Ekmekcioğlu, Ö., Koc, K. and Özger, M. (2022). Towards flood risk mapping based on multi-tiered decision making in a densely urbanized metropolitan city of Istanbul. Sustainable Cities and Society, 80 (November 2021), 103759. 10.1016/j.scs.2022.103759".

decades, causing death tolls of over 250 lives. Apart from this negative scheme representing the entire Turkey, the sense of flood disaster in Istanbul, the most densely populated city of Turkey, draws attention more strikingly. Here, the number of floods that occurred in Istanbul city during the last 20 years was nearly two hundred (Özeyranlı Ergenç and Barış, 2018), and it is distinctively at high risk of flood hazards (Ekmekcioğlu et al, 2021a). Overall, proposing a remedy to mitigate the number of floods and their unintended consequences can increase the resilience of cities against unfortunate events.

The concept of flood risk is composed of two main pillars, i.e., flood hazard and flood vulnerability (Skakun et al, 2014). Hazard refers to the geographic and frequency distribution of intensity measures of a threatening natural event in a particular location (Wang and Sebastian, 2021). Meanwhile, vulnerability is explained by the lack of resistance to damaging events based on various dimensions such as community-based, i.e., population density (Baky et al, 2020) and income level (Kron, 2005), or land use-based (Masood and Takeuchi, 2012) resulting in significant entity losses. Hence, this study was designed to produce flood hazard, flood vulnerability, and flood risk maps for the metropolitan city of Istanbul on a district level based on the hybrid use of several multi-criteria decision-making (MCDM) methods. To accomplish this goal, a comprehensive literature survey was conducted to designate the decision framework comprising vulnerability and hazard criteria along with the active participation of relevant authorities during the multi-stage focus group discussion (FGD) session. The main objective of the current work is to illustrate the utilization of multi-step comprehensive MCDM techniques, including analytic hierarchy process (AHP), analytic network process (ANP), decision-making trial and evaluation laboratory (DEMATEL), and visekriterijumska optimizacija i kompromisno resenje (VIKOR) methods for the assessment of a densely urbanized city in terms of flood risk. Identification of the most triggering factors, regarding both hazard and vulnerability aspects of flood risk concept, is another motivation of this research containing the implications to combat potential flood incidents by early diagnosis of strategic decisions for how to provide resistance and response against cascading effects of floods and improve operations for recovery.

The novelty of this study that is expected to contribute to the flood risk management (FRM) literature is four-folded and summarized as:

- AHP was performed to compute hazard criteria weights because of the absence of inter-relationship among hazard criteria. Meanwhile, the ANP technique was adopted to the vulnerability cluster as its criteria contain interdependent relationships among themselves. The FRM literature heavily relies on the AHP method for criteria assessment while overlooking the ANP technique.
- Integrating the DEMATEL technique is an initial attempt in the FRM literature to define the ANP structure for criteria assessment.
- The judgments of participants in FGD were considered at each level of the framework refinement, including identifying flood risk criteria, determining the roles of each criterion on flood risk in Istanbul, and constructing the ANP structure. Such a comprehensive framework development approach has rarely been adopted in the literature.
- The application of the VIKOR method was conducted for the first time in the flood risk mapping literature, whereas the robustness of the adopted methodology and the stability of the outcomes were vindicated through sensitivity analysis.

Overall, the proposed multi-step MCDM framework is expected to assist decision-makers in practicing the most effective strategies to combat flood events in metropolitan cities. Generating a flood risk map of Istanbul by considering the strengths of each method is expected to shed light on FRM practitioners to offer more effective and sustainable strategies.

4.2 Literature on Flood Mapping Based on MCDM Approach

The hard-to-repair effects of global warming and climate change make it difficult to engender sustainable cities, particularly with the distresses caused by human-made stressors. Floods are currently one of the most substantial natural hazards, causing disruption of social life and generating environmental and economic challenges (Chen et al, 2021). In recent years, a significant increase in the number of urban floods has prompted scholars to diagnose the potential events in advance to take necessary measures by considering proactive approaches (Koc et al, 2021; Nguyen et al, 2019; Pour et al, 2020). Some of these measures comprise the generation of risk-based management strategies such as producing flood risk maps. Recently, there have been plenty of studies regarding flood mapping conducted through an expanded spectrum of methodologies in the pertinent literature, such as computational techniques (Vasconcellos et al, 2021), entropy weighting method (Malekinezhad et al, 2021), and hydrodynamic model engaged with data assimilation technique (Jafarzadegan et al, 2021). In addition, several machine learning methods, such as adaptive neuro-fuzzy inference system (ANFIS), artificial neural network (ANN), random forest (RF), support vector machine (SVM), and decision trees (DT), have been operated by various scholars to detect flood-prone areas (Andaryani et al, 2021; Costache et al, 2021; Luu et al, 2021; Towfiqul Islam et al, 2021). The abovementioned methodologies investigate the flooding concept in terms of quantitative approaches. Here, MCDM tools take the significance of both quantitative and qualitative manners into account in flood mapping attempts. Besides, MCDM approaches can benefit by taking expert knowledge into account, as the roles of stakeholders are undeniable in effective FRM strategies (Ekmekcioğlu et al, 2021b).

A few of the past efforts comprising the utilization of MCDM tools for flood mapping are presented in Figure 4.1. Most researchers employed AHP or fuzzy AHP methods to produce flood hazard maps of various watersheds, municipalities, or cities (Das, 2018; Dung et al, 2021; Hategekimana et al, 2018b; Papaioannou et al, 2015; Vojtek and Vojteková, 2019). Only a few researchers evaluated the flood vulnerability of the regions (De Brito et al, 2018). The main reason for the high volume of flood hazard studies is that flood events are essentially associated with internal dynamics of nature, explained by the “hazard” concept. However, the notion of “risk” should be considered once the anthropogenic factors are involved. Therefore, the research society has embraced the concept of flood risk mapping in recognizing two main pillars, i.e., hazard and vulnerability (Nasiri et al, 2016). In this respect, Zou et al. (2013) considered both hazard and vulnerability criteria for grading the towns in Jingjiang district, China in terms of five main classes, i.e., very low to very high. Likewise, Chen et al. (2015) developed an integrated spatial multi-criteria decision making (MCDM) framework to assess the flood risk for mining sites in Bowen Basin, Australia. They considered six criteria, i.e., five for hazard (rainfall, evapotranspiration, topography, drainage network, and flow measurements) and one for vulnerability (land cover). Criteria weights were calculated via the AHP method. Ekmekcioğlu et al. (2021b) constituted a fuzzy AHP-TOPSIS model to examine stakeholder perceptions in flood risk management. Among several criteria based on hazard and vulnerability clusters, they found that a return period of a storm event had the highest weight, followed by the imperviousness and storm water pipe network. Tang et al. (2021) performed a spatial multi-criteria analysis based on AHP for evaluating coastal watersheds in south-eastern China, considering three dimensions of flood risk, i.e., hazard, exposure, and vulnerability. They concluded that peak discharge, maximum daily rainfall, age of people, the proportion of wetland, and reservoir storage capacity were the most determinant five indicators in quantifying the spatiotemporal dynamics of flood risk. The existing body of research shows that the multiple utilization of MCDM methods such as AHP, ANP, DEMATEL, and VIKOR with their diverging advantages have not been surveyed in flood risk mapping studies. In addition, considering interrelationship among the criteria through the DEMATEL approach to draw dependencies required in the ANP method has been overlooked in the pertinent literature. Besides using AHP, DEMATEL, and ANP methods in criteria assessment, this study adopted the VIKOR method for alternative evaluation, which has limited implementations in the flood risk mapping literature. Hence, the methodology adopted in this study is expected to contribute to the theory regarding robust methodological framework, as well as practice through proposing effective flood risk mitigation measures.

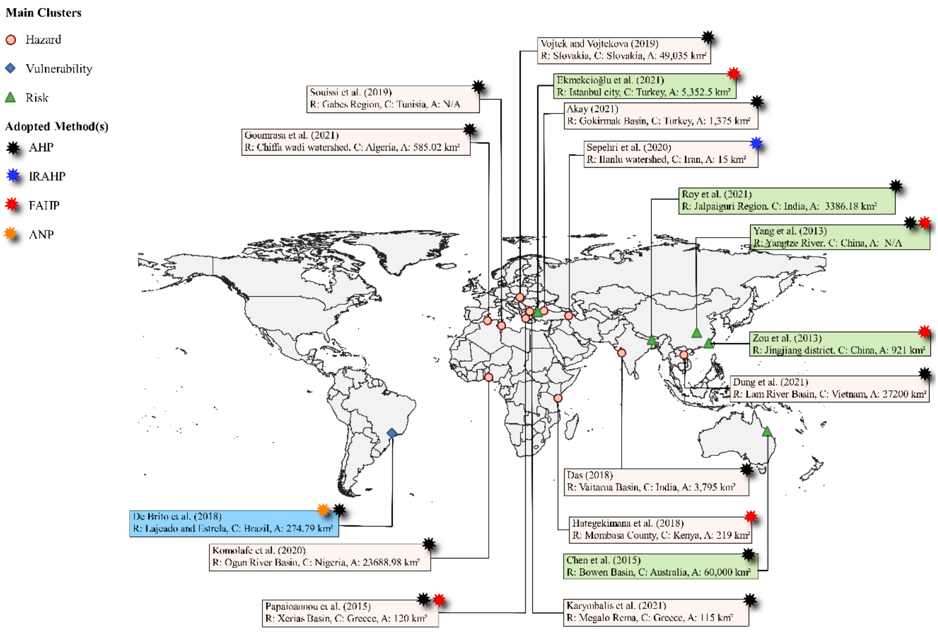

Figure 4.1 : Worldwide MCDM studies on flood mapping.

4.3 Study Area and Data

Istanbul is in the northwest part of Turkey, ascending between the Black Sea and the Marmara Sea. The city is divided by the Bosphorus into two sides, i.e., the European side and the Asian Side. Istanbul comprises 39 districts, and the European and Asian sides possess 25 and 14 districts, respectively (Figure 4.2). The most populated city across Turkey, Istanbul hosts nearly 16 million residents with its 5461 km² surface area. 65% of the entire population is on the European side, while the rest of 35% is on the Asian side. Sultangazi is the most densely populated district, with nearly 54 thousand people/km² while Sile registers as the smallest district of the city, with 44 people/km² (URL-10). Istanbul's land structure can be regarded as sloping, such that the maximum slopes for European and Asian sides are 20% and 14%, respectively. The northwest and the northeast parts of the city are mostly dominated by forests, i.e., broad-leaved forest, coniferous forest, and mixed forest. Non-irrigated arable lands cover the southwest, and the urban areas mostly agglomerate at the center of the city according to the land cover maps extracted through CORINE (coordination of information on the environment) land cover dataset (URL-12). Between October and February, the highest precipitation values are observed, and the lowest precipitation values are recorded between May and August. The monthly average rainfall is 690.5 mm, and the mean annual temperature is 16.2 oC in the city (URL-1). Bagcilar, Gaziosmanpasa, and Kadikoy are the most flooded districts in the last two decades, while Adalar has not been exposed to any flooding incident (Özeyranlı Ergenç and Barış, 2018). In addition, climate change, along with land use and land cover alterations because of the rapid urbanization in the city, led to serious flood events. The storm events that have 100-years and 300-years of recurrence intervals caused significant flood incidents in Bahcelievler (2007) and Bagcilar (2009), respectively (Güçlü and Şen, 2016). Another event has occurred in 2008 on the Asian side of the city, and Kadikoy was significantly affected, while Esenler has suffered from flooding in 2014, causing dramatic property losses in the largest bus terminal of Istanbul (Ekmekcioğlu et al, 2021a).

This research considered two main pillars, i.e., hazard and vulnerability, of flood risk concept, each containing five criteria. The criteria were selected based on a comprehensive literature survey and refined with the FGD sessions containing divergent perceptions of FRM stakeholders. Storm water pipe network (km/built km²), slope, imperviousness, return period of a storm event (year), and distance to water (km/surface area km²) were determined for hazard cluster. For the vulnerability cluster, vulnerable structures (built year), population density (number of people/district area km²), vulnerable population (age), education level, and income level were designated. Table 4.1 summarizes the criteria employed in the current research. Note that all criteria were divided into four sub-criteria except for the population density (URL-5), income level (URL-6), storm water pipe network (URL-2), and distance to water (from Google Earth) as they have unique values for each district. Concerning slope criterion, we generated the digital elevation model of the entire city with 30x30 resolution data taken from (URL-8) and calculated the mean slope values of each district. The imperviousness of the districts was determined according to the average curve number values computed based on the global curve number map (250x250 m resolution) produced by Jaafar et al. (2019). In addition, the rainfall records comprising the data between 2005 and 2021 were obtained from meteorological stations for each district (URL-1). Based on these records, historical storm events were derived, and the number of storm events corresponding to different return intervals, i.e., up to 2 years, 2 to 10 years, 10 to 50 years, and over 50 years, was determined.

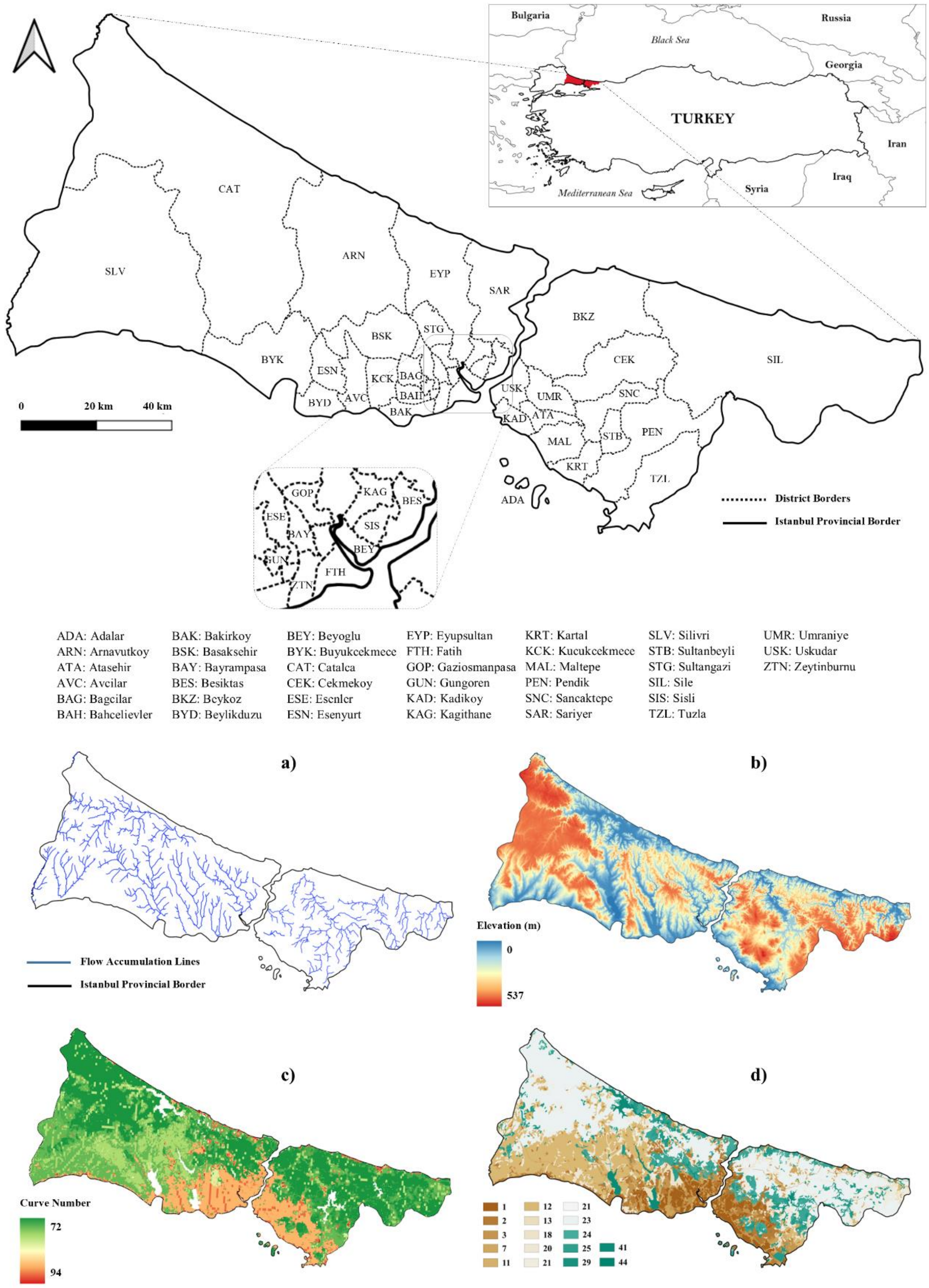

Figure 4.2 : Study area (Legend for LU/LC (d): 1: Continuous urban fabric, 2: Discontinuous urban fabric, 3: Industrial or commercial units, 7: Mineral extraction sites, 11: Sport and leisure facilities, 12: Non-irrigated arable land, 13: Permanently irrigated land, 18: Pastures, 20: Complex cultivation patterns, 21: Land principally occupied by agriculture, 22: Agro-forestry areas, 23: Broad-leaved forest, 24: Coniferous forest, 25: Mixed forest, 29: Transitional woodland-shrub, 41: Water bodies).

Table 4.1 : Summary of the utilized criteria.

Clusters	ID	Criteria	Data Format	Splitting Criterion	Sub-criteria	Data source
Vulnerability (V)	V1	Vulnerable structures	Year	Nature of the data	• <1969 • 1969 - 1982 • 1983 - 2012 • 2013 - 2018	Konukcu et al. (2017) URL-3
	V2	Population density	Number of Residents/km²	–	–	URL-4 URL-5
	V3	Vulnerable population	Age	Literature (J. Tang et al., 2021)	• <10 • 10 - 19 • 20 - 64 • >64	URL-5
	V4	Education level	-	Literature (Tekeli-Yeşil et al., 2011)	• Non-literate • Literate • Up to high school • Bachelor or more	URL-6
	V5	Income level	Turkish Lira/Month	–	–	URL-6
Hazard (H)	H1	Storm water pipe network	km/built km²	–	–	URL-2
	H2	Slope	%	Expert Judgement	• <1% • 1% - 4% • 5% - 10% • >10%	URL-8
	H3	Imperviousness (Curve number)	-	Expert Judgement	• 71 – 76 • 77 - 82 • 83 - 88 • 89 – 94	Jaafar et al. (2019)
	H4	Return period of storm event	Year	Literature (J. Tang et al., 2021)	• < 2 • 2-10 • 11-50 • > 50	URL-1
	H5	Distance to water	km/built km²	–	–	URL-1

4.4 Methodology

4.4.1 Framework Development

This study aims to prioritize the districts of Istanbul for their susceptibility to the flood risk based on a hybrid usage of MCDM methods aided with focus group discussion (FGD) performed with 10 participants who have adequate experience in FRM practices in Istanbul (Table 4.2). A multi-step methodology was adopted to achieve the study objective, as illustrated in Figure 4.3. The initial step covers a thorough literature survey to identify flood risk factors, resulting in a list of hazard and vulnerability criteria. Then, the FGD (comprising 3 sub-sessions) was arranged with professionals dealing with FRM practices in Istanbul based on mainly three objectives; to refine the decision framework suitable to flood risk issue in Istanbul (Session 1), to decide the most appropriate analysis procedure (Session 2), and to determine the most applicable threshold value required to draw a proper relationship datum line among included criteria (Session 3). Each FGD session was conducted sequentially, such that the outcomes of each session were operated to form the subsequent session and analysis steps of this study. Accordingly, five vulnerability and five hazard criteria were determined to be included in this study at the end of Session 1. Besides, participants agreed upon that there is no interrelationship in hazard cluster, while network structure needs to be discovered in vulnerability cluster (Session 2). This step was followed by the distribution of the DEMATEL questionnaire to the participants, and individual judgments were collected. Separate judgments of experts were aggregated, and three different threshold values, i.e., average (AVRG), mean-plus-standard-deviation (MPSD), and maximum mean de-entropy (MMDE), were calculated to complete the DEMATEL analysis. Based on the calculated threshold values, three network diagrams were drawn regarding the vulnerability cluster and discussed with FGD participants at Session 3. According to the consensus on a threshold value, the causal relationship diagram (CRD) was drawn, and the decision matrix has been formed for ANP analysis. All steps regarding DEMATEL-ANP were adopted to the vulnerability cluster, while hierarchical representation resulting in AHP analysis was performed for the hazard cluster. Here, ANP and AHP matrices were considered by the same expert group (Table 4.2) through individual judgments to determine criteria weights. This step was the last contribution of the experts who attended the FGD sessions of this study. Then, values attributed to each district regarding each criterion were captured through report review, national statistics, and institutional collaboration and used to perform the VIKOR method. To explore the difference in the analysis results based on the change in the v (weight for the strategy of maximum group utility) value used in the VIKOR method, sensitivity analysis was performed. Finally, a district-based flood risk map of Istanbul was generated to assist the decision-making process in FRM practices in the city.

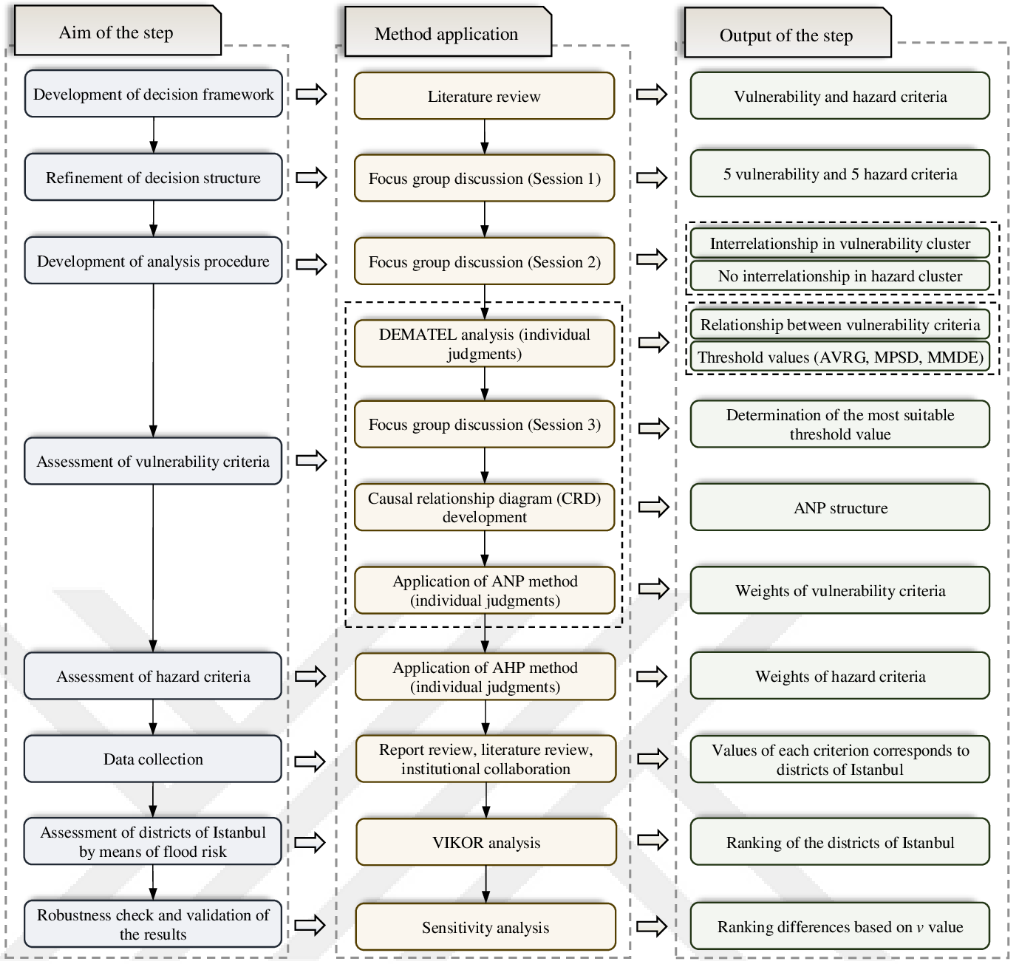

Figure 4.3 : Research flow.

4.4.2 Focus group discussion

Focus group discussion (FGD) is a commonly used qualitative data collection method, enabling an in-depth analysis of issues in various disciplines (Nyumba et al, 2018). In FGD, participants are selected purposively based on their background and involvement in a particular subject that requires diverging viewpoints of several stakeholders. The method enables interaction among participants, combining various perspectives to obtain an in-depth understanding and turn distributed information into valuable and refined insight (Koc et al, 2021). Ten participants with sufficient experience in FRM practices in Istanbul attended FGD to contribute to this study (Table 4.2). Considering the disadvantages of including a few or a very high number of participants, the sample size was adequate. The sample size was also as suggested or considered in the literature (Ajayi and Oyedele, 2017; Budayan et al, 2020; Koc et al, 2021).

Table 4.2 : Profile of the respondents.

ID	Role	Stakeholder group	Division	Background	Experience in FRM
E1	Coordinator	Disaster management entity	Infrastructure	Civil engineering	30
E2	Planning engineer	Disaster management entity	Planning	Civil engineering	15
E3	Engineer	Disaster management entity	Meteorology	Meteorological engineering	12
E4	Landscape architect	Municipality	Planning	Architecture	13
E5	Engineer	Municipality	Infrastructure	Civil engineering	14
E6	Planning manager	Municipality	Planning	Architecture	25
E7	Technical office manager	Water and sewerage administration	Infrastructure	Civil engineering	19
E8	Civil works manager	Water and sewerage administration	Infrastructure	Environmental engineering	25
E9	Associate professor	University	Hydraulics	Civil engineering	18
E10	Associate professor	University	Environment	Environmental engineering	15

The FGD applied in this study comprises three major sessions conducted sequentially for diverging objectives. In the first session, flood risk criteria that can be effectively used for flood risk in Istanbul were identified and categorized into two main clusters as hazard and vulnerability. Hazard cluster covered five criteria, i.e., storm water pipe network, slope, imperviousness, return period of a storm event, and distance to water; while vulnerable structure, population density, vulnerable population, education level, and income level were determined as the vulnerability criteria. Despite some participants highlighted other criteria such as the number of households, transportation density, and emergency plan of the districts, the group agreed on the final list and not to include these criteria for several reasons such as keeping the complexity of the framework on a manageable level and difficulty in attaining or representing the required data quantitatively. It is also important to note that sub-criteria (splitting criterion) of slope and imperviousness criteria was also indicated by the respondents. Meanwhile, focus group participants ensured the sub-criteria of other criteria that were identified by the literature survey (Table 4.1). In the second session, experts were inquired to provide the role of each criterion and their relationships in the context of flood risk in Istanbul. At the end of the session, all agreed that the vulnerability cluster includes criteria that have interrelationships within themselves, while criteria in the hazard cluster are independent of each other. Thus, the DEMATEL-ANP network was settled for the vulnerability cluster and the AHP framework for the hazard cluster. Once the individual judgments were captured to perform DEMATEL analysis, three threshold values were calculated to be used in ANP analysis, i.e., AVRG, MPSD, and MMDE algorithm. Three network diagrams were presented to participants to choose the one that illustrates the relationships among vulnerability criteria on a sufficient and profound vein in the third session of FGD (Figure 4.4). It is important to note that the experts could also provide new diagrams if they thought it explained the relationship better than the ones calculated through AVRG, MPSD, or MMDE. At the end of this session, all experts acknowledged the diagram drawn through the threshold value attained with AVRG.

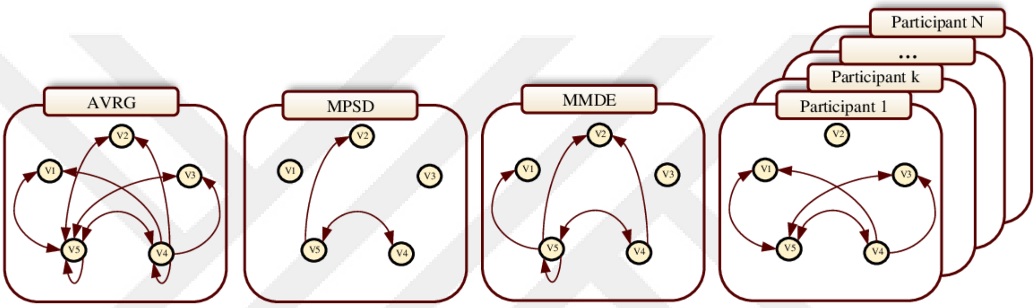

Figure 4.4 : Alternative network diagrams.

4.4.3 MCDM applications

MCDM methods can provide a valuable basis for prioritization studies and have been applied in many research domains. In flood risk management literature, several MCDM methods have been used for diverging viewpoints, such as AHP (Zou et al, 2013), ANP (De Brito et al, 2018), TOPSIS (Ekmekcioğlu et al, 2021b), VIKOR (Akay, 2021), PROMETHEE (Hossein Nasiri et al, 2013), and DEMATEL (Ali et al, 2020a). Based on a diligent investigation of the strengths and weaknesses of these methods, this study adopted a hybrid usage of AHP, ANP, DEMATEL, and VIKOR methods for flood risk mapping of Istanbul city as part of a comprehensive evaluations. Table 4.3 demonstrates the main advantages and disadvantages of the adopted methods and the core processes. Detailed information regarding the analysis procedures adopted in AHP (Das, 2018), DEMATEL (Costa et al, 2019), ANP (Shahpari et al, 2020), and VIKOR (Opricovic and Tzeng, 2004) applications can be found at the corresponding references.

Table 4.3 : Comparison of adopted MCDM methods.

Method	Year of development	Core process	Time required to collect data	The purpose of use in this study	Main advantages	Main disadvantages
AHP	1970s	Pairwise comparison among criteria and/or alternatives	Moderate	Criteria assessment for criteria without interrelationship	Hierarchic representation of the subject makes it easier to comprehend the problem. Consistency analysis is applicable.	Interrelationship among criteria is not considered.
ANP	1980s	Pairwise comparison among criteria and/or alternatives	Moderate / Much	Criteria assessment for criteria with the interrelationship	Interrelationship among criteria is considered. Consistency analysis is applicable.	Complex relationships can complicate the decision framework, hindering its ease of comprehension.
DEMATEL	1970s	Influence of factors on each other	Much	Evaluation of interrelationship among criteria	The method reveals the interrelationship among criteria.	The impact of each criterion on the others is investigated, which makes it harder for respondents to pay attention throughout the questionnaire survey.
VIKOR	1990s	Maximum group utility and minimum individual regret	Less	Ranking of alternatives based on evaluated criteria	Higher ranked alternatives are closer to the ideal solution. It can appropriately be used with many alternatives and criteria.	The method is prone to the rank reversal issue if a new alternative is added or removed.

For the initial evaluation of the proposed decision framework, the hazard cluster was subjected to the AHP method. On the other hand, the ANP method was applied to the vulnerability cluster since there were independent criteria in the hazard cluster while interrelationships existed in the vulnerability cluster. The vulnerability cluster includes five criteria as vulnerable structures (V1), population density (V2), vulnerable population (V3), education level (V4), and income level (V5). Similarly, the hazard cluster also comprised five criteria such as storm water pipe network (H1), slope (H2), imperviousness (H3), the return period of the storm event (H4), and distance to water (H5). Details of the ten criteria regarding attained data format, splitting criterion, sub-criteria, and the data source are shown in Table 4.1. Population density (the number of residents/km^2), income level (Turkish Lira/Month), storm water pipe network (km/built km^2), and distance to water (km/built km^2) criteria were not divided into their sub-criteria since the collected data included a single and exclusive value for each district, which can directly operate in the decision matrix. However, other criteria were divided into sub-criteria with respect to the percentage that covers the districts with diverging values as criteria values differentiate from one part of the districts to other. For instance, the vulnerable structure (V1) criterion was divided into four sub-criteria due to the data's nature (Table 4.1). The origin of the data indicates the distribution of the buildings in each district with respect to their age corresponding to each sub-criterion, the sum of which equals 1. Likewise, vulnerable population, education level, slope, imperviousness, and return period of storm event were also considered based on four sub-criteria since the entire district does not have the same and exclusive value for these criteria (Table 4.1). Each was divided into four sub-categories based on either the literature survey (vulnerable population, education level, return period of storm event) or expert judgment during FGD (slope, imperviousness). Then, the decision matrix was formed by taking the percentages of each sub-criterion regarding criteria comprising sub-criteria and exclusive values of each district in terms of criteria without sub-criteria.

During the FGD, individual judgments of experts were captured regarding pairwise comparisons in AHP and ANP analyses for hazard and vulnerability clusters, respectively. Fundamentally, interrelationships among criteria can be determined through expert views qualitatively in ANP analysis. However, to draw a network diagram required for the ANP method, one of the most eminent methods to deal with interrelationships, the DEMATEL method can also be used as a more robust alternative (Costa et al, 2019). Root causes of the problems and corresponding countermeasures can be clarified with the DEMATEL method, making the method an effective alternative to the other MCDM techniques. Therefore, this study adopted the DEMATEL-ANP approach for criteria assessment regarding the vulnerability cluster. In DEMATEL analysis, individual judgments were collected during FGD and aggregated with their arithmetic means (average matrix). This step was followed by normalization (normalized direct relation matrix), and then the calculation of the total relation matrix. By taking the column sums (D) and row sums (R), the effect and cause values of each criterion were computed. Then, D+R (prominence) and D-R (net effect) values were attained for each criterion and placed at the vertical and horizontal axes, respectively. To draw the causal relationship diagram (CRD), three threshold values were calculated as AVRG (0.7877), MPSD (0.9575), and MMDE (0.8643). Since FGD participants suggested the diagram developed via AVRG threshold value, a corresponding network structure was used for the ANP analysis. In the ANP application, a similar data collection procedure with AHP (pairwise comparisons) was adopted for each sub-cluster. The judgments of participants were used to form a normalized and then weighted super matrix. At the final step of the ANP analysis, the weighted super matrix was raised to power k (sufficient) to form the limit matrix that was stabilized. Hence, all criteria weights were determined either with AHP or DEMATEL-ANP approaches. It is important to note that sub-criteria weights (of criteria containing sub-criteria) were calculated through the AHP method regardless of the cluster (either vulnerability or hazard clusters) since interrelationships cannot be considered in these sub-criteria. The consistency ratio (CR) of each expert was calculated individually, and revised judgments were inquired if CR was calculated as higher than 0.1. All experts were found consistent and thus aggregated decision matrix was formed by taking the geometric mean of them.

AHP and ANP methods are practical in criteria assessment, yet there exist other powerful MCDM tools for alternative rankings. AHP can be regarded as a proper method for multi-tier relationships and criteria assessment, while the TOPSIS method is beneficial in one-tier relationships and alternative ranking (Ertuğrul and Karakaşoğlu, 2008). Here, TOPSIS and VIKOR methods follow a similar logic, i.e., closeness to the ideal solution (IS). However, some argue that the TOPSIS method does not take the relative importance of distance to the negative and positive IS into account and leads to an erroneous prioritization (Opricovic and Tzeng, 2004). Thus, in the last step of the comprehensive evaluation, VIKOR analysis was performed for alternative prioritization. In this context, the decision matrix was formed by coupling criteria weights (AHP-DEMATEL-ANP analysis) and district scores (captured from statistics and related institutions). Best values in the VIKOR method were determined by taking the maximum of the criteria with sub-criteria. Regarding criteria without sub-criteria, the best values of population density and distance to water (shore length/area) were computed by taking the maximum of district scores, while that of income level and storm water pipe network were determined by taking the minimum of the district scores. The worst values of criteria in VIKOR analysis were calculated directly in an opposite way that was explained for best values. Subsequently, utility measure ($\tilde{S}_i$), regret measure ($\tilde{R}_i$), and VIKOR index ($\tilde{Q}_i$) values were calculated for each district to perform prioritization. At the last step of the VIKOR method, the v value was taken as 0.5 to illustrate a balance regarding the strategy of maximum group utility. Besides 0.5, sensitivity analysis was carried out by setting the v value as 0, 0.25, 0.75, and 1 (Büyüközkan and Görener, 2015) to explore the impact of v value on the variations in the districts' risk scores. Finally, the flood risk of each district of Istanbul was determined with $\tilde{Q}_i$ value, such that the higher the value of $\tilde{Q}_i$, the lower the flood risk of the corresponding district. Based on the calculated $\tilde{Q}_i$ values, flood vulnerability, flood hazard, and flood risk map of Istanbul were generated to provide a sufficient decision-making input for the practitioners.

4.5 Results

4.5.1 Criteria assessment

In this study, weights of criteria in the vulnerability cluster were determined through the DEMATEL-ANP model. The total relation matrix of the DEMATEL analysis is shown in Table 4.4. Bold values in the table indicate influence scores that are higher than the threshold value calculated via the AVRG method (0.7877). To draw the CRD, prominence and net effect values were calculated, as shown in Table 4.5. The findings show that the most prominent factors were education level (8.7605) and income level (9.4820), while the most influential one was also education level, with a net effect value of 0.4775. By setting the prominence values at the x-axis and net effect values at the y-axis, the role of each vulnerability criterion on the CRD can be represented (Figure 4.5). The figure shows a clear flow from the V4 to all the other vulnerability criteria. In addition, V5 was also found to be a dyadic criterion such that it not only affects all the others but is also influenced by them. Note that the arrows in the figure were determined based on the threshold values (bolded relationships in Table 4.4).

Table 4.4 : Total relation matrix of vulnerability cluster.

V	V1	V2	V3	V4	V5
V1	0.4992	0.7015	0.6119	0.7247	**0.8704**
V2	0.6369	0.5869	0.6801	0.7528	**0.8834**
V3	0.5751	0.7410	0.4954	0.7559	**0.8643**
V4	**0.8376**	**0.9305**	**0.8189**	**0.8208**	**1.2112**
V5	**0.8914**	**0.9586**	**0.7998**	**1.0873**	**0.9578**

Table 4.5 : Causal relationship diagram of vulnerability criteria.

V	D (sum of rows)	R (sum of columns)	D + R (Prominence)	D - R (Net effect)
V1	3.4077	3.4403	6.8480	-0.0326
V2	3.5402	3.9185	7.4587	-0.3783
V3	3.4317	3.4061	6.8378	**0.0257**
V4	4.6190	4.1415	8.7605	**0.4775**
V5	4.6949	4.7872	9.4820	-0.0923

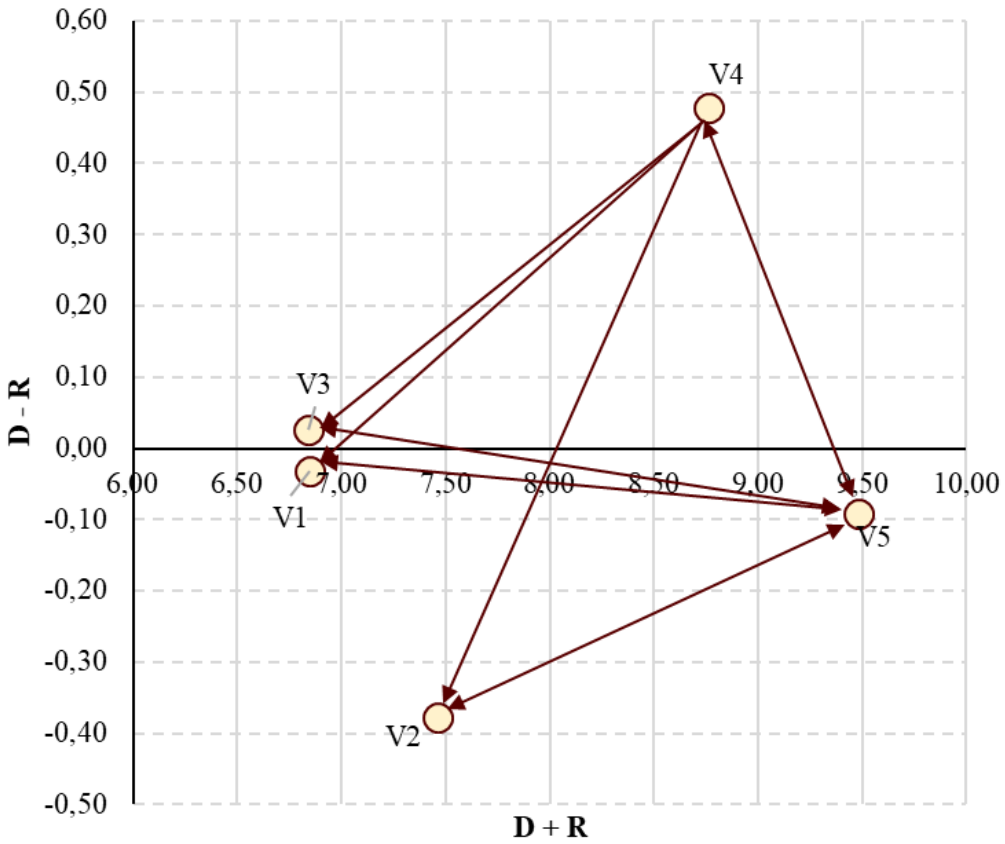

Figure 4.5 : Causal relationship diagram of vulnerability criteria.

Table 4.6 shows the weights of main criteria, hazard criteria, and all sub-criteria calculated by using the AHP method, as well as vulnerability criteria computed with ANP analysis. The findings show that the vulnerability (0.6227) was nearly two times more influential on the flood risk in Istanbul city compared to the hazard cluster (0.3773). The results of ANP analysis highlighted the importance of income level (0.2957), education level (0.2512), and population density (0.2410), while the AHP analysis results focalized the cruciality of the return period of a storm event (0.4328), storm water pipe network (0.1865), and imperviousness (0.1654) criteria.

Table 4.6 : Criteria weights.

Main criteria	Weight	Criteria	Criteria weight	Sub-criteria	Sub-criteria weight	Overall weight
Vulnerability (V)		Vulnerable structures (V1)	0.1299	< 1968	0.5156	0.0417
				1969 −1982	0.2995	0.0242
				1983 −2012	0.1245	0.0101
				2013 −2018	0.0604	0.0049
		Population density (V2)	0.2410	−	−	0.1501
		Vulnerable population (V3)	0.0822	< 10	0.5034	0.0258
	0.6227			10 −19	0.1393	0.0071
				20 −64	0.0512	0.0026
				> 64	0.3061	0.0157
		Education level (V4)	0.2512	Non-literate	0.4760	0.0745
				Literate (without an education)	0.2979	0.0466
				Up to high school	0.1531	0.0239
				Bachelor or more	0.0730	0.0114
		Income level (V5)	0.2957	−	−	0.1841
Hazard (H)		Storm water pipe network (H1)	0.1865	−	−	0.0704
		Slope (H2)	0.1270	< 1%	0.0524	0.0025
				1% −4%	0.1107	0.0053
				5% −10%	0.2559	0.0123
				> 10%	0.5810	0.0278
		Imperviousness (H3)	0.1654	71 −76	0.0562	0.0035
				77 −82	0.1178	0.0074
	0.3773			83 −88	0.2549	0.0159
				89 −94	0.5711	0.0356
		Return period of a storm event (H4)	0.4328	< 2	0.0571	0.0093
				2 −10	0.1024	0.0167
				11 −50	0.2511	0.0410
				> 50	0.5893	0.0962
		Distance to water (H5)	0.0882	−	−	0.0333

4.5.2 Citing according to surname of author

This study prioritized the districts of Istanbul using the VIKOR method. Values attributed to Istanbul districts for each criterion that were used to calculate $\tilde{S}_i$, $\tilde{R}_i$, and then $\tilde{Q}_i$ are shown in Table 4.7. Prioritization was performed regarding $\tilde{Q}_i$ values in descending order. In the table, an increase in the values of a district regarding a criterion is associated with an increase in $\tilde{Q}_i$ values and therefore decrease in the flood risk. The most vulnerable and hazard-prone districts regarding each criterion are stated in Table 4.7 with bolded values. The results show that Fatih and Gungoren were the most vulnerable districts regarding vulnerable structures and population density, respectively. Variously, Arnavutkoy was the most vulnerable district regarding the remaining vulnerability criteria (i.e., vulnerable population, education level, and income level). Concerning hazard criteria, Catalca had the worst condition for the storm water pipe network, while the slope of the Adalar was quite critical for flood hazards. Imperviousness was the highest in Bahcelievler, while the distance to water (shore length/district surface area) was highest in Beyoglu. The precipitation history of the city also illustrates that the return period of a storm event was highest in Besiktas. The comprehensive assessment showed that Gungoren, Bagcilar, Bayrampasa, Esenler, and Bahcelievler were the riskiest districts with the flood risk. Sensitivity analysis depicted in Figure 4.6 also highlights the slight difference in the ranking of these districts (ranged between 1 to 8) as the v value changes, which supports the robustness of the proposed results. The results revealed that Arnavutkoy, Sultanbeyli, Umraniye, and Uskudar were the most unsteady districts to weight for maximum group utility.

To increase the depth of the analysis, the VIKOR method was also applied to only hazard and only vulnerability criteria. Accordingly, flood hazard, flood vulnerability, and flood risk map of Istanbul were generated as shown in Figure 4.7. Note that the districts with $\tilde{Q}_i$ values close to zero display the most prone areas to hazard, vulnerability and risk in terms of flooding. Figure 4.7 illustrates that the districts with considerably high hazard potential (low VIKOR index) are predominantly placed on the European side of the city. The districts with more hazard potential, compared with their counterparts on the Asian side, are Cekmekoy and Beykoz. Chiefly, the storm water pipe network criterion contributed to these results, as it is particularly associated with the inadequate drainage capacity of the districts. In addition, Bagcilar, Gungoren, and Esenler (all on the European side and close to each other) were the most vulnerable districts over the entire city. The vulnerable population chiefly contributed to this outcome. Sultanbeyli and Umraniye were the most vulnerable districts on the Asian side (13th and 15th in overall). Income level played a significant role for Sultanbeyli and the vulnerable population for Umraniye.

Besides, in order to shed light into the effects of utilized criteria on the district hazard, vulnerability and risk scores, five hazard and five vulnerability maps were also generated separately. The methodology was akin to the generation of hazard and vulnerability maps of Istanbul. In this context, we considered only one criterion in the decision matrix to calculate $\tilde{Q}_i$ values for districts that correspond to that criterion.

Once the VIKOR indices of all the districts are calculated, the map of Istanbul was generated for the corresponding criterion, as shown in Figure 4.8. The primary aim of adopting this methodology was to achieve consistency in all the generated maps in this study. Such that values pertaining to each map ranges between 0 and 1, according to the calculation by the VIKOR method. It is important to note that validating the obtained results is essential in MCDM studies. Even though the information regarding the historical flood records is limited in Istanbul, there were some studies that investigated the flood-prone locations in the city. For instance, Ergenç and Barış (2018) found that Bagcilar, Esenler, and Bayrampasa were the most vulnerable districts to flood risk, and those districts were found as 2nd, 3rd, and 4th riskiest districts in this research. In addition, an official report prepared for the Istanbul Metropolitan Municipality (URL-9) showed that the Bagcilar and Bahcelievler were among the riskiest districts in line with Üstün and Anagün (2016) and this research; such that those districts were in the 2nd and 5th place in terms of flood risk, respectively (Table 4.7). Furthermore, Ekmekcioğlu et al. (2021a) acquired similar findings on the city's flood risk by using different techniques. They concluded that Bayrampasa and Bagcilar were the riskiest districts on the European side. On the other hand, the researchers found Atasehir to be one of the riskiest districts on the Asian side of the city, which was the 1st and 15th riskiest district on the Asian side and overall, according to the VIKOR analysis (Table 4.7).

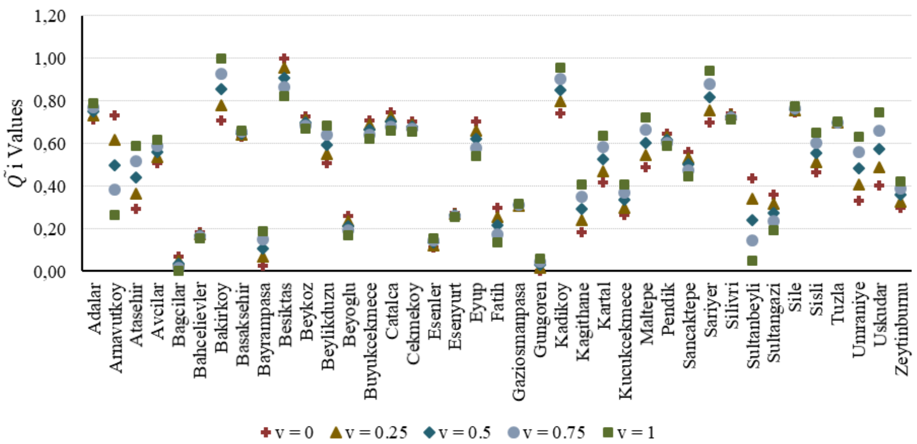

Figure 4.6 : Sensitivity analysis based on the variation in weight for the strategy of maximum group utility.

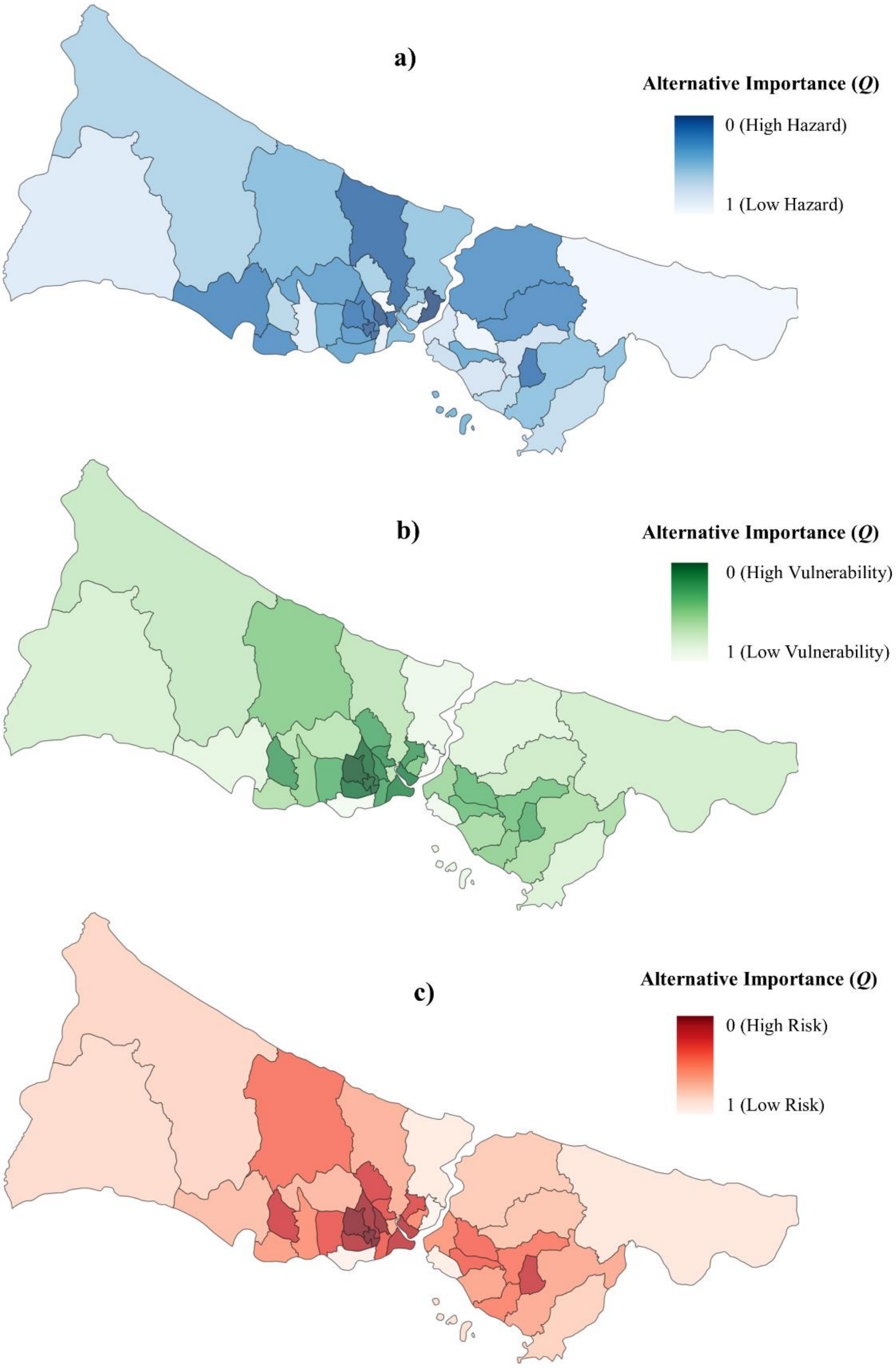

Figure 4.7 : District-based flood maps for Istanbul. a: Hazard, b: Vulnerability, c: Risk.

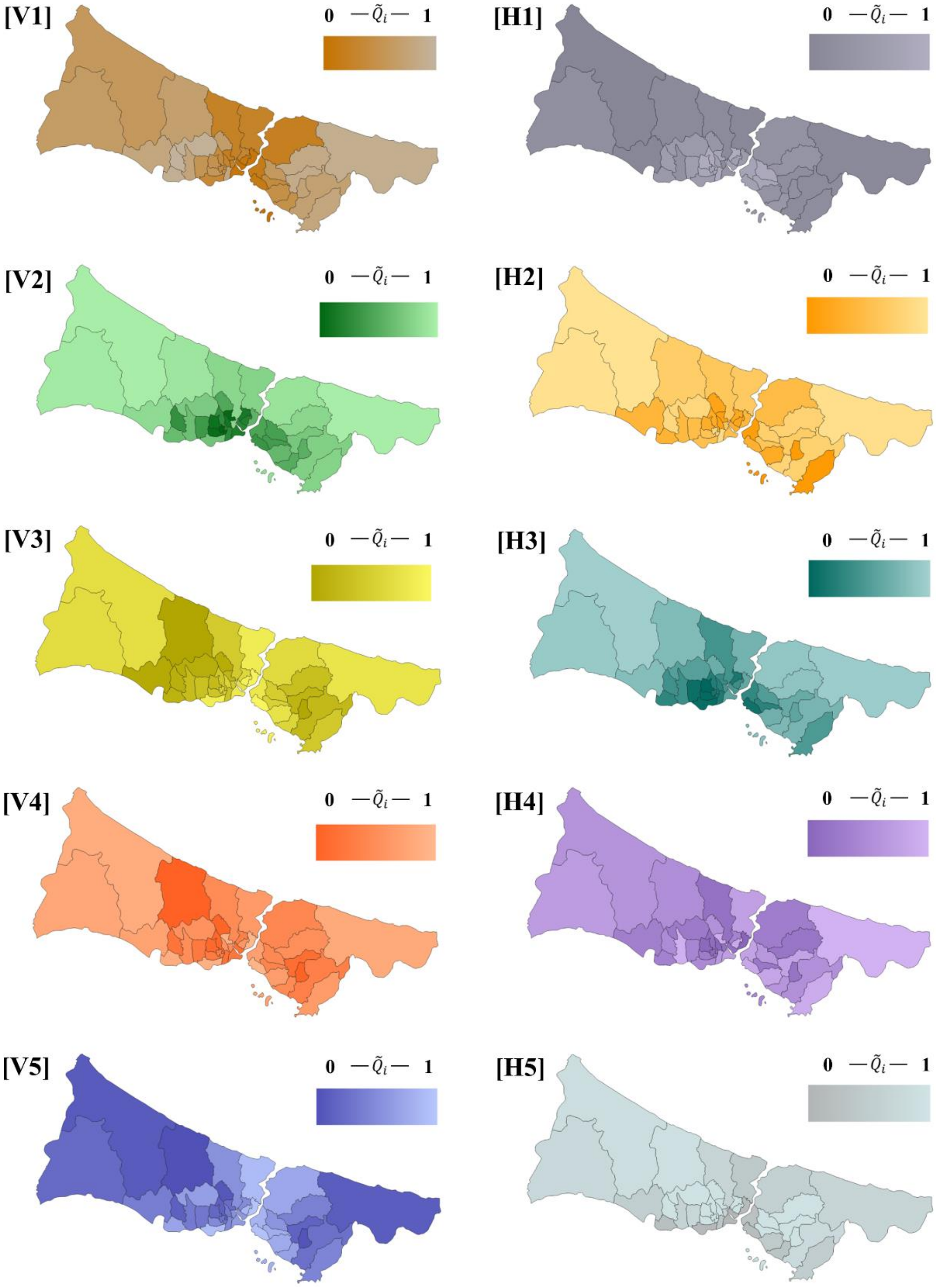

Figure 4.8 : VIKOR index values calculated for each criterion on district-level.

Table 4.7 : District scores and rank.

Districts	V1	V2	V3	V4	V5	H1	H2	H3	H4	H5	$\tilde{S}_i^*$	$\tilde{R}_i^*$	$\tilde{Q}_i^*$	#
Adalar	0.033	0.145	0.029	0.091	0.098	0.024	**0.019**	0.048	0.118	0.033	0.638	0.145	0.750	34
Arnavutkoy	0.065	0.148	**0.018**	**0.015**	**0.000**	0.002	0.042	0.046	0.120	0.032	0.487	0.148	0.499	17
Atasehir	0.060	0.088	0.028	0.071	0.084	0.045	0.040	0.033	0.098	0.033	0.581	0.088	0.441	15
Avcilar	0.068	0.118	0.026	0.067	0.053	0.011	0.037	0.036	0.144	0.030	0.589	0.118	0.563	21
Bagcilar	0.062	0.033	0.023	0.039	0.029	0.058	0.038	0.014	0.081	0.033	0.410	0.058	0.034	2
Bahcelievler	0.063	0.020	0.027	0.064	0.057	0.049	0.040	**0.014**	0.089	0.033	0.455	0.074	0.169	5
Bakirkoy	0.057	0.122	0.029	0.118	0.145	0.031	0.040	0.015	0.125	0.018	0.700	0.145	0.854	38
Basaksehir	0.073	0.135	0.021	0.066	0.063	0.029	0.041	0.039	0.101	0.033	0.602	0.135	0.648	27
Bayrampasa	0.051	0.039	0.028	0.076	0.053	0.036	0.036	0.032	0.081	0.033	0.465	0.053	0.109	3
Besiktas	0.037	0.113	0.032	0.133	0.184	0.030	0.036	0.038	**0.025**	0.018	0.648	0.184	0.910	39
Beykoz	0.049	0.147	0.028	0.065	0.077	0.011	0.039	0.053	0.105	0.029	0.603	0.147	0.698	30
Beylikduzu	0.072	0.117	0.025	0.096	0.075	0.024	0.037	0.034	0.106	0.022	0.608	0.117	0.595	23
Beyoglu	0.033	0.056	0.030	0.040	0.063	0.038	0.037	0.036	0.128	**0.000**	0.459	0.084	0.214	6
Buyukcekmece	0.068	0.145	0.025	0.082	0.053	0.001	0.039	0.046	0.101	0.029	0.590	0.145	0.665	28
Catalca	0.063	0.150	0.028	0.092	0.013	**0.000**	0.045	0.054	0.125	0.032	0.601	0.150	0.703	32
Cekmekoy	0.070	0.144	0.024	0.070	0.053	0.015	0.040	0.050	0.101	0.033	0.600	0.144	0.680	29
Esenler	0.059	0.064	0.025	0.037	0.023	0.057	0.037	0.029	0.092	0.033	0.455	0.064	0.134	4
Esenyurt	0.073	0.070	0.021	0.045	0.023	0.031	0.041	0.035	0.112	0.033	0.484	0.086	0.264	9
Eyup	0.054	0.144	0.027	0.070	0.060	0.002	0.042	0.039	0.097	0.031	0.566	0.144	0.621	26
Fatih	**0.031**	0.043	0.030	0.054	0.063	0.021	0.039	0.037	0.126	0.006	0.449	0.089	0.215	7
Gaziosmanpasa	0.048	0.001	0.025	0.102	0.036	0.044	0.036	0.034	0.142	0.033	0.501	0.090	0.310	12
Gungoren	0.060	**0.000**	0.027	0.064	0.049	0.039	0.043	0.021	0.091	0.033	0.427	0.049	0.029	1
Kadikoy	0.046	0.080	0.035	0.131	0.150	0.037	0.037	0.020	0.132	0.019	0.687	0.150	0.850	37
Kagithane	0.053	0.042	0.029	0.068	0.060	0.070	0.039	0.025	0.110	0.033	0.528	0.074	0.295	11
Kartal	0.060	0.105	0.028	0.073	0.074	0.023	0.040	0.044	0.122	0.025	0.595	0.105	0.527	19
Kucukcekmece	0.063	0.085	0.026	0.059	0.051	0.035	0.039	0.018	0.122	0.031	0.528	0.085	0.336	13
Maltepe	0.060	0.115	0.030	0.088	0.083	0.012	0.036	0.042	0.125	0.028	0.619	0.115	0.605	24
Pendik	0.065	0.137	0.025	0.064	0.045	0.004	0.040	0.046	0.123	0.032	0.581	0.137	0.619	25
Sancaktepe	0.071	0.125	0.021	0.041	0.025	0.007	0.039	0.043	0.135	0.033	0.540	0.125	0.505	18
Sariyer	0.050	0.143	0.031	0.087	0.128	0.001	0.041	0.045	0.130	0.026	0.682	0.143	0.818	36
Silivri	0.064	0.149	0.029	0.083	0.032	0.008	0.044	0.054	0.123	0.032	0.617	0.149	0.729	33
Sultanbeyli	0.066	0.108	0.018	0.016	0.004	0.010	0.033	0.041	0.094	0.033	0.424	0.108	0.242	8
Sultangazi	0.064	0.098	0.021	0.025	0.006	0.022	0.035	0.041	0.121	0.033	0.466	0.098	0.276	10
Sile	0.071	0.150	0.026	0.089	0.017	0.001	0.044	0.055	0.149	0.031	0.634	0.150	0.761	35
Sisli	0.040	0.049	0.033	0.087	0.112	0.035	0.033	0.034	0.143	0.033	0.599	0.112	0.558	20
Tuzla	0.068	0.143	0.025	0.080	0.054	0.005	0.032	0.039	0.137	0.028	0.613	0.143	0.699	31
Umraniye	0.064	0.094	0.026	0.069	0.061	0.050	0.038	0.039	0.120	0.033	0.594	0.094	0.484	16
Uskudar	0.048	0.095	0.030	0.089	0.104	0.039	0.033	0.033	0.133	0.022	0.626	0.104	0.575	22
Zeytinburnu	0.069	0.061	0.027	0.048	0.056	0.054	0.043	0.024	0.124	0.025	0.532	0.089	0.359	14

4.6 Discussions

4.6.1 Assessment of the adopted methodology

This research comprises implementing a multi-step comprehensive MCDM procedure to prioritize the districts of Istanbul in terms of flood risk. To achieve this goal, two of the commonly employed MCDM tools, i.e., AHP and ANP, were used in assessing two main pillars of the flood risk concept: hazard and vulnerability. In this context, AHP was performed to compute hazard criteria weights because of the absence of inter-relationship among criteria, while the ANP methodology was adopted to the vulnerability cluster as its sub-criteria contain interdependence relationships between each other. It is also worth noting that the network structure of the ANP was determined by employing the DEMATEL approach. This study comprises an elaborative MCDM implementation amplified by FGD sessions. Compared to the existing literature, there are some pros (such as adopting DEMATEL and VIKOR methods aided with FGD sessions) and cons (such as implementing fuzzy set theory) of this study. Here, Table 4.8 illustrates the pros, cons, and the analogy considered in this research contrary to the past efforts in the pertinent literature. One of the most distinguishing features of this study is the adoption of both AHP and ANP structures. Even though De Brito et al. (2018) also employed these methods, the authors considered comparing AHP and ANP performances for the evaluation of vulnerability criteria weights. This study adopted both methods for their varying methodological advantages and peculiarities. Despite De Brito et al. (2018) used the ANP method similar to this study, the authors of this study employed one of the widely used prominent and robust analytic methods, i.e., DEMATEL prior to ANP to provide a robust network scheme for ANP analysis. Furthermore, although the DEMATEL method was adopted in flood mapping domain, this study can be qualified as an initial attempt in flood risk mapping literature incorporating five hazard and five vulnerability criteria as other studies are limited to the assessment of flood susceptibility (Ali et al, 2020b; Kanani-Sadat et al, 2019) and flood hazard mapping (Jahantigh and Jannat, 2019). Similarly, there were some attempts for flood susceptibility mapping through hazard criteria (Akay, 2021) and vulnerability mapping using morphometric indices previously (Meshram et al, 2020). However, this study offers the application of the VIKOR method on the flood risk mapping for the first time considering both hazard and vulnerability pillars of flood risk. Meanwhile, including various stakeholders with different flood perceptions is also of significance. In this study, 10 (including AHP and ANP questionnaires and FGD sessions) experts' judgments were considered. This number is higher than most of the studies in the literature except the study of De Brito et al. (2018). Potential readers may refer to their study for a detailed examination of expert judgments as the researchers carried out valuable work to include diverse stakeholders. Moreover, this study differentiates from its counterparts in the inclusion of FGD sessions. Only three studies conducted FGD sessions, i.e., Chen et al. (2015) and Ekmekcioğlu et al. (2021b) for flood risk mapping and DeBrito et al. (2018) for vulnerability mapping, while this study has valued the FGD participants' opinions in each level of the framework refinement including the identification of flood risk criteria, determining the roles of each criterion on flood risk in Istanbul and constructing the ANP structure.

Despite these facts, there are still some issues that are addressed neither in previous researches nor in this study. One can exemplify this with the integration of probabilistic approaches into the MCDM tools in flood risk mapping. At this point, involving the Monte Carlo simulation with the conventional AHP and ANP methods could contribute valuably to the body of knowledge. It is important to note that despite providing a robust variable assessment scheme, calculation procedures are more complex in Monte Carlo analytical hierarchy process (MCAHP) and Monte Carlo analytical network process (MCANP) methods. In this research, Monte Carlo simulation was not integrated with the adopted MCDM methods since the flow of focus group discussions can be effortlessly interrupted by the complexity in the calculation processes. A systematic FGD (comprising three sub-sessions) was performed in this study to perform four MCDM methods sequentially. Including additional steps that are required for Monte Carlo simulation might lose the participant's attention and endanger the achievement of the study objective. Thus, interested researchers should also consider this aspect of the adopted MCDM methods, as participant judgments are the primary data sources in MCDM-based FRM studies. In addition, despite fuzzy set theory being adopted in four of the examined studies (Table 4.8), it was not considered in this study. The reasons above for not including Monte Carlo simulation are also valid for not including fuzzy set theory in this study, i.e., to minimize complex computing procedures that might interfere with FGD discussion. There is a trade-off between methodological complexity aiding to achieve more robust criteria weights and maintaining the participants' attention, assisting them to provide more reliable judgments. In this context, adoption of both probabilistic and fuzzy approaches (such as Monte Carlo Fuzzy AHP/ANP/DEMATEL/VIKOR) could add significant value to the methodology proposed in this study while posing additional risks to the data collection process (particularly with FGD), attention of participants and the practical utilization of the proposed model. Hence, comparing the performances of standalone MCDM methods, Monte Carlo integration, fuzzy integration, and fuzzy Monte Carlo integration regarding computational time along with allocating the required time for data collection, respondents' attention, calculated criteria weights, and generated flood risk map would be a crucial area ripe for future research studies.

Table 4.8 : Comparison of research methodology with existing studies.

Reference	Region, Country	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Wang et al. (2011a)	Dongting, China	N/A	H&V	10	FAHP	X	✓	10	X	X	✓	X	X
Yang et al. (2013)	Yangtze, China	N/A	H&V	16	AHP& FAHP	X	X	N/A	X	X	✓	X	X
Zou et al. (2013)	Jingjiang, China	921	H&V	13	FAHP	X	X	6	X	X	✓	X	X
Chen et al. (2015)	Bowen, Australia	60,000	H&V	9	AHP	X	X	N/A	✓	X	X	X	X
DeBrito et al. (2018)	Lajeado, Brazil	274.79	V	11	AHP& ANP	X	✓	117	✓	✓	X	X	✓
Das (2018)	Vaitarna, India	3,795	H	9	AHP	X	X	N/A	X	X	X	X	X
Meshram et al. (2020)	Bamhani, India	6,520	M	14	SAW	✓	X	N/A	X	X	X	X	X
Ekmekcioğlu et al. (2021b)	Istanbul, Turkey	5,461	H&V	13	FAHP	✓	✓	14	✓	X	✓	X	X
Roy et al. (2021)	Jalpaiguri, India	3386.18	H&V	10	AHP	X	X	N/A	X	X	X	X	X
This study	**Istanbul, Turkey**	**5,461**	**H&V**	**10**	**AHP & ANP**	✓	✓	**10**	✓	✓	**X**	**X**	✓

4.6.2 Impacts of criteria on flood risk

Prior studies highlighted the importance of investigating water-related problems in terms of both qualitative and quantitative manner. Here, existing literature recognizes the critical role of MCDM applications in determining efficient FRM practices. To accomplish a straight-head preliminary action, flood risk mapping, and early diagnosis of most explanatory variables is of utmost significance in response to the potential unfortunate events. Thus, this research employed the AHP method to determine the criteria weights of main clusters, i.e., hazard and vulnerability. The AHP and the ANP methods were used to calculate the weights of the criteria of hazard and vulnerability, respectively. Therefore, the first objective was to obtain the weights of hazard and vulnerability clusters. The leading finding emerging from the analysis was that the vulnerability cluster is nearly two times more influential on the flood risk compared to the hazard cluster. Among the vulnerability cluster, income level had a higher criteria weight than others, such that income level not only affects all vulnerability criteria but also is affected by others according to the CRD diagram (Figure 4.5). In line with the results, Chen et al. (2021) also found income level as one of the significant parameters in terms of social vulnerability and highlighted the fact that people who have low-income were more sensitive than those who have high-income against flood events. In a different perspective, Rentschler and Salhab (2020) associated income level with the adequacy of infrastructure and poor land-use planning and stated that the low-income neighbourhoods are more prone to even small floods that are frequently occurred while the high-income neighbourhoods are more equipped with sophisticated drainage facilities. Besides, most of the populations who have low income levels and live in the regions susceptible to flooding face challenges in relocating to other places and sticking to the actual properties for their livelihood (Mohanty et al, 2020). In addition, education level was the criterion with the second-highest weight, while it was also found as the essential factor based on the DEMATEL results. Education level influences the rest of the vulnerability criteria, i.e., vulnerable structures, population density, vulnerable population, and income level, while it is only affected by income level (Figure 4.5). This finding can broadly be supported by the work of Eryılmaz Türkkan and Hırca (2021), in which they highlighted the positive relationship between education and income levels regarding food risk perception. Likewise, Shah et al. (2017) showed that the educated and high-income households were in better positions to mitigate flood risk than those low-educated and low-income households based on the evaluations performed considering different assets and capabilities of each group. Chen et al. (2021) also highlighted the importance of education level, such that it significantly represents the social vulnerability and ability to combat flood incidents. Another criterion with a weight value quite close to that of education level is population density. This result also reflects those of Darabi et al. (2019) and Balica et al. (2013) who also found population density as one of the determining factors in terms of flood risk. It is worth noting that the population density was affected by education level and income level based on the findings obtained by DEMATEL. On the one hand, population density and GDP per unit area are in considerably positive correlation not only with the number of flood-induced casualties but also the economic losses because of property damage. On the other hand, the number of flood-affected people increases with a decrease in per capita GDP, while economic losses due to flood incidents unsurprisingly increase when the per capita GDP increases (Hu et al, 2018).

Among the hazard cluster, the return period of a storm event outperformed its counterparts regarding criteria weights with a significant difference (Table 4.6). The return period of a storm event represents the temporal reflection of extreme rainfall events (Goumrasa et al, 2021). Considering the widespread impact of climate change, conventional flood maps that are produced according to the different return periods do not represent the actual dynamics of rivers, and so the actual conditions of the regions (Jafarzadegan et al, 2021). Therefore, not only temporal variations of storm events but also spatial characteristics of the regions are of utmost importance in flood risk assessment. For instance, storm events that have a 50-years return period can cause massive damages in some areas (Dahri and Abida, 2017), while most of the hazardous events could have occurred once the rainfall is a matter of 100-years return period in different regions (Phakonkham et al, 2021). However, these facts cannot be extrapolated to all regions, such that De Brito et al. (2018) highlighted that cities might be considered a top priority in terms of flood risk if a significant amount of people live in areas prone to be flooded against the rainfall events represented by 2-years of the probability of occurrence. One can also compare the Netherlands and Vietnam regarding the coastal flooding; such that despite two of the countries have made significant investments to the flood protection systems, the Netherlands can be protected from the storm events that have a return period of up to 10,000 years, while the latter can only be protected against flooding with return periods of up to 30 years (Rentschler and Salhab, 2020).

Other essential determinants in the hazard cluster were found as storm water pipe network and imperviousness with a slight difference. Several studies have illustrated the importance of drainage density on flood mapping, including susceptibility

(Choubin et al, 2019; Zhao et al, 2018) and hazard assessments (Elnazer et al, 2017; Ogden et al, 2011). Papaioannou et al. (2015) also found curve number, which typifies a(n) perviousness/imperviousness, as among the most crucial criteria in hazard factors based on both AHP and fuzzy AHP analysis. Yet, there are similarities and differences between the obtained results and the existing findings in the literature. For instance, Vojtek and Vojteková (2019) concluded that the slope was the most conditioning factor with the highest relative importance, while the curve number was the second least effective attribute in the flood susceptibility assessment. This can be explained by the nature of the employed methods, which are based on the subjective evaluation of the experts and specialization of the respondents. Overall, the findings of this study are substantially in agreement with those obtained in the pertinent literature. The following sub-section explains the implications and recommendations to the FRM practitioners and authorities, assisting them in putting the main outcomes of this research into practice.

4.6.3 Recommendations for flood risk management practitioners

A monolithic FRM embodied multi-disciplinary approach is required to mitigate or even entirely extinguish the hazards against the potential flood incidents. In this regard, establishing a comprehensive strategic framework that not only provides the active participation of the stakeholders (Almoradie et al, 2015) but also enables the activities of a stakeholder in tandem with others, which is a central issue for effective FRM. Therefore, this study considered the opinions of the main stakeholders of Istanbul in terms of flood risk and applied a multi-step integrated MCDM approach for generating a district-based flood risk map of the city. As discussed above, income level and education level are the key determinants of the vulnerability of the districts (Table 4.7). One can argue that providing the balance between the regions in terms of both income level and education level is a top-tier governmental issue. Despite ameliorating the income inequality is challenging for particular regions (Vu, 2021), relevant authorities can form policies and strategies for budget development for the low-income neighbourhoods allocated to carry out an efficient post-disaster recovery in case of flood events. In addition, the level of education is associated with the awareness of the community (Elmaghraby et al, 2021; Hong and Chang, 2020); such that educational institutes, i.e., universities, can play a crucial role in raising the public’s awareness, especially in low-educated districts, such as Arnavutkoy and Sultanbeyli in our case.

Although population density is another top-tier issue considering some extreme situations, such as received immigration due to the conflicts that occurred in the neighbouring countries, municipalities can take some precautions. For instance, a straight head planning and homogeneous distribution of investment decisions may enable the dissemination of population from overpopulated to the underpopulated regions, such as Catalca and Sile in this study. The orientation towards these areas can also be provided by incentive-based approaches, such as tax deductions and committing flood-protected areas, and granting compelling supports for the renovation of the houses of low income residents (Pathak et al, 2020). Even though vulnerable structures were found as the fourth important criterion among five based on the ANP structure, assessing the potential risk buildings is of significance especially in historical cities like Istanbul. By determining these areas, disaster coordination authorities should be prepared for building evacuation, satisfying the public relief in both pre- and post-flood incidents (Khan and Rahman, 2007).

This research also found several factors as the most influential attributes regarding the flood hazards. Although the return period of a storm event was obtained as the first-order factor, it is an undeniable fact that the climatic conditions have practitioners' hands tied. However, increasing awareness in people who live in hazardous areas according to the return period of a storm event criterion, i.e., Bagcilar, Bayrampasa, and Besiktas in our case, could be a substantial way to focus on other amendable factors, such as population density for improved resilience against flood events. An effective FRM strategy can also be held by authorities through improving the drainage capacity of the regions (Santos et al, 2020); such that the storm water pipe network was found as the second influential factor among hazard criteria in this study. Here, increasing the investments particularly in risky places in terms of inadequate storm water pipe network could be suggested to enhance drainage facilities (Akhter et al, 2020). In addition, different conventional techniques, such as channelization, river restoration, stream remediation, and preventing the clogging in drain inlets through continuous monitoring, could be valuable tools applicable to these areas (Solín and Rusnák, 2020). The water and sewerage administrations can be assigned to this task as they have critical responsibilities in storm water handling and disposal from settlements (Bodur, 2018). In addition, the spreading of decentralized infrastructures in risky zones might have a significant impact on reducing the total runoff and help increase the surface drainage towards the infrastructural systems, thus reducing damages caused by floods (Apollonio et al, 2018). Apart from the conventional techniques, more sustainable methods (such as low-impact development strategies and best management practices) can be prominent instruments, especially in densely urbanized areas to provide gradual accumulation of surface water mitigating local and downstream flooding. In this regard, countries might pattern themselves on China, which started a national program, called “Sponge Cities”, incorporating the green spaces with the urban areas to mitigate the effects of surface flooding (Grežo et al, 2020). It is worth mentioning that these techniques not only enable groundwater recharge but also enhance the landscape aesthetic (Kuller et al, 2018). Municipalities may encourage the individuals who put those nature-based techniques (such as rain gardens and green roofs) into the practice by providing convenience in other administrative services. One can also state that another action that can be taken by the FRM authorities is the regulation of land use, which is a function of imperviousness. The flood risks can be reduced by preventing housing in unauthorized places and realizing regulations to build a sustainable environment (Gralepois, 2020).

Furthermore, effective strategies regarding the constitution of flood-protected areas mostly rely on integrating comprehensive and interactive spatial planning into the FRM practices. Here, concrete activities should be realized from a local to national scale to improve the commitment to each level of policies, such as enhanced land-use planning and improved watercourse regulations (Vojtek and Vojteková, 2018). In a similar vein, examining the literature, particularly for spatial planning in flood risk, evaluations exhibit the substantial role of flood maps intensified with geo-database for taking prospective and strategic actions. They are ground materials serving as practical instruments to manage risks, policies, and planning mechanisms by enabling enhanced pictures for comparing historical flood events and changes in land-use characteristics. It is also important to note that including stakeholders from different disciplines is the only way for establishing rational planning and thus providing decision support systems comprising predominated policies. On the one hand, branching the governance tree through the participation of various authorities having divergent socio-technical expertise plays an important role in improving the quality and implementation of existing plans. On the other hand, coping with the obstacles mostly encountered in hierarchical governance is of significance as the participation of various actors might lead to different legal mandates and political drivers, resulting in a multiplicity of interrelationships (Ran and Nedovic-Budic, 2016). Hence, a dialogue among responsible groups should be satisfied for both enabling the reduced horizontal and vertical hierarchical scheme and providing a consensus on the actions to be taken within the scope of an overall FRM system (Grežo et al, 2020).

This study also seeks to be responsive to the most prevalent questions encountered in exploring new stories. Therefore, the generic of the current research was assessed through a set of questions, i.e., five Ws and one H (5W1H), positioning at the center of problem-solving to highlight the vitality of efforts devoted to dealing with flood risk issue in this study (Figure 4.9). To provide a deeper insight into the flood risk practitioners, a hypothetically generated, simple but systematic usage of the proposed framework is presented in Figure 4.10.

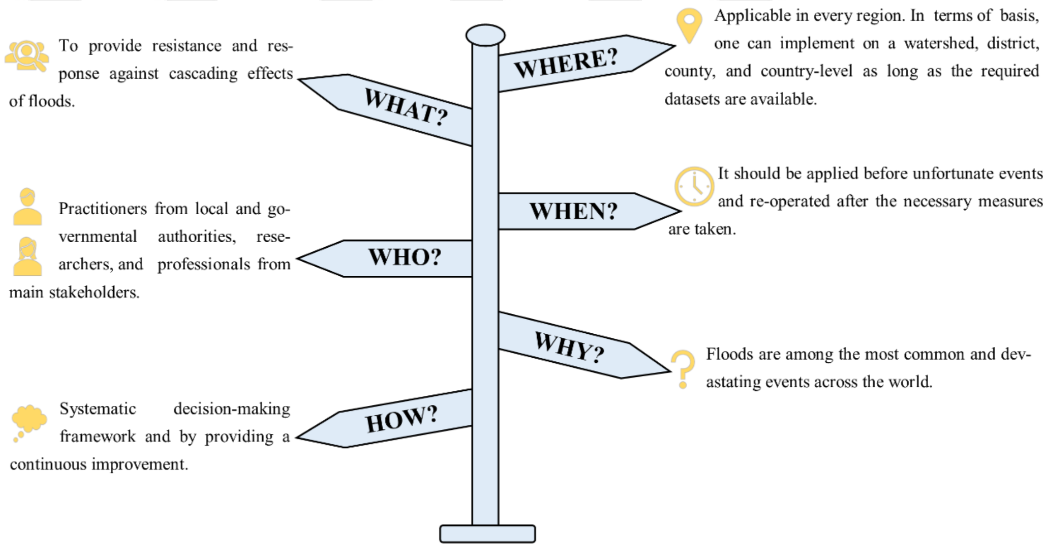

Figure 4.9 : Responses to 5W1H.

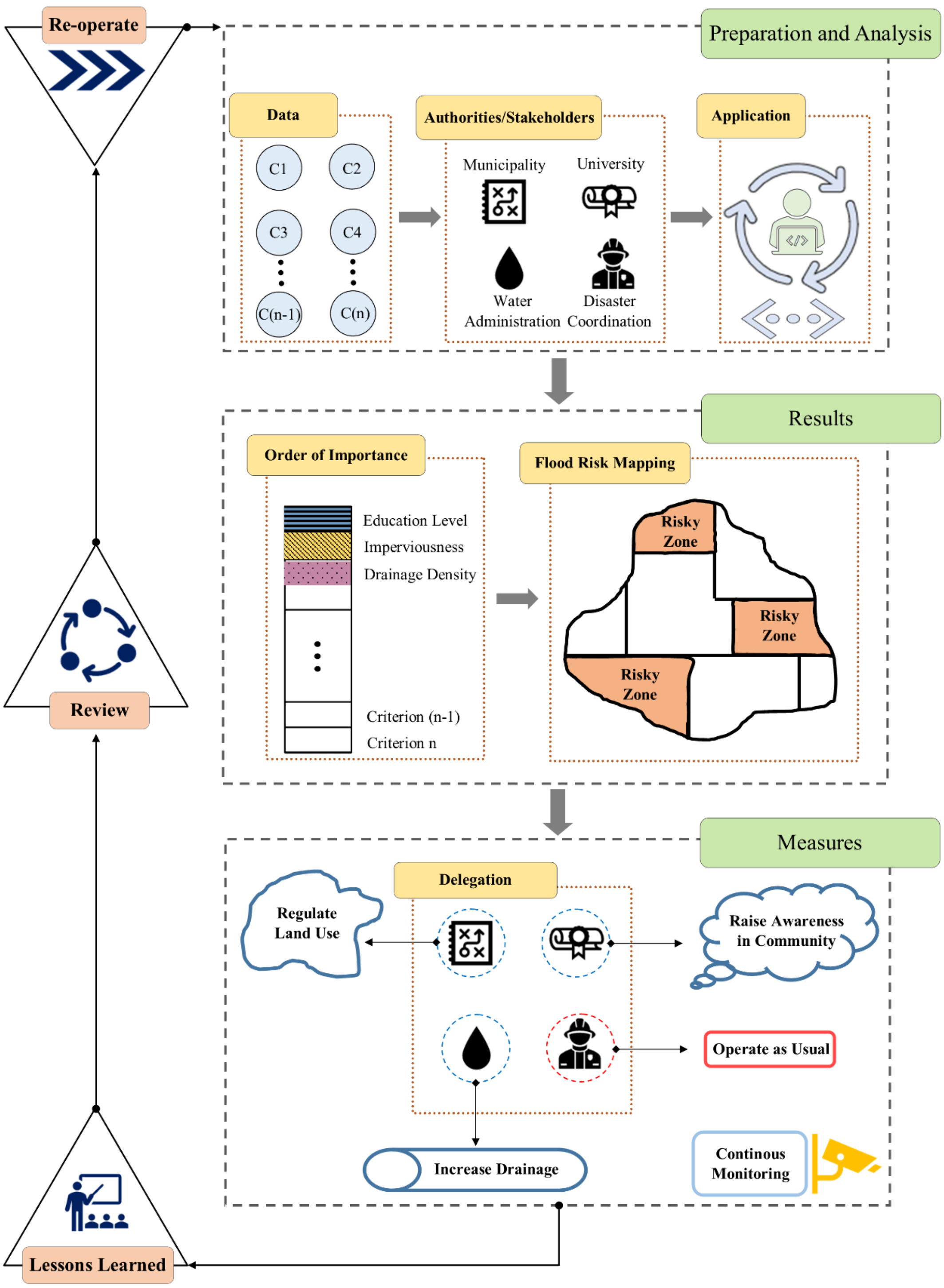

Figure 4.10 : Practical utilization of the proposed framework.

4.7 Concluding Remarks

This study offers a multi-step MCDM methodology to prioritize the districts of Istanbul with respect to flood risk and thus generate a comprehensive flood risk map to contribute to the decision-making process for flood risk mitigation. In this context, the AHP method was adopted to evaluate hazard criteria, while the vulnerability cluster was subjected to the DEMATEL-ANP method. Data attributed to each district regarding each criterion were combined with criteria weights calculated through these methods to perform VIKOR analysis. All the required subjective evaluations regarding MCDM applications were made with the aid of focus group discussion. Sensitivity analysis was also performed to ensure the robustness of the adopted methodology and the stability of the research findings. Hence, a generic and comprehensive flood risk map of Istanbul was generated based on ten criteria, and the results showed that the most densely populated and urbanized areas of Istanbul are under significant flood risk.

The findings of this study can contribute a lot to the decision entities of the city, allowing them to make effective resource allocation, select the most appropriate risk mitigation measures, and give priority to districts that have a high flood risk. Despite comprehensive assessment of the districts of Istanbul providing a significant insight into flood risk dynamics of the city, this study still poses some limitations that need to be considered in future studies. First, this study adopted several MCDM methods and provide an easy-to-implement framework for decision-makers. However, inherent fuzziness and probabilistic approach have not been considered in this study. Hence, future studies may include fuzzy and Monte Carlo versions of the MCDM methods while keeping the complexity of the framework at a manageable level. In addition, generated flood risk map of the city highly depends on the subjective judgments of the experts contributed to this study, mainly with an engineering background. In this context, the number of experts can be increased in future studies by including those from other sectors than engineering. Finally, the results were assessed by taking the real-life observations regarding historical flood events into the consideration. However, it is worth mentioning that the previous records can be associated with the findings regarding the flood hazard. Consideration of the risk level of districts based on multi-dimensional effects of floods (i.e., economic, environmental, and social) that can validate the attained results is a challenging task due to the absence of adequate information such as economic consequences of floods, hard-to-measure nature of qualitative context regarding social and environmental effects, and transformation in the land use and demographics of the districts. Despite the stability of the prioritization results was ensured with the sensitivity analysis carried out in the VIKOR application, validation with past flood events in terms of social, economic, and environmental manners still would be a valuable research direction for flood risk management literature. Although potential sources for data curation were diligently investigated within the scope of this research, alternative materials and strategies can be considered by interested researchers. For instance, imperviousness GIS layers provided by European Environment Agency (URL-13) and CORINE land cover dataset (URL-12) can be used for imperviousness criterion, while different products with finer resolution can be utilized in the generation of slope criterion. It is also worth mentioning that using extended meteorological records regarding the derivation of the return period of a storm event criterion can enhance the accuracy of models. With the improvements in the comprehensive methodology presented in this paper, flood risk management practices in cities can be effectively managed and related implementations can help create flood-resistant communities.

5. CONCLUSIONS AND RECOMMENDATIONS

Floods pose a significant threat to living life by causing casualties and property losses. They also have vital impacts on the sustainability of the built environment. Climate change as a result of global warming is an additional issue in terms of occurrences of flood incidents, and thus the number of people has been affected. Therefore, determination of flood-prone areas is crucial before encountering the unrecoverable consequences of floods. Recent advances in MCDM techniques have facilitated the generation of flood maps by determining the relationship between the flood conditioning factors and flooding incidents. These facts have driven the research society to conduct deep investigations for the comprehensive flood risk assessment along with the identification of the main drivers and major consequences of floods. This thesis chiefly aimed the identification of risky districts of Istanbul with respect to the flooding events. It is worth mentioning that the prioritization of the risky zones was carried out ona district-based since administration is carried out by district level units and local municipalities in Istanbul.

To accomplish the abovementioned holistic approach, various multi-criteria decision-making (MCDM) algorithms were adopted to the flood-related datasets acquired from different sources. Accordingly, Chapter 2 utilized one of the commonly adopted MCDM techniques, i.e., fuzzy analytic hierarchy process (FAHP), in which the reason behind the inclusion of fuzzy set theory is to deal with inherent uncertainty of human decision-making process. The results of the Chapter 2 illustrated that Bayrampasa, Bagcilar, and Esenler districts were found to be the highest importance in terms of flood risk among 39 districts of Istanbul owing to their dense population. This finding was also reinforced with the historically observed flooding events in Istanbul. Hence, the outcomes of this study not only support the result of previous studies, but also event-based risk scores of the previous flood events at a district level.

Furthermore, Chapter 3 incorporated an additional method, namely Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), to the FAHP in order to ensure the stability of the attained results as the TOPSIS provides significant advantage in assessing one-tier relationships and alternative ranking. In Chapter 3, a novel philosophy has been considered as an initial attempt in the literature by demonstrating the perception differences of stakeholders in flood risk concept. In this sense, judgments of a total of fourteen experts from four different stakeholders, i.e., local and metropolitan municipalities, disaster management and coordination centres, water and sewerage administrations, and universities, were first acquired and subjected to the hazard and vulnerability datasets. Finally, flood risk, flood hazard, and flood vulnerability maps of Istanbul were generated based on the opinions of these stakeholders and separate flood risk maps were visualized according to each stakeholder along with the two pillars of the risk concept, i.e., hazard and vulnerability. Based on the findings that emerged from these analysis, disaster management and coordination authorities and local municipalities consider the flood hazard and vulnerability clusters with almost similar importance, whereas water and sewerage administrations considered hazards and universities considered vulnerability as more significant than the other. In addition, high perception differences were observed between experts from universities and water and sewerage administrations, while there were considerable perception similarities among other stakeholders.

Within the scope of this thesis, interrelationships among flood risk criteria were also examined in Chapter 4. A novel methodological approach has been considered with the separate utilization of analytic hierarchy process and analytic network process. The AHP was performed to compute hazard criteria weights because of the absence of inter-relationship among hazard criteria, while the ANP technique was adopted to the vulnerability cluster as its criteria contain interdependent relationships among themselves. At this point, DEMATEL technique was integrated to the framework in order to refine the ANP structure. It is important to note that focus group discussions were considered at each level of the evaluations to increase the warranty of the adopted framework. Also, VIse KriterijumsaOptimiz acija I Kompromisno Resenje (VIKOR) method was applied for district prioritization in Istanbul. Besides, stability of the prioritization results was ensured with the sensitivity analysis carried out in the VIKOR application. The leading finding emerging from the analysis was that the vulnerability cluster is nearly two times more influential on the flood risk compared to the hazard cluster. Moreover, income level had a higher criteria weight than others among the vulnerability cluster, while the return period of a storm event outperformed its counterparts regarding criteria weights among the hazard cluster. The overall discussions also depicted that the findings of this study are substantially in agreement with those obtained in the pertinent literature.

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APPENDICES

APPENDIX A: AHP Questionnaire

APPENDIX A

COMPREHENSIVE FLOOD RISK ASSESSMENT AND IDENTIFICATION OF THE POTENTIAL FLOOD MITIGATİON STRATEGIES

Which of the following factors increases the risk of flooding more than the other? Note: If the factor in the row is more important, you should answer as (X); if the factor in the column is more important, you should answer as (1/X).

Main Clusters	Vulnerability	Hazard
Vulnerability	1.0	
Hazard	////////////	1.0

Vulnerability	VS	PD	VP	EL	IL	TN	NH	LU
VS	1.0							
PD	///	1.0						
VP	///	///	1.0					
EL	///	///	///	1.0				
IL	///	///	///	///	1.0			
TN	///	///	///	///	///	1.0		
NH	///	///	///	///	///	///	1.0	
LU	///	///	///	///	///	///	///	1.0

VS: Vulnerable structures	IL: Income Level
PD: Population Density	TN: Transportation Network
VP: Vulnerable Population	NH: Number of households
EL: Education Level	LU: Land use

Hazard	SP	SL	IM	RP	NR
SP	1.0				
SL	///	1.0			
IM	///	///	1.0		
RP	///	///	///	1.0	
NR	///	///	///	///	1.0

SP: Storm water pipe network	RP: Return Period of a storm event
SL: Slope	NR: Number of rainy days
IM: Imperviousness	

Figure A.1 : AHP Questionnaire for main clusters

Vulnerable Structures	<1968	1969-1982	1983-2013	2014-2018
<1968	1.0			
1969-1982	/ / /	1.0		
1983-2013	/ / /	/ / /	1.0	
2014-2018	/ / /	/ / /	/ / /	1.0

Vulnerable Population	<9	10-19	20-64	>64
<9	1.0			
10-19	/ / /	1.0		
20-64	/ / /	/ / /	1.0	
>64	/ / /	/ / /	/ / /	1.0

Education Level	Non-literate	Literate	Up to high school	Bachelor or more
Non-literate	1.0			
Literate	/ / /	1.0		
Up to high school	/ / /	/ / /	1.0	
Bachelor or more	/ / /	/ / /	/ / /	1.0

Land use	Commercial and Industrial	Residential	Rural	Forestry
Commercial and Industrial	1.0			
Residential	/ / /	1.0		
Rural	/ / /	/ / /	1.0	
Forestry	/ / /	/ / /	/ / /	1.0

Figure A.2 : AHP Questionnaire for vulnerability cluster

Slope	%0-%2	%2-%5	%5-%10	> %10
%0-%2	1.0			
%2-%5	/ / /	1.0		
%5-%10	/ / /	/ / /	1.0	
> %10	/ / /	/ / /	/ / /	1.0

Imperviousness (Curve number)	71-76	77-82	83-88	89-94
71-76	1.0			
77-82	/ / /	1.0		
83-88	/ / /	/ / /	1.0	
89-94	/ / /	/ / /	/ / /	1.0

Return Period	< 2 years	2 – 10 years	11 – 50 years	> 50 years
< 2 years	1.0			
2 – 10 years	/ / /	1.0		
11 – 50 years	/ / /	/ / /	1.0	
> 50 years	/ / /	/ / /	/ / /	1.0

Figure A.3 : AHP Questionnaire for hazard cluster

CURRICULUM VITAE

Name Surname : Ömer EKMEKCİOĞLU

Place and Date of Birth :

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EDUCATION :

- **B.Sc.** : 2014, Yıldız Technical University, Faculty of Civil, Civil Engineering Department
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- 2015-2017 Koroglu Engineering Ltd. (Infrastructural Design Engineer).
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