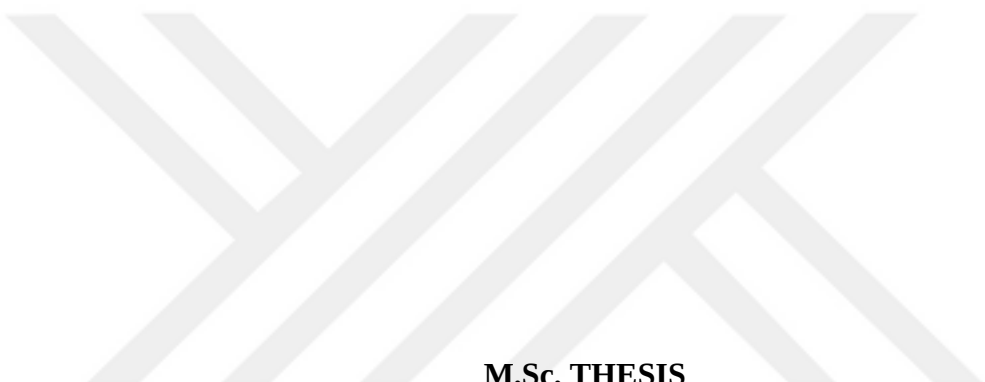


ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**INTEGRATING GIS AND MULTI-CRITERIA DECISION MAKING
TECHNIQUES (AHP AND TOPSIS) FOR EARTHQUAKE HAZARD MAP
GENERATION AND ANALYSIS – CASE OF KÜÇÜKÇEKMECE REGION**



M.Sc. THESIS

Penjani Hopkins NYIMBILI

Department of Geomatic Engineering

Geomatic Engineering Programme

Thesis Advisor: Assoc. Prof. Dr. Turan ERDEN

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M.Sc. THESIS

**Penjani Hopkins NYIMBILI
(501141640)**

Department of Geomatic Engineering

Geomatic Engineering Programme

Thesis Advisor: Assoc. Prof. Dr. Turan ERDEN

MAY 2017

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**CBS VE ÇOK ÖLÇÜTLÜ KARAR VERME TEKNİKLERİNİN (AHY ve
TOPSIS) DEPREM TEHLİKE HARİTASI ÜRETİMİ VE ANALİZİ ODAKLI
BÜTÜNLEŞTİRİLMESİ: KÜÇÜKÇEKMECE ÖRNEĞİ**

YÜKSEK LİSANS TEZİ

**Penjani Hopkins NYİMBİLİ
(501141640)**

Geomatik Mühendisliği Anabilim Dalı

Geomatik Mühendisliği Programı

Tez Danışmanı: Doç. Dr. Turan ERDEN

MAYIS 2017

Penjani Hopkins - NYIMBILI, a **M.Sc.** student of **İTÜ Graduate School of Science Engineering and Technology** student ID **501141640**, successfully defended the thesis entitled “**INTEGRATING GIS AND MULTI-CRITERIA DECISION MAKING TECHNIQUES (AHP AND TOPSIS) FOR EARTHQUAKE HAZARD MAP GENERATION AND ANALYSIS – CASE OF KÜÇÜKÇEKMECE REGION**”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assoc. Prof. Dr. Turan ERDEN**
ISTANBUL Technical University

Jury Members : **Assoc. Prof. Dr. Himmet KARAMAN**
ISTANBUL Technical University

.....
Assoc. Prof. Dr. Arif Çağdaş AYDINOĞLU
GEBZE Technical University

Date of Submission : 5 May 2017
Date of Defense : 8 June 2017





To my family and friends,



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May 2017

Penjani Hopkins NYIMBILI
(Geomatic Engineer)

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ABBREVIATIONS

AHP	: Analytical Hierarchical Process
CI	: Consistency Index
CR	: Consistency Ratio
DEM	: Disaster and Emergency Management
DSS	: Decision Support System
SDSS	: Spatial Decision Support System
EHM	: Earthquake Hazard Map
FEMA	: Federal Emergency Management Agency
DEM	: Disaster and Emergency Management
GIS	: Geographic Information Systems
MCDA/M	: Multi-Criteria Decision Analysis/Making
RI	: Random Consistency Index
SMCDA	: Spatial Multi-Criteria Decision Analysis
TOPSIS	: Technique for Order Preference by Similarity to Ideal Solution
UNISDR	: United Nations International Strategy for Disaster Reduction



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INTEGRATING GIS AND MULTI-CRITERIA DECISION MAKING TECHNIQUES (AHP AND TOPSIS) FOR EARTHQUAKE HAZARD MAP GENERATION AND ANALYSIS – CASE OF KÜÇÜKÇEKMECE REGION

SUMMARY

Earthquake disasters and related hazards have continued to cause severe impacts on human lives and livelihood resulting in widespread socio-economic and environmental damages worldwide. These significant risks associated with earthquakes are not likely to recede in the future posing serious threats to many communities and populations unless intervention measures are undertaken. To this effect, there has been rising need and recognition of comprehensive and effective disaster and emergency management (DEM) efforts required for relevant planning, response and development of strategy for risk reduction and mitigation. Recent developments in geospatial technologies have emerged that have opened new opportunities in issues of DEM with increasing demand for spatial data now becoming more and more required to meet the demands in aiding the increasingly complex decision making process by emergency managers involving large number of stakeholders across multi-disciplinary teams and conflicting evaluation alternatives. This has led to the development of scientific methods known as Multi-Criteria Decision Analysis (MCDA) that greatly improve the quality of the decision-making process to make it more explicit, rational and efficient. These combined attributes of the method enable a real participatory process involving stakeholders, conflicting criteria and multiple teams involved in emergency management, which are critical for successfully implementing sustainable disaster management mitigation strategies.

In this study, MCDA techniques of Analytical Hierarchical Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) integrated with GIS, were used to produce earthquake hazard and risk maps for earthquake disaster monitoring and analysis for a case study region of Küçükçekmece in Istanbul, Turkey. Five (5) main criteria and parameters that have the strongest influence on the impact of the earthquake on the study region were determined as topography, distance to epicentre, soil classification, liquefaction, and fault/focal mechanism. Using the AHP approach (pairwise comparison technique), the weights of the parameters that affect the earthquake ground motion at the study area were determined and an earthquake hazard map was produced using GIS software (ESRI ArcGIS). These weights were also used as input into the TOPSIS method for generation of earthquake hazard map. This TOPSIS map result was subsequently used, for comparison and analysis with the output from the AHP technique. The model outputs generated were comparable with each other showing how closely they matched and from statistical analysis performed, had a high correlation. The map outputs also reflected the cooperate opinions of experts involved in earthquake disaster and risk assessment, thus more comprehensive. To analyze the earthquake risk for the study region, population and building data were used with the AHP and TOPSIS hazard map outputs to map the elements at risk for potential loss assessment. Thus, demonstrating the potential of

integrating GIS and MCDA by use of AHP and TOPSIS in generating hazard maps for more effective disaster and risk management of earthquakes.

This study further reviewed and analysed selected spatial decision support systems (SDSSs) related to GIS-based applications in earthquake DEM ranging from simulation based, early warning and rapid response and loss estimation systems. These are broadened into global systems to include HAZTURK, QLARM, SELENA, DBELA, CATS, PAGER and regional and local systems comprising of ELER, HAZUS-MH, KOERILoss, MAEviz, EQRM and LNECLOSS. From the analysis of SDSS usage worldwide and in Turkey, HAZTURK software was recommended for implementation of earthquake risk and loss estimation studies in Turkey based on its significant comparative advantages over other SDSS and suitability and applicability to the local conditions of Turkey, which have been discussed in this study. Key challenges to be addressed range from issues in spatial data acquisition, quality, interoperability, data exchange and lack of coordination among associated institutions involved in earthquake DEM and recommendations as well as future functional improvements and developments of HAZTURK software, to this effect, have been characterised for successful implementation in Turke

CBS VE ÇOK ÖLÇÜTLÜ KARAR VERME TEKNİKLERİNİN (AHY ve TOPSIS) DEPREM TEHLİKE HARİTASI ÜRETİMİ VE ANALİZİ ODAKLI BÜTÜNLEŞTİRİLMESİ: KÜÇÜKÇEKMECE ÖRNEĞİ

ÖZET

Depremler ve yol açtığı tehlikeler insanoğlu ve çevresi üzerinde yaygın sosyo ekonomik ve çevresel yıkımlarla sonuçlanan şiddetli etkilere yol açmaktadır. Önlemler alınmaksızın depremlerle ilişkilendirilen bu risklerin gelecekte insan topluluklarını ciddi anlamda etkilemesi kaçınılmazdır. Bu etkiler, planlama, müdahale ve risk azaltma stratejisinin geliştirilmesine bağlı olarak etkin ve kapsamlı bir Afet ve Acil Durum Yönetimi ihtiyacını doğurmaktadır. Mekansal teknolojilerdeki son gelişmeler mekansal verinin gün geçtikçe karmaşık bir hal alması ve mekansal veriye olan talebin artmasıyla Afet ve Acil Durum Yönetimi problemlerinin çözümünde yeni olanaklar yaratmaktadır. Bu durum verilecek kararların net olması, anlamlı ve etkin bir biçimde başarılması amacıyla karar verme sürecinin kalitesinin iyileştirilmesi sağlayan Çok Ölçütlü Karar Analizi (ÇÖKA) yöntemlerinin geliştirilmesine ön ayak olmuştur. ÇÖKA yöntemleri afet yönetimine dahil olan paydaşların, karar gruplarının ve ilgili ölçütlerin süreç içinde katılımcı bir biçimde yer almalarına olanak sağlamaktadır.

Temel bir yaklaşımla, çok ölçütlü mekansal bir karar problemi, ilgili değerlendirme ölçütlerine dayanarak bir veya birden fazla seçenek içerisinde mekansal olarak tanımlanmış bir seçeneğin seçilmesini içermektedir. Seçenekler mekansal olarak tanımlanmakta ve analizin sonuçları bu mekansal düzenlenişe göre şekillenmektedir. CBS terminolojisi içinde, seçenekler, ölçüt değerleriyle ilişkilendirilmiş olan noktasal, çizgisel ve alansal objelerin toplamı olmaktadır.

Çok ölçütlü mekansal karar analizi, mekansal veri setlerinin birbirleriyle bütünleştirilmesi ve birbirine dönüşümüyle bir bileşke karar çıktısını oluşturan işlemlerden ibaret olmaktadır. Çok ölçütlü karar verme süreçleri, girdi harita verisi ile çıktı harita verisi arasındaki ilişkiyi tanımlamaktadır. Bu süreçler, belirli karar verme kurallarına göre mekansal verilerin düzenlenmesini ve karar vericinin tercihlerini içermektedir. Mekansal çok ölçütlü karar analizin önemli bir özelliği ölçüt değerlerine dayanan mekansal olguların değerlendirilmesini ve değerlendirme ölçütlerine dayanan karar vericinin tercihlerini içermesi olmaktadır.

Karar seçeneklerinin belli bir düzen içinde sıralanmasını başaran prosedür karar kuralı olarak adlandırılmaktadır. Karar verici, karar kuralı yardımıyla seçeneklerin en iyi şekilde nasıl sıralanacağını veya hangi seçeneğin öbürüne tercih edileceğini belirlemektedir. Karar kuralı, seçenek bilgisiyle karar vericinin tercihlerini, bütünsel bir değerlendirme için birleştirmektedir. Literatürde çok ölçütlü karar problemini çözmeye yönelik birçok karar kuralı tanımlanmış ve uygulama alanı bulmuştur. Özellikle CBS tabanlı karar vermede toplam karar kuralları (additive decision rules) en iyi bilinen ve geniş çapta uygulama alanı bulan çok ölçütlü karar verme yöntemleridir. Bu çalışmada çok ölçütlü karar kurallarından AHY ve TOPSIS yönteminin birlikte kullanılması amaçlanmaktadır.

1970’li yıllarda Thomas Saaty tarafından geliştirilen AHY birden fazla ölçüt içeren karmaşık problemlerin çözümünde kullanılan çok ölçütlü bir karar verme yöntemidir. AHY, karmaşık problemleri amaç-ölçütler-alt ölçütler-seçenekler hiyerarşisi kurularak çözmeye olanak sağlamaktadır. AHY, genel olarak, problemi parçalara ayırma ve hiyerarşi oluşturma (decomposition), karşılaştırmalı karar verme ve tercih matrisinin oluşturulması (comparative judgement) ve önceliklerin sentezlenmesi (synthesis of priorities) olmak üzere üç temel prensibe dayanmaktadır. Parçalara ayırma prensibinde hiyerarşik bir yapı yaratılmakta ve problem bu hiyerarşik yapıya göre çözülmektedir. Karşılaştırmalı karar verme aşamasında ölçütler, çiftler şeklinde belirlenmekte ve birbirleriyle karşılaştırmalı olarak incelenmektedir. Her bir hiyerarşi düzeyinde belirlenen ağırlıklar genel bir ölçekte toplanıp sentezlenerek seçeneklerin önceliklendirilmesi aşamasında kullanılmaktadır.

TOPSIS yöntemi ise, pozitif ideal çözüme (v_{+j}) olan uzaklığı en az ve negatif ideal çözüme (v_{-j}) uzaklığı en fazla olan seçeneği karar vericiye sunmaya ve tüm seçenekleri pozitif ideal çözüme benzerliğe göre sıralamaya yardımcı olmaktadır.

v_{+j} tüm ölçütlere göre en iyi performans değerine sahip ideal bir seçeneği temsil ederken; v_{-j} ise tüm ölçütlere göre en kötü performans değerine sahip bir seçeneği göstermektedir.

Yöntemin CBS tabanlı uygulaması aşağıdaki işlem adımlarını içerecek şekilde yapılmaktadır:

- Olanaklı seçenek grubunun belirlenmesi,
- Çeşitli ölçüt değerlerinin (x_{ij}) boyutsuz ölçüt değerlerine (v_{ij}) dönüştürülerek her bir ölçüt harita tabakasının standartlaştırılması,
- Her bir ölçüte atanan ağırlıkların (w_j), $\sum_j w_j = 1$ şartını sağlayacak şekilde tanımlanması,
- Standartlaştırılmış ölçüt harita tabakasının içerdiği her v_{ij} değerinin ilgili w_j , ağırlığıyla çarpılarak ağırlıklandırılmış ve standartlaştırılmış harita tabakalarının oluşturulması,
- Ağırlıklandırılmış ve standartlaştırılmış harita tabakaları için maksimum değerin (v_{+j}) saptanması (Bu değer ideal çözümü saptamaya yardımcı olmaktadır),
- Ağırlıklandırılmış ve standartlaştırılmış harita tabakaları için minimum değerin (v_{-j}) saptanması (Bu değer negatif ideal çözümü saptamaya yardımcı olmaktadır),
- Seçeneklerin ideal çözüme olan uzaklıklarının hesaplanması
- Seçeneklerin negatif ideal çözüme olan uzaklıklarının hesaplanması
- Seçeneklerin pozitif ideal çözüme olan benzerliklerinin (C_{i+}) hesaplanması
- 0 ile 1 arasında değerler alabilecek olan C_{i+} değeri 1 değerine yaklaştıkça ideal çözüme ulaşılmaktadır.
- Seçeneklerin benzerliğe göre sıralanması.

Tüm seçenekler büyükten küçüğe benzerliklerine göre sıralanmakta ve en büyük C_i değerine sahip seçenek en iyi seçenek olarak seçilmektedir.

Bu çalışmada, çok ölçütlü karar kurallarından olan Analitik Hiyerarşi Yöntemi (AHY) ve İdeal Çözüme Benzerliğe Göre Tercih Sıralaması Tekniğinin (Technique for Order Preference by Smilarity to Ideal Solution-TOPSIS) CBS ortamında deprem tehlike haritası üretimi ve analizinde birlikte kullanımı ve birbiriyle bütünleştirilmesi başarılmaktadır. Pilot bölge olarak İstanbul, Küçükçekmece Bölgesi seçilmiştir. Deprem tehlike haritasının üretilmesi ve analiz edilmesi amacıyla daha önceden belirlenen beş ölçüt temel alınmıştır. Bunlar: Topoğrafya, Depremin Merkezine Uzaklık, Toprak Sınıfı, Sıvılaşma Potansiyeli ve Fay Mekanizasyonudur. Öncelikle AHY'nin ikili karşılaştırma özelliğinden yararlanarak ve bu beş ölçüt temel alınarak ölçüt ağırlıkları belirlenmiş, CBS ortamında deprem tehlike haritası üretilmiştir. AHY'den elde edilen ölçüt ağırlıkları baz alınarak, CBS ortamında TOPSIS yöntemi uygulanarak deprem tehlike haritası üretilmesi başarılmıştır. TOPSIS uygulanarak üretilen harita çıktısı ile AHY'den elde harita çıktısı karşılaştırma ve analiz işlemine tabi tutulmuştur. Üretilen model çıktılarının birbiriyle karşılaştırılabilir olduğu görülmüş, yapılan istatistiksel analizler sonucu birbirleriyle yüksek korelasyona sahip olduğu saptanmıştır. Üretilen harita çıktıları deprem risk değerlendirmesine katılan uzmanların ortak tercihlerini de yansıtmaktadır. Çalışma bölgesinin deprem riskinin analiz edilebilmesi amacıyla, nüfus ve bina verisi de analiz işlemine dahil edilmiş, potansiyel kayıp değerlendirilmesi amacıyla kullanılmıştır.

Bu çalışmada ayrıca, deprem özelinde, afet ve acil durum yönetiminde simülasyon tabanlı sistemlerden hasar tahmin sistemlerine kadar geniş bir spektrumda uygulanma olnağı bulan mekansal kara destek sistemlerinin incelenmesi ve analizi de başarılmıştır. Global sistemler olarak HAZTURK, QLARM, SELENA, DBELA, CATS, PAGER, bölgesel ve yerel sistemler olarak ise ELER, HAZUS-MH, KOERILoss, MAEviz, EQRM and LNECLOSS incelenmiştir. Dünyadaki ve Türkiye'deki mekansal karar destek sistemleri incelendiğinde HAZTURK'ün deprem risk ve hasar tahmini açısından benzer örneklerine göre avantaja sahip olduğu belirlenmiştir. Bu çalışmada ayrıca ülkemiz özelinde mekansal veri elde etme, mekansal veri kalitesi, veri değişimi, kurumlar arası koordinasyon eksikliği gibi temel konularda anahtar zorluklar da belirlenmiştir.



1. INTRODUCTION

Earthquake disasters pose significant risks and have caused devastating loss of lives and damage to infrastructure worth hundreds of billions of dollars (USD) in value resulting in huge socio-economic and environmental losses in many regions worldwide. In the last decade, recent major and catastrophic earthquake occurrences of magnitudes greater than six, such as; the 2010 Haiti and Chile, 2011 Japan, 2013 Pakistan, 2014 China and 2015 Nepal have taken place. According to official estimates, magnitude 7.0 earthquake in Haiti of 2010 killed 316,000 people, injured 300,000 and 1.3 million people were displaced, 97,294 houses were destroyed and a further 188,383 damaged (USGS, 2014). Barely seven (7) years after the event, at present, many people still live in tent cities that sprung up after the disaster. Other notable examples within the recent years are the earthquakes of 2011 Japan (magnitude 9.0; more than 18,000 casualties including those still missing), 2011 Christchurch New Zealand (magnitude 6.3; about 185 deaths, around 2,000 injured – 164, seriously), 2013 Pakistan (825 casualties), 2014 China (magnitude 6.2; more than 700 casualties, the strongest quake to hit in 14 years), 2015 Nepal (magnitude 7.8; more than 8,000 casualties with fatalities also reported in India, Tibet, and Bangladesh. The United Nations (UN) estimated 8 million people were affected, marking the deadliest disaster on record in the Himalayan nation). These colossal statistics emphasize the devastating impact of earthquakes, and the need for organized and rapid disaster preparedness and response being critical in the wake of the devastation that can follow, especially in countries that are not prepared for such an event. For instance, the Munich Re's NATCatSERVICE global database on natural hazards, in 2008, recorded 750 loss events, out of which only 12 % were from earthquakes. However, 43% of all casualties and 43% of the overall economic losses globally were caused by earthquakes (Munich Re Group, 2011).

Worldwide, in no more than a decade ago, earthquakes have caused the death of over half a million people (Armaş and Rădulan, 2014). According to the UNISDR (2012) report, eight (8) out of the ten (10) most populous cities in the world lie in the locality

of earthquake fault-lines. The earthquakes impact within urban environments can be shown in the vulnerability of building structures, infrastructure, natural environment and people (Armaş and Rădulan, 2014).

Generally, it is expected that earthquakes will cause the deaths of populations in urban regions in the near future, in larger numbers than recorded in the past (Bilham, 2009). There are a lot of well-known and documented hotspots for impending catastrophic earthquakes (Dilley, 2005). For example the megacity of Istanbul, Turkey, with its estimated more than 15 million inhabitants is at a 30 - 70 % probability risk of a major earthquake ($M_w \geq 7$), occurring in the next 30 years (Parsons, 2004). As a result, natural risk within the aspect of rising urban vulnerability has continued to prevail as an issue of priority for the 3rd millennium (e.g., Parker and Mitchell, 1995; Wenzel et al, 2007).

In Turkey, recent catastrophic earthquakes that adversely affected urban areas were the 1999 Kocaeli (Izmit)/Düzce and the 2011/2 Van (Eastern Turkey) events within the Marmara Region. The 1999 Izmit, Kocaeli magnitude 7.4 earthquake resulted in the death of 17,127 people and injured 43,959, with over nearly half a million people left without shelter (Marza, 2004). The 2012 Van earthquake struck near the city of Van in eastern Turkey at a magnitude of 7.1 causing death of approximately 604 people and injuring 4,152 damaging over 11,000 buildings leaving nearly 60,000 people without homes.

The occurrence of these tragic earthquake disaster events further underscore the relevance and critical importance of the increasing need for effective disaster management for risk mitigation. Issues related to disaster and emergency management (DEM) have stimulated growing research globally with technological advances especially in fields of geospatial technologies and computing, to quantify and carry out hazard detection and analysis, risk assessments and monitoring. Geospatial technology is utilized for collection, analysis and visualisation of geographic information via geographic information system (GIS). During a disaster, geospatial technology (GIS) can be used to integrate different data types for easier accessibility and can provide time critical information to responders and decision makers, and provide powerful visualization in form of *hazard maps*, for coordinating disaster preparedness, response and recovery efforts.

The vulnerability to earthquake hazards and related disaster risks influence the decisions to be made towards efforts to reduce the possible impacts. This scenario is generally, too complex, inter-related and should therefore be structured in a well-organized manner using developed scientific methods known as Multi-Criteria Decision Analysis (MCDA), integrated with use of GIS to assist and analyse various aspects in the process. MCDA, in the recent past, has been widely used in variety of research, industrial and operational domains and it characterises decision-making involving many and conflicting criteria (Lamit, 2011). The quality of decisions is immensely enhanced by the use of MCDA, by making the process more explicit, rational and efficient, leading to choices that can be easily justified and explained. These combined characteristics permit the development of a comprehensive decision-making process that incorporates conflicting criteria, stakeholders from inter-disciplinary functions involved in emergency management.

1.1 Problem Statement

The emergence of new opportunities in earthquake emergency planning and management issues have been stimulated by recent advances in geo-technology domains, with increasing demand for spatial data now required for complex decision making by emergency managers involving large number of stakeholders across multi-disciplinary teams and criteria. For this, spatial MCDA approaches offering a variety of techniques such as AHP and TOPSIS can be utilized to uncover and integrate decision makers' preferences to solve GIS-based planning and emergency management problems. Additionally, spatial decision support systems (SDSS) have been explicitly developed. These are decision support systems (DSS) that are used to aid and improve the quality of decision making by employing quantitative approaches with use of geographic information that is stored within the GIS as applied to earthquake emergency management.

Within this context, this study seeks to review and discuss SDSS usage for earthquake disaster management in the world with special reference to Turkey's experience. It becomes imperative, from key findings of the review, to recommend a suitable SDSS for implementation of earthquake risk and loss estimation studies in Turkey based on significant comparative advantages over other SDSS, suitability and applicability to the local conditions of Turkey. Key challenges ranging from technical and

institutional, may exist that inhibit the successful implementation of the recommended SDSS in Turkey and therefore, need to be highlighted and addressed.

The possible prediction and monitoring of earthquake disasters requires rapid and continuous data and information generation/acquisition approaches which cannot be effectively achieved using conventional methods. To this effect, a scientific technique of MCDA, integrated with GIS, can be applied to assist and analyse various aspects in the earthquake disaster management and risk monitoring/analysis process.

Following the two most recent catastrophic earthquake events of 1999 Kocaeli and 2011 Van that took place in Turkey, and the impending high probability risk of earthquakes of magnitude greater than 7 occurring in Turkey, in the next 30 years according to Parsons et al. (2004), a lot of scientific studies and activities have taken place which propose that successful earthquake disaster and mitigation activities should be based on the DEM cycle. In all the four phases of the DEM cycle, *earthquake hazard maps (EHM)* are required to be generated via GIS for risk identification in most hazardous areas and timely response to the correct locations, planning equipment mobilization, asset removal or retrofit, damage assessment and recovery efforts as part of disaster mitigation activities. Within the domain of DEM, determination of the hazard map outputs as speedily and as accurately as possible is crucial. Therefore, a vital need for the DEM procedure arises for minimizing the conflicts and uncertainties that may arise in the determination of hazard maps (Erden and Karaman, 2012).

1.2 Purpose of Thesis

The main aim of this study is to explore and demonstrate the potential of integrating GIS and MCDA for effective earthquake disaster and emergency management (DEM) with particular reference to use of two (2) GIS-MCDA widely popular techniques known as AHP and TOPSIS, in generating hazard maps for earthquake disasters. In this context, it is aimed to develop a methodology for earthquake risk and hazard mapping using GIS modeling integrated with MCDA techniques of AHP and TOPSIS by the determination of the weights of the parameters of the earthquake hazard map that strongly affects the earthquake ground motion and influences the effects of the earthquake at the study area. In achieving this objective, a comparison of the two methods is required for analysis of the potential risks associated with the most hazardous regions simulated on a GIS environment as visualized from each of the

generated earthquake hazard maps and therefore, the applicability of these techniques for earthquake hazard risk and loss assessment can then be discussed.

The other objective of the study is to review the usage of SDSS for earthquake disaster management in the world with special reference to Turkey, and discuss key issues, challenges and recommendations for appropriate SDSS software implementation in Turkey. The focus is directed towards conducting research on SDSS within the framework of DEM, examination of the current landscape of the main SDSS tools used worldwide and their application for earthquake studies with particular reference to the experience, future trends and implementation challenges in Turkey.





2. DISASTER AND EMERGENCY MANAGEMENT

2.1 Disaster and Emergency

Within the framework of disaster management, the word *disaster* as defined according to UNISDR, is a “serious disruption of the functioning of a community involving far-reaching human, material, economic or environmental losses and impacts, that exceeds the ability of the affected community to cope using its own resources” (UNISDR 2007). The term *disaster* denotes a sudden and unforeseen event. When occurs at the household level, a disaster could result in a major illness, loss of life, significant social or economic misfortune (Saltbones, 2006). Disaster impacts may include injury, disease and other negative effects on human physical, mental and social well-being, together with damage to property, destruction of assets, loss of services, social and economic disruption and environmental degradation (UNISDR, 2007). When occurring at the community level, it could be a fire, building collapse resulting from earthquake, flood, livelihood destruction, an epidemic or displacement through conflict. Whereas, at the district or provincial level, a bigger number of people can be affected. Most of the disasters result in the inability of those affected to cope with outside assistance such as; at household level, dealing with help from neighbours, at national level; assistance from organizations such as the United Nations, International Federation of Red Cross, several non-governmental organizations (NGOs) and government agencies, etc. Since the limiting factor in disaster response is most often the coping capacity of the affected, a key approach when responding to disasters is reducing its consequences by improving the resilience of those affected (Saltbones, 2006).

Emergency is a threatening condition or situation generated by the real or imminent occurrence of an event that requires urgent action or immediate attention (UNISDR, 2007; VUSSC, 2007). Effective emergency action can avoid the escalation of an event into a disaster (UNISDR, 2007).

2.2 Comparison of disaster and emergency

There is often confusion in the use of the words ‘disaster’ and ‘emergency’ with some using these terms interchangeably for the same meaning.

However, a disaster and an emergency are two different situations: An *emergency* is a situation in which a community is capable of coping while a *disaster* is a situation in which the community is incapable of coping (VUSSC, 2007).

An *emergency* is a situation generated by the real or imminent event occurrence that requires urgent action and immediate attention of emergency resources. While on the other hand, a *disaster* is a natural or human-induced event which causes negative impacts on people, goods, services and/or environment exceeding the affected community’s capability to respond; thereby, the community seeking the assistance of government and international agencies (VUSSC, 2007).

2.2.1 Disaster classifications

Disasters are often classified by their *causes* – *natural* vs. *human (non-natural)*, and speed of *onset* – *sudden* vs. *slow*.

Natural disasters occur naturally (or from forces of nature) in proximity to and pose a threat to people, structures or economic assets. Natural disasters are caused by seismic, geological, biological, hydrological or meteorological conditions or processes in the natural environment e.g., earthquakes, floods, landslides, volcanic eruptions, tsunamis, cyclones, hurricanes, typhoons (VUSSC, 2007). Figure 2.1 below shows examples of classifications of natural disasters.



Figure 2.1: Examples of natural disaster classifications (EM-DAT, 2015).

Human-made disasters are principally and directly caused by identifiable human actions whether deliberate or otherwise (VUSSC, 2007). These disasters caused by humans have included industrial and transportation accidents, collapse of buildings and release of hazardous materials (Saltbones, 2006). Apart from “technological disasters” (such as hazardous materials spill, nuclear accident, power outage, etc), these are mainly associated with situations in which civilian populations suffer casualties, property losses, losses of basic services and means of livelihood resulting from civil strife, unrest, war, or other conflicts or policy implementation. In many instances, people are forced to leave their homes, resulting in aggregations of refugees or internally and/or externally displaced persons as a consequence of civil strife/conflict, a major fire, oil spill, an aeroplane crash, epidemic, terrorism, etc. (VUSSC, 2007). There are natural disasters that are *increased* by human activity especially in today’s society which is becoming more complex; where people are increasingly responsible, directly or indirectly for consequences of events previously attributed to forces beyond their control. Many of the natural hazards would not have occurred or would have had a lower impact on communities had it not been for actions by people such as deforestation for firewood or building materials resulting in landslides especially during heavy rainfall e.g. in Central and South America; overgrazing of cattle allowing desertification in the Sahel region (semi-arid region of West and North-Central Africa); removal of wetlands eliminating a natural mitigating element for the damage caused by tropical storms; uncontrolled housing construction close to beaches increasing risks from tsunamis and storms; political systems turning droughts into famine (Saltbones, 2006).

Disasters of *sudden onset* are characterized by little or no warning with minimal time to prepare before occurrence e.g. earthquake, tsunami, volcano, cyclone, etc. *Slow onset* disasters are adverse events that are slow to develop. First the situation develops; the second level is an emergency and this then degenerates into the third level which is a disaster, e.g., drought, epidemic, civil strife, etc (VUSSC, 2007).

2.2.2 Disaster types in World

Worldwide, natural disasters continue to pose a very serious threat to millions of people, their livelihood and significant losses both to human lives, the environment and infrastructure worth billions of dollars (USD) in value.

Earthquake disaster occurrences are prime among the disaster types causing the most devastation and accounting for the most losses affecting millions of people and destroying infrastructure. Other top major natural disasters occurring worldwide include floods, landslides, storms, cyclones, tsunamis, volcanic eruptions, fires, hurricanes, droughts.

In the last decade, China, the United States, India, the Philippines and Indonesia together make up the top five (5) countries most frequently hit by natural disasters such as storms, floods, landslides, earthquakes, cyclones, tsunamis (EM-DAT 2016).

Comparing the occurrence of natural disasters at present year 2015 with the past trends over the last 30 years from the year 1980, an estimation of the major disasters, number of events, losses in economic value and impact can be highlighted in Figure 2.2 below.

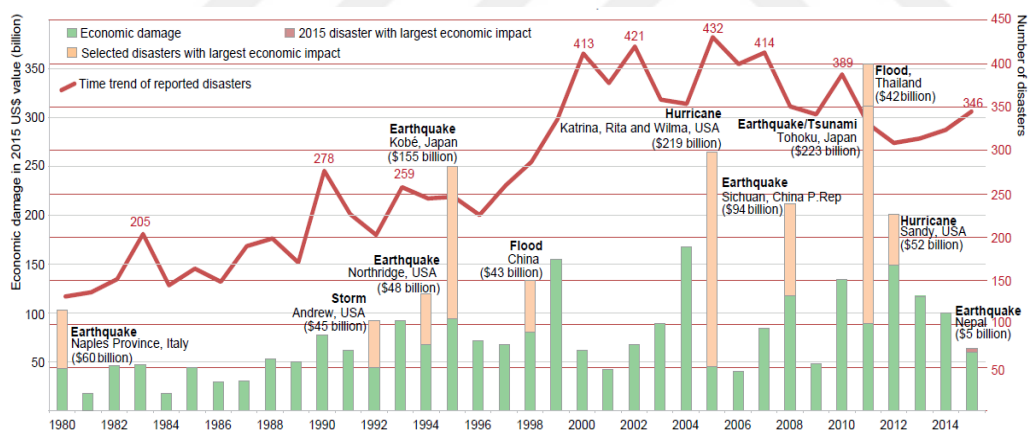


Figure 2.2 : Present and past trends of natural disaster occurrences, impacts and economic losses in value of USD (1980-2015) (EM-DAT, 2016).

Figure 2.3, shows the trends in the last 25 years of the number of occurrences of natural disasters and the total number of people resultantly affected.

In the recent year 2015, a comparison can be made of the statistics of human impact in terms of both deaths and population affected as a result of natural disaster occurrence against the average in the last decade between the years 2005 and 2014 as shown in Figure 2.4. As can be noted in the figure, earthquakes triggering resultant

tsunami disasters have caused the highest number of deaths (42,381) in the last decade followed by storms (17,778), extreme temperatures and floods. Floods, on the other hand have affected the most number of people (over 85 million), followed by droughts and storms (over 35 million people), in the last decade. Over the last 10 years, the Asian continent has registered the highest percentage of deaths (55.6%) caused by natural disasters, followed by the Americas with 31.6%, Europe at 8.6%, Africa (3.9%) and the least being the Oceania regions with 0.2%.

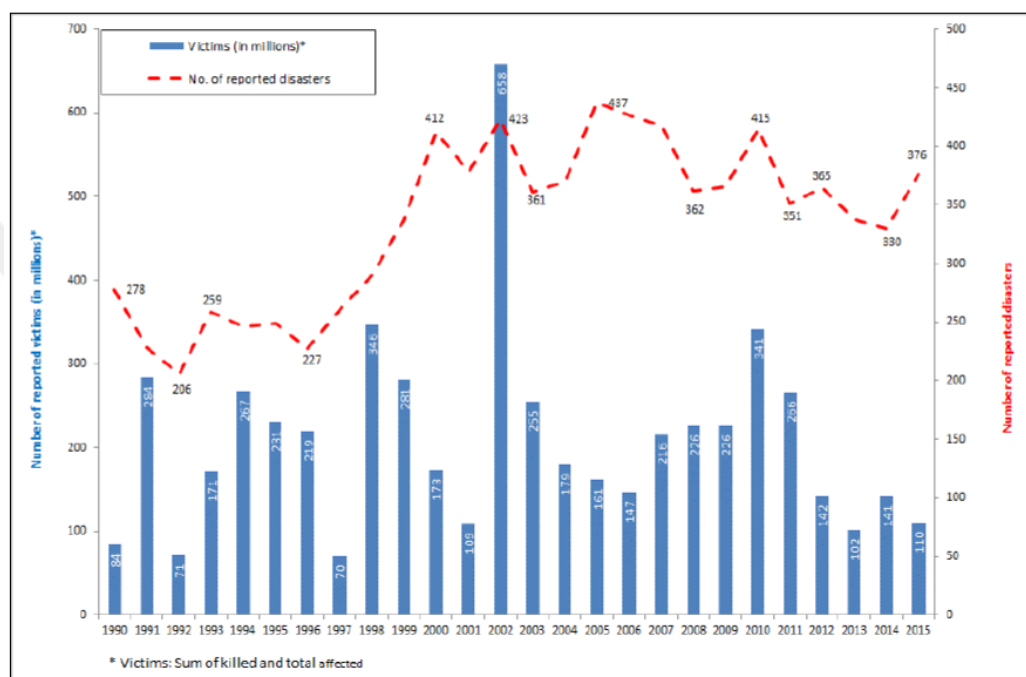


Figure 2.3: Trends of the number of natural disaster occurrences and the total number of affected people (1990-2015) (EM-DAT, 2016).

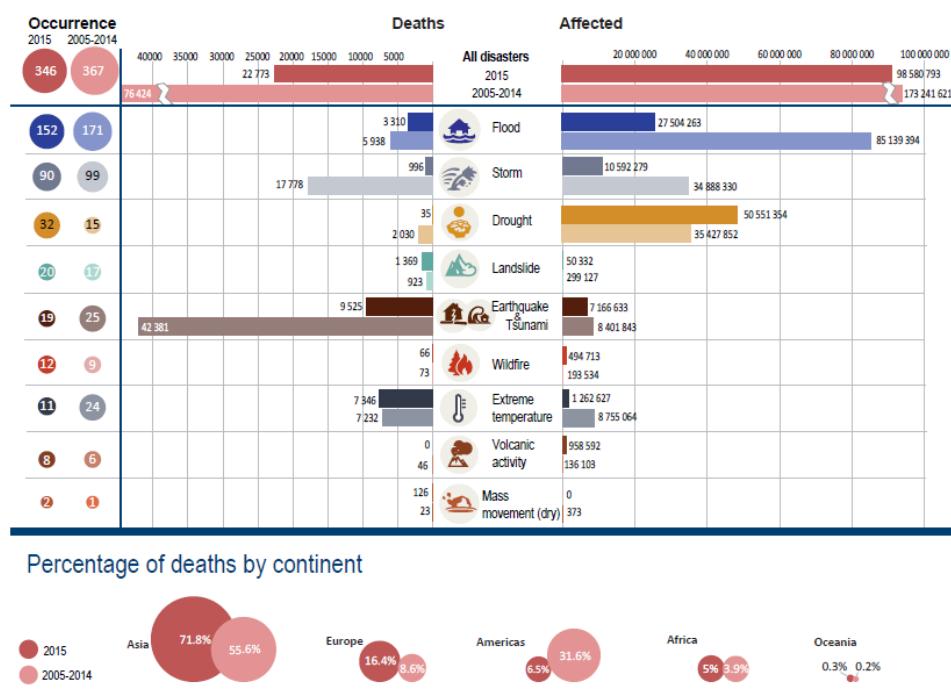


Figure 2.4 : Comparison of natural disaster occurrence and human impact between the year 2005 - 2014 (EM-DAT, 2016).

The following map inserts, Figure 2.5 and Figure 2.6, depict a global and regional overview of the total frequency of natural disaster occurrence by country over the last 30 years between the years 1974 and 2003 and between years 1986 and 2015, respectively.

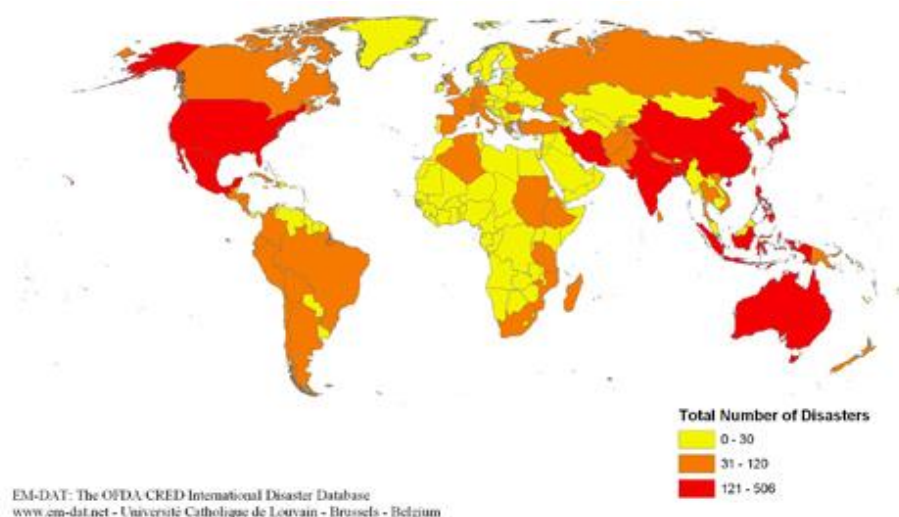


Figure 2.5 : World map - total number of natural disaster events by country, 1974-2003 (EM-DAT, 2015).

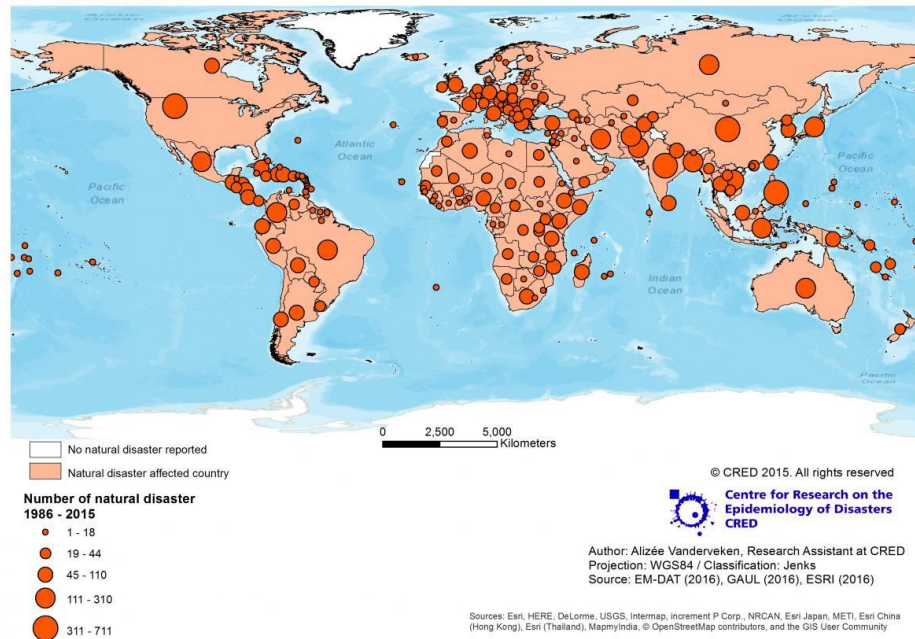
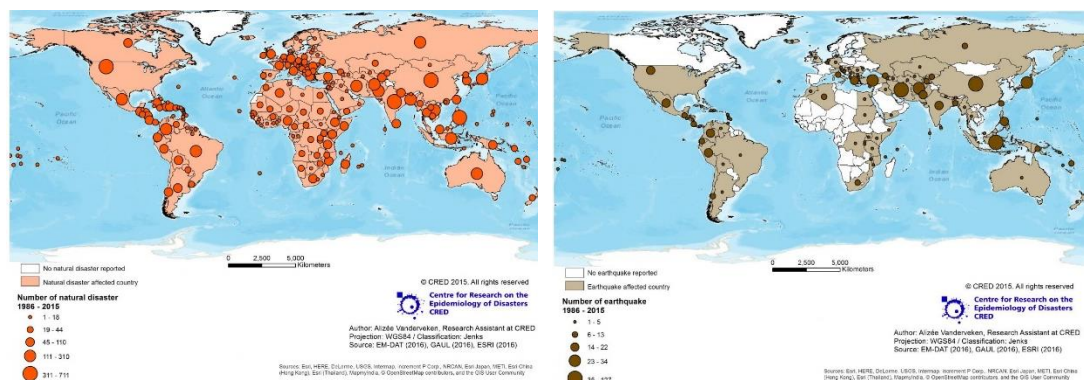


Figure 2.6 : World map - number of natural disaster events by country, 1986-2015 (EM-DAT, 2016).

2.2.3 Disaster types in Turkey

Turkey is concurrently faced with natural disasters that lead to severe human and infrastructure losses as a result of its geological, topological form and climatic factors/conditions (Gunok and Pinar, 2009). From the following map inserts and statistics, it can be observed that earthquakes occur most frequently in Turkey, followed by floods and landslides. Further, Turkey ranks in the top percentile worldwide as having one of the highest number of disasters.



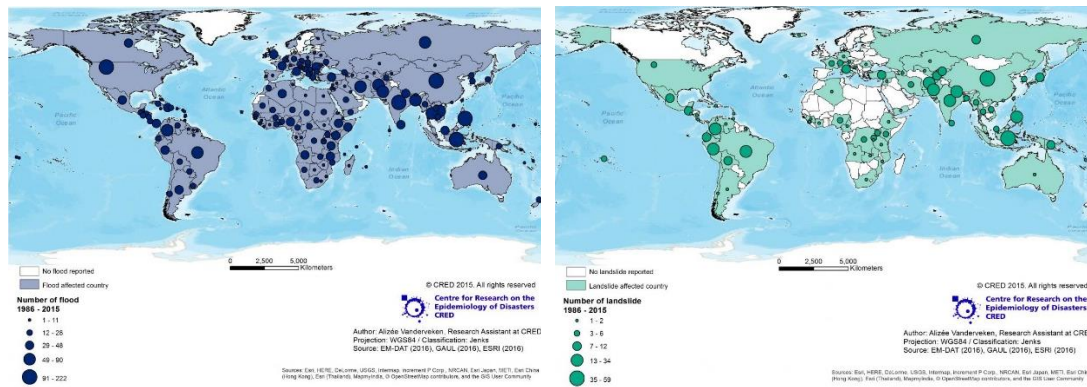


Figure 2.7 : Total number/frequency of natural disasters and occurrences of earthquakes, floods and landslides worldwide by country, 1986-2015 (EM-DAT, 2016).

In the last 116 years or so, between the years 1900 and 2016 in Turkey, there have been over 237 disasters recorded that have caused severe impacts resulting in 92,121 deaths and negatively affecting 8,951,999 people's livelihood, accounting for in excess of 26 billion USD in economic losses (EM-DAT, 2016). Of these disasters, over 90% of total deaths, and damage cost has been caused by earthquakes, followed by floods (Table 2.1).

Table 2.1: Total disaster occurrences by type, economic damages and human losses and affected populations in Turkey from 1900 to 2016 (EM-DAT, 2016).

Disaster Type	Deaths	No. of people affected	Total cost of damage ('000 USD)	% damage cost	% affected	% deaths
Earthquake	89,236	6,924,329	24,685,400	91.7%	25.7%	1.00%
Epidemic	613	204,855	-		0.8%	0.01%
Extreme temperature	100	8,450	1,000		0.0%	0.00%
Flood	1,408	1,785,023	2,195,500	8.2%	6.6%	0.02%
Landslide	293	13,481	26,000		0.1%	0.00%
Mass movement (dry)	407	1,075	-		0.00%	0.00%
Storm	49	13,636	2,200		0.1%	0.00%
Wildfire	15	1,150	-		0.00%	0.00%
Total	92,121	8,951,999	26,910,100			

The pie-chart figures below highlight the total number of people affected by disaster type and total cost of resultant economic losses and damages.

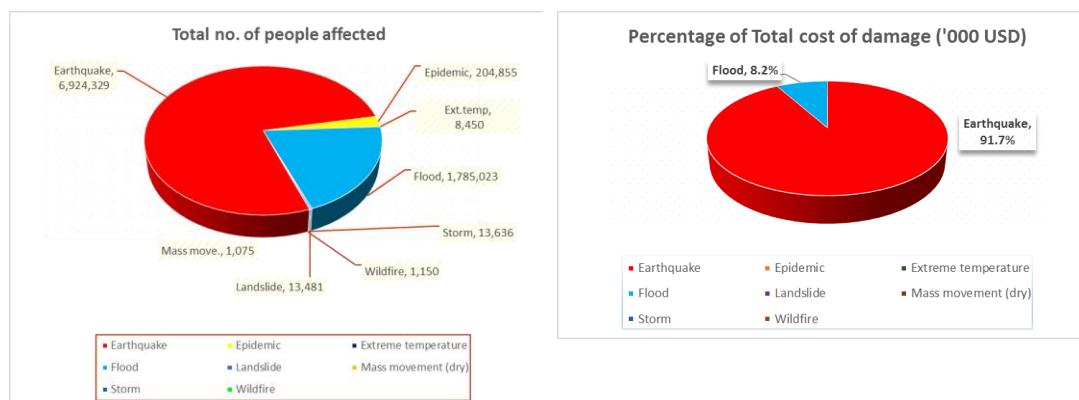


Figure 2.8 : Total number of people affected by disaster type and total cost of resultant damages in USD in Turkey from 1900 to 2016 (EM-DAT, 2016).

The following table shows the top 10 natural disasters, severely affecting the highest number of people in Turkey from 1900 to 2016 (EM-DAT, 2016). Earthquakes and floods adversely affected the most number of people.

Table 2.2: Top 10 disaster occurrences by type, economic damages and human losses and affected populations in Turkey from 1900 to 2016 (EM-DAT, 2016).

Disaster Type	Date of event	No. of people affected
Earthquake	28-Jun-98	1,589,600
Earthquake	17-Aug-99	1,358,953
Flood	20-May-98	1,240,047
Earthquake	30-Oct-83	834,137
Earthquake	18-Sep-84	375,038
Earthquake	18-Oct-84	375,035
Earthquake	13-Mar-92	348,850
Earthquake	22-Jul-67	326,073
Flood	04-Nov-95	306,617
Earthquake	01-May-03	290,520

A summary of the total number of people affected by top 10 major disasters - earthquakes and floods, is given in Figure 2.9 below.

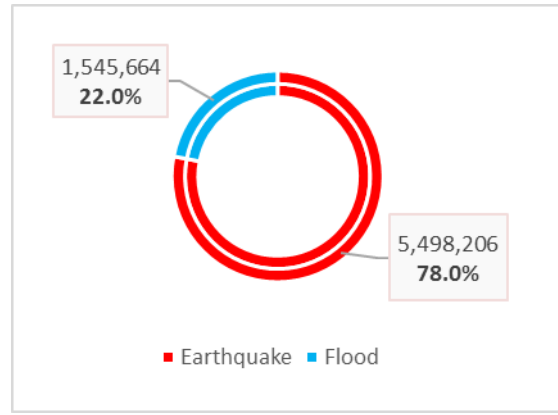


Figure 2.9: Total number of people affected by top 10 (major) disasters in Turkey from 1900 to 2016 (EM-DAT, 2016).

The largest number of deaths resulting from the major disasters in Turkey since the year 1900, are all caused by earthquakes as shown in Table 2.3.

Table 2.3: Largest number of deaths all caused by earthquake disasters in Turkey from the years 1900 to 2016 (EM-DAT, 2016).

Type	Date	Total deaths
Earthquake	29-Apr-03	6,000
Earthquake	26-Dec-39	32,962
Earthquake	26-Nov-42	4,000
Earthquake	20-Dec-42	3,000
Earthquake	26-Nov-43	2,824
Earthquake	01-Feb-44	3,959
Earthquake	19-Aug-66	2,394
Earthquake	06-Sep-75	2,385
Earthquake	24-Nov-76	3,840
Earthquake	17-Aug-99	17,127

A summary chart showing the number of deaths in Turkey, all caused by earthquakes since the year 1900 is as shown in Figure 2.10. The highest number of deaths, 32,962 people, ever recorded was in 1939 and the most recent was the tragic 1999 Kocaeli and Duzce earthquakes, in which 17,127 people were killed.

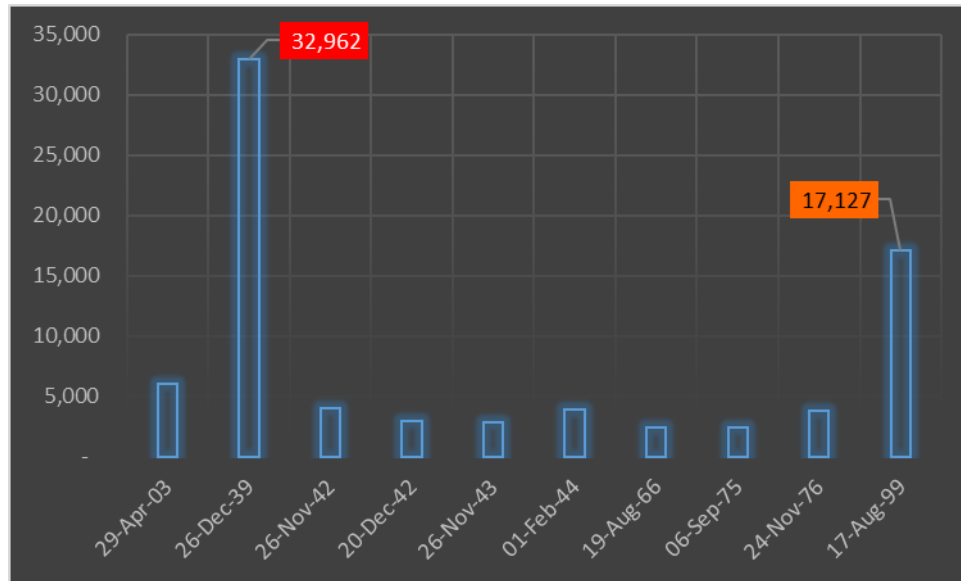


Figure 2.10: Largest number of deaths, all caused by earthquake disasters in Turkey from 1900 to 2016 (EM-DAT, 2016).

In consideration of all these disaster occurrences, it is imperative that a well functional and effective DEM in Turkey is implemented that should serve to mitigate the disaster effects.

2.3 Risk, Hazard, Vulnerability and Exposure

Hazard is an event or physical condition (FEMA, 1997) or something that creates or is the potential for a natural or human-caused event to occur with negative consequences such as loss of life, property damage, and adverse social and environmental impacts (Bureau of Reclamation, 2010; VUSSC, 2007) or potential harm which threatens the social, economic and natural capital of a community (Pine, 2008). Hazards can be categorized into *natural hazards* (earthquakes, floods, etc), *technological hazards* (hazardous materials spill, power outage, nuclear accident etc.), *human-induced hazards* (terrorist attacks, bombing, mass destruction, etc) and *compounded hazards* which combine different kinds of hazards such as urban fires after an earthquake occurrence (Pine, 2008).

Risk is the measure of the expected losses due to a hazard event occurring in a given area over a specified future time period. Risk is a function of the probability of a particular hazardous event and the resulting losses it would cause. The risk level depends upon the nature of the hazard, vulnerability of the elements which are affected

and economic value of those elements (Vasilescu et al, 2008). *Risk* (R) can therefore be determined as a product of *hazard* (H), *vulnerability* (V) and *exposure* (E), i.e., $R = H \times V \times E$.

Vulnerability is the susceptibility of damage or harm by a hazard (Saltbones, 2006). It is the extent to which a community's structure, services or environment/geographic area is likely to be damaged or disrupted by particular hazard impact (VUSSC, 2007; Vasilescu et al, 2008). Vulnerability of people living in a substandard apartment house to a drought would differ from their vulnerability to an earthquake (Saltbones, 2006). Vulnerabilities can be aggregated into *physical* and *socio-economic* vulnerability. *Physical vulnerability*, is based on the physical condition of people and elements at risk, such as buildings, infrastructure etc; and their proximity, location and nature of the hazard. It also relates to the technical capability of buildings and structures to resist the forces acting upon them during a hazard event.

Socio-economic vulnerability, is the degree to which a population is affected by a hazard due to the socio-economic conditions of the people which also determine the intensity of the impact. For instance, people who are poor and living by the sea coast do not have funds to construct strong concrete houses. Owing to this, they are generally at risk and lose their shelters whenever a strong wind or cyclone event occurs. Because of their poverty situation, they too, are not able to rebuild their houses (Vasilescu et al, 2008).

Exposure is the duration and/or extent of a particular hazard. In earthquakes, this could not only be the duration of the tremor, but the duration of the aftershocks, some of which may almost be as severe as the original event. The exposure could also be a measure of the number of people affected and even the extent to which they are left exposed. The terms, 'exposure' and 'vulnerability' may be used by some in a similar manner (Saltbones, 2006).

When a community is exposed to hazards and likely to be adversely affected by its impact, then it is said to be at 'risk'. In this study, the term, 'Disaster management' is basically used to mean 'disaster risk management' which includes all measures which reduce disaster-related losses of life, property or assets by either reducing the hazard or vulnerability of the elements at risk (Vasilescu et al, 2008).

2.4 Earthquake Risk/Management

Wahlstrom et al. (2004) characterise seismic risk, in terms of the components *seismic hazard*, *seismic vulnerability* and *value of elements of risk* (in both human and economic terms). Earthquake hazards can be single, sequential or combined, both in their origin and effects. For instance, earthquakes may set off other earthquakes (e.g. Pinar et al, 2001) and/or resultant events such as landslides (e.g. Huang and Li, 2009), tsunamis (e.g. Strunz et al, 2011) or fires (e.g. Girgin, 2011) which can even cause more devastation than the initial hazard (e.g. Korup, 2010).

Earthquake risk is a measure that aggregates, over a specified time, the probability and consequences of a set of earthquake scenarios (Beer and Ismail-Zadeh, 2003). The risk can therefore be estimated from earlier definition, as the probability of harmful consequences or expected losses (of lives and property) and damages (e.g. injury to people, disruption of economic activity, damage to the environment) due to an earthquake resulting from interactions between *seismic hazards* (H), *vulnerability* (V), and *exposure* (E). Conventionally, *earthquake risk* (R) is expressed by the convolution of these three parameters: $R = H \times V \times E$. Each of those factors is disaggregated into the more specific parameters that comprise it. *Seismic hazard* is typically inter-related with the past seismicity, geological and geophysical parameters (e.g. peak ground acceleration, seismic intensity, seismic wave propagation and attenuation, site effect). *Vulnerability* depends on the quality of building structures, ground condition, and population features. Infrastructure, critical facilities, and important communication system represent the *values exposed* to damage due to an earthquake and should be taken into account in risk estimation. The right framework for dealing with earthquake risk estimation and risk management problems should encompass all the supporting elements (Babayev et al, 2010).

Risk management characterises the full scope of procedures and tasks that eventually give rise to policies and risk mitigation measures being implemented (Dan et al, 2014). All the undertakings for earthquake risk management are structured within the open-ended process of the Disaster and Emergency Management (DEM) cycle that consists of four (4) phases namely, *Response*, *Recovery*, *Preparedness* and *Mitigation*, all inter-related to each other.

2.5 Disaster and Emergency Management

DEM involves efforts and procedures aimed at improving the resilience of communities and thereby avoiding or lessening natural disaster impacts (Baharin et al, 2009). DEM can be described as a continuous process constituting a set of activities before, during and after an event, classified into four main phases: mitigation, preparedness, response and recovery (Horita and Albuquerque, 2013).

The objective of the DEM process is to avert the disasters before they take place and since disasters cannot be avoided in every instance, that is when the DEM cycle intercedes. DEM subsists for the preparation of anticipated disasters, mitigation of the probable losses, responding in time to the appropriate place, and recovery of the losses as soon and as well as possible (Erden and Karaman, 2012). Preparedness and mitigation are pre-disaster activities while response and recovery are considered as during (disaster) and post-disaster activities, respectively. Though there is increasing recognition that these activities considerably overlap each other. Some recovery activities may take place concurrently with response efforts.

2.5.1 Phases of DEM

DEM is classified into four (4) main phases: mitigation, preparedness, response and recovery (Horita and Albuquerque, 2013), as shown in Figure 2.11.

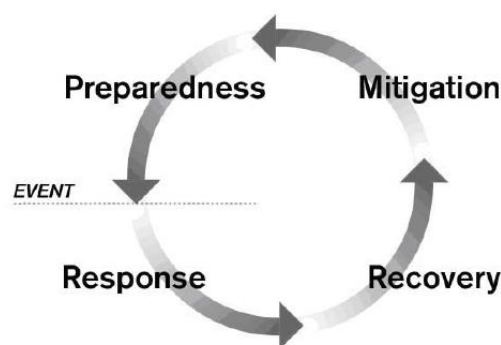


Figure 2.11 : Disaster and emergency management (DEM) life cycle (NCHRP RRD, 2009).

Mitigation – activities that eliminate or reduce the probability of event occurrence or effects of disaster. Examples are building codes and zoning, land use management, vulnerability analyses, public education.

Preparedness – activities undertaken in short term before disaster to enhance planning and resource efforts to improve operational capabilities on how to respond. Preparedness plans, emergency exercises/training, warning systems are some of the examples.

Response – efforts that begin when a disaster is imminent or immediately after event to minimize the hazards created by a disaster. Examples include search and rescue (SAR), emergency shelter and relief.

Recovery – short or long term activities after event to return the community to normal (pre-emergency condition). The affected areas should ideally be restored to a condition equal to or better than they were before the disaster occurred. Examples are temporary housing, grants, medical care (VUSSC, 2007; Vasilescu et al, 2008).

Across all these phases, emergency agencies utilise GIS information, which plays a pivotal role in making sure that the disaster impacts are lessened. For this reason, it is critical to ensure the accurate, timely and complete information about the current state of environmental variables, as well as on the scientific predictions about the impending changes and their related impacts (Horita and Albuquerque, 2013). Since each phase in emergency management life cycle is geographically and spatially inter-related (Erden and Coskun, 2007), according to Thomas et al. (2002), GIS tools have demonstrated how indispensable they are by supporting the decision-making process.

2.5.1.1 Mitigation

Activities carried out in the long-term after disaster and before another strikes that are designed to avoid disasters and to lessen the impact. Usage of GIS tools in disaster management allows spatial representation of areas at risk and risk levels associated with a particular hazard, which can guide decision-making. Activities include identifying and modifying hazards, assessing and lessening risk vulnerability. Geospatial assets can inform mitigation planning by enabling to visualize and measure the effects of alternative mitigation plans. Simulation models can help planners make effective decisions in this phase. Geospatial analysis can support cost-benefit-analysis by comparing the cost of changes. Geospatial tools have particular benefit due to their ability to allow the evaluation of multiple alternatives relatively rapidly (NRC, 2007; VUSSC, 2007).

2.5.1.2 Preparation

Preparedness activities encompass identification of geospatial data requirements, dataset development, and sharing across agencies e.g. framework and primary data development on infrastructure, hazards and risks, assets location, of use for response and recovery tasks, establishing common data standards, metadata compilation and making likely difficult decisions about attributes (NRC, 2007). Geospatial tools (including GIS and SDSS) may be used for displaying distribution of hazards and risks at present or likely existent in future scenarios. Local and regional planners are thus, enabled to work with disaster managers to plan sustainable futures through averting higher-risk alternatives. For instance, evacuation routes could be planned hinged on demographics, existing roads capacity, and traffic volume as a function of day and time (NRC, 2007).

2.5.1.3 Response

GIS technology can quickly provide users with accurate information on the exact location of an emergency situation to determine where the trouble areas are, thus enhancing quick and effective response (VUSSC, 2007). Activities include image acquisition, processing, analysis, dissemination, and conversion to information products. Additional geospatial data needs to be collected, summarized, and converted into maps, reports, and other products. After an event, geospatial tools could be used to provide damage estimates. Alternatively, real-time data from in-situ monitoring could be used with geospatial models to determine conditions during an event. Utilization of dynamic models can assist guide and enhance response activities (NRC, 2007).

2.5.1.4 Recovery

Mapping and geo-spatial data can provide a comprehensive display on level of damage sustained by cause of the disaster event (VUSSC, 2007). Activities consist of use of geospatial information and analysis to assist managers direct the recovery process, that includes urban search-and-rescue grid and status, tracking progress of repairs, locating populations, sites identification for temporary housing and services, and showing the operational status of hospitals and clinics (NRC, 2007).

2.6 Earthquake DEM

Some of the main activities that are conducted during each of the DEM phases for an earthquake disaster are as illustrated in Table 2.4.

In all these phases, *hazard maps* of the respective areas are required in order to effectively plan relevant activities in each of the phases. The main input for all these phases is the *earthquake hazard map (EHM)*. Despite the EHM being required in all phases of the DEM process, some phases need it more speedily than the others. For instance, the preparedness phase is most often associated with pre-disaster stages, and so there is enough time allowance to generate a hazard map for simulating the disaster for a particular area of interest (AOI) (Erden and Karaman, 2012; Karaman and Erden, 2014).

Table 2.4 : Examples of measures undertaken during each DEM phase for an earthquake disaster, adapted from (Haigh, 2011).

Disaster Phase	Activity measures in each phase
Mitigation/Prevention	Seismic design
	Retrofitting of vulnerable buildings
	Installation of seismic isolation/seismic response control systems
Preparedness	Construction and operation of earthquake observation systems
	Preparation of hazard maps
	Food and material stock piling
	Emergency drills
	Construction of early warning systems
Response	Preparation of emergency kits
	Rescue efforts
	First aid treatment
	Fire fighting
	Monitoring of secondary disaster
	Construction of temporary housing
Recovery	Establishment of tent villages
	Disaster resistant reconstruction
	Appropriate land use planning
	Livelihood support
	Industrial rehabilitation support

On the other hand, during the response phase, crucial information of the disaster such as magnitude, depth, location, etc is known beforehand and therefore producing the hazard map within a short time becomes the most vital requisite. Across all the phases

of DEM cycle, loss assessment outcomes are utilized. For adequate preparation and mitigation of the losses, hazard maps are necessary for identifying areas of risk and most hazardous regions for planning asset removal or retrofit, responding to right place and in time with appropriate equipment, assessing the loss and damage amounts, and recovery efforts. Within the whole DEM process, minimizing uncertainties and conflicts that may arise from stakeholders and experts across inter-disciplinary functions involved in emergency management takes high priority for decision making (Erden and Karaman, 2012; Karaman and Erden, 2014).



3. DSS AND SDSS

New opportunities have emerged in earthquake emergency planning and management issues, brought about by the recent technological developments in fields of geo-technologies as a result of the increasing demand for spatial data required by emergency managers for complex decision-making involving multiple stakeholders across inter-disciplinary functions, teams and criteria. This has led to the emergence and development of decision support systems (DSS) and spatial decision support systems (SDSS).

A DSS is a computer-based system which supports decision-makers in organizing information and models to solve problems (Sauter, 1997; Turban, 1990) by transferring, analysing, filtering and processing the appropriate data (Erden, 2012).

GIS can be a powerful tool used for the purposes of analysis, for the reason that, each phase in the DEM life cycle is geographically and spatially inter-related (Erden and Coskun, 2010). As stated by Thomas et al. (2002), geo-technologies remain at the centre of the emergency management life cycle with GIS being the tool that supports the decision-making process for carrying out assessment and analysis of geographic phenomena.

SDSS are designed to provide the vital information required by decision-makers where location issues are involved in decisions. SDSS may be used for selection of optimum locations for response teams, design of evacuation routes or allocating evacuees to shelters (NRC, 2007). An SDSS is a DSS used to aid and improve the quality of decision-making by employing quantitative approaches with use of geographic information that is stored within the GIS.

The theory of SDSS is explained in many examples (Crossland et al, 1995; Greene et al, 2011) and the related applications (Sharifi et al, 2004; Liu et al, 2007; Maktav et al, 2011). Due to the complex nature of the decision-making process, MCDA have been developed (Gheorghe and Armas, 2015). MCDA are approaches for guiding decision-

making through a critical process that allows evaluation of different alternatives or scenarios according to multiple criteria (attributes and/or objectives), which are often conflicting (Sugumaran and DeGroote, 2011).

Multi-criteria Spatial Decision Support System (MC-SDSS), a category of SDSS, is based on the concept of integrating GIS and MCDA, resulting from the need to make GIS capabilities more suited for enhancing decision-making and planning (Sugumaran and DeGroote, 2011). Hence, using information critical for making decisions such as value judgements, preferences, priorities, arguments, opinions, attitudes, etc. usually among conflicting interest parties (Malczewski and Rinner, 2015) of multi-disciplinary emergency management teams such as planners, geologists, risk engineers, local authorities, etc.

3.1 Overview of SDSS for Earthquakes

Numerous SDSS have been used to assist in the management of disasters, particularly, across all the phases of DEM namely, preparedness, mitigation, response and recovery, in the aftermath of earthquake disasters.

A case study of the use of SDSS for seismic risk in Bucharest, Romania is discussed by Gheorghe and Armas (2015). The main objective of the research was to identify a suitable shelter within a highly populated historical centre. A spatial multi-criteria evaluation (SMCE) module from ILWIS 3.4 open source GIS and remote sensing software platform was applied in the decision-making process and the multi-criteria approach was selected due to the complexity of the problem. Tang and Zhao (2012) in their study presented a distinctive DSS system for earthquake risk assessment and mitigation. The architecture of this system is based on GIS and artificial intelligence and several other components that include earthquake hazard and damage forecasting in different building structure types, system performance analysis and post-earthquake emergency response management. An SDSS for resource allocation in earthquake search and rescue (SAR) operation was proposed by Rasekh and Vafaeinezhad (2012) for an earthquake prone district in Tehran, Iran. GIS was utilized as a DSS tool for damage assessment, routing and resource distribution, and task allocation of trained rescue teams after an earthquake for disaster response operations. Pollino et al. (2011) in their study applied SDSS for earthquake early warning and post-event emergency

management by proposing development of an innovative open source GIS system as an integrated component of a seismic early warning system (EWS).

Secondary effects of an earthquake, such as tsunamis, landslides, fires, are also a critical part of a comprehensive and integrative risk assessment (Deichmann et al, 2011). However, in this study, only SDSS that are directly related to earthquake disaster risk management are considered. DEM of earthquake risks is a process that involves pre-, co- (during) and post-seismic phases as depicted in Figure 3.1 (Erdik et al, 2014).

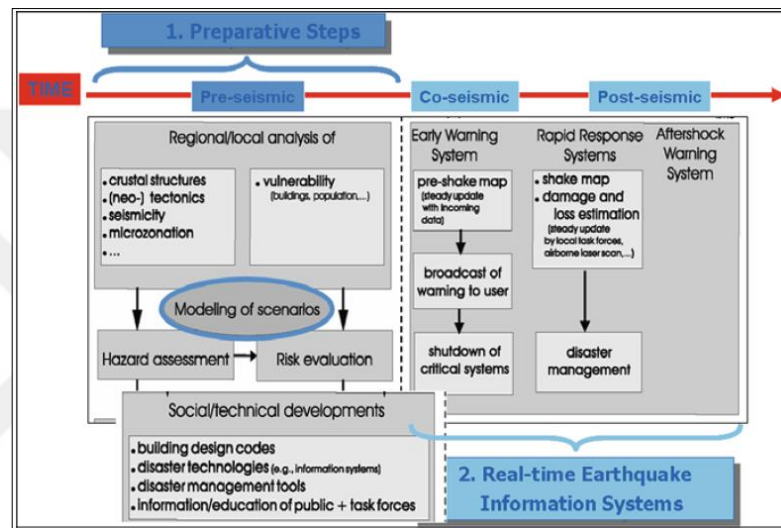


Figure 3.1 : Pre-, co- and post- earthquake risk DEM activities (Erdik et al, 2014).

SDSS aid in the function of building national or regional multi-disciplinary databases that are useful as a basis for developing earthquake scenarios both as a preliminary planning tool (pre-disaster phase) and to effectively communicate earthquake risks, warnings/alerts, to support emergency efforts in real or near real-time, and identify high-risk zones through display (post-disaster phase) (Levi et al, 2015). SDSS that are scenario or simulation-based are used in the planning and preparedness stages within the pre-seismic phase (pre-disaster) for conducting earthquake hazard assessment and risk evaluation against local/regional vulnerability and socio-technical development analyses (Erdik et al, 2014). For hazard assessment, in pre-disaster geological observations, GIS can address the need for analysis of quantitative observational parameters on landforms, land cover and tectonic features (Philip, 2010). Geological, seismic or soil maps are produced for microscale zonation (Deichmann et al, 2011).

Within the co-seismic phase (during disaster), SDSS tools that relate to earthquake early warning (EEW) systems are used that involve the generation of real-time or near real-time ground motion estimation maps as products of real-time seismology, and/or generation of alarm signals directly from on-line instrumental data (Erdik et al, 2014).

SDSS applied within the post-seismic phase (post-disaster), immediately after the earthquake occurs, relate to rapid response and loss estimation systems. These provide rapid assessment of the distribution of ground shaking intensity (shake maps) or physical damage and casualties (loss maps) from production of earthquake loss information (casualties, building, lifeline and facility damages and economic losses) immediately after an earthquake. These maps can be useful in directing the search and rescue (SAR) teams and operations to the most needed areas and thereby aiding relevant emergency management agencies or authorities in undertaking emergency action. After occurrence of an earthquake, the shaking and damage distribution maps are produced automatically based on the ground motion intensity measurement data acquired from field stations, building inventory and the fragility relationships (Erdik et al, 2014).

There are a lot of SDSS applications developed worldwide, available in the literature for earthquake disaster risk management. Even so, only the main SDSS are discussed in this study. There are a range of near real-time loss estimation SDSS tools dealing with earthquake risk management activities which may be classified under two general categories depending on the size of the area they cover: global, and regional and local systems.

3.2 Global SDSS

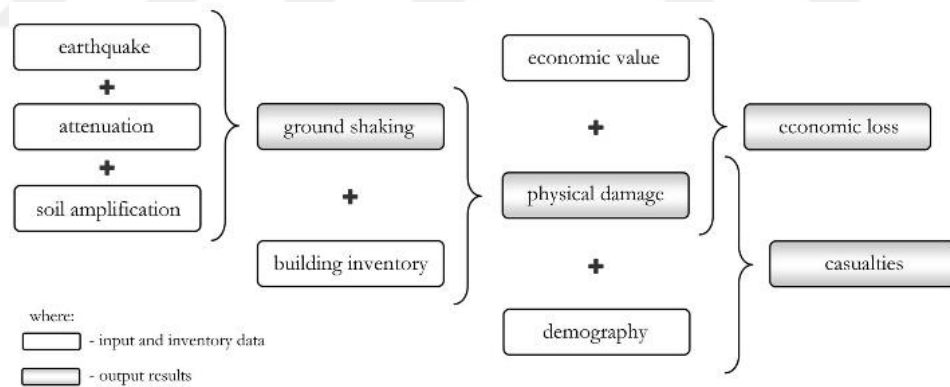
The global near real-time loss estimation SDSS are included in summary as shown in Table 3.1.

SELENA (Molina and Lindholm, 2005), is a post-disaster open source software for seismic risk and loss assessment relying on the principles of capacity spectrum methods (CSM), following the same approach as the loss estimation tool of the United States HAZUS-MH (FEMA, 2003) with a logic tree based weighting of input parameters that reportedly permits the computation of confidence levels.

Table 3.1 : Summary list of selected global SDSS for earthquakes.

SDSS	Region applicable	Developer/ Owner
SELENA (Molina and Lindholm, 2005)	Europe, Worldwide	NORSAR
HAZTURK (Karaman et al, 2008a)	Turkey, Worldwide	Karaman et al., 2008a
DBELA (Crowley et al, 2004)	Europe, Worldwide	ROSE School/EU-Centre
Emergeo/NHEMATIS (Daniell, 2009)	Worldwide	EmerGeo, EPC
CATS (Daniell, 2009)	USA, Worldwide	FEMA, DTRA
OpenQuake (Silva et al, 2013)	Worldwide	GEM, Silva et al., 2013
OpenRisk (Porter et al, 2007)	Worldwide	AGORA, USGS, OpenSHA
GDACS (Erdik et al, 2014)	Worldwide	OCHA/EC
QLARM/ QUAKELOSS (Trendafiloski et al, 2009)	Worldwide	WAPMERR
PAGER (Erdik et al, 2014)	Worldwide	USGS, FEMA

SELENA is open for any user-defined input data and therefore, can be applied to any built environment worldwide (Erdik et al, 2014; Url-1). GIS software platform can be used at various resolution levels to visualize predicted losses graphically. Unlike HAZUS which is connected to the ESRI ArcGIS software, SELENA functions independently of any GIS software (Erdik et al, 2014). A flowchart of how SELENA works in principle, is as shown in Figure 3.2.

**Figure 3.2** : Principle flowchart of analysis using SELENA (Url-1).

HAZTURK, an earthquake loss assessment software was developed by Karaman et al. (2008a), based on modification to MAEviz in conformity to the data structure of Turkey. HAZTURK, customized to local conditions of Turkey, was developed to enable assessment of earthquake risk and its potential damage to structures and human casualties. Components of hazard, fragility and inventory which form the foundation

of loss assessment studies for earthquakes are encompassed in HAZTURK (Karaman et al, 2008a).

Other global SDSS for earthquake risk and loss estimation include: DBELA (Displacement-Based Earthquake Loss Assessment) (Crowley et al, 2004); EmergGeo/NHEMATIS (Natural Hazards Electronic Map and Assessment Tools Information System), modelled after HAZUS, is a multi-hazard tool that integrates GIS, multiple relational national databases, expert rule-based system, and quantitative models combined with population and infrastructure characterization for earthquake hazard impact and risk assessment (Daniell, 2009; Erdik et al, 2014; Url-2); CATS (Consequence Assessment Tool Set), is a windows-based tool for predictions of hazards and their consequences from both natural and man-made sources, considering earthquakes as well as hurricanes and explosives (Daniell, 2009); OpenQuake (Silva et al, 2013), is open source web-based providing for viewing, modelling, exploring and managing earthquake risk within an integrated environment (Url-3); OpenRisk (Porter et al, 2007), modelled after HAZUS is an open source suite, and is entirely in Java, UML format and also uses the USGS earthquake loss estimation software called ResRisk (Daniell, 2009); GDACS (Global Disaster Alert and Coordination System) collects earthquake hazard information and by combining this with demographic and socio-economic data, provides near real-time alerts and impact estimations and disseminates disaster maps and satellite images - through a multi-hazard disaster impact assessment service about disasters worldwide and tools to facilitate coordinated international relief efforts and response (Erdik et al, 2014; Url-4); QLARM/ formerly QUAKELOSS (World Agency of Planetary Monitoring Earthquake Risk Reduction), provides loss estimates for earthquakes at a global scale applied after earthquake occurrence where alerts disseminated consist of number of fatalities, injured, and mean damage to building structures expected within the affected settlements (Erdik et al, 2014; Url-5); PAGER (Prompt Assessment of Global Earthquakes for Response), is an automated system that rapidly estimates earthquake shaking and the scope and impact of major earthquakes worldwide, informing emergency responders, government and aid agencies, and media of scope of the potential disaster (Erdik et al, 2014; Url-6).

3.3 Regional and local SDSS

There exists quite a number of regional systems (specific to regions) and local systems (specific to a facility, city or country) in several parts of the World, with capabilities of evaluating damage and casualties in near real time, after occurrence of major earthquakes (post-disaster phase) (Erdik and Fahjan, 2006). Nearly all these systems are hinged on the demand assessment in near real-time from dense strong motion instrument arrays and damage estimation on basis of prior knowledge of inventory of elements exposed to hazard and related fragility relationships (Erdik et al, 2014). These regional and local systems are included in summary provided in Table 3.2.

Table 3.2 : Summary list of regional and local SDSS for earthquakes.

SDSS	Region applicable	Developer/ Owner
ELER (Erdik et al, 2008)	Europe	JRA-3, NERIES
HAZUS-MH (NIBS and FEMA, 2003)	USA	FEMA, NIBS
EPEDAT (Eguchi et al, 1997)	USA	EQE International
EQRM (Robinson et al. 2005, 2006)	Australasia	Geoscience Australia
CAPRA-GIS (Anderson, 2008; Url-7)	Central America	EIRD
SIGE/ ESPAS (Di Pasquale et al, 2004)	Europe	OSSN
KOERILoss/ StrucLoss (Erdik and Aydinoglu, 2002; Erdik et al. 2003a,b)	Turkey, Europe	KOERI, Bogazici University
LNECLOSS (Sousa et al, 2004; Url-8)	Europe	LNEC
QuakeIST (Ferreira et al, 2014)	Europe	IST, University of Lisbon
RiskScope (Schmidt et al, 2007)	Australasia	NIWA and GNS
MAEviz (MAE, 2009)	USA	University of Illinois
TELES (Yeh et al, 2006)	Taiwan	NCREE
READY (Midorikawa, 2005)	Japan	Yokohama City
SUPREME (Yamazaki et al, 1995; Inomata and Norito, 2012)	Japan	Tokyo Gas Company
IERREWS (Erdik et al. 2003a, b)	Turkey	Bogazici University, Turkey
IGDACS (Bıyıkoglu et al, 2012)	Turkey	IGDAS

ELER, was developed through a Joint Research Activity 3 (JRA3) of the EU Project NERIES (NETwork of Research Infrastructures for European Seismology), (Erdik et al, 2008). ELER, an open source tool, applied in post-disaster phase, provides rapid estimation of earthquake shaking and losses in the Euro-Mediterranean region and consists of two modules of analysis namely; Earthquake Hazard Assessment (EHA) – which estimates ground motion intensity and parameters distribution and Earthquake

Loss Assessment (ELA) module which uses ground motion intensity and parameter information from EHA module, and demography and building inventory information. The ELA module estimates earthquake losses (damage and casualty) using three levels of analysis, level 0, 1 and 2 as shown in Figure 3.3. The availability of demographic and building inventory data essentially controls the differentiation of these three analysis levels (Demircioglu et al, 2009; Erdik et al, 2010).

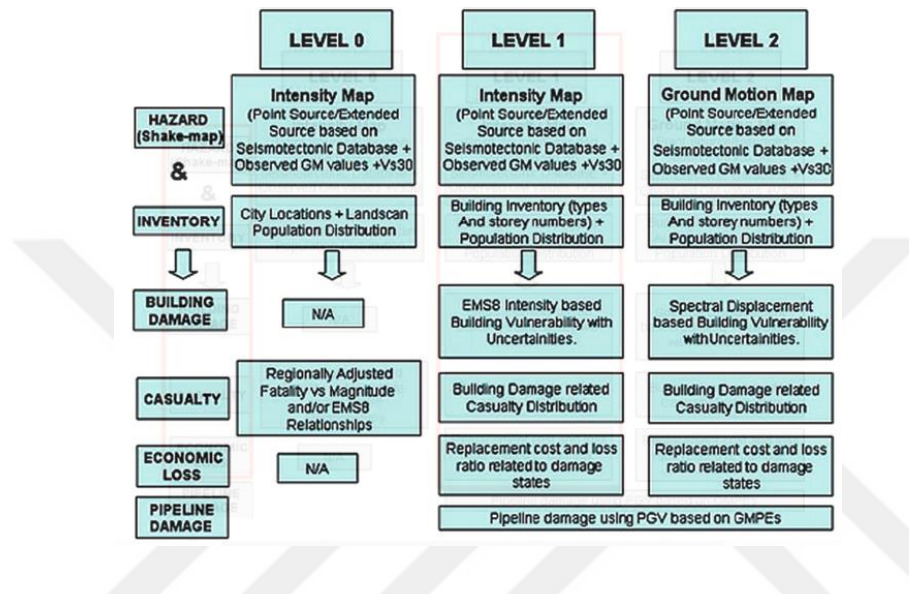


Figure 3.3 : The three (3) levels of analysis incorporated in the ELER software (Erdik et al, 2014).

Newer ELER software (ELER v3.1, 2010) include pipeline damage and economic loss estimation tools, continuously undergoing updates (Erdik et al, 2014; Url-9).

The rest of the selected main SDSS include: HAZUS-MH (Hazards United States Multi-hazard) (NIBS and FEMA, 2003) which was developed by the United States Federal Emergency Management Agency (FEMA) and the National Institute for Building Sciences (NIBS) for the purpose of estimation, prediction and mitigation of losses caused by earthquakes (HAZUS component), hurricane winds and floods (Whitman et al, 1997; Kircher et al, 2006), built on ESRI ArcGIS platform with an enhanced version, HAZUS-MH MR2, released in 2006, to include capability for conducting rapid post-event loss assessment sources (Erdik et al, 2014) ; LNECLOSS (Sousa et al, 2004), is an earthquake loss assessment software package integrated with GIS, which contains modules to calculate earthquake scenario bedrock input, local effects of soil, fragility analysis, human and economic losses (Zonno et al, 2009); KOERILoss/ StrucLoss (Kandilli Observatory and Earthquake Research Institute Loss

Estimation/ Earthquake and Structural Department of Gebze Institute of Technology) (Erdik and Aydinoglu, 2002; Erdik et al. (2003a), Erdik et al. (2003b)), a scenario-based tool for earthquake, building loss and casualty estimations, based on MapInfo GIS platform enabling multiple user options that consist of estimations of damage (Daniell, 2009); MAEviz (Mid-America Earthquakes visualization) (MAE, 2009), is an open source windows-based system with reliance on internet connectivity that integrates spatial data and visual information to perform earthquake risk assessment and analysis and enables users to add their own hazard data and establish damage estimates with options for multiple mitigation strategies and earthquake hazard impact estimation on lifelines and socio-economic systems (Daniell, 2009; Url-10).

Other regional SDSS for earthquake risk and loss estimation include: EPEDAT (Early Post-Earthquake Damage Assessment Tool) (Eguchi et al, 1997); EQRM (Earthquake Risk Management), an open source tool developed for Australian Cities (Robinson et al, 2006); CAPRA-GIS (Central American Probabilistic Risk Assessment), an open source system (Anderson, 2008); SIGE/ ESPAS (Earthquake Scenario Probabilistic Assessment) (Di Pasquale et al, 2004); QuakeIST (Ferreira et al, 2014); and RiskScape, developed for regional scenarios in New Zealand (Schmidt et al, 2007).

Some examples of local SDSS used in earthquake emergency management and disaster mitigation consist: TELES (Taiwan Earthquake Loss Estimation System) (Yeh et al, 2006); READY (Real-time Earthquake Assessment Disaster System in Yokohama City, Japan) (Midorikawa, 2005); SUPREME (Super-dense Real-time Monitoring of Earthquakes) (Yamazaki et al, 1995; Inomata and Norito, 2011; Url-11).

Examples of local systems utilised in Turkey are: IERREWS (Istanbul Earthquake Rapid Response System and Early Warning System) (Erdik et al, 2003a, b) designed and operated by Bogazici University with the logistical support of the Governorate of Istanbul, First Army Headquarters and Istanbul Metropolitan Municipality (Erdik et al, 2014); and IGDACS (Istanbul Natural Gas Earthquake Response System) (Bıyıkoglu et al, 2012), developed by IGDAS (Istanbul Gas Distribution) which is the primary natural gas provider in Istanbul, is a real time risk mitigation system (Erdik et al, 2014).

3.4 SDSS experience in Turkey

Following the severe earthquake that affected urban areas of Marmara Region of Turkey in 1999, there have been a lot of comprehensive studies undertaken of earthquake risk and loss assessment using; ELER tool, for rapid earthquake estimation of shaking and losses all through the Euro-Mediterranean region (Erdik et al, 2010; Hancılar et al, 2010); HAZTURK software, developed based on MAEviz to visualize earthquake risk and its likely destruction to structures and people (Karaman et al, 2008a) and other studies for seismic risk assessments in Istanbul (Atakan et al, 2002; Ansal et al, 2009; Sahin et al, 2016).



4. MULTI-CRITERIA DECISION ANALYSIS (MCDA)

4.1 Background

A geographic information system (GIS) is a computer system that allows the collection, storage, manipulation, visualization and analysis of spatial data and interpretation of relationships and trends. Since the 1960s, computer-based GIS systems and technologies have been utilized, evolving into three extensive application areas. The first, being the use of GIS as a *database* of information for acquisition, coordination and accessing geographic data. Secondly, more recently, GIS has been used as an *analytical* tool, characterised by modelling or logical and mathematical relationships among spatial data such as map layers to generate new derivative information and maps. Building on these two applications of GIS, a newer application has emerged in its use as a *decision support system* (providing a means of assisting in decision-making from analysis outputs) in multi-criteria decision analysis (MCDA) methods, through the integration of GIS and MCDA (Eastman, 1995; Tisza, 2014). The underlying motivation for integrating GIS and MCDA emanates from the need to make capabilities of GIS more relevant for planning and decision-making (Sugumaran and DeGroote, 2011). GIS as a technology itself, is not well adapted for the acquisition, storage, processing, analysis and visualization of data and information, vital for complex decision making such as value judgements, preferences, conflicting criteria, attitudes, opinions, etc. MCDA methods assist in minimizing the disagreements over values among conflicting decision-makers and other parties of interest (Feick and Hall, 1999; Jankowski and Nyerges, 2001).

MCDA is a collection of approaches and techniques for solving decisions or evaluating complex problems having many, conflicting goals and criteria (Voogd, 1982; Zeleny, 1982). GIS-MCDA or GIS-based MCDA, at a principle level, is a set of techniques and procedures that transforms and combines geographic data (input or criterion maps) and decision-maker's preferences (criterion weights) into an overall value for each decision/evaluation alternative or decision/output map. This implies that analysis

results do not only depend on the geographical distribution of the alternatives but also on the value judgements incorporated in the process of decision-making (Qin, 2013; Malczewski and Rinner, 2015).

The MCDA approach: enhances the limitations of GIS for decision-making, guides decision-makers through a vital process of clarifying evaluation criteria (attributes and/or objectives), defines values relevant to the decision environment and aids decision-makers in understanding outputs of GIS-based decision-making processes. This includes trade-offs among policy objectives and use of the results in a systematic and structured way for developing policy recommendations. This approach further helps to develop a more constructive, creative, rational, unbiased and justifiable procedure to decision problems rather than merely identifying the 'best' solution (Bell et al, 2003; Nyerges and Jankowski, 2010; Malczewski and Rinner, 2015). MCDA is well-structured to accomodate a cooperative planning and decision-making environment allowing participation of multiple experts and stakeholders. Furthermore, MCDA results can handle varied data sets, both quantitative and qualitative, as well as data through expert opinion (Mendoza and Martins, 2006).

The integration of GIS capabilities and MCDA approaches provides support to decision-makers throughout the phases of the decision-making process namely, intelligence, design and choice. This integration is necessary in overcoming decision-making difficulties resulting from consideration of lots of factors, extent of the inter-relationships and spatial patterns among them and complexity of the decision problem that may exceed the decision-makers' cognitive abilities (Malczewski, 1999).

The integration of GIS and MCDA can be achieved at three (3) levels, *weak coupling*, *tight coupling* and *full integration*. *Weak coupling* involves use of specific software or tools for the varied analysis steps and communication between these tools which can at times be complex, is handled manually. Despite the advantage of this procedure having low cost of development, consideration of the spatial relationships between alternatives during MCDA evaluation steps are ignored due to the definite separation existing between these steps, and the risks of errors is high as a result of human intervention in data transfer. Technical differences also exist in the case where developed interfaces are unable to link different systems and automate data transfer processes resulting from inter-operability issues. *Tight coupling* incorporates connection between the two systems, GIS and MCDA, under a single interface where

one field (usually MCDA) is implemented as a module or script within GIS, which is used as a base. In ESRI ArcGIS software, this is achieved by using the *weighted overlay* tool. Visualization of criteria maps can be done having pre-set weights determined by the user's preferences, which are manually entered. This integration though achieving a much better communication between GIS and MCDA systems, still has some drawbacks relating to flexibility and interactivity. The most ideal system is a *fully integrated* GIS-MCDA that should offer spatial analysis and multi-criteria functionalities allowing the user direct access at any time during analysis. Directly on a map, the user is able to visualize different spatial elements of problems resulting from interactions with different processes and parameter modifications (Mendoza and Martins, 2006).

4.2 Framework for GIS-Based MCDA

GIS-based MCDA, used interchangeably with the term, *spatial multicriteria analysis (SMCA)*, differs from conventional MCDA due to the inclusion of an explicit geographic component. That is, both data on criterion values and geographic location of alternatives is needed for GIS-based MCDA, which are processed to acquire decision-making information. GIS-based MCDA can be viewed as a process that combines and transforms geographical data (input) into a resultant decision (output), as shown in Figure 4.1. This process is defined by the relationship between input maps and output map using MCDA procedures or decision rules that involve geographic data utilization, preferences of decision-makers and data manipulation in conformity to the specified decision rules (Malczewski, 1999).

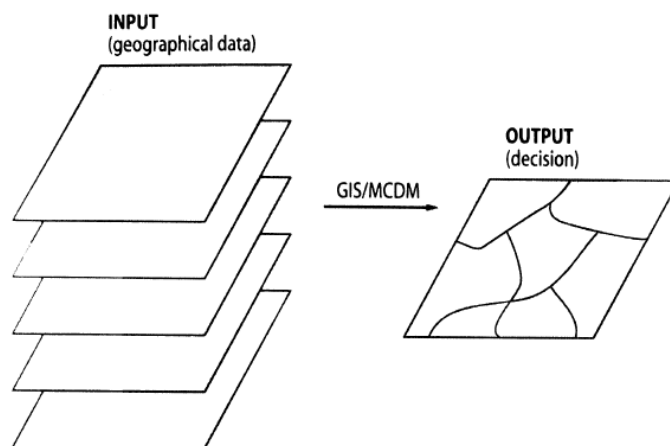


Figure 4.1 : GIS-based MCDA: input – output perspective (Malczewski, 1999).

Within the sequence of activities related to the GIS-MCDA, the framework for GIS-MCDA incorporates seven (7) elements namely: evaluation problem, evaluation criteria, alternatives, criteria weights, decision rules, sensitivity analysis and outcomes (recommendations for action) (Malczewski, 1999). Their relationships are as depicted in Figure 4.2.

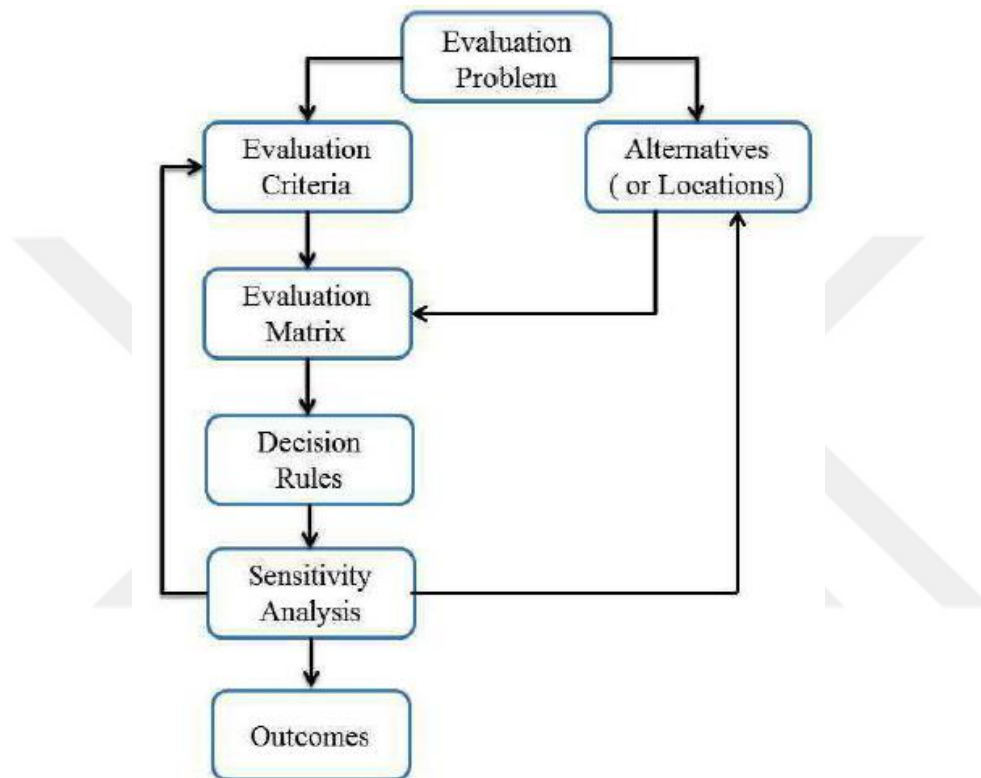


Figure 4.2 : Framework for GIS-based MCDA (Malczewski, 1999; Qin, 2013).

Recognition and definition of the *evaluation (or decision problem)* is the starting point of any GIS-MCDA. At this phase, GIS assists in storage, management and analysis of data so as to better address the problems. Once the decision problem is identified, selection and establishment of a set of relevant *evaluation criteria* follows, which are associated with geographic entities and entity relationships thereby able to be represented in form of maps known as *criterion (or attribute) maps* or *data layers* in a GIS. An *evaluation criteria map* represents unique geographical attribute of alternative decisions used for performance evaluation of the alternatives (locations or areas).

The third step involves identification of the *alternatives (or locations)*, where each alternative is linked with a set of evaluation criteria based on the value structure. The

fourth step comprises *criterion weighting*, incorporating decision maker's preferences with respect to the evaluation criteria into the decision model. The weights express the importance levels of each criterion relative to other evaluation criteria under consideration. The derivation of criterion weights is vital to the determination of decision-maker's preferences and their incorporation into the judgement analysis. The evaluation criteria, alternatives and criteria weights (input data) can be principally structured as an *evaluation (or decision) matrix*.

Selection of the *decision rules*, combines results of the preceding three steps so that ultimately, the one-dimensional measurements (geographic data layers) and judgements (preferences and uncertainty) are integrated to obtain the ordering and overall assessment of the alternatives. This is achieved by selection and use of a suitable *decision rule* or *aggregation function*. A *decision rule* dictates how this integration takes place, how best to rank (or order) alternatives or decide which of these alternatives is preferred over another depending on their performances, eventually yielding from the best decision selection, a final decision taken known as *outcome* or *decision* or *criterion outcome*. In this study, AHP and TOPSIS techniques are used as decision rules for integrating criterion maps and related criterion weights.

After obtaining a ranking of alternatives, *sensitivity analysis* should be performed to test the robustness. Sensitivity analysis is a procedure for determining how the recommended action is affected by changes in the inputs of the analysis, i.e. identifying how changes in inputs (geographical data and the decision maker's preference) affect the outputs (ranking of alternatives). The ranking is considered robust if variations to the input data marginally affects the output. If the present result is discovered not to be satisfactory, information about the output may be used to return to the step of problem formulation. The sensitivity analysis can be perceived as an exploratory process where decision-makers obtain a deeper understanding of the problem structure. This assists to learn how the evaluation criteria, criteria weights and other decision elements interact to determine the most preferred outcome and which of these elements can be important sources of disagreements among decision-makers or stakeholders. The final step depicts the *analysis (or evaluation) outcomes* whose results can be communicated using visualization techniques such as maps, graphs, etc (Malczewski, 1999; Qin, 2013).

4.3 MCDA Methods

There are two (2) general categories of MCDA namely, multi-attribute decision analysis (MADA) and multi-objective decision analysis (MODA) whose distinction is made based on the classification of evaluation criteria into attributes and objectives (Malczewski, 1999; Malczewski, 2006). The principal differences that exist between MADA and MODA are the model principles (data vs mathematical oriented) and alternative options/plans (user-defined vs model generated). Problems associated with MADA are assumed to have a preset, finite number of alternatives and whose solution is approached more, through a selection process as opposed to a design process. MODA problems are regarded as continuous since the optimal solution can be anywhere within the locality of viable results from an infinite set of alternatives. Thus, the terms *discrete* and *continuous* decision problems, are occasionally used to refer to MADA and MODA problems, respectively (Hwang and Yoon, 1981; Malczewski, 2004; Malczewski, 2006). Mostly used GIS-MCDA are shown in Figure 4.3. In this study, MADA methods of aggregation and ideal point models are used.

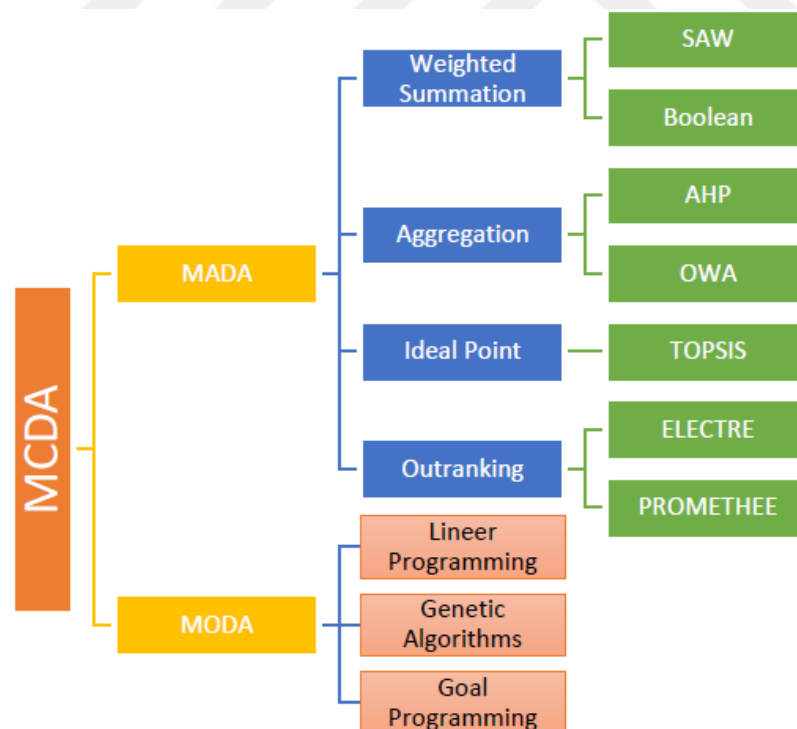


Figure 4.3 : Classification of MCDA methods (Malczewski, 2006).

There are numerous MCDA methods but only two (2) main groups will be considered in this study. These are the techniques using *aggregation* – Analytical Hierarchy Process (AHP) developed by Saaty (1980) and the other method using *ideal point* known as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) developed by Hwang and Yoon (1981). These techniques are explained in more detail in the following sections.

4.3.1 AHP

4.3.1.1 Introduction

Analytical Hierarchical Process (AHP) is one of the most commonly used and popular techniques since the inception of MCDA methods, applied to solve wide range of decision problems requiring consideration of large number and variety of criteria so as to acquire most optimum and viable results and outcome through a systematic evaluation procedure from available alternatives. The decision problem in AHP is broken down into a hierarchical form of sub-problems and criteria more easily understandable so they can be separately analysed and through systematic evaluation of elements and assignment of weights, comparisons are made, selecting the most feasible alternative as the best solution. AHP is nowadays, extensively applied in business, social, industrial, operational, management and research areas, stimulating growing interest especially with integration of GIS within the research community spanning fields of environmental, transportation and urban planning, agriculture, forestry, waste management, hydrology, geology/geomorphology, natural hazard and risk management. In this study, AHP is selected to determine the factor weights of the influencing parameters in an earthquake hazard scenario and integrated with GIS for simulating results of AHP on a spatial environment, generating an earthquake hazard map (EHM).

4.3.1.2 Development of AHP

AHP emerged around the mid-1970s when it was first developed by Prof. Thomas L. Saaty, and later from the 1980s and 1990s, its increasing applications in wide research areas and its effectiveness in complex decision making led more MCDA users into opting to using AHP techniques, which allows consideration of both objective and subjective factors in ranking and selection of decision alternatives. Being one of the

most widely used tools, many decision-makers and researchers have successfully applied AHP in different fields that include planning, business, management, engineering fields, site and selection of optimal alternatives, resource allocations, forecasting, conflict resolution, optimization, public policy decisions, environment and health care (Vaidya and Kumar, 2006; Bhushan and Rai, 2004). Additionally, the central reason for the popularity of AHP for mapping hazard risks and its elements is its straightforward implementation within a GIS environment allowing for users to quickly derive weights associated with criteria map layers. Availability of software packages that have incorporated AHP (pairwise comparison) approach into GIS has also led to the popularity use of AHP (Malczewski and Rinner, 2015). Further, AHP's flexibility enables it to be integrated with other different techniques (such as linear programming, fuzzy logic, etc.), allowing the user to maximize the full benefits from combined approaches thereby better achieving the desired goal and it can also be used as a consensus building tool especially in emergency management circumstances that involve group decision-making or multiple stakeholders (Vaidya and Kumar, 2006; Malczewski, 2004; Malczewski, 2006). Therefore, this study employed the use of AHP technique.

4.3.1.3 Basic principles

AHP technique assists in structuring complex problems, measurements and synthesizes rankings whose model structure can then be modified easily and applied to any decision-making problem with provision of basic mathematical tools for criteria evaluation. Criteria can be converted easily to numerical values even though they are subjective (Bhushan and Rai, 2004).

The AHP approach involves first breaking down the decision problem into a hierarchy of sub-problems, easily comprehensible and that can be subjectively evaluated. Conversion of the subjective evaluations into numerical values and their subsequent processing to rank each alternative on a numerical scale is done (Bhushan and Rai, 2004). Systematic evaluation of the various elements in the built hierarchy structure is accomplished by comparison of the elements to one another, two at a time, by *pairwise comparison*. This approach greatly reduces the conceptual complexity of the decision-making analysis in AHP (Saaty, 1980). The *pairwise comparison* is the proportional

assessment of the dominance of a component over another with respect to the pairwise comparison scale (Table 4.1).

Table 4.1 : Pairwise comparison scale for AHP criterion evaluation (Saaty, 1980).

Intensity of importance	Definition
1	Equal importance
2	Weak or slight
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, very strong
9	Extreme importance
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i

The procedures and methodology of AHP for any decision problem can be described in four (4) general steps and can be summarized by process flowchart in Figure 4.4.

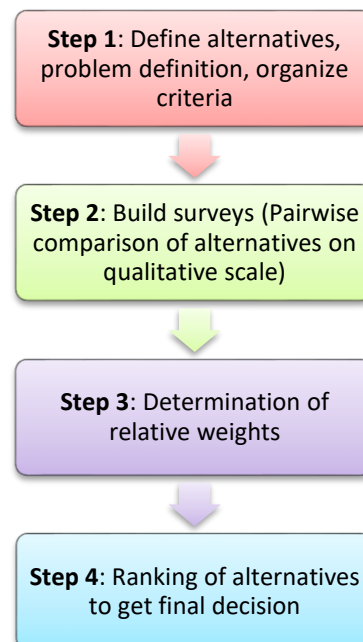


Figure 4.4 : AHP process flow chart.

Step 1, begins with stating and definition of the decision problem and identification and determination of the goal, main and sub-criteria and alternatives, that influence the behavior. The decision problem is structured and decomposed into a hierarchy of goals, criteria, sub-criteria and alternatives. The relationships and impact of criteria and alternatives on each other can easily be observed and interpreted once the hierarchy structure is constructed. Figure 4.5 illustrates the goal, hierarchy structured into the main criteria (C_n) and sub-criteria that have an effect on the result and choice in the presence of alternatives (L_n).

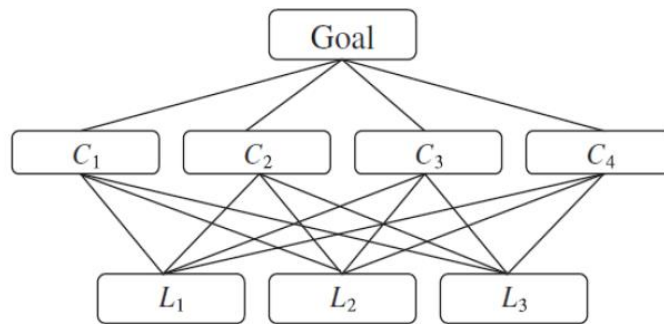


Figure 4.5 : Illustration of hierarchy structured into criteria and sub-criteria and alternatives (Malczewski, 2006).

Step 2, involves *pairwise comparison* on a qualitative scale where data is collected from decision-makers, experts or stakeholders corresponding to the hierarchical structure, resulting in development of a pairwise comparison matrix. Usually, experts are given a questionnaire from which preferences and opinions are obtained that represent each criterion in comparison to others. Criteria is evaluated, as a rule, based on range of values, from 1 to 9, as shown in Table 4.1 (Bushan and Rai, 2004; Aitzhanov, 2016). Scores 1,3,5,7,9 are regarded as levels of main evaluation while scores, 2,4,6,8 may also be used to express comparison with more precision.

Each of the elements in the matrix is compared with another at a higher level in pairs with respect to the importance on the related subject. At each of the levels, a hierarchy is constructed by the comparisons and the outcome of this, will be a positive pairwise comparison matrix $A = a_{ij}$ as shown in equation 4.1, created by the decision-maker, that has reciprocal elements of comparisons for all $a_{ji} = 1/a_{ij}$, and for $i, j = 1, 2, \dots, n$ (Harker, 1989).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (4.1)$$

Step 3, involves computation of the relative weights for each element of the hierarchy. After the pairwise comparison matrices are formed, the weight vector, $W = [w_1, w_2, \dots, w_n]^T$, is calculated, referred to as the Saaty's eigenvector procedure. This is achieved via two (2) procedures. First, by normalization of the pairwise comparison matrix using the given formula in equation 4.2.

$$a_{ij}^* = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}, \text{ for all } j = 1, 2, \dots, n \quad (4.2)$$

The second procedure is *calculation of the weights* by formula, in equation 4.3.

$$w_i = \frac{\sum_{j=1}^n a_{ij}^*}{n}, \quad \text{for all } i = 1, 2, \dots, n \quad (4.3)$$

There exists a relationship between the vector weights, w , and the pairwise comparison matrix, A , as noted by Saaty (1980), and this is defined in the following equation 4.4.

$$Aw = \lambda_{max} w \quad (4.4)$$

The *consistency index (CI)*, which provides a measure or estimate of the departure from consistency of the judgements is given by equation 4.5.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4.5)$$

Where λ_{max} is the maximum eigenvalue of the pairwise comparison matrix, and n is the order of the matrix. Comparisons made by AHP are subjective and the inconsistency is tolerated through the redundancy amount in the approach (Bhushan and Rai, 2004).

To complete the calculation procedures, using equation 4.5 above, the *consistency ratio (CR)* is computed using equation 4.6 below, where the *random index (RI)* is obtained from the consistency index of a randomly generated pairwise comparison matrix (Saaty, 1980).

$$CR = \frac{CI}{RI} \quad (4.6)$$

The RI, is the consistency index of a randomly generated pairwise comparison matrix and whose value increases with the number of elements being compared, i.e., increases with increasing number of elements being compared (Malczewski, 1999). The values of RI from matrices of order 1–10 can be found from Saaty's (1980) work in a standard table (Table 4.2) using random generated matrices for each size of matrix, n (Harker, 1989).

Table 4.2 : Random Inconsistency Index (Saaty, 1980).

n	1	2	3	4	5	6	7	8	9	10
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

At each hierarchy level, there is too, a control process for the pairwise comparisons. If $CR < 0.10$, the ratio indicates an acceptable level of consistency in the pairwise comparisons. If $CR \geq 0.10$, the ratio values are reflective of inconsistent judgements and in such cases, the user should re-examine the original values in the pairwise comparison matrix, A and repeat the procedure. By use of equation 4.7 below, the measure of the pairwise comparisons of all the individuals involved in the decision process are combined by taking the geometric means of all (Saaty, 1980; Malczewski, 1999).

$$a_{ij}^{hp} = \sqrt[q]{\prod_{q=1}^Q a_{ij}^q} \quad (4.7)$$

where a_{ij}^q is an element of matrix A of an individual q ($q = 1, 2, \dots, Q$), and a_{ij}^{hp} is *geometric mean* of all individuals a_{ij}^q . The *group CR* is calculated according to equations 4.5 and 4.6.

Step 4, finally, is the aggregation of the relative weights of the decision elements by multiplying them successively from down to the beginning of the hierarchy. This is done to ascertain the best alternatives/strategies.

In summary, AHP is built around three (3) main concepts: the AHP is *analytic* – key strength of AHP being the mathematical and logical reasoning approach for decision-

making; *structuring problem as a hierarchy* – where complex problems are reduced into sub-problems to be handled individually more easily and; its *definition of a process for decision-making* – where a methodical approach is well defined that incorporates all inputs, learnings, revisions, from decision-makers and stakeholders to arrive at a collective decision rationally (Bhushan and Rai, 2004).

4.3.1.4 Application areas

As earlier highlighted, the AHP has been successfully applied in many wide ranging decision and management problem domains spanning across different disciplines and research areas that include project planning, marketing, healthcare, defence, social sciences, economic forecasting, new product pricing, policy evaluation, energy, research and development, manufacturing, etc. In addition to being applied successfully in all these areas, AHP has developed as a widely accepted approach and methodology for decision-making and as a technique, evolved over the years to be applied in conjunction with other mathematical modelling, and analysis techniques (Bhushan and Rai, 2004) such as GIS and other decision support systems.

AHP has been applied widely in various applications spanning across areas such as marketing (Davies, 2001), energy policy (Kim and Min, 2004), resource allocation (Cheng and Li, 2001), suitability analysis (Banai-Kashani, 1989), site selection for fire services (Erden and Coskun, 2010), environmental impact assessment (Ramanathan, 2001) and risk analysis (Millet and Wedley, 2002).

Related applications of AHP have been found in disaster and emergency management through studies done by Rashed and Weeks (2003). Other works include generation of earthquake hazard zonation map by Pal et al. (2007) in India, landslide susceptibility in Greece by Ladas et al. (2007), earthquake investigations triggering multiple landslides in Pakistan and India by Kamp et al. (2008). Landslide risk index map was produced by Abella and Westen (2007) for Cuba, Lin (2008) conducted post-earthquake landslide studies, Anbazhagan et al. (2010) calculated hazard index for seismic hazards and produced seismic microzonation maps, Vahidnia et al. (2009) conducted landslide susceptibility zonation. Ganapathy (2011) used AHP for microzonation mapping in India. Erden and Karaman (2012) too, used AHP with GIS for generating earthquake hazard mapping for Küçükçekmece region of Istanbul. By providing decision-makers with the opportunity to organize the criteria and alternative

outcomes of a decision problem in a hierarchical structure, AHP aids in the decision-making process (Erden and Karaman, 2012). For this reason, AHP was considered in this study.

4.3.2 TOPSIS

4.3.2.1 Introduction

TOPSIS technique was originally developed by Hwang and Yoon (1981) and is extensively applied in many varied decision making problems. This technique is based on the concept that the definition of the best alternative is one that should, simultaneously, be closest to (have the shortest euclidean distance from) the *positive ideal solution* (PIS) and farthest away from the *negative ideal solution* (NIS). By means of the closeness index, the final ranking is acquired (Sánchez-Lozano et al, 2013).

The central elements to consider in this approach are that: the benefit of any index must increase or decrease uniformly so that the best value of index will depict the positive ideal and the worst value will characterize the negative ideal solutions; and the distance or separation measure of an alternative from a positive or negative ideal may be computed using the euclidean distance (from the 2nd power) or sum of absolute value structure from linear distances (Asghar and Mohammad, 2008; Sarvar et al, 2011).

The ideal solution is determined by a hypothetical alternative for which all criterion values match with maximum criterion values in the database constituting the satisfactory solutions whereas, the negative ideal solution is one for which all criterion values are associated with attainable minimum criteria values (Pirdavani et al, 2009; Dharmarajan and Sharmila, 2016).

In usage, TOPSIS has been applied successfully to solve various decision making problems that include selection and evaluation problems with a finite number of alternatives essentially due to its intuitiveness, ease of understanding and implementation. Further, TOPIS has been proved to be one of the best techniques in resolving rank reversal issues and has a robust logical approach that expresses the basis of human preference. In this study, the extension and use of TOPSIS for disaster and emergency management problems has arisen in a large part from the following reasons

and advantages: a robust logic that guides and represents rationale of human choices; a scalar value that characterizes both the best and worst alternatives, simultaneously; is a simple computational process easily programmable and integrated in other decision support systems such as GIS; and the performance measures of all alternatives on attributes can be visualized in a GIS environment (Dharmarajan and Sharmila, 2016). A lot of studies are prevalent in literature applying TOPSIS for resolving MCDA problems (Chen, 2000; Chu and Lin, 2002; Wang and Lee, 2009; Boran et al, 2009).

4.3.2.2 Basic principles

The principal procedures of the TOPSIS technique for the selection of the best alternative from among those available involves seven (7) steps: establishing a decision matrix, normalization of the decision matrix, obtaining weighted normalized decision matrix, determining positive and negative ideal solutions (PIS and NIS), computation of separation measures from PIS and NIS, relative closeness to ideal solution and aggregation operations for ranking of alternatives. The main TOPSIS procedure described is as shown in flow chart in Figure 4.6.

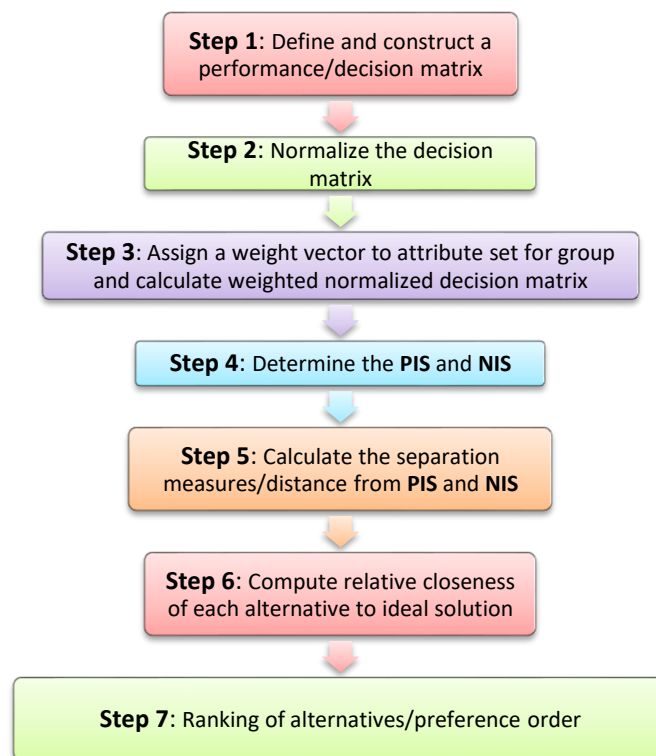


Figure 4.6 : TOPSIS process flow chart.

The procedures and methodology of TOPSIS are as described.

Step 1: Construction of the decision/performance matrix of a set of alternatives on a given criteria set. This matrix consists of alternatives A_i (for $i = 1, 2, \dots, n$), criteria C_j (for $j = 1, 2, \dots, m$), and measures of performance X_{ij} (for $i = 1, 2, \dots, m; j = 1, 2, \dots, n$) or rating of the alternatives with respect to the criteria or intersection of each alternative and criteria. The outcome of this task by the decision maker is to find the best alternative and/or to rank the whole set of alternatives (Rao, 2007). This therefore results in a matrix, $(X_{ij})_{m \times n}$, whose structure is expressed in equation 4.8.

$$D = \begin{matrix} & \begin{matrix} C_1 & C_2 & \dots & C_n \end{matrix} \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} & \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \end{matrix} \quad (4.8)$$

Step 2: Normalization of all the elements in the decision matrix to the same dimensionless units is done, so that all possible criteria in the decision problem can be considered by using equation 4.9 (Saaty, 1980; Rao, 2007).

$$r = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}, i = 1, 2, \dots, m; j = 1, 2, \dots, n \quad (4.9)$$

Step 3: Calculate the weighted normalized decision matrix. The weighted normalized value, V_{ij} computed by equation 4.10.

$$v_{ij} = w_j r_{ij}, i = 1, 2, \dots, m, j = 1, 2, \dots, n \quad (4.10)$$

where, W_j is the weight of the j^{th} criterion or attribute and $\sum_{j=1}^n w_j = 1$.

Step 4: Determine the positive ideal (best) and negative ideal (worst) solutions calculated from equations 4.11 and 4.12.

Positive ideal solution:

$$A^* = \{v_1^*, \dots, v_n^*\}, \quad v^* = \{\max(v_{ij}), j \in J; \min(v_{ij}), j \in J'\} \quad (4.11)$$

Negative ideal solution:

$$A^- = \{v_1', \dots, v_n'\}, \quad v' = \{\min(v_{ij}), j \in J; \max(v_{ij}), j \in J'\} \quad (4.12)$$

where J and J' denote the subsets of beneficial and non-beneficial criteria, respectively. V_j^* reflects the positive ideal (best) value from among the values of considered criteria for various alternatives. For beneficial criteria situation (i.e., those for which greater values are desired for given application), V_j^* shows the higher criterion value while for non-beneficial criteria (i.e., criteria for which lower values are desired for the given application), V_j^* indicates lower criterion value.

V_j' indicates the negative ideal (worst) value from among the considered criterion values for different alternatives. For the beneficial criteria case (i.e., criteria whose higher values are desirable for the given application), V_j' reflects the lower criterion value while for non-beneficial criteria situation (i.e., those of which lower values are desired for given application), V_j' shows the higher criterion values (Rao, 2007).

Step 5: Calculating the separation measure (distance) for each alternative from the positive and negative ideal solution by the Euclidean distance in equations 4.13 and 4.14.

The separation from the positive ideal alternative is given by:

$$S_i^* = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^*)^2}, \quad i = 1, \dots, m \quad (4.13)$$

The separation from the negative ideal alternative is given by:

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j')^2}, \quad i = 1, \dots, m \quad (4.14)$$

Step 6: Compute the relative closeness to the ideal solution, C_i^* . The relative closeness of the alternative A_i with respect to A^* is given by equation 4.15.

$$C_i^* = S_i' / (S_i^* + S_i^-), \quad 0 < C_i^* < 1 \quad (4.15)$$

C_i^* is a value between 0 and 1. The option with C_i^* closest to 1 is closer to the ideal solution and therefore should be selected (Malczewski, 1999).

Step 7: Rank the alternatives by order of preference from the most preferred to the least preferred feasible solutions. This is done by arranging the alternatives in descending order of C_i^* . The larger the index value indicates a good performance of the alternative implying that the best alternative is the one with value of C_i^* closest to 1 (greatest relative closeness to the ideal solution) (Malczewski, 1999; Pirdavani et al, 2009; Dharmarajan and Sharmila, 2016).

4.3.2.3 Application areas

TOPSIS approaches have been applied in several domains that include waste management (Carver, 1991), environmental planning (Pereira and Duckstein, 1993), water resources (Tkach and Simonovic, 1997), agriculture (Salt and Dunsmore, 2000), urban and regional planning (Sante-Riveira et al, 2011), manufacturing analysis (Wang and He, 2008), aeronautical industry (Wang and Chang, 2007), financial performance measurement for highway bus industry (Feng and Wang, 2001), purchasing and outsourcing (Kahraman et al, 2009)

Selected literature from related works for disaster and emergency management highlight the application studies of TOPSIS such as in engineering risk assessment (Wang and Elhag, 2006), oil spill accident response investigations (Krohling and Campanharo, 2011), drought monitoring (Roshan et al, 2016), identification of natural hazards and urban area classification (Najafabadi et al, 2016), flood vulnerability assessment (Ozturk and Batuk, 2011).

In review of the effective utilization of TOPSIS in a wide range of applications and in disaster and emergency management studies, TOPSIS was considered for use in this study.

5. CASE STUDY: KÜÇÜKÇEKMECE REGION, ISTANBUL

This section is focused on the case study of Küçükçekmece region in Istanbul, Turkey for the implementation of GIS-based MCDA methods of AHP and TOPSIS to determine earthquake hazard monitoring criteria as input into generation of earthquake hazard maps (EHMs) simulated on a GIS environment. The AHP technique is used to determine the weights of the parameters that have influence on earthquake effects, which are used as input for EHM production. These weights from AHP are then used as further input into the TOPSIS technique for subsequent generation of an EHM map for vulnerability and hazard risk assessment. The resulting map outputs from the two methods are then compared, analysed and discussed.

5.1 Study Area

Turkey is situated within the Mediterranean portion of the Alpine-Himalayan orogenic system that extends from Europe to Asia, identified with high ranges of mountains and shallow, more or less uniform zones of seismicity, making it one of the most seismically active regions in the world as can be observed from Figure 5.1. To this effect, Turkey has a long and well-documented record of earthquake events (Erdik et al, 1985; Smyth et al, 2004).

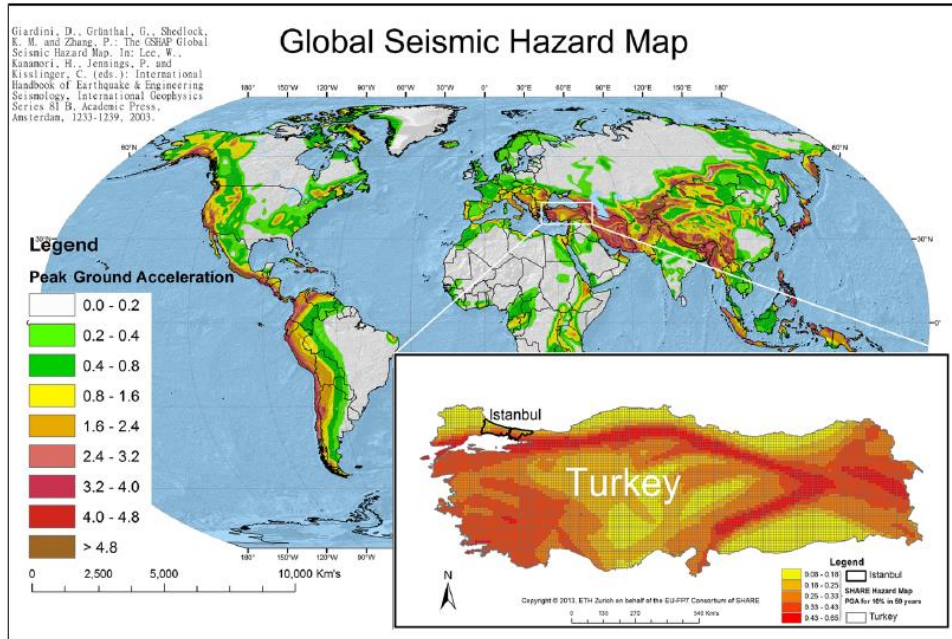


Figure 5.1 : Global seismic hazard map and study area location (Giardini et al, 2003).

Istanbul is the largest and most urbanized city, in Turkey with regard to population, industry, and infrastructure. Regrettably, it is also one of the most seismically active cities in Turkey. According to Parsons (2004), the probability of a $M \geq 7$ earthquake rupturing beneath the Marmara Sea at the southern part of Istanbul is approximately 35-70% within the next 30 years. This has caused anxiety and roused communities, citizens and researchers into undertaking safeguards and precautions against likely earthquake occurrences. Extensive technical and scientific studies have been conducted in the region and all commend that the preparedness of Istanbul against earthquakes must be in accordance with the mitigation, response and recovery activities based on the DEM cycle (Karaman and Erden, 2014).

This study focuses on generation of EHMs for the Küçükçekmece region in Istanbul, extending over an area of approximately, 36 km² (Figure 5.2), which are required for thorough hazard mapping and vulnerability risk/loss assessment as part of DEM.

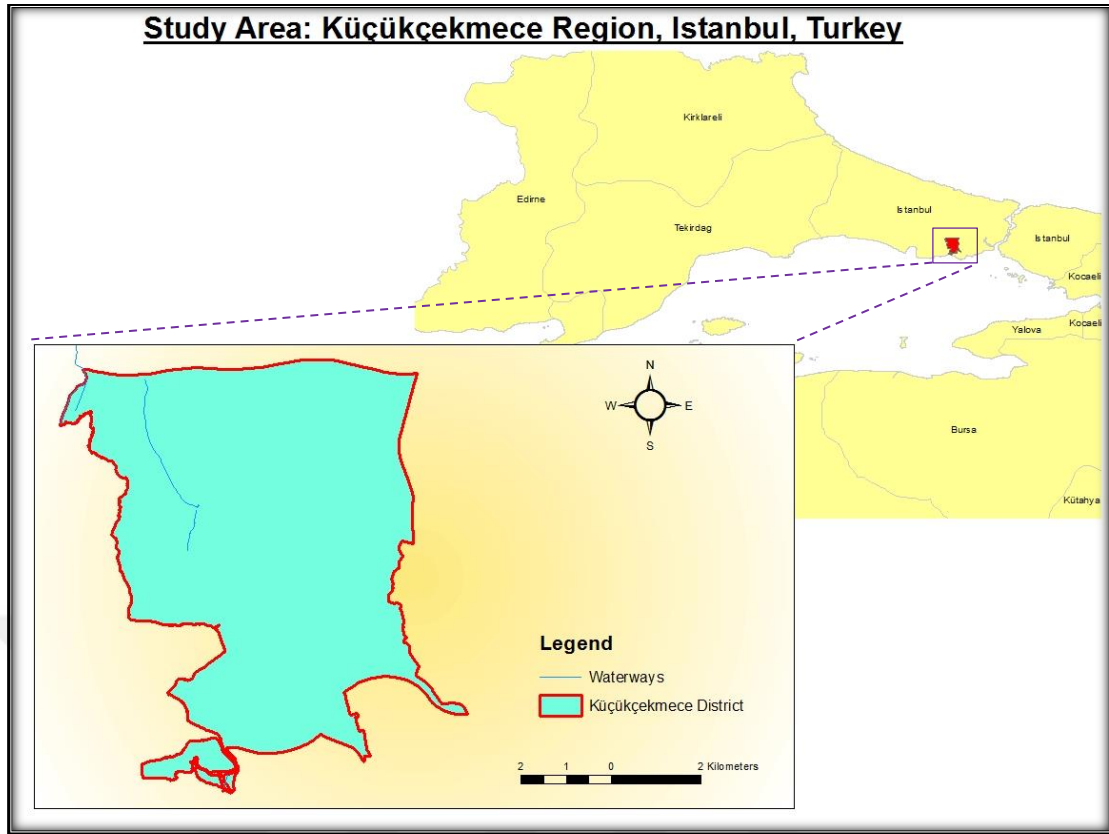


Figure 5.2 : Study area: Küçükçekmece region in Istanbul, Turkey.

5.2 Framework for the Study

The proposed approach in the generation of earthquake hazard maps (EHMs) for hazard and risk assessment is based on the two (2) MCDA methods of AHP and TOPSIS, integrated with GIS. The spatially referenced data as map layer (evaluation criterion) inputs into a GIS (ESRI ArcGIS 10.3) are combined and processed into resultant hazard maps as outputs using both AHP and TOPSIS techniques. These resultant hazard maps are then compared and analysed.

The approach involves the procedures highlighted in Figure 5.3. The first step is identification of the evaluation criteria that include determination of the parameters that influence the effects of earthquakes to be simulated on a GIS environment. These criteria in form of input map layers are then standardized and appropriate factor weights assigned based on experts' opinions and preferences using the pairwise comparison technique of the AHP model. By use of a spatial GIS model (generated using the ModelBuilder tool of the ArcGIS 10.3 Software), these attained weights for

each of the criteria (map input layers) are combined using the spatial analyst tool's *weighted sum* function after relevant classifications are done for all the criteria generating the resultant earthquake hazard map.

The GIS-based TOPSIS approach utilizes the determined weights obtained from AHP method as input. Within the ArcGIS 10.3 software, again by a created spatial GIS model (using *ModelBuilder* tool) the raw input criterion (attribute) map layers are first standardized and normalized so as to attain non-dimensional attribute values (between 0 and 1) for comparison (comparable units). The corresponding weights from AHP are then applied to each of the criteria by multiplying each value of the standardized layer by the corresponding weight to obtain a weighted standardized map layer (weighted decision matrix). Identification of the **Positive Ideal Solution (PIS)** (determined from the maximum value for each of the weighted standardized layers) and the **Negative Ideal Solution (NIS)** (determined from the minimum value for each of the weighted standardized layers) is done from which the separation measures/distances from the PIS and NIS for each of the criteria is determined.

The relative closeness to the ideal point for each criteria is computed and then the ranking of the preference order is done by arranging the alternatives in descending order through a classification process using the Spatial Analyst tool's *Reclassify* function, to generate the resulting earthquake hazard map. The principle ArcGIS operations applied in this procedure include *raster to vector* and *vector to raster* conversions, spatial analyst tool's *overlay - weighted sum* function, for applying weights and combining layers, map algebra tool's *math* and *raster calculator* functions and *algebra expressions* for performing the required TOPSIS algorithms.

The results of each of the generated earthquake hazard maps (EHMs) from both AHP and TOPSIS are compared and analyzed.

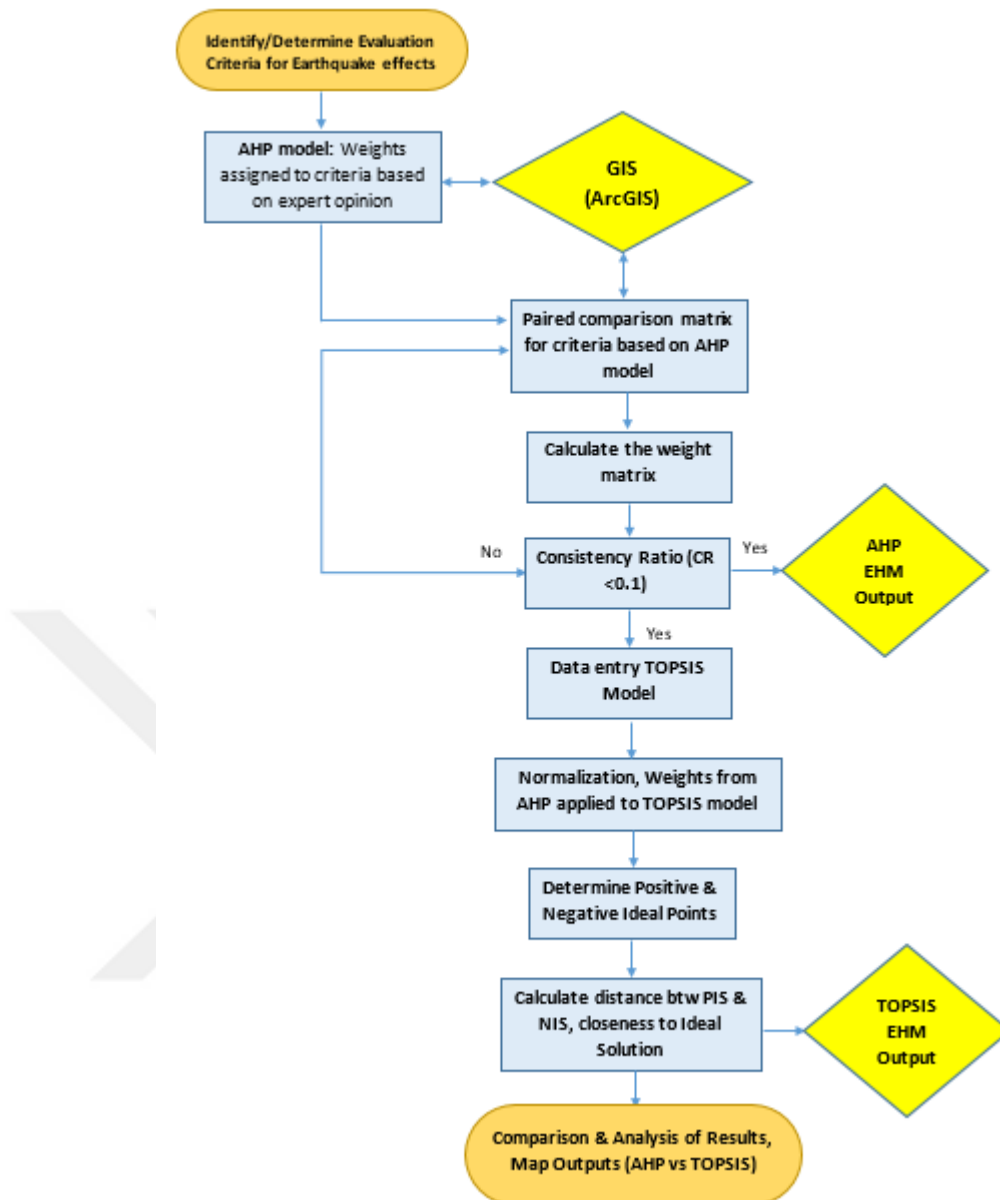


Figure 5.3 : Framework for the study.

5.3 Criteria Selection for Earthquake Hazard Mapping

Within the context of earthquake disasters, a hazard is characterized as an input ground motion parameter of an anticipated earthquake for the affected region. The other components of seismic loss assessment, besides hazard (exposure) are vulnerability (sensitivity), inventory (value) and integrated visualization (losses). When evaluating physical and economic impacts, translating damage resulting from disaster into loss of

value, integrated visualization is a vital framework that utilizes hazard, vulnerability and inventory components (Karaman et al, 2008a).

For earthquake hazards, information about the attenuation models, earthquake scenario, soil classification, fault/focal mechanism, liquefaction potential and topography of area are required. These main parameters have significant influence on the impact and resultant effects of earthquakes on a study area and are thus broadly used as input for the attenuation models (Karaman and Erden, 2014). Attenuation model/relation or ground motion model is used to simulate the earthquake effects over a particular region and is described by seismologists as a mathematical expression relating specific strong motion parameter of ground shaking to one or more seismological earthquake parameters. The source of the earthquake, distance of wave propagation from source and site, fault type, soil and geological profile underneath the site and local site condition type, quantitatively describe these seismological parameters (Lee et al, 2002; Karaman et al, 2008a). Therefore, the criteria for this study were selected based on those required in attenuation relations. As there are over 300 attenuation relations worldwide applicable to particular regions, the most general form of the attenuation relation is structured as given in equation 5.1 (Boore and Atkinson, 2008).

$$\ln Y = F_M (M) + F_D(R_{JB}, M) + F_S (V_{s30}, R_{JB}, M) + \varepsilon \sigma_T \quad (5.1)$$

where, (ln) represents the natural logarithm, Y, is the strong motion parameter of interest, F_M , F_D , and F_S , represent the magnitude scaling, distance function, and site amplification, respectively, while M is the moment magnitude, R_{JB} is the Joyner–Boore distance (nearest distance to the surface projection of the fault, which is almost equal to the distance to the epicentre distance for events of $M_w < 6$), and V_{s30} is the inverse of the time averaged shear-wave slowness from the surface to a depth of 30m, $\varepsilon \sigma_T$ is a random error expression (Boore and Atkinson, 2008).

From this equation, we can derive the five (5) basic criteria determined for earthquake hazard map generation which are magnitude and faulting type, soil type and source-to-site distance and use of two extra criteria of liquefaction potential and field topography, for a more realistic strong ground motion simulation in alignment with

the next-generation attenuation models (NGA) (Atkinson and Boore, 2007; Campbell and Bozorgnia, 2007) and new codes such as Eurocode 8 (CEN, 2004).

The map layers representing these criteria were obtained from relevant authorities that included the Istanbul Municipality. The map layers were visualized using ArcGIS 10.3 software by classifying them into four (4) class representations for this study with reference to scientific codes and assumptions in conformity to the cartographic presentation rules of visualization of having less than seven (7) tone values (Schoppmeyer, 1978). This classification is done to assist decision-makers to quickly understand the situation and geographic distribution by a mere glance of the resulting hazard maps where class value of 4 represented major/highest risk cell areas while class value of 1 represented no/lowest risk cell areas (Karaman and Erden, 2014). Both manual and natural breaks (jenks) methods were used in this study for classifying the map layer data. The value ranges of the criteria/parameters and their matching class values were as depicted in Table 5.1.

Table 5.1 : Criteria class value ranges, corresponding class values and their hazard risk levels, adapted from (Erden and Karaman, 2012).

Criteria	Class Values			
	1	2	3	4
	No/Low Risk	→→→→	→→→→	Major Risk
1 FT (field topography) [<i>degrees</i>]	0-10	10-15	15-30	>30
2 DS (source-to-site distance) [<i>km</i>]	22.21-19.80	19.80-17.38	17.38-14.97	14.97-12.55
3 SC (soil classification) [<i>m/s</i>]	800-760	760-360	360-180	180-50
4 LP (liquefaction potential)	104-103	103-102	102-101	101
5 FM (fault/focal mechanism)	0.45-0.53	0.53-0.61	0.61-0.68	0.68-0.76

All the processes involved in the GIS data manipulation and analysis leading to the final production of the resulting hazard map outputs were carried out by using the ArcGIS 10.3 software *ModelBuilder* application. This allowed the structuring of an automated GIS for both AHP and TOPSIS approaches.

The following included the main spatial analyses in ArcGIS 10.3 software that were performed on the five (5) criteria map layer inputs: map data conversions (*raster to vector* and vice versa), *extract by mask* for boundary study region delineation, *near distance analysis*, *field calculator*, *raster calculator*, *overlay – weighted sum* for aggregation of map layers and application of weights, and reclassification into the 4

class values using the natural breaks (jenks), resulting in the final AHP and TOPSIS earthquake hazard maps.

5.3.1 Field topography (FT)

In earthquake hazards, the effect of topography is a vital factor that amplifies seismic energy, especially in highly seismic areas that are densely populated. The topography of the site has an amplification effect on the earthquake ground motion with respect to the height and slope angle (Erden and Karaman, 2012; Karaman and Erden, 2014). Further information can be obtained from the Eurocode 8 standards, part 5 (CEN, 2004).

5.3.2 Source-to-site distance (DS)

Earthquake effects attenuate (diminish) as the distance from the epicentre (source) of earthquake increases. Conversely, the effects of earthquakes increase as the distance from the source to the site of varied locations at region of interest reduces. Therefore, the effect of distance with regard to the magnitude of earthquake is a very important factor for simulation of the resulting hazard map. The source-to-site distance criteria was modelled by classifying the distance into 4 classes and involved several processes within ArcGIS environment.

5.3.3 Soil classification (SC)

Model of how a site behaves in the event of an earthquake can be determined by the strength of the soil and geological conditions, hence the type of soil. For example, if a site has hard soil (rocky), the ground shaking effects of an earthquake is less than at site with softer soil. The classifications of soil were aggregated by using detailed soil maps of the study region obtained from the Istanbul Municipality. These soil maps were based on the classification scheme of the National Earthquake Hazards Reduction Program, U.S. (NEHRP) (2004). The soil classes were determined using the shear velocity values (in m/s) at 30 metres in classification, where soil properties are detected for every metre for up to 30 metres depth beneath the ground surface. For higher velocities in hard soils, the ground shaking intensity is felt less and transfer rate is faster and vice versa for soft soils, where the velocities and transfer rates are slower, resulting in ground shaking effects being felt more.

5.3.4 Liquefaction potential (LP)

The liquefaction potential index (LPI) is relevant for spatial analysis of liquefaction hazard (Erden and Karaman, 2012) related to presence of water beneath the soil and site surface influencing earthquake effects.

5.3.5 Fault/focal mechanism (FM)

Through an attenuation law, according to Ambraseys (1995) and Boore (1997), the level of hazard at a particular site can be acquired by an assessment of the effects of the seismic source zone, described by its geometry and relationship of recurrence.

During an earthquake occurrence, the resulting rupture (or break) involves just a portion of the fault (defined as the resulting fracture of the Earth's crust, Elnashai and Di Sarno, 2008). The 'focus' or 'hypocentre' is the point under the surface at which an earthquake originates and the intersection point of the projection of the focus to the surface of the Earth, is known as the 'epicentre' (Erden and Karaman, 2012; Karaman and Erden, 2014) as illustrated in Figure 5.4.

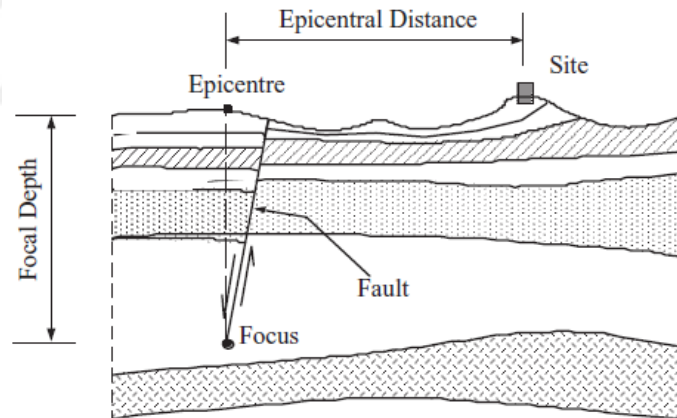


Figure 5.4 : Definition of earthquake source parameters (Elnashai and Di Sarno, 2008).

The definition of the fault/focal geometry of earthquakes is characterized by the positions and orientation of the foot and hanging wall. The focal mechanism of an earthquake is thus described by the three angles: strike (or azimuth), dip and rake (or slip) (Stein and Wyssession, 2003) and can be visualized and determined as in Figure 5.5 (Elnashai and Di Sarno, 2008).

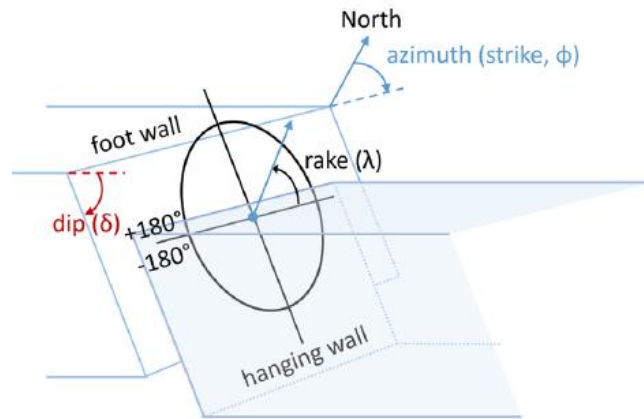


Figure 5.5 : Definition and visualization of fault/focal mechanism (Elnashai and Di Sarno, 2008).

The type of faults can be defined using these three angles. The type of fault is a very significant element in the simulation procedure of the earthquake hazard map (EHM) because it influences the occurrence and effects of the earthquake. The main fault types and associated focal parameters are shown in Table 5.2.

Table 5.2 : Basic fault types by focal parameters, adapted from (Erden and Karaman, 2012).

Fault type	Dip angle (δ°)	Rake angle (λ°)
Normal	$40 < \delta < 70$	Negative
Thrust	$10 < \delta < 40$	Positive
Strike-slip	$\delta = 90$	$0 = \text{sinistral} / 180 = \text{dextral}$
Oblique-slip	$0 < \delta < 90$	Negative = normal oblique Positive = reverse oblique

In the region of study, the fault line applied is known as the Main Marmara Fault (MMF) and is composed of various fault types. With reference to the focal parameters of the MMF, this fault line was modelled for various fault types and possible earthquake effects in ArcGIS by taking consideration of the measurements previously done on the fault itself under the Marmara Sea defining the strike, dip and rake angles in different locations. These focal parameters utilized were obtained from previous studies and measurements done for the MMF by Pulido et al. (2004), Sato et al. (2004), and Ansal et al. (2009). From all the three studies for the focal mechanism of the MMF, significant differences in the focal mechanism were shown in various locations at the

fault line. Table 5.3, depicts the line segments and point locations of the focal parameters.

Table 5.3 : MMF focal parameters (Pulido et al, 2004); Sato et al, 2004; Ansal et al, 2009).

<i>(Pulido et al. 2004)</i>							<i>(Sato et al. 2004)</i>						
FID	Segment	Long	Lat	Strike	Dip	Rake	FID	Depth	Long	Lat	Strike	Dip	Rake
1	CMB1	27.570	40.735	81.5	90	180	1	10.1	27.7213	40.8132	0	80	-10
2	CMB2	28.800	40.870	81.5	90	180	2	11.2	27.8441	40.8169	70	90	-180
3	NBF1	28.800	40.870	110	90	-135	3	7.1	28.6669	40.8362	280	90	170
4	NBF2	29.305	40.732	110	90	-135	4	10.6	28.8606	40.7832	120	50	-100
5	As1a1	28.477	40.835	81.5	90	180	5	9.6	29.1313	40.7606	0	60	-30
6	As1a2	28.800	40.870	81.5	90	180	6	6.5	29.0901	40.6297	240	50	-120
7	As1b1	28.160	40.800	81.5	90	180	7	9.3	29.0109	40.5939	190	65	-40
8	As1b2	28.477	40.835	81.5	90	180	8	5.3	29.0215	40.7201	120	40	-65
9	Asp21	28.800	40.870	110	90	-135	9	5.4	28.0273	40.7642	70	90	-180
10	Asp22	28.970	40.825	110	90	-135	<i>(Ansal et al. 2009)</i>						
							FID	Segment	Long	Lat	Strike	Dip	Rake
							1	CMBe	28.8700	40.8900	81.5	90	180
							2	CMBw	27.5900	40.8000	81.5	90	180

The geographic coordinates of the line segments and point locations and the focal parameters determined were inputted into ArcGIS and the MMF was displayed as a line feature for modelling earthquake effects for the study area as illustrated in Figure 5.6.

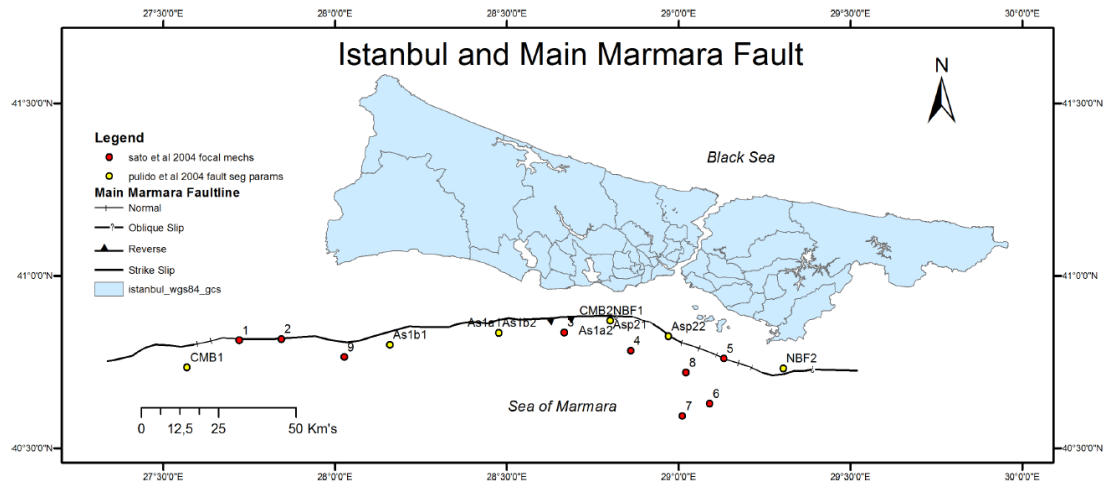


Figure 5.6 : Visualization of Main Marmara Fault (MMF) and locations of focal parameters (Erden and Karaman, 2012).

The fault mechanism effect was determined and classified based on the fault type effect model of Boore and Atkinson (2008), which is one of the most recent and comprehensive relationships to be applied for this study region and has its main benefit over other models, of incorporating parameters for each relevant type of fault in modelling the earthquake effects (Erden and Karaman, 2012).

5.4 AHP Model

5.4.1 Pairwise comparison of criteria

In this study, determination of weights to be applied to each of the five (5) criteria map reclassified layers for resulting earthquake hazard map generation, was based on the pairwise comparison technique of AHP where each of the elements/criteria was compared two at a time. The compared reclassified map layers were field topography (FT), source to site distance (DS), soil classification (SC), liquefaction potential (LP), and fault mechanism (FM).

A survey was conducted through questionnaires that were prepared and filled in by ten (10) respondents reflecting their preferences and expert opinions. These constituted people, academics and stakeholders from various disciplines such as Civil, Geomatics, Geology, and Geophysics Engineers related to the subject area of earthquake disasters and emergency management.

The sample of the questionnaire in Table 5.4 was used to determine the criteria weights of the reclassified map layer data according to the pairwise comparison scale of Saaty (1980) (Table 4.3).

The sample respondent's preference matrix and the final group judgment matrix reflecting all the respondents' preferences and opinions was arrived at using the *geometric mean* computation approach suited for aggregation of group judgments, as is shown in Table 5.5.

From the final group judgment matrix, the weights of the each of the reclassified map criteria layers were computed using the appropriate formula from earlier AHP weight calculation steps (section 4.3.1.3). The λ_{max} , CI and CR were also computed. Since the consistency ratio (CR) determined for all the pairwise comparison matrix was 0.01,

which is less than 0.1, this was indicative of consistent judgements used in the whole approach. The weights for all the five (5) map criteria layers determined is as shown in last column of Table 5.6.

Table 5.4 : Pairwise comparison questionnaire for AHP EHM (Erden and Karaman, 2012)

<i>Criteria</i>	<i>Pairwise Comparisons</i>																	<i>Criteria</i>
	Extreme	Very, very strong	Very strong	Strong plus	Strong importance	Moderate plus	Moderate importance	Weak or slight	Equal importance	Weak or slight	Moderate importance	Moderate plus	Strong importance	Strong plus	Very strong	Very, very strong	Extreme	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
field topography (FT)																		DS
																		SC
																		LP
																		FM
source to site distance (DS)																		SC
																		LP
																		FM
soil classification (SC)																		LP
																		FM
liquefaction potential (LP)																		FM
Name, Family name																		
Title																		
Discipline																		

Table 5.5 : Pairwise comparison matrix for one respondent (a) and for final group judgment (b).

<i>(a)</i>						<i>(b)</i>					
Criteria	FT	DS	SC	LP	FM	Criteria	FT	DS	SC	LP	FM
FT	1	0.17	0.25	0.33	1	FT	1	0.17	0.21	0.20	0.70
DS	6	1	3	5	7	DS	5.99	1	1.70	1.96	3.32
SC	4	0.33	1	3	4	SC	4.82	0.59	1	1.28	1.85
LP	3	0.20	0.33	1	3	LP	5.12	0.51	0.78	1	2.27
FM	1	0.14	0.25	0.33	1	FM	1.42	0.30	0.54	0.44	1
$\lambda_{\max} = 5.2$		CI = 0.04		CR=0.04 < 0.1		$\lambda_{\max} = 5.1$		CI = 0.01		CR=0.01 < 0.1	

Table 5.6 : Criteria, their class value ranges and their calculated criteria priority/weight.

Criteria	Class Values				Weights/ Priorities
	1	2	3	4	
	No/Low Risk	→→→→	→→→→	Major Risk	
1 FT (field topography) [degrees]	0-10	10-15	15-30	>30	0.06 (6%)
2 DS (source-to-site distance) [km]	22.21- 19.80	19.80- 17.38	17.38- 14.97	14.97- 12.55	0.38 (38%)
3 SC (soil classification) [m/s]	800-760	760-360	360-180	180-50	0.24 (24%)
4 LP (liquefaction potential)	104-103	103-102	102-101	101	0.22 (22%)
5 FM (fault/focal mechanism)	0.45-0.53	0.53-0.61	0.61-0.68	0.68-0.76	0.10 (10%)

5.4.2 GIS analyses

The spatial model generated for the AHP analysis was built using the *ModelBuilder* application of ArcGIS 10.3 for calculation, managing and automation of all the related processes for the map criteria layers up to the generation of the EHM.

5.4.2.1 Field topography (FT)

For the field topography (FT) criteria, an available digital elevation model (DEM) data of the study area was used as the main input to derive the amplification elements of topography. Figure 5.7 shows the slope raster map created from the available DEM data using the *surface - slope* tool from the spatial analyst toolbox.



Figure 5.7 : Slope raster map created from DEM map data.

From the DEM data, slope angles of the associated cells and the data was reclassified using the *reclassify* tool into the 4 classes (1 to 4) in accordance with the Eurocode guidelines and their corresponding value ranges as shown in Table 5.1. The field topography map layer output data is as shown in Figure 5.8.

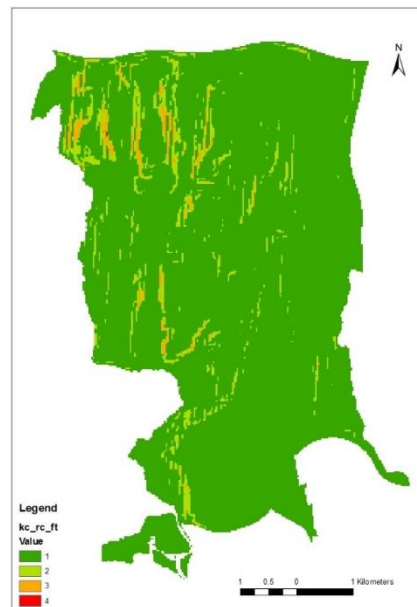


Figure 5.8 : Field topography reclassified raster map layer.

5.4.2.2 Source-to-site distance (DS)

For the source-to-site distance (DS) criteria, the objective was to create a distance distribution map of the study region from user-generated point shapefile locations of the epicentre (source) as inputs. Firstly, in order to determine the source-to-site distance values, using ArcGIS 10.3 software, a raster map file was used for defining the border for the study area. Based on the resolution of the raster map file of the study area, the value field of the raster file was converted into an integer value. Then the raster map file was converted to square gridded polygon feature consisting of rectangular polygons of pixels (using the raster to polygon tool). With higher resolution of the raster file, the number of rectangular polygons created increases. After this conversion of raster to polygon, a distance field was added to the polygon for subsequent distance calculations to be done. The next step, was to convert the rectangular polygon to point shapefiles within the rectangles so that the distance from point to raster (polygon) features could easily be computed in ArcMap, to the center of every pixel of the raster file by help of point-based shapefiles. For the distance calculation, the geographic coordinates of every point were added and the distance was computed for each point by using the geographic coordinates of the epicenter and all other points within the study region. After the distance calculations, the point-based shapefile was spatially joined with the polygon-based shapefile at the region of study (using the *feature to point* analysis tool) resulting in all the polygon-based rectangles having a unique distance value for their centers. The resulting polygon-based shapefile was then converted back to a raster map file of the study region with the associated horizontal distance values from the epicentre (source) X and Y location added to each feature at the study region (Erden and Karaman, 2012; Karaman and Erden, 2014). The resulting raster map was then finally, classified using the *reclassify* tool into the 4 classes based on Table 5.1. The output raster map of the source-to-site distance criteria map layer is as shown in Figure 5.9.

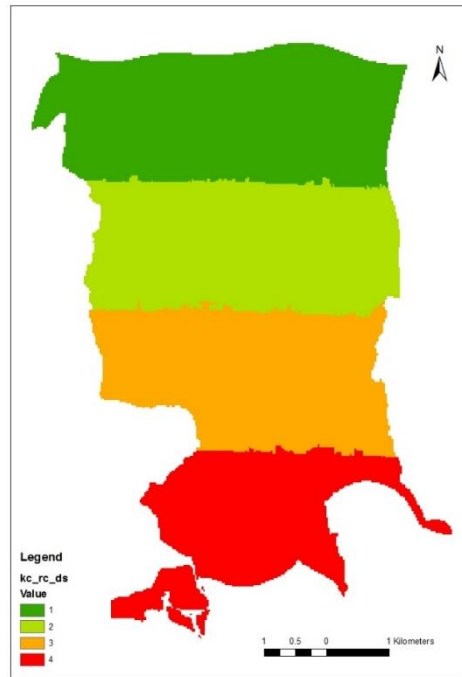


Figure 5.9 : Source-to-site distance reclassified raster map layer.

5.4.2.3 Soil classification (SC)

For the soil classification (SC) criteria, the data input into GIS was the soil map of study region in raster (polygon) file format containing the numerical values of the attribute values of the shear velocity at 30m depth. This was converted to raster map file format in ArcGIS, and reclassified using the *reclassify* tool into the associated class value ranges for each class from 1 to 4 (Table 5.1). The resulting raster map of the soil classification criteria map layer is as shown in Figure 5.10.

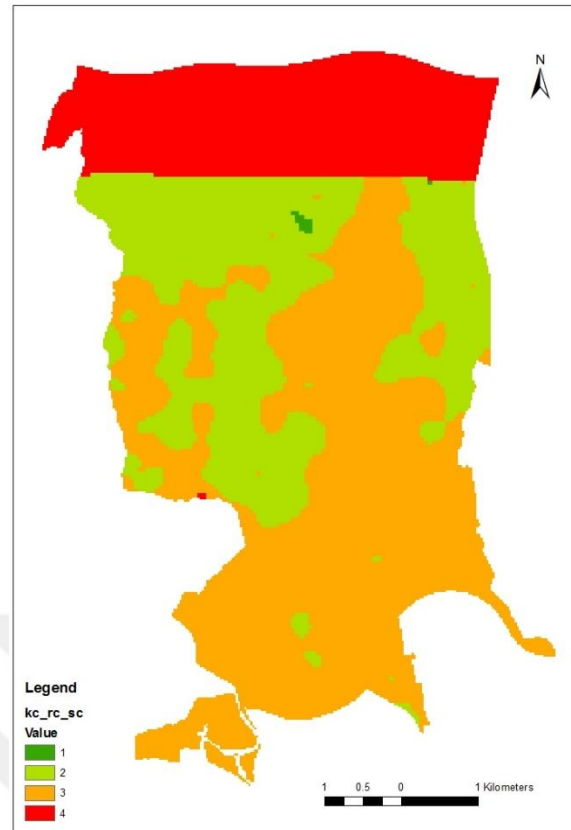


Figure 5.10 : Soil classification reclassified raster map layer.

5.4.2.4 Liquefaction potential (LP)

For the liquefaction potential (LP) criteria, the GIS data input was the liquefaction potential map for the study area which was acquired from the Istanbul Municipality Microzonation Project. This input map was directly produced as a vector map containing attribute data representing numerical values. The numerical values represented the probability of liquefaction risk, ranging from 105 for high liquefaction potential to 101 for no/low liquefaction risk (Erden and Karaman, 2012; Karaman and Erden, 2014). In ArcGIS, the vector map file was converted into raster map file format and reclassified using the *reclassify* tool into the 4 classes based on their corresponding class value ranges of Table 5.1. The output raster map of the liquefaction potential criteria is as shown in Figure 5.11.

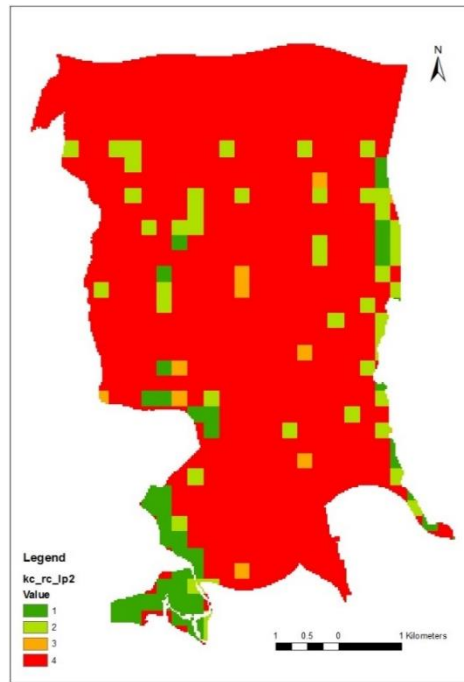


Figure 5.11 : Liquefaction potential reclassified raster map layer.

5.4.2.5 Fault mechanism (FM)

The fault mechanism effects was modelled based on the description of the focal mechanism and the source-to-site distance exponential. In ArcGIS, the fault line classification with reference to Table 5.2 was done using the previous studies of MMF as was shown previously in Table 5.3.

From Boore and Atkinson (2008), the fault mechanism effect varies as the moment magnitude of likely earthquake changes. Therefore, the moment magnitude of the earthquake scenario is also taken into account by user input into the model. The constant parameters for simulation of the fault mechanism effects are also included in the model as characterized by Boore and Atkinson (2008). As could be observed on the visualization map of the MMF in Figure 5.6, there are different types of faults in effect for the region of study and therefore, in ArcMap (ArcGIS), the *near-feature* determination tool was used to determine the nearest portions of the MMF to the region of study vector map. This resulted in the corresponding fault types being assigned to the sites at the region of study, stored as attribute table values of the vector map. The effect of the fault mechanism was modelled using the fault types in the following two procedures. The first procedure was aimed at computing the pure effect of the fault mechanism and the second step, was to acquire the effect of the fault mechanism by

distance to corresponding fault line using formula and parameters of Boore and Atkinson (2008). The combined effect was then computed by obtaining the exponential of the focal and distance aggregations. The initial input for the model was a raster map file of study region allowing the generation of a cell-based map. An integer value was obtained from the conversion of the value field of the raster map file so as to enable conversion of the raster map file to a vector map. After obtaining the integer value, the raster map file was then converted to a vector (polygon) consisting of rectangular polygons of pixels (Erden and Karaman, 2012; Karaman and Erden, 2014).

The second input for the model in ArcMap was a polyline feature representing the fault line and focal mechanism. Using the *near* tool, the closest fault lines to sites at the study area were computed with numerical values stored in attribute tables. Other parameters such as moment magnitude, and period were manually entered in attribute tables (as user input) (Karaman and Erden, 2014). The final computations of the effect of fault mechanism were finalized and the resulting vector (polygon) map was converted to a raster map file using the *polygon to raster* tool and reclassified using the natural breaks (jenks) method into the 4 class values in Table 5.1. The resulting raster map of the focal mechanism criteria is as shown in Figure 5.12.

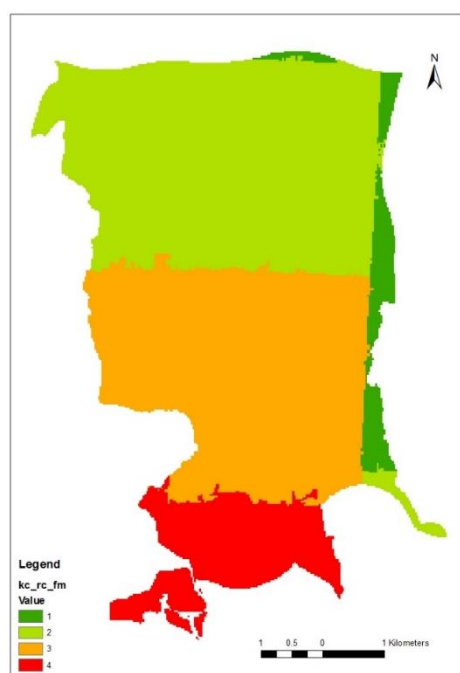


Figure 5.12 : Focal mechanism reclassified raster map layer.

All the five (5) processed and reclassified criteria map layers were subsequently used as input in AHP and TOPSIS models for final earthquake hazard map (EHM) generation.

5.4.3 AHP earthquake hazard map

The weights of the five (5) reclassified map layer derived from the AHP pairwise comparison technique were used as input into ArcGIS to be applied to all the five (5) reclassified map layers and aggregated into one map layer creating the earthquake hazard map (EHM). The spatial analyst's toolbox's *weighted sum* tool in ArcGIS was used to overlay each of the five (5) reclassified raster map layers and multiply them with each of their corresponding weights determined from the AHP pairwise comparison technique and sum the raster maps together into one output raster.

Figure 5.13 illustrates the dialog window of the *Weighted Sum* function that allowed the summing of the five (5) reclassified criteria map layers used as input rasters from the working environment and the user edit for manually inputting and applying the corresponding weights of each layer resulting into generation of a *weighted hazard output raster map* as shown in Figure 5.14.

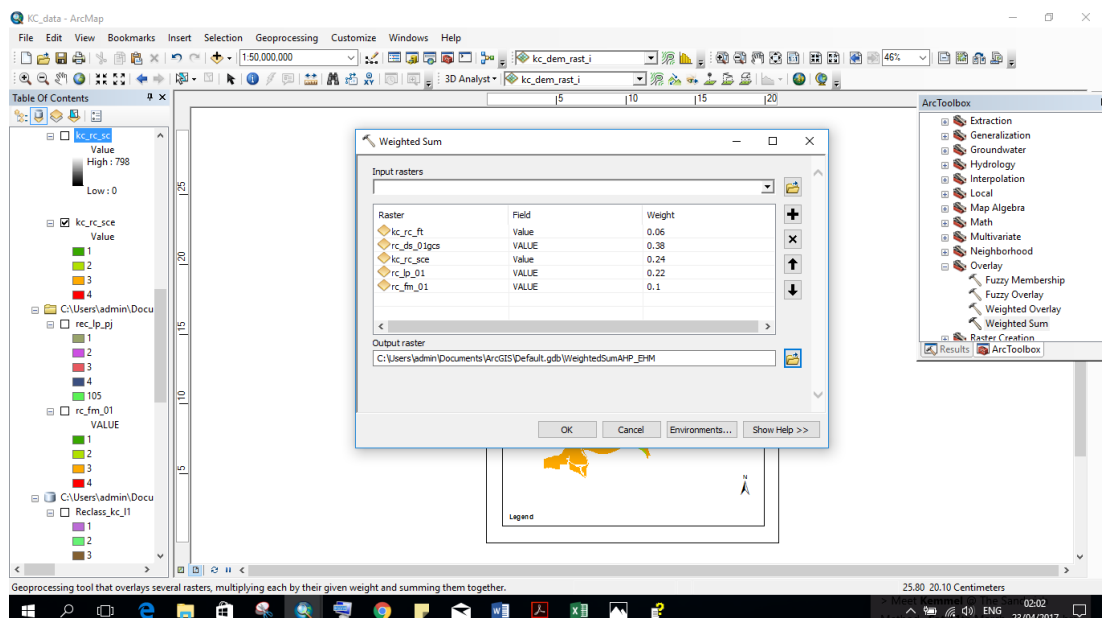


Figure 5.13 : Weighted sum tool dialog box in ArcGIS 10.3.

The *weighted sum hazard output raster map* showed the distribution of the areas at risk ranging from low to high risk as shown in Figure 5.14.

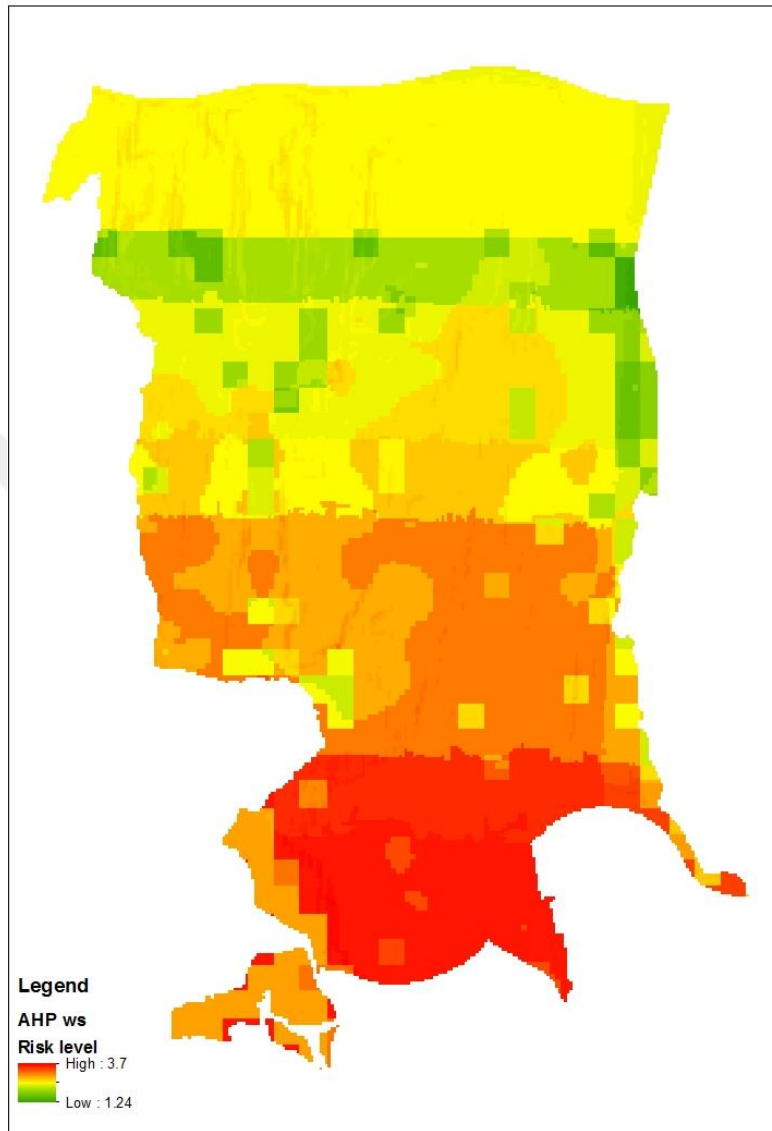


Figure 5.14 : Weighted sum hazard output raster map.

After the weighted sum analysis process, the weighted sum EHM output raster was normalized and reclassified into the 1 to 4 classification based on risk levels and class values based on Table 5.1 and the resulting AHP earthquake hazard map (EHM) was generated as in Figure 5.15.

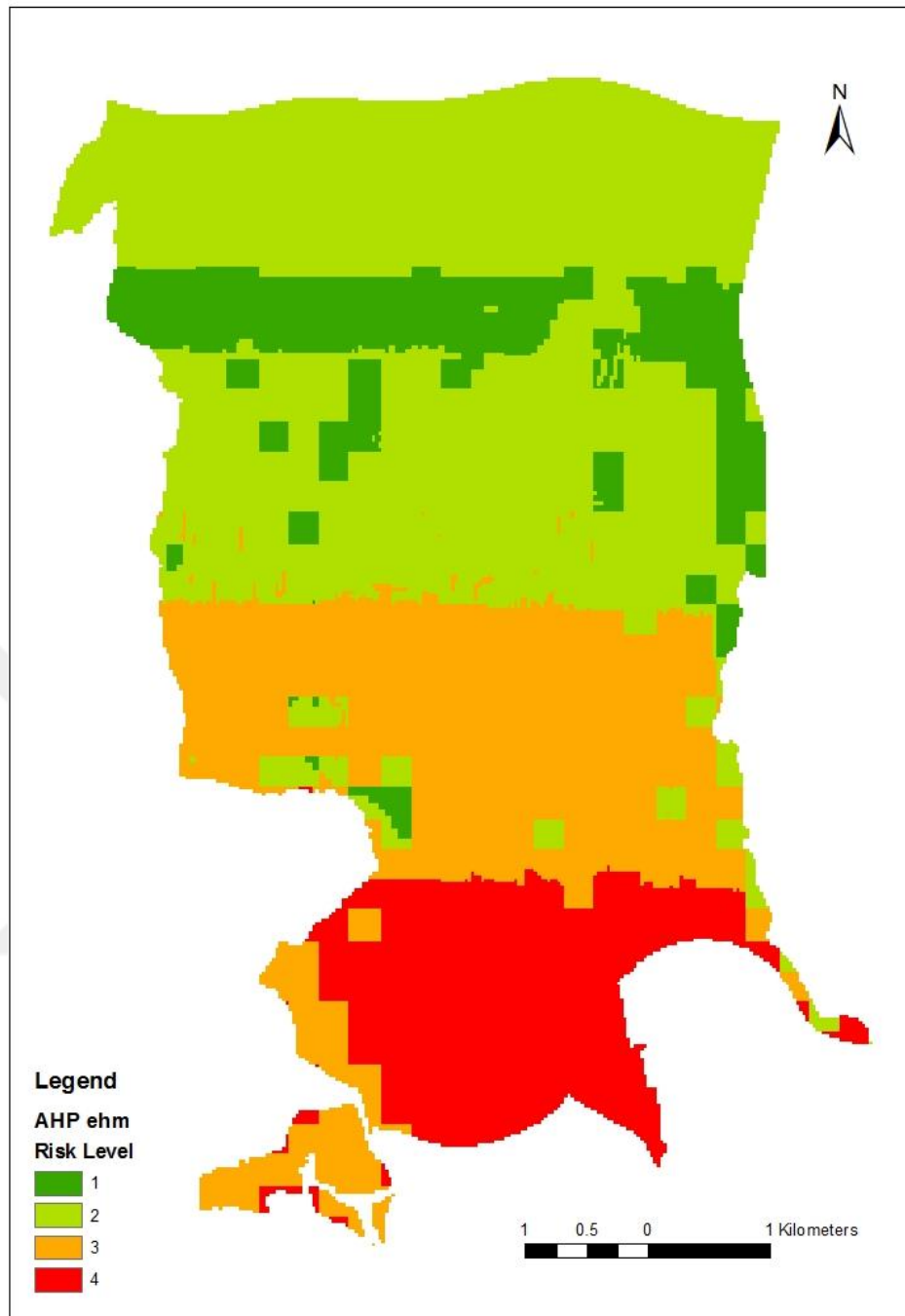


Figure 5.15 : AHP earthquake hazard map (EHM).

The AHP model created using the *ModelBuilder* application tool for all the processes and calculation steps in ArcGIS applied to all the map criteria layers is as shown in Figure 5.16.

5.5 TOPSIS Model

The TOPSIS approach begins with the creation of a TOPSIS model using the Model Builder toolbox in ArcGIS to aid in the sequencing of calculation procedures and management of spatial analysis processes involved, leading to the production of the resultant earthquake hazard map (EHM). The raw inputs into the TOPSIS model were the already defined and determined five (5) criteria map layers for earthquake hazard mapping, i.e., field topography (FT), source to site distance (DS), soil classification (SC), liquefaction potential (LP), and fault mechanism (FM).

The main calculation procedures as elaborated in section 4.3.2.2 and 5.2, involve standardization and normalization of each of the criterion map layer inputs, generating the weighted standardized map layers for each criteria map by multiplying each value of the standardized map layers with their corresponding weights obtained from the AHP pairwise technique, identifying and determining the maximum value (ideal point) and minimum value (negative ideal point) for each of the five (5) weighted standardized map layers, computing the separation measures (distances) between the ideal and negative ideal point and each of the five (5) criteria map layers, determining the relative closeness to the ideal solution and ranking of the preference order by arranging the map criteria output according to the classification values as with the AHP hazard map for comparison and analysis.

5.5.1 GIS analyses

In the model created within ArcMap (ArcGIS), each of the five (5) criteria map layers were added to the display as raw input data. All the map layers were converted from raster to vector (polygon) map file formats using the *raster to polygon* tool for easier manipulation in the subsequent processes, to be converted back to raster map file in the final processing stages. This conversion was also important as it enabled much faster processing of the map data in vector file format than in raster file formats. Before the raster map data layers could be converted to vector data, their value fields were converted into integer values by use of the *raster calculator* function. Attribute fields were then added to the map layers for accomodating the several data calculation processes to follow.

5.5.1.1 Standardization

The standardization of each of the criteria map layers was done using the *field calculator* tool by equation 4.9 entered in ArcMap as an expression, so as to transform the raw criterion values for each map layer into dimensionless value scores ranging from 0 to 1 ensuring that criteria measured on different scales was comparable. Figure 5.17 shows an example of the standardization operation and calculation performed on the soil classification criteria map layer and the resulting attribute table values.

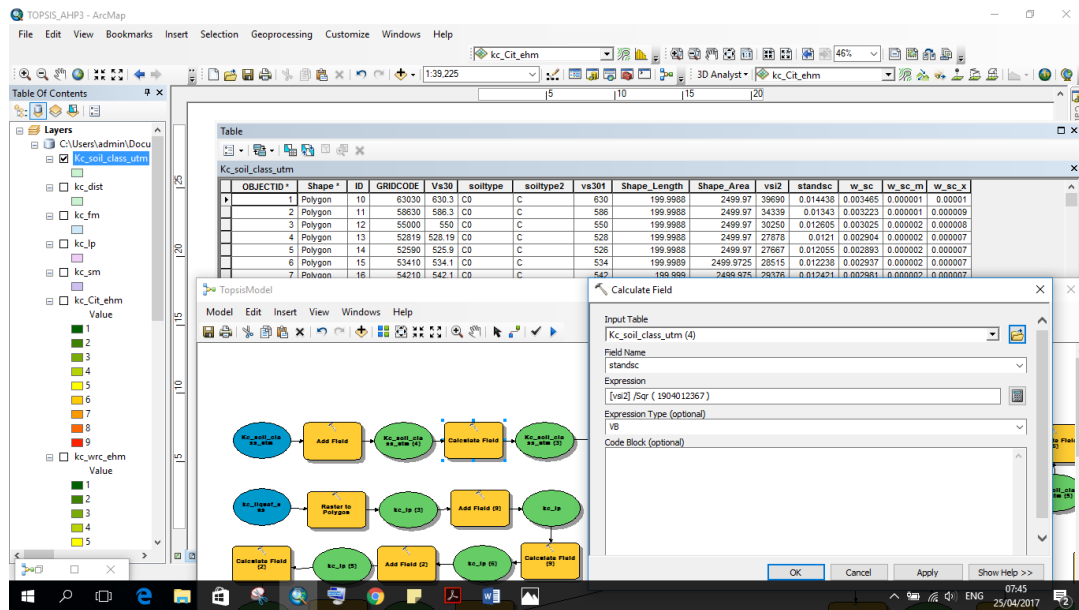


Figure 5.17 : Standardization on the soil classification criteria map layer.

5.5.1.2 Weighted standardization

The next step involved obtaining the weighted decision matrix by multiplying each value of the standardized map layers with their corresponding weights obtained from the AHP resulting in creation of weighted standardized map layers, using the *field calculator* tool in ArcMap. Figure 5.18 shows example of weighting operation performed on standardized soil classification criteria map layer.

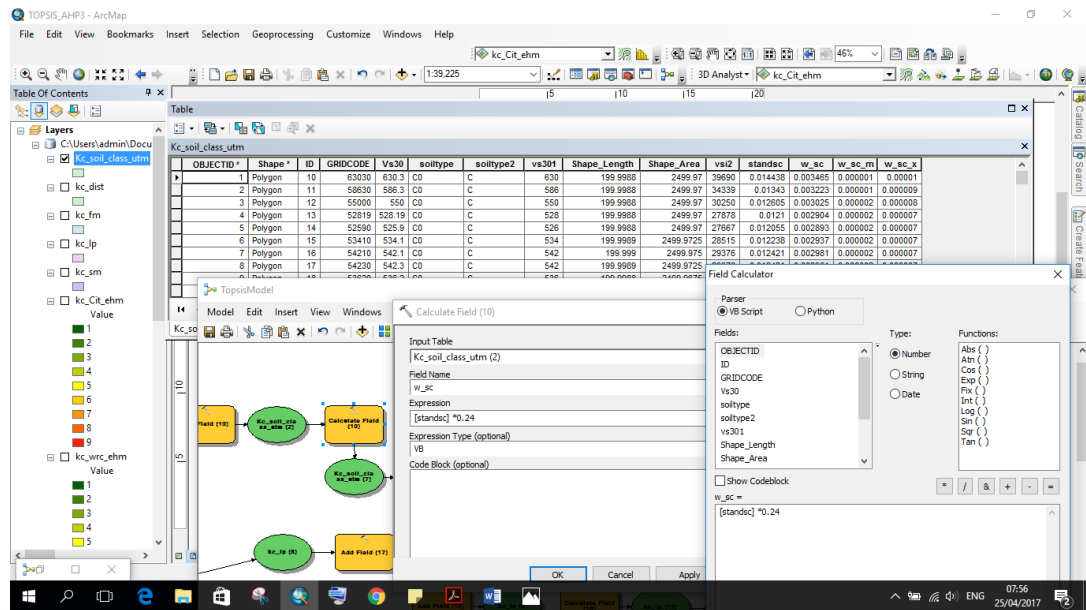


Figure 5.18 : Weighting on standardized SC criteria map layer.

5.5.1.3 Determination of PIS and NIS

The procedure that followed was the identification and determination of the positive ideal point (maximum value) and negative ideal point (minimum value) for each of the five (5) weighted standardized map layers. The determination of the PIS and NIS for each of the map criteria is different and has to be selected based on the desired objective of the study which is to map earthquake hazard risks with the focus being on identifying areas with the highest risk level or the most hazardous areas. Based on this goal, the highest risk level is the ideal point (maximum) and the lowest risk level is the negative ideal point (minimum). This definition of the desired goal can best be appreciated by use of a modified table of criteria value ranges and their corresponding PIS and NIS values as illustrated in Table 5.7. For example, the field topography (FT) map criteria layer has its highest class values associated with the PIS (maximum value) while its lowest class values correspond to the NIS (minimum value); same for fault mechanism (FM) criteria. For the soil classification (SC), the PIS (maximum value) corresponds to the lowest class values while the NIS (minimum value) is associated with the highest class values; same for the source-to-site (DS) and liquefaction potential (LP) map criteria.

Table 5.7 : Relationship of criteria class values with PIS and NIS for TOPSIS.

Criteria	NIS (Minimum)	NIS class values	VS	PIS class values	PIS (Maximum)	Weights from AHP
FT (field topography) [degrees]	0.000000	Lower		Higher	0.002034	0.06 (6%)
DS (source-to-site distance) [km]	0.003810	Higher		Lower	0.001984	0.38 (38%)
SC (soil classification) [m/s]	0.004395	Higher		Lower	0.000275	0.24 (24%)
LP (liquefaction potential)	0.022712	Higher		Lower	0.021847	0.22 (22%)
FM (fault/focal mechanism)	0.007959	Lower		Higher	0.012777	0.10 (10%)

These criteria class values from Table 5.7 reflect the general pattern of increasing or decreasing values with respect to the PIS and NIS. The actual highest or lowest class value ranges for each of the map layers is obtained from the summary statistics in their respective attribute table data and used for the subsequent calculations to determine the PIS and NIS for each of the five (5) map criteria layers using the *field calculator* tool. Figure 5.19 shows an example of summary statistics for soil classification weighted standardized criteria map layer for identifying and determining the PIS (0.000275) and NIS (0.004395) values.

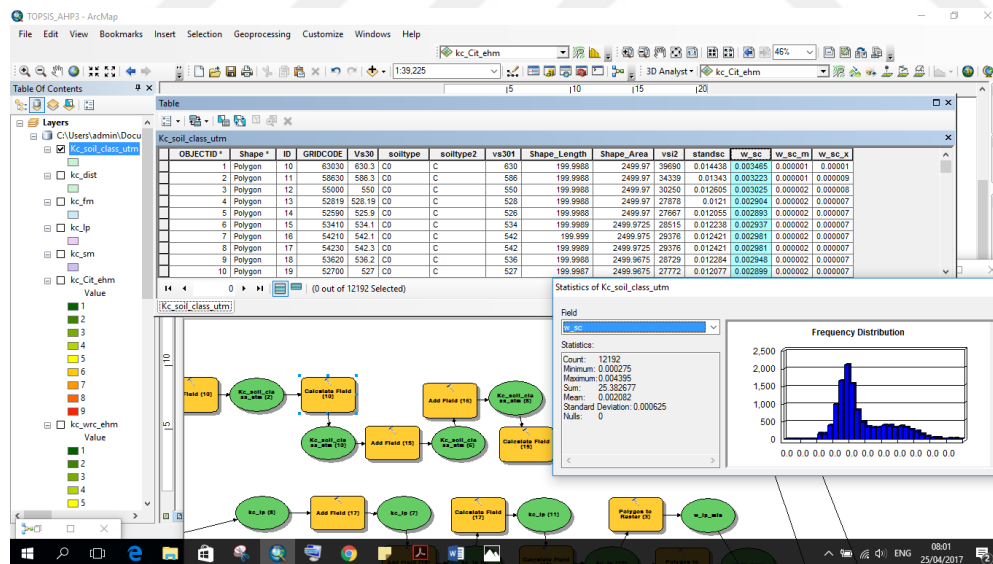


Figure 5.19 : Summary statistics for SC weighted standardized criteria map layer for identifying the PIS (0.000275) and NIS (0.004395) values.

5.5.1.4 Separation distance between PIS and NIS

The maximum and minimum values representing the PIS and NIS were determined for each of the five (5) weighted standardized criteria map layers and used for performing subsequent computations and calculations as input into the calculation of the separation measures from the ideal and the negative ideal solutions for each of the map layer inputs.

The separation measures (distances) between the PIS and NIS and each of the five (5) map criteria is achieved by summation of all the PIS determined for each map criteria layer in the previous step as well as the NIS for each criteria map layer with reference to equations 4.13 and 4.14. Figures 5.20 and 5.21, shows the separation distances operations and computations performed on the weighted soil classification criteria map layer for the PIS and NIS, respectively.

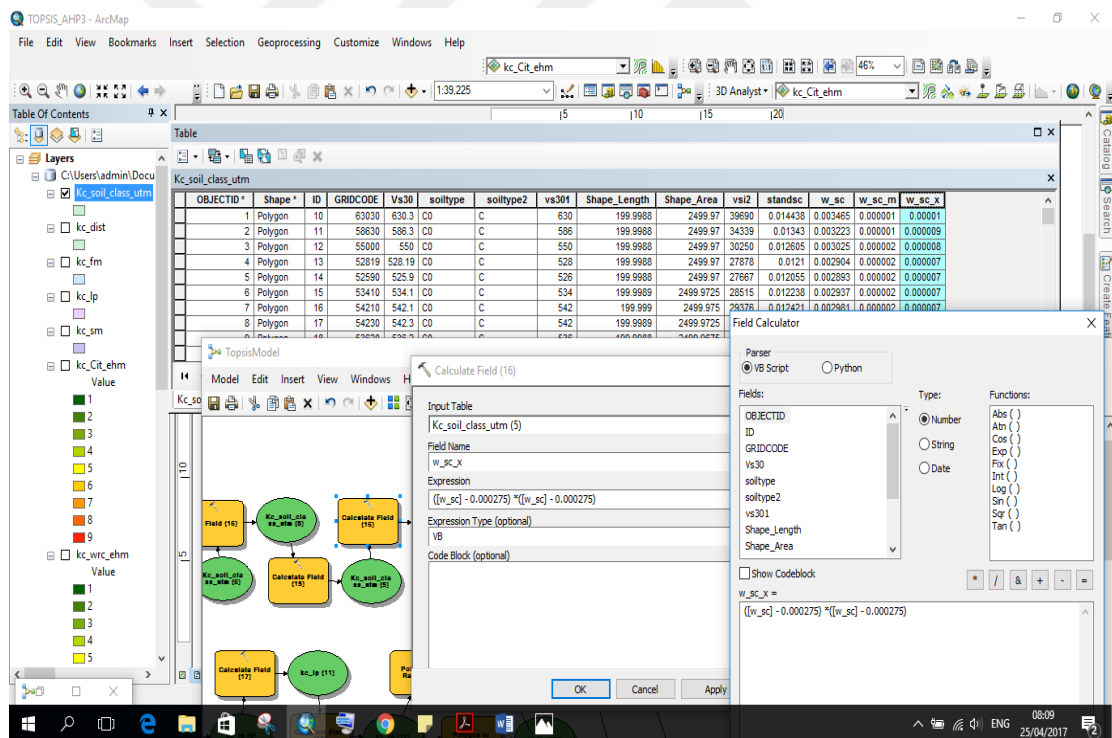


Figure 5.20 : Separation distance computation performed on the weighted soil classification criteria map layer for the PIS.

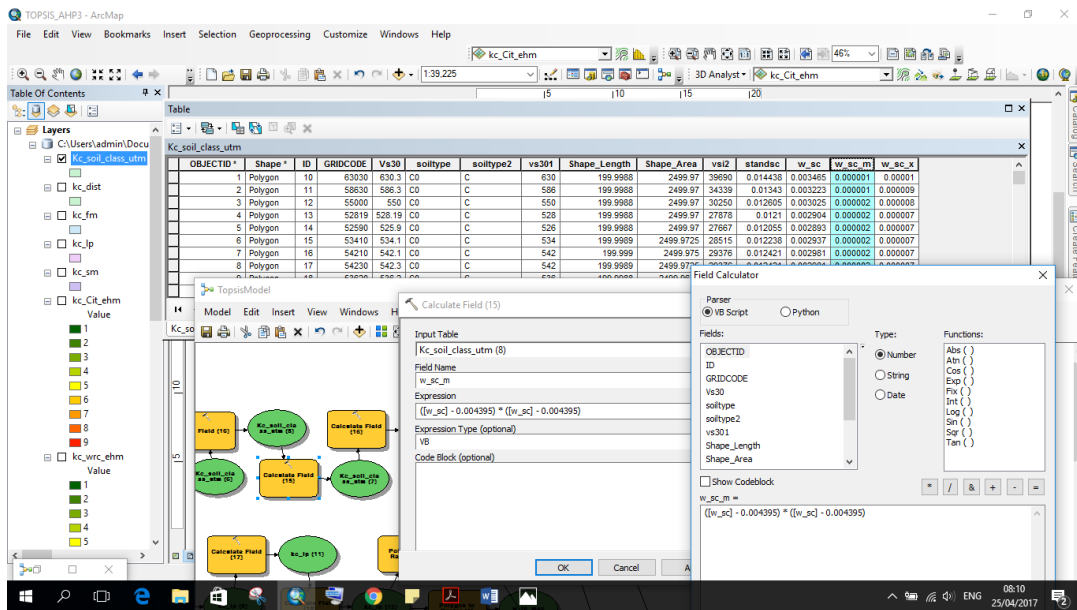


Figure 5.21 : Separation distance computation performed on the weighted soil classification criteria map layer for the NIS.

5.5.1.5 Relative closeness to ideal solution determination

Conversion of vector (polygon) to raster is done at this stage for each PIS and NIS feature layer created for each of the five (5) criteria map layer inputs using the *polygon to raster* tool. This operation results in generation of two raster map features representing the maximum and minimum from the corresponding attribute values of each of the five (5) weighted standardized criteria map layers. This results in generation of ten (10) map layers, five (5) representing the maximum (PIS) and the other five (5), minimum (NIS). Figures 5.22 and 5.23 illustrates the conversion from vector to raster and subsequent generation of two map features representing the maximum and minimum value for the soil classification weighted standardized criteria map layer.

Then combination of the raster map file for all the five (5) created PIS (maximum) raster maps and those of the other five (5) NIS (minimum) raster map files, by use of the spatial analyst's weighted sum tool was done. When applying the weighted sum analysis, the weight is assigned a value of 1 for each of the five (5) criteria representing both the 5 PIS (maximum) and 5 NIS (minimum) raster maps created as shown in Figures 5.24 and 5.25.

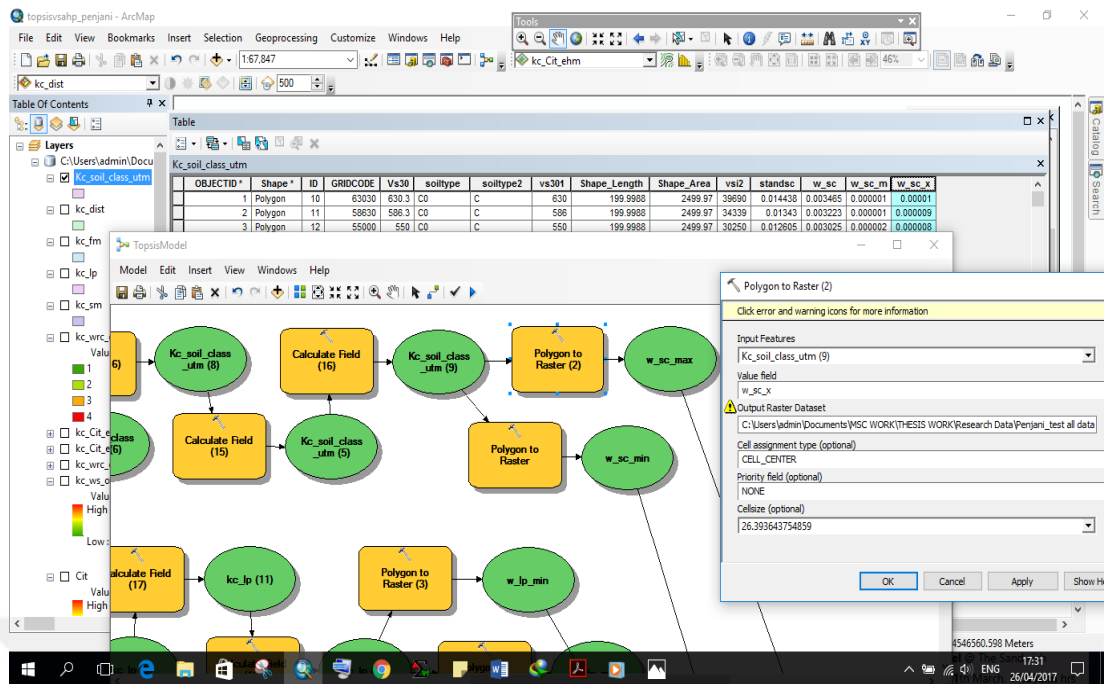


Figure 5.22 : Polygon to raster conversion resulting in creation of map feature representing the maximum value for the soil classification weighted standardized criteria map layer.

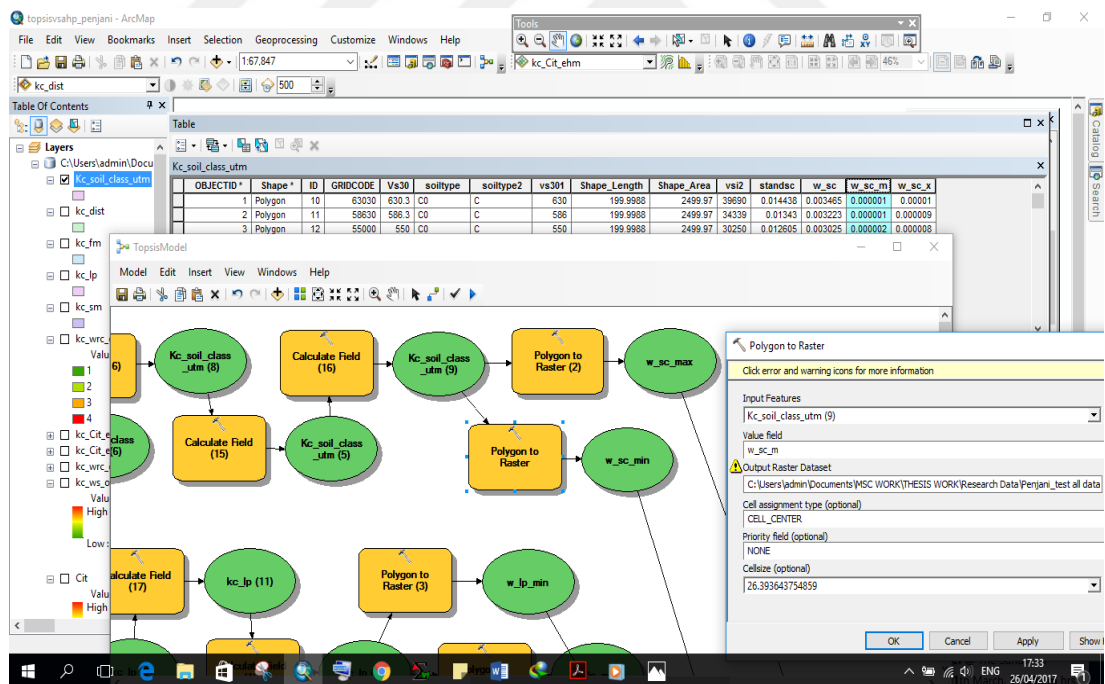


Figure 5.23 : Polygon to raster conversion resulting in creation of map feature representing the minimum value for the soil classification weighted standardized criteria map layer.

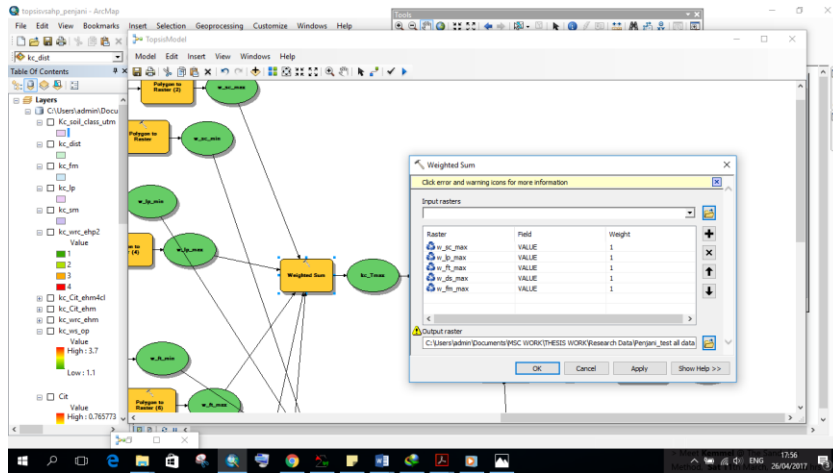


Figure 5.24 : Weighted sum operation for combining the five (5) raster map layers representing the PIS (maximum).

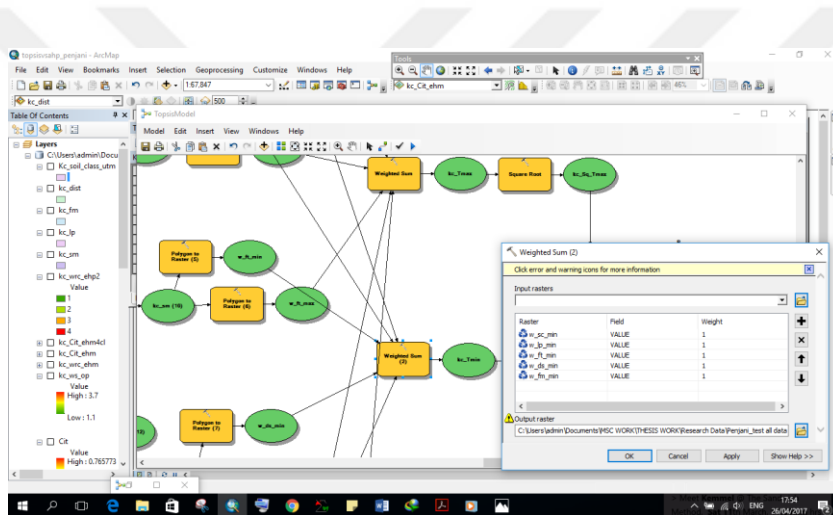


Figure 5.25 : Weighted sum operation for combining the five (5) raster map layers representing the NIS (minimum).

The square root of the generated PIS and NIS raster map layers is thereafter computed using the *Math Trigonometric* tool as per equation 4.13 and 4.14 to obtain the two resulting map layers, each representing the separation from the PIS and NIS. Determining the relative closeness, C_i^* to the PIS for each criteria map layer can then be performed by the *raster calculator* tool using the related calculations as per equation 4.15, as illustrated in Figure 5.26.

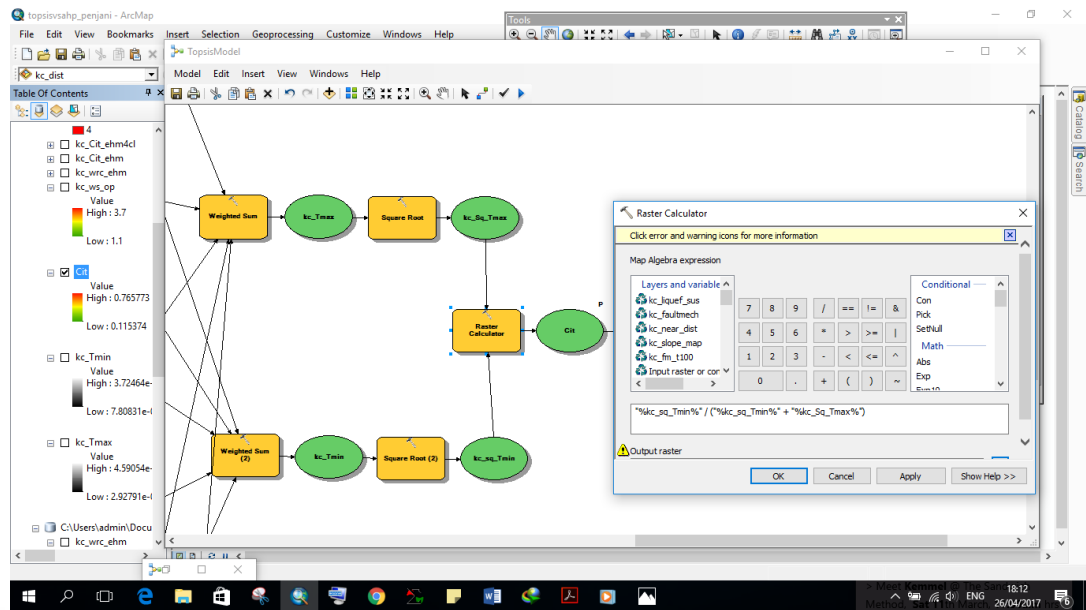


Figure 5.26 : Relative closeness to ideal solution computation using the raster calculator resulting in generation of a hazard map output.

The hazard map created from the relative closeness to ideal solution computation procedure showing the distribution of the risk level of areas from low to high risk, is as shown in Figure 5.27.

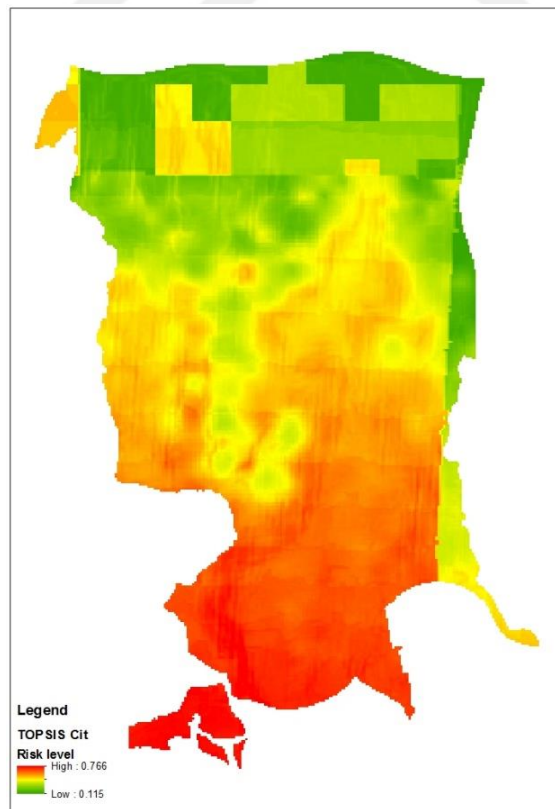


Figure 5.27 : Hazard map output created from relative closeness to ideal solution computation.

5.5.1.6 TOPSIS earthquake hazard map

At this point, the model parameters are saved and can be added to the mapping display. Finally, the preference order is ranked by arranging the map criteria through the classification of values desired in the same order of 1 to 4 as from AHP map output result (EHM) where class value of 1 represents lowest risk and 4 represents highest risk. This is achieved by use of the *reclassify* tool and is done to change the order and values of the pixels for comparison with AHP hazard map result, as illustrated in Figure 5.28.

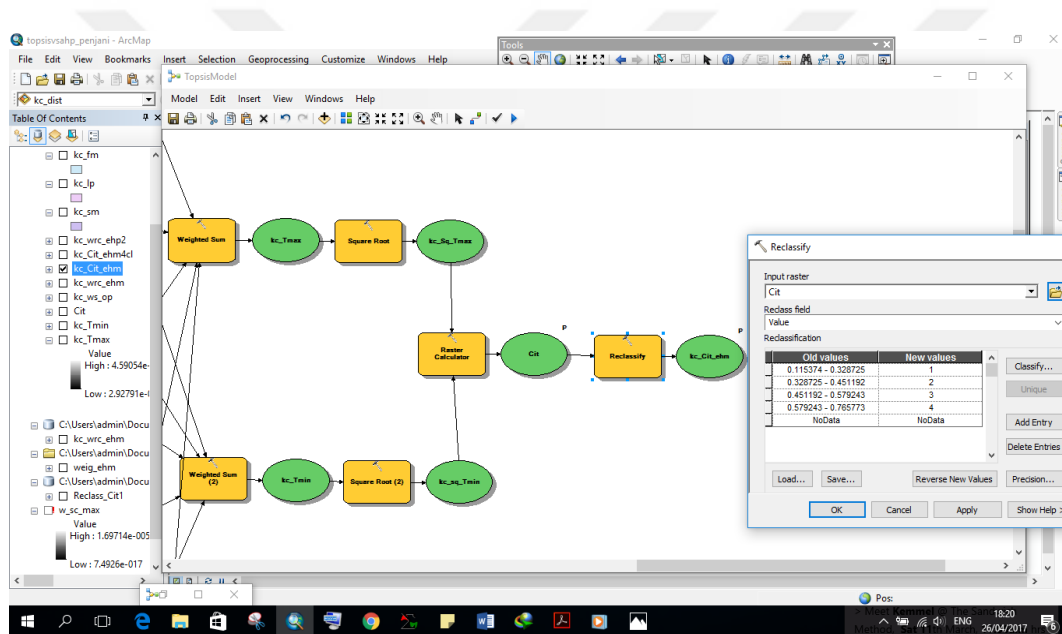


Figure 5.28 : Creation of earthquake hazard map (EHM) using reclassify tool

This results in the creation of TOPSIS earthquake hazard map as shown in Figure 5.29, to be compared and analyzed.

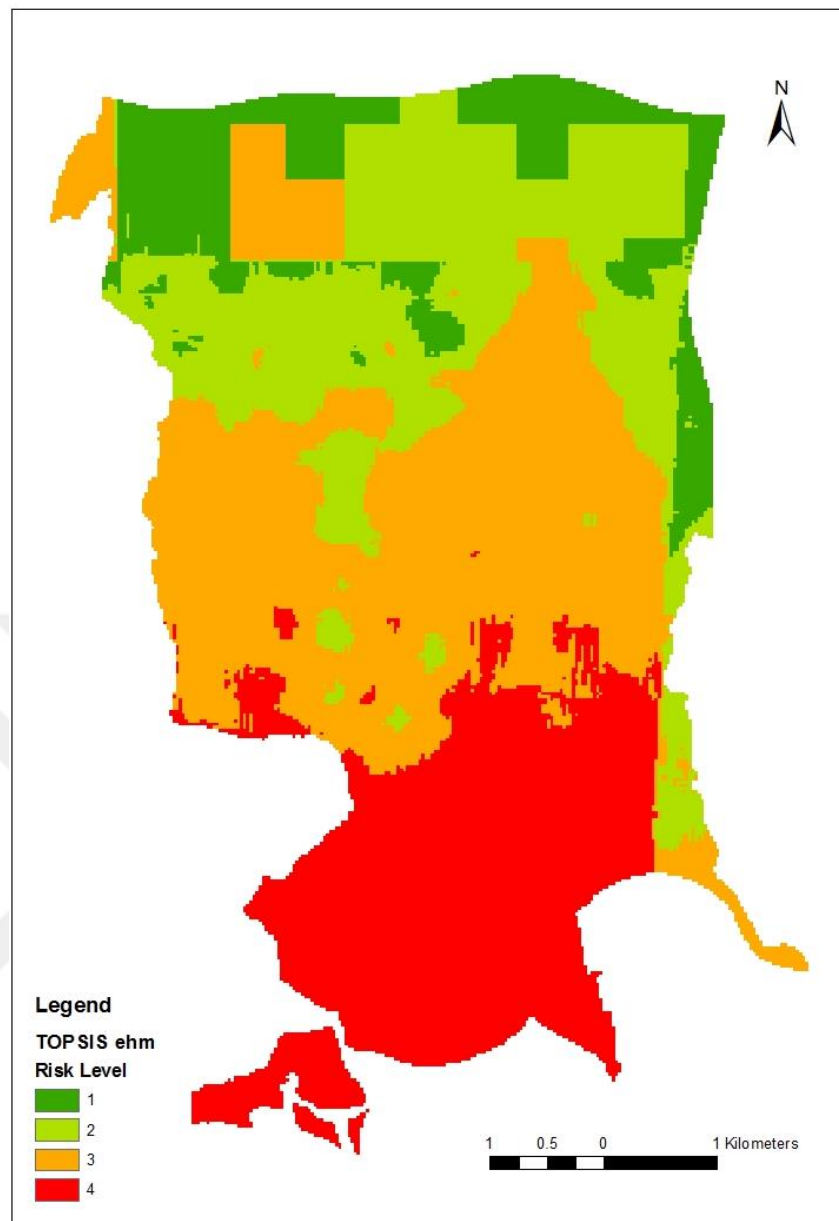


Figure 5.29 : TOPSIS earthquake hazard map (EHM).

The TOPSIS model created using the ModelBuilder application for all the processes and calculation steps in ArcGIS is shown in Figure 5.30. An extended zoomed in view of the model is as shown in Figure A.1 and A.2 (Appendix A).

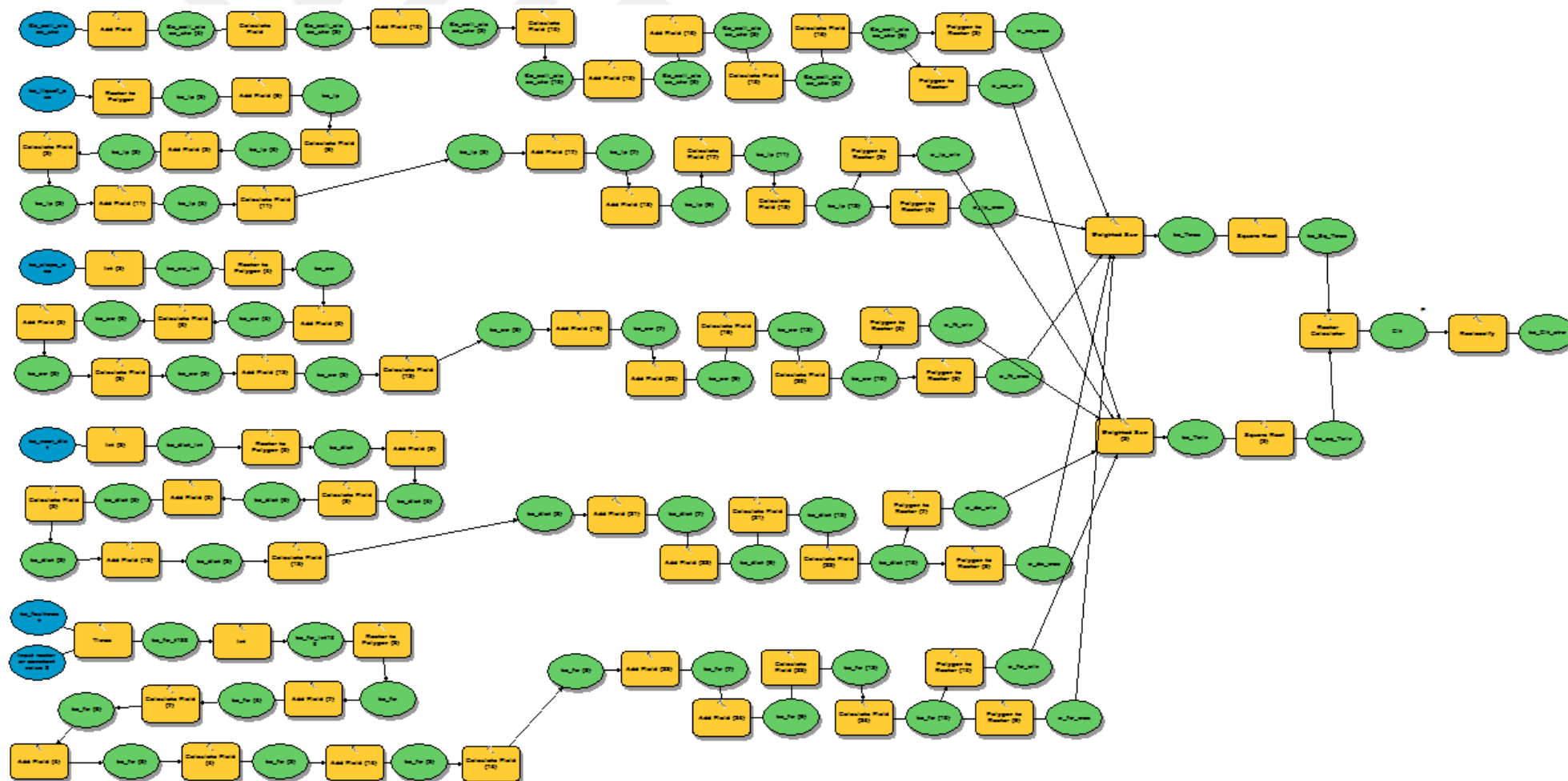


Figure 5.30 : TOPSIS ModelBuilder process flow chart created in ArcGIS.

6. RESULTS AND COMPARISON

6.1 Comparison of AHP and TOPSIS Results

The resulting earthquake hazard maps of the study region, Küçükçekmece, were generated using both MCDA methods of AHP and TOPSIS successfully, achieving our main objective of the study as shown in Figure 6.1.

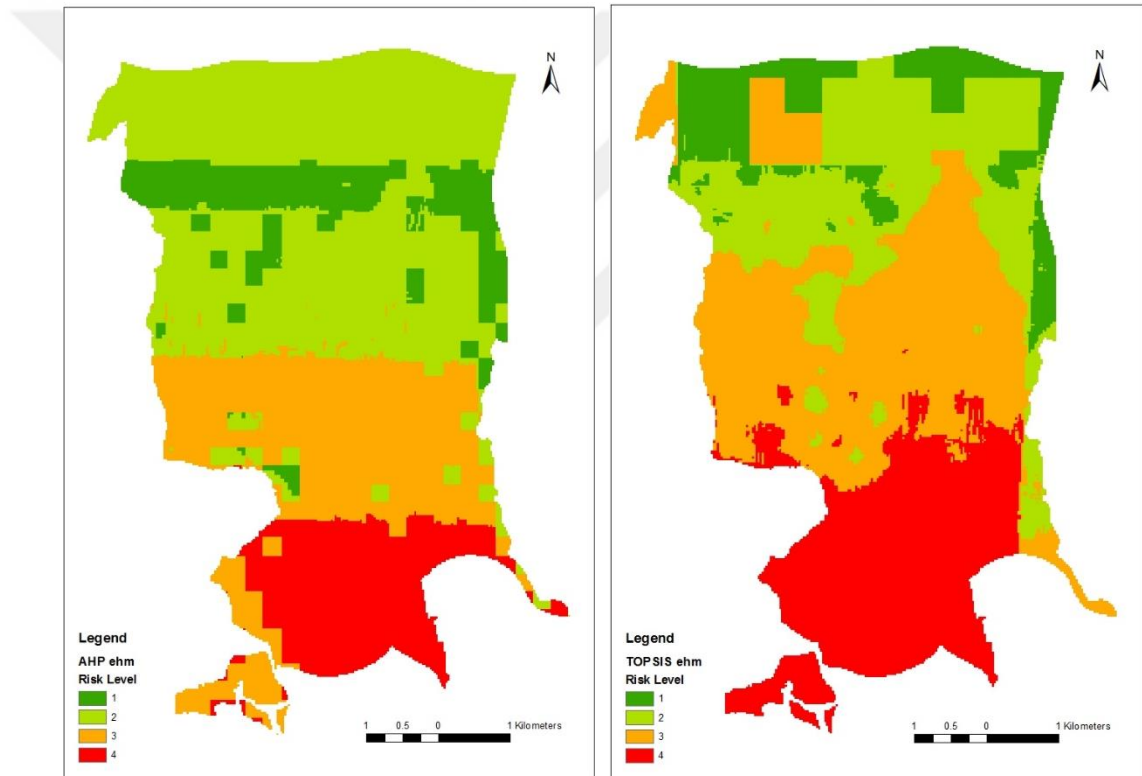


Figure 6.1 : AHP (left) and TOPSIS (right) earthquake hazard maps (EHMs).

The resulting simulations of earthquake hazard maps from AHP and TOPSIS were both based on the criteria and parameters that were determined to comprehensively model the effects of earthquakes. These parameters selected and used as map layer inputs into the AHP and TOPSIS models, were: field topography (FT), source-to-site distance (DS), soil classification (SC), liquefaction potential (LP) and fault/focal mechanism (FM).

The resulting hazard maps were both classified from a rating ranging from 1 to 4 classes, where 1 represents areas of low/no risk and 4 depicts areas at highest/most risk to earthquake effects.

As can be observed from Figure 6.1, a visual comparison between the AHP and TOPSIS earthquake hazard maps revealed similar patterns of risk level. For both maps, areas to the extreme south are at the most risk shown in red colour (*risk level 4*), those at medium to high risk level in orange (*risk level 3*) were areas around the middle section of the study region with the TOPSIS map covering relatively more of these areas than the AHP map and of a wider distribution towards the northern part of region. In the AHP map, the low to medium risk areas in olive green/light green (*risk level 2*) covered almost the entire northern half of the whole study region with a strip of low risk areas (dark green) (*risk level 1*) stretched across this section from the west to east direction approximately equally dividing the *risk level 2* areas (in light green). While in the TOPSIS map, the *risk level 2* (in light green) areas were relatively distributed towards the northern section of the study area as well, though having some pockets of the *risk level 3* areas (in orange) concentrated around the north-western and extreme north-western parts. The *risk level 1* areas (in dark green) for the TOPSIS map, are spread towards the extreme northern part of the study region, extending somewhat narrowly along the boundary regions in the northern and north-eastern zones while for the AHP map, these areas cover the northern parts in a relatively thin strip running across from west to east nearly equally dividing the low to medium risk (*risk level 2*) areas in light green into two parts, and also have some areas concentrated thinly in the eastern boundary region.

Statistical approaches were also used to provide a more accurate and detailed comparison of these two hazard map outputs. Using the MapCalc Learner's Software (version 2 Build 37, Red Hen Farming Systems, LLC), a number of statistical tools and analyses were conducted. By a *correlation* function of the AHP with the TOPSIS map, the *correlation coefficient* (*pearson correlation coefficient*) was determined as 0.727. This indicated a strong correlation between the two maps, with similar class distribution patterns as inferred from the visual interpretation.

In order to quantify the similarity pattern in each location of the classified study region by risk level with respect to their corresponding risk level class values, a statistical analysis function called *relate* was performed on the AHP and TOPSIS maps. At each

of the locations within the classified study region, the *relate* function identifies similar class values in the AHP map and compares them with the TOPSIS map. The results of the analysis were in form of a map output as shown in Figure 6.2.

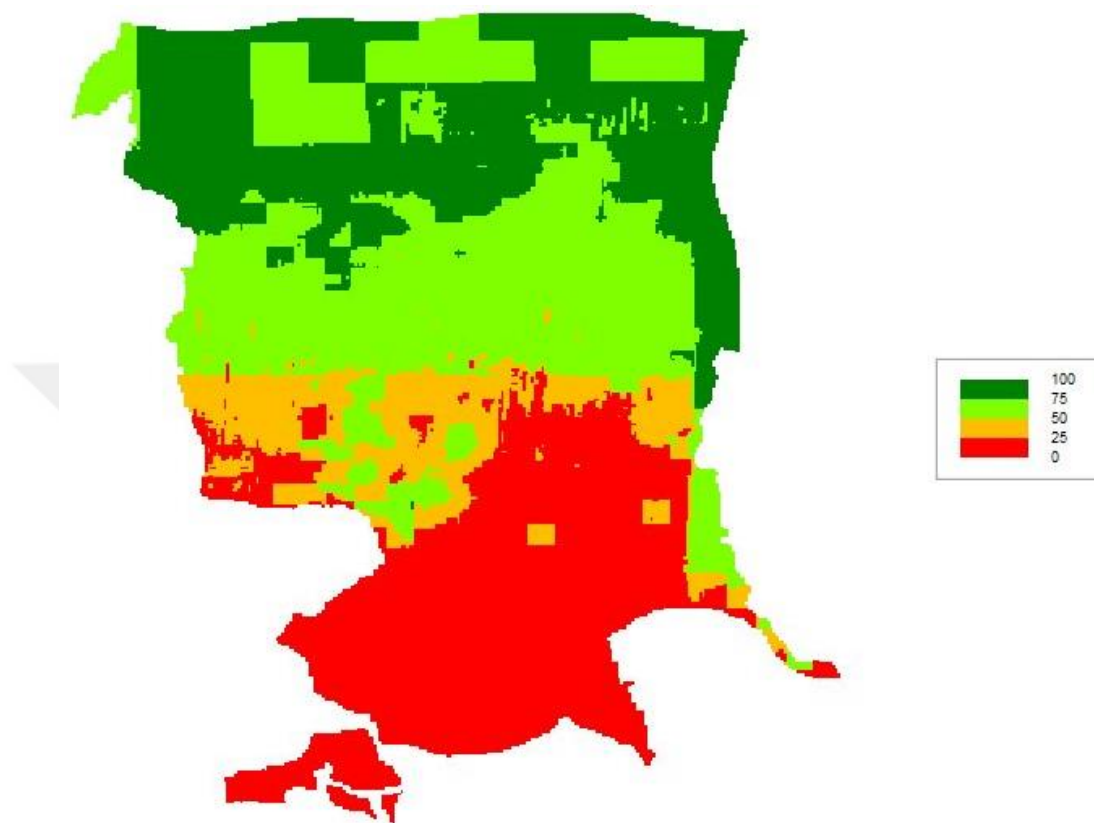


Figure 6.2 : Similarity classification hazard map using *relate* function comparison analysis of class values between AHP and TOPSIS hazard maps.

This similarity classification hazard map output indicates the similar class value distribution representative of the risk level classification of both the AHP and TOPSIS hazard map outputs.

To provide more statistical insight into revealing how the two hazard map outputs, AHP and TOPSIS coincide with each other spatially, an overlay, *crosstab* operation was conducted and the results were as summarized in a cross-tab table as depicted in Table 6.1.

Table 6.1 : Coincidence Table for Map 1 = AHP, with Map 2 = TOPSIS for crosstab operation.

Risk Level Class	AHP Map		TOPSIS Map		No. of Cross	% of Total	% AHP Map Area	% TOPSIS Map Area	% Average
	Value	No. of Cells	Value	No. of Cells					
1	1	6,146	1	11,029	3,728	4.23	60.7	33.8	47.23
	1	6,146	2	8,889	1,662	1.89	27.0	18.7	22.87
	1	6,146	3	14,464	717	0.81	11.7	5.0	8.31
	1	6,146	4	14,687	35	0.04	0.6	0.2	0.4
<i>Weighted Summary Scores for AHP Map, Class 1, Score = 9,343; Average score = 1.52</i>									
2	2	23,101	1	11,029	7,301	8.29	31.6	66.2	48.9
	2	23,101	2	8,889	6,077	6.9	26.3	68.4	47.34
	2	23,101	3	14,464	9,092	10.32	39.4	62.9	51.11
	2	23,101	4	14,687	575	0.65	2.5	3.9	3.2
<i>Weighted Summary Scores for AHP Map, Class 2, Score = 49,031; Average score = 2.12</i>									
3	3	12,923	2	8,889	1,047	1.19	8.1	11.8	9.94
	3	12,923	3	14,464	4,434	5.03	34.3	30.7	32.48
	3	12,923	4	14,687	7,316	8.3	56.6	49.8	53.21
<i>Weighted Summary Scores for AHP Map, Class 3, Score = 44,660; Average score = 3.46</i>									
4	4	7,136	2	8,889	103	0.12	1.4	1.2	1.3
	4	7,136	3	14,464	221	0.25	3.1	1.5	2.31
	4	7,136	4	14,687	6,761	7.67	94.7	46.0	70.39
<i>Weighted Summary Scores for AHP Map, Class 4, Score = 27,913; Average score = 3.91</i>									

A crosstab procedure performs an overlay of the two raster maps, AHP with TOPSIS, by comparing pixel class values on the same positions in both the classified maps resulting in a crosstab table which identifies how often each AHP class values jointly occurs with each TOPSIS class values. For each AHP/TOPSIS combination, this is represented as a count of all the cell locations. The occurring combinations of class names, identifiers and values of pixels in the first input map (the AHP map) and those of pixels in the second input map, (the TOPSIS map) are stored. These combinations give an output cross table (Table 6.1). The cross table includes the combinations of input values, classes, the number of pixels that occur for each combination and the area for each combination.

For example, reading across the first row of Table 6.1, AHP risk class value 1 (Lowest risk) contains 6,146 cells distributed throughout the map while the total count for the risk class value 1 (Lowest risk) in the corresponding TOPSIS map is 11,029 cells. The next segment column of the table denotes that this combination occurs 3,728 times for

4.23 percent of the total map area. This combination further accounts for 60.7% of all occurrences of class 1 AHP values $((3,728/6,146)*100)$ while for the class 1 TOPSIS value occurrence, the coincidence is weaker accounting for only 33.8% of all occurrences of the class 1 TOPSIS values. In the next row, the class 1 AHP/class 2 TOPSIS occurrence indicates 1,662 cells for less than 2% (1.89%) of the map. The coincidence statistics for the class 2 AHP risk level classes show that 7,301 cells (8.29%) occur with the class 1 TOPSIS and 6,077 cells (6.9%) occurs with the class 2 TOPSIS. The class 2 AHP/class 2 TOPSIS coincidence accounts for 68.4% of the occurrence of all class 2 TOPSIS occurrences.

With regard to one of the main motivations for use of MCDA techniques, being the ability to incorporate opinions and preferences of multiple stakeholders, experts cutting across many disciplines involved in decision making, both resulting earthquake hazard maps from AHP and TOPSIS reflected this very critical influencing factor by use of weights applied to the earthquake criteria and parameters. Based on a pairwise comparison technique of AHP, the preferences of the earthquake parameters were ranked and weighted with respect to the different disciplines from which the experts involved in earthquake studies and disaster management were surveyed. This formed a very important element for comparing the results of how the different disciplines evaluated the earthquake criteria.

The AHP and TOPSIS earthquake hazard maps produced were also used to estimate the vulnerability and elements at risk analysis in terms of the number of people potentially affected and loss/damage to buildings with respect to the hazard class level. To achieve this, both population and building data were used based on district and sub-district boundary level information. The results of the analysis were as shown in Table 6.2.

Generally, from the statistics computed, the estimated population as well as the number of buildings within the risk level class 4 (highest risk) for the TOPSIS map is the highest at 242,263 people (accounting for about 47.3% of total population) and this class area includes 18,778 buildings (44.7% of total number of buildings) indicating the high potential of impact likelihood for these areas which have high vulnerability.

Table 6.2 : Comparison between AHP and TOPSIS hazard maps by estimated number of people affected and buildings at risk.

Hazard Maps	Class Risk Level Scale	Buildings (No. of)				Population (No. of people)			
		1	2	3	4	1	2	3	4
		Low	—	→	Major	Low	—	→	Major
AHP model		2,727	13,790	13,814	11,692	41,111	150,183	219,891	162,771
TOPSIS model		3,174	8,062	11,977	18,778	30,111	161,183	78,301	242,263
Comments:		best match		close match		close match	close match		

Hazard Maps	Class Risk Level Scale	Buildings (%)				Population (% of people)			
		1	2	3	4	1	2	3	4
		Low	—	→	Major	Low	—	→	Major
AHP model		6.5%	32.8%	32.9%	27.8%	7.2%	26.2%	38.3%	28.4%
TOPSIS model		7.6%	19.2%	28.5%	44.7%	5.9%	31.5%	15.3%	47.3%
Comments:		best match		close match		close match	close match		

For the AHP map, most of the population and number of buildings are distributed around the medium to high risk (risk level 2 and 3). For the population affected, the AHP and TOPSIS maps show close match for the number of people in both risk level classes 1 and 2 with a variance ranging about 1.3% to 5.3%. For the buildings, both AHP and TOPSIS maps, indicate a close match in the risk level classes 1 and 3 region with a variance ranging from only 1.1% to 4.4%, respectively. This demonstrates the high correlation in both maps showing good compatibility.

6.2 SDSS Usage

In the review of the usage of SDSS for earthquake disaster management in the world and Turkey, the research findings highlight Turkey's experience of SDSS utilization and the main tools currently in use.

The main SDSSs used in Turkey for earthquake risk assessment and loss estimation as part of DEM are thus briefly examined.

KOERILoss, has been used for earthquake, building loss and casualty estimations in Istanbul, Izmir, Bishkek and Tashkent regions and for undertaking rapid loss assessment in relation to the Istanbul Earthquake Rapid Response System (IERRS) (Erdik et al, 2014).

Significant applications of the MAEviz tool in performing earthquake risk and loss assessments for building and other facilities to determine both structural and non-structural damages have been carried out for the Zeytinburnu District of Istanbul (Elnashai et al, 2007).

CATS has been tested for the earthquakes in regions around the world that include Izmit and Duzce, in Turkey. CATS, besides earthquake disasters, also takes into account; ground failures, tsunamis, and fires (Daniell, 2009).

An application of DBELA methodology was conducted in the Marmara region, Turkey for earthquake loss assessment and impact on building stock (Bommer et al, 2006; Bal et al, 2008).

A comparative study by Strasser et al. (2008) of European earthquake loss estimation SDSS for damage estimation for an earthquake scenario in Istanbul, Turkey was undertaken. This used inventory of building stock and population database of the Istanbul Metropolitan Municipality (IMM) and selection of European earthquake loss estimation and risk assessment tools that included: KOERILOSS, SELENA, SIGE and DBELA. The comparative results from the SDSS used, exhibited a tolerable level of agreement in terms of the total number of damaged buildings, and showed a fairly consistent spatial distribution of damaged buildings with overall estimates falling within predicted value ranges. However, with reference to social losses, the forecasts from the various SDSS approaches used revealed a large degree of scatter, mostly attributed to differences in assumed casualty rates.

HAZTURK was applied in a proposed study by Unen et al. (2010) for undertaking analysis of seismic performance of utility lifeline networks in Zeytinburnu district of Istanbul, Turkey. A methodology based on an interdependent network analysis tool developed into the MAEviz software to model frequently connected lifeline utility networks was used. HAZTURK was subsequently used for conducting analysis on earthquake damage of Istanbul's building inventory and buried pipeline inventory of Zeytinburnu district.

For the 2011 Van earthquake event that occurred in Eastern Turkey, an evaluation of SDSSs for rapid loss assessment conducted, revealed **that ELER-based rapid loss assessment results proved to be very close to the final losses due to the more accurate**

earthquake source location while the other SDSSs that included PAGER and QLARM-based loss estimates, showed a large range of losses (CEDIM, 2011; Wenzel et al, 2012; Erdik et al, 2012).

Megacity Indicator System for Disaster Risk Management (MegaIST) was proposed in a study by Mentese et al. (2015). This methodology uses input data for physical indicators such as building, casualty data from ELER software which has to be transformed within a GIS environment into smallest units at sub-district level in Istanbul for use at managerial level.

Perilis (2012), using ELER, conducted a study for rapid earthquake risk assessment at urban scale as applied to Istanbul.

From a study by Sahin et al. (2016), a new version of an integrated earthquake simulation (IES) SDSS for Istanbul in Turkey is being developed after the originally developed system in Japan. This version of IES is being applied to Zeytinburnu district of Istanbul and is built on a MATLAB environment and with data acquired using GIS databases, incorporating site response and structural analysis of existing buildings. In consideration of all the earthquake risk and loss assessment SDSSs used in earthquake studies in Turkey, as discussed by Sahin et al. (2016), none of these have been able to render an integrated system such as the one proposed, that is capable of generating physical models of urban areas including soil and structural systems.

From these findings, an SDSS, known as HAZTURK (Hazards Turkey) was selected and recommended for effective earthquake disaster management in Turkey based on its significant advantages over other earthquake loss estimation software. With regard to the research on SDSSs used in earthquake risk assessment and loss estimation, a comparison and analysis of some of the main tools related to their applicability for use in Turkey can be discussed in the following section.

7. DISCUSSION

We can discuss the study results and findings of our research in conformity to our initially set out objectives of applying MCDA techniques of AHP and TOPSIS for earthquake hazard mapping and risk/vulnerability assessment as well as to review and analyse the usage of SDSS related to GIS-based applications in the field of earthquake DEM in the world and Turkey, so as to recommend a suitable application for implementation in Turkey.

7.1 Discussion on AHP and TOPSIS Model Implementation

In the study, MCDA techniques of AHP and TOPSIS were both applied to generate earthquake hazard map results of the case study area of Küçükçekmece in Istanbul. Five (5) main evaluation criteria were determined and used as main inputs for simulation of earthquake effects in form of generated hazard maps for both AHP and TOPSIS approaches. From the comparison and analysis of the map outputs, the results indicated that both maps showed a high correlation and good compatibility, based on visual interpretation (Figure 6.1), correlation computation (pearson's coefficient of 0.727), similarity classification hazard map using relate function (Figure 6.2), spatial coincidence analysis using the crosstab operation (Table 6.1) and mapped elements at risk in terms of vulnerability of population and buildings for earthquake hazard risk level areas (Table 6.2) ranging from lowest to highest.

The most hazardous areas with the highest risk levels were identified to be generally located in the extreme southern part of the study region extending towards the middle sections. These regions of highest risk to earthquake effects also revealed the highest vulnerability in terms of almost between 60-70% of the estimated total population and number of buildings. This accounted for approximately over 350,000 people that stand to be affected and over 30,000 building structures at risk of damage in the event of an earthquake. It is therefore imperative, based on these preliminary findings and results, that appropriate measures and activities in relation to DEM need to be conducted

across relevant authorities from state to community level actors to ensure readiness and preparedness of the potentially affected communities at risk.

Both AHP and TOPSIS hazard map outputs were comparable to each other, demonstrating the increased effectiveness and suitability of these methods integrated with GIS, for conducting earthquake monitoring and disaster management studies.

The unique suitability for each of these techniques for use in this study can be discussed. For the AHP method, the reduction of a complex decision problem such as earthquake hazard mapping is readily decomposed to make it simpler. By analyzing criteria elements two at a time, *pairwise comparison* is used to determine the weights of the evaluation criteria for earthquake hazard mapping. These weights reflected the preferences of about ten (10) experts surveyed across different disciplines involved in earthquake studies. As the *consistency ratio* for the weight determination was less than 0.1, this indicated the consistency and robustness of the preferences thereby increasing the reliability of the resultant AHP and TOPSIS hazard map outputs.

In the TOPSIS approach, according to Pereira and Duckstein (1993) and Malczewski (1996), the technique is much more suited for implementation in raster data structures such as raster map data used in our study in GIS (ESRI ArcGIS) environment for production of the resultant earthquake hazard map as raster output data.

Besides allowing the ranking based on relative distance of each desired alternative to the ideal point which in our study, was defined as the area identified to be of highest hazard risk level, the TOPSIS method eliminates some of the difficulties linked with inter-dependence among attributes such as the criteria determined and used in our study. It does not make assumption of the preference independence of attributes, i.e. the alternatives are considered as inseparable bundles whereas assumed otherwise in other methods (Zeleny, 1982; Pereira and Duckstein, 1993). Since in spatial decision problems such as the one in our study of earthquake hazard mapping, complex inter-dependence among the attributes may be difficult to verify (Malczewski, 1999; Malczewski and Rinner, 2015).

Apart from the inherent weaknesses that exist in any method of MCDA, there could be some limitations with regard to the accuracy, resolution and up-to-datedness of the data that could affect the reliability of the final earthquake hazard map outputs for both the AHP and TOPSIS models. Further, preferences of the decision-makers' perception

of which earthquake parameter has the greatest influence for modelling the resultant effects in an earthquake hazard map, may cause some levels of dominance of some criteria map layers due to the applied weighting factors. In order to ascertain the sensitivity of the AHP and TOPSIS models to changes on the earthquake criteria parameter, different types of sensitivity analysis techniques could be carried out. Chen et al. (2010) identified three (3) of the most common methods for analysing the sensitivity of the criteria by changing; the values, the relative measure of importance and weights of the criteria.

7.2 Discussion on SDSS Implementation in Turkey

From the results of the research conducted, HAZTURK (Hazards Turkey) was selected and recommended as the SDSS for effective earthquake disaster management in Turkey.

HAZTURK has emerged as one of the main SDSSs offering significant advantages that have led to its suitability and increasingly predominant use over other earthquake loss estimation software in Turkey which are briefly discussed.

From a study by Erden and Karaman (2012) and Karaman and Erden (2014) applying MCDA techniques, HAZTURK was used to produce comparatively higher spatial resolution earthquake hazard maps whose resolution could be increased further, whilst considering the longer time required for processing and analysis. The use of MCDA methods, such as AHP significantly reduced the computation time for building the model structure by almost *three times*.

HAZTURK uses a structural-based analysis method focusing on a single building structure e.g. location of single building unit for loss estimation calculations as opposed to other SDSSs such as HAZUS, ELER and LNECLOSS which use a regional based approach for loss estimation calculations. Given a scenario where a building is bordered by different earthquake hazard prone area boundaries, these other SDSSs assume the hazard index for the zones instead of that of the actual building units (as is the case for HAZTURK) for more accurate damage and loss estimation calculations. Any over-estimation or under-estimation of the hazard index may result in collapse of building structures while other structures may remain standing, respectively. This is

very important especially for retrofit of building structures since every single building has a unique hazard value assignment.

It is very crucial for an SDSS to be able to use and integrate data from different sources and parts of the world. A datum transformation module is thus incorporated in the HAZTURK software, enabling usage and integration of spatial data having different geographic coordinate systems from all over the world. HAZUS, on the other hand, is limited for use only in the US, pre-set to the NAD83 datum.

HAZUS and LNECLOSS are limited in the use of the fragility curves for modelling vulnerability of buildings due to earthquake impacts. Conversely, HAZTURK uses customized, user-defined fragility curves for building codes in Turkey and worldwide, in addition to the use of fragility curves for US specified building codes.

A complementary module, for post-earthquake ignition vulnerability assessment has been developed within HAZTURK. HAZTURK can therefore be used to conduct vulnerability assessment of fires that are triggered by occurrence of an earthquake caused by strong ground shaking (Yildiz, 2013). Consequently, ignitions resulting from damage to gas and electrical systems, overturning of electrical and heating appliances or flammable materials, etc. are considered. HAZUS, ELER, and LNECLOSS do not have this additional module.

HAZTURK has a linear hazard analysis function that considers the inter-dependency of individual components of lifeline network systems such as natural gas pipelines, water, and electric power; for earthquake damage and loss estimation. HAZTURK is able to utilize in a topological model, lifeline utility network data in GIS format for modelling loss and damage estimations for each segment or component of the network (Unen, 2010) as opposed to other SDSSs such as ELER. HAZUS also has capability for carrying out inter-dependence analysis of lifeline networks.

Non-structural elements (NSE) of building structures such as appendages to buildings (e.g. chimneys), building contents (e.g. ceilings, door and window frames) and services and utilities (e.g. plumbing, gas, sewerage lines) are considered in a non-structural hazard analysis function of HAZTURK software. Other SDSSs such as ELER only take into account, the structural elements of buildings such as slabs, footings, and columns for earthquake damage and loss estimation analysis. One of the other drawbacks of ELER are that it does not have a command-line interface in case a

user opts to execute automated, scheduled or event triggered runs (Crowley et al, 2010).

Despite the considerable advantages that HAZTURK has over other SDSSs, its successful implementation in Turkey is limited due to some challenges which must be addressed and overcome. These barriers must be considered if the proper establishment and implementation of HAZTURK for earthquake disaster risk and loss estimation is to be achieved in Turkey.

Main implementation and application challenges in Turkey as well as future developments and recommendations are given in the subsequent section.





8. CONCLUSIONS AND RECOMMENDATIONS

Past and recent tragic earthquake events in the world have underpinned the increasing need for development and integration of scientific approaches such as MCDA techniques with geospatial and decision model systems such as GIS and SDSS to support effective DEM. These tools are utilized by emergency managers and decision-makers for simulating disaster effects through visualization for easier interpretation of outputs in form of hazard maps.

In this study, GIS-based MCDA methods of AHP and TOPSIS were successfully implemented to generate earthquake hazard maps of a case study area of Küçükçekmece in Istanbul, Turkey. A framework for the study was established from which a design of both AHP and TOPSIS approaches was conducted starting with definition of the decision problem which was our main objective, i.e. to produce hazard maps for earthquake disasters. Five (5) criteria parameters were determined as inputs into the AHP and TOPSIS hazard mapping from an existing attenuation relationship that comprehensively modelled the effects of earthquakes on a GIS environment. By the *pairwise comparison* technique, these parameter weights were determined using the AHP method that incorporated the preferences of the experts involved in earthquake research and studies. These weights were then applied to the five (5) processed criteria map layer inputs in ArcGIS 10.3 software to generate an earthquake hazard map (EHM) using *ModelBuilder* application of ArcGIS that created an automated process flow of the GIS operations. The criteria weights determined from AHP were subsequently used in the TOPSIS approach for generation of another EHM. The resulting hazard maps produced from AHP and TOPSIS were compared and analyzed in terms of the distribution pattern of the areas at risk across the study region based on a hazard rating level scale from 1 (low risk) to 4 (highest risk). Vulnerability and elements at risk analysis was also conducted using population and building data to estimate potential impacts of earthquake effects especially in the most hazardous regions.

The AHP and TOPSIS map results generated were compatible based on comparison analysis from visual interpretation that displayed similar spatial distribution risk patterns, high *correlation coefficient* (of 0.727), similarity classification hazard map using a *relate* function, spatial coincidence analysis using the *crosstab* operation, and elements at risk mapped in terms of the vulnerability of population and buildings.

The study results further demonstrated the applicability of AHP and TOPSIS for earthquake hazard mapping and DEM studies despite some limitations that may exist to affect the reliability of outputs with regard to the accuracy, resolution and currentness of the input data. Sensitivity analysis would examine the robustness measure for both AHP and TOPSIS results. The AHP and TOPSIS framework for hazard mapping established can be applied further to other disaster types due to its versatility and simplified approach following the creation of *ModelBuilder* application workflow for automating all the GIS processes.

For the achievement of our secondary objective of our study, a research on the SDSS usage in the world and Turkey for effective earthquake DEM implementation in Turkey was conducted.

The types of SDSSs involved in earthquake DEM are associated with their applications before, during and after earthquake events. SDSSs that are scenario or simulation based, those that are concerned with early warning systems and the ones that are related to rapid response and loss estimation systems are applied pre-, during- and post-earthquake phases, respectively. A range of the main SDSSs from the many near real-time earthquake risk assessment and loss estimation tools developed worldwide have been analysed and classified into whether they are global or regional and local systems. The global SDSSs include QLARM, PAGER, CATS, HAZTURK, SELENA, DBELA while the regional and local systems consist of ELER, HAZUS-MH, KOERILoss, MAEviz, EQRM, LNECLOSS. In Turkey, case studies of SDSSs that have been developed and applied in earthquake risk and loss estimation studies following the tragic 1999 Kocaeli and Duzce earthquakes, namely HAZTURK, MAEviz, ELER, KOERILoss, LNECLOSS, DBELA have been compared. Out of these, HAZTURK has emerged as the main SDSS recommended for implementation for Turkey, and its comparative advantages over other SDSSs have been discussed. These include, usage of a structural based analysis method focusing on a single building structure for hazard value assignment in earthquake loss estimation calculations,

datum transformation module, capability to use customizable, user-defined fragility curves for building codes in Turkey and the world, complementary module for post-earthquake ignition vulnerability assessment, capability for carrying out interdependence analysis of individual elements of lifeline networks such as natural gas pipelines and consideration of non-structural elements (NSE) of building structures.

In analysing the developments and usage of SDSSs worldwide and in Turkey, key issues with regard to the challenges encountered in the establishment and successful implementation of HAZTURK have to be considered. The challenges to be addressed range from issues in spatial data collection, duplication, quality and exchange, absent standardization, interoperability issues, budget limitations, regulatory issues, lack of coordination among relevant institutions involved in earthquake DEM. Proper utilization of HAZTURK with GIS as the backbone is supported within a framework of a well-established SDI. In building a firm SDI for effective DEM, metadata and middleware become very vital to enable integration and geographic data exchange/sharing of different formats and from multiple sources.

Functional improvements to HAZTURK are also being proposed in a continued effort to support and increase the effectiveness of the software for earthquake DEM. As the DEM process involves multiple stakeholders across many disciplines, consensus in making critical decisions is of high priority. MCDA techniques such as AHP and TOPSIS, that incorporate preferences of experts and others involved in emergency management issues can be very useful and also can reduce critical decision-making time by minimizing the conflicts that could exist among decision-makers in emergency situations. Therefore, a module should be built into HAZTURK and other SDSSs for using MCDA methods such as AHP, TOPSIS techniques etc., within a user-friendly interface for decreasing the map computation and simulation time besides incorporating cooperate opinions of decision-makers. As rapidness is a very critical component of DEM, this would greatly enhance response and recovery efforts. In the incorporation of MCDA methods, comparisons of which techniques yield best results should also be validated in HAZTURK software to produce earthquake risk and hazard maps. The proposed integrated module should also have flexibility to support multi-hazard analysis functionality since earthquake events trigger secondary disasters such as tsunamis, floods, volcanic eruptions, landslides, nuclear disasters, etc and

incorporate an expanded modelling function comprising traffic, network and demographic data for evacuation route planning analysis and determination for Istanbul and Turkey.

Within the context of successful implementation of SDSSs for earthquake DEM in Turkey, particularly, usage of HAZTURK, a firm base requiring political will, strengthening of institutional and administrative responsibilities and capacities, regulatory environment, building technical capacity and public/community engagement should be established.



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APPENDICES

APPENDIX A: Expanded views of TOPSIS ModelBuilder process flow in ArcGIS.



APPENDIX A.1 : TOPSIS Model process flow for soil classification (SC), li

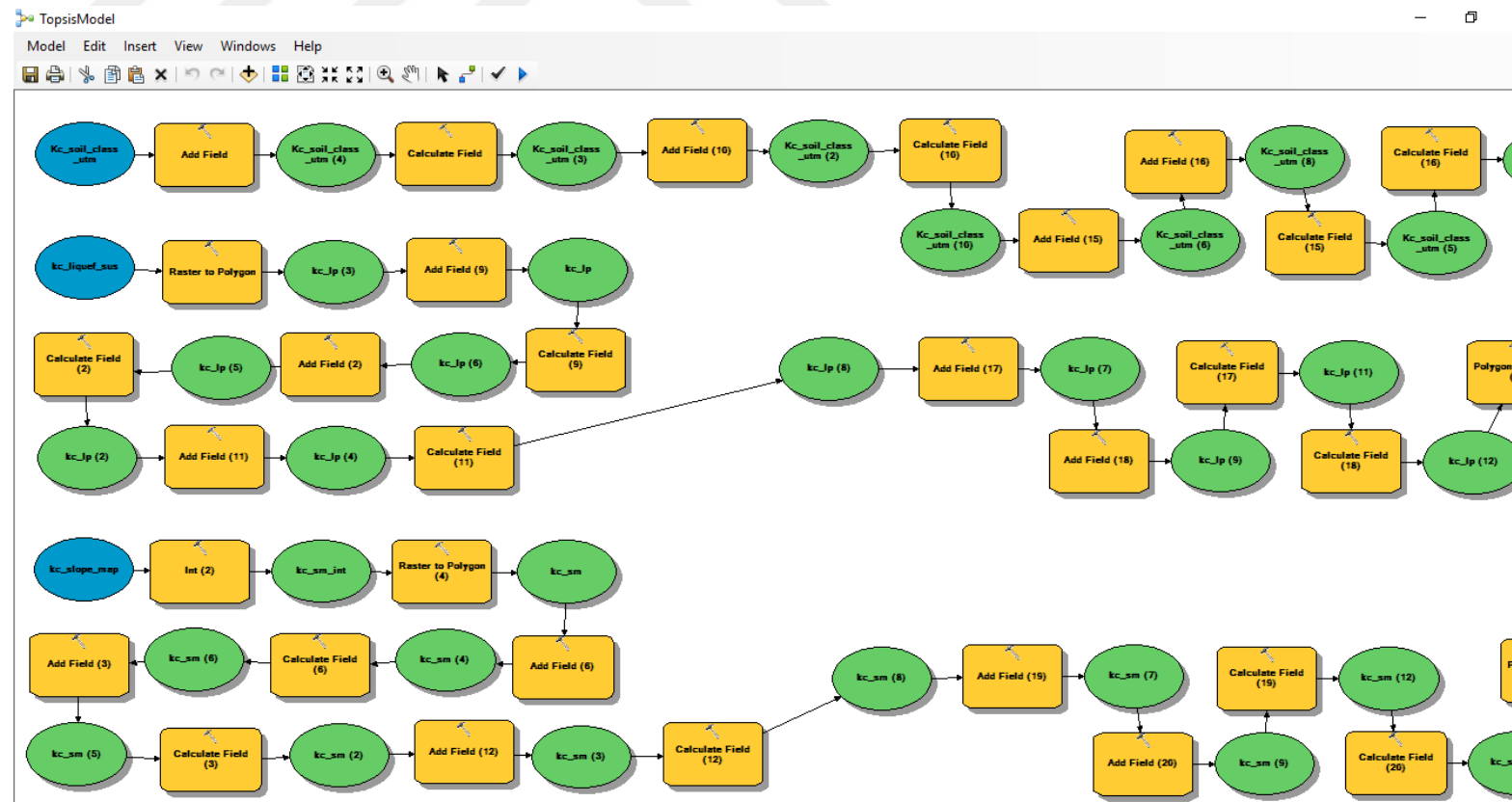


Figure A.1 : TOPSIS Model process flow for soil classification (SC), liquefaction potential (LP) and field topography (FT) criteria map layers for EHM generation.

APPENDIX A.1 (continued): TOPSIS Model process flow for soil classification (SC), liquefaction potential (LP) and field topography (FT) criteria.

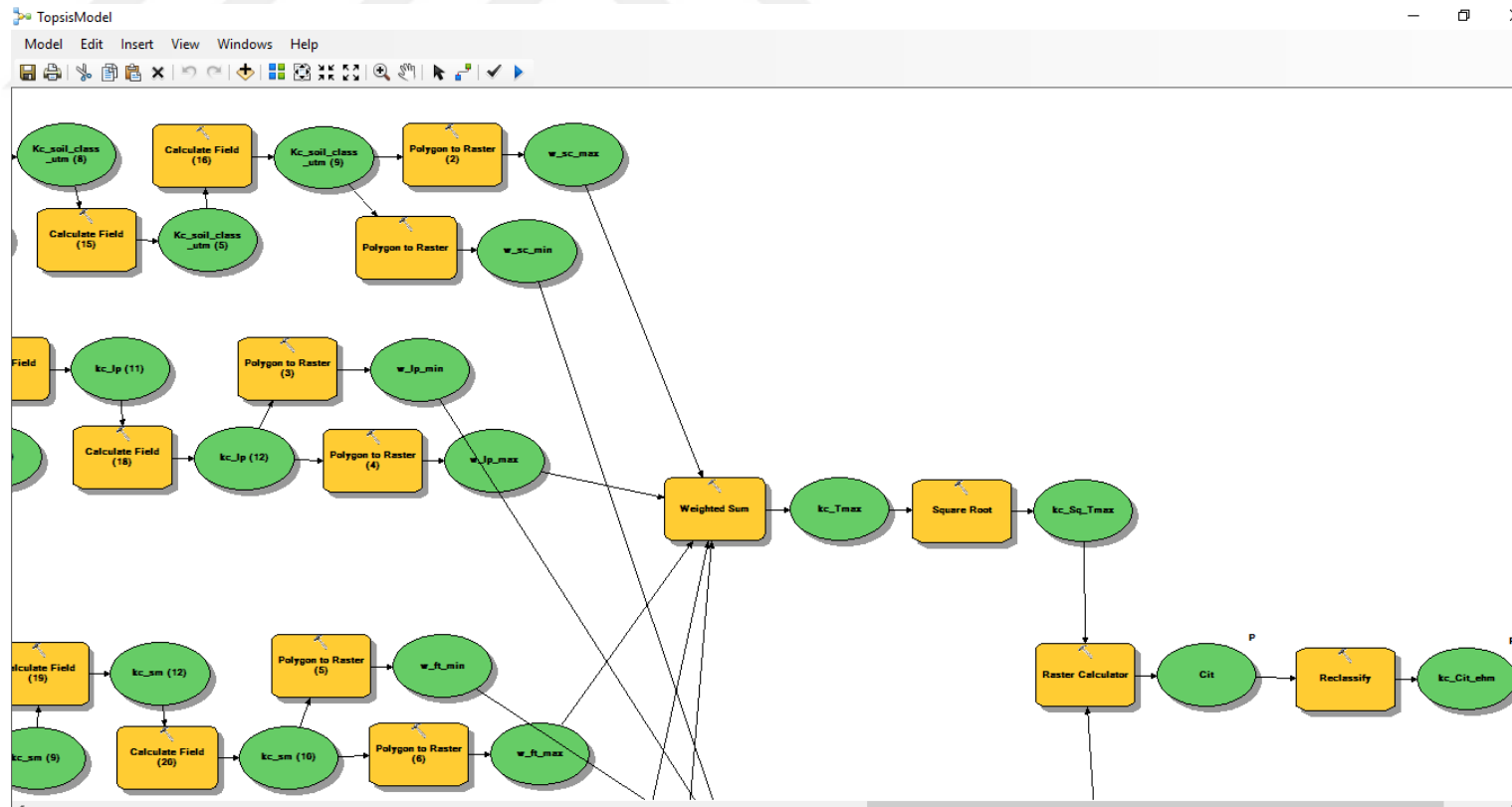


Figure A.1 (continued): TOPSIS Model process flow for soil classification (SC), liquefaction potential (LP) and field topography (FT) criteria map layers for EHM generation.

APPENDIX A.2 : TOPSIS Model process flow for source-to-site distance (DS) and fault mechanism (FM) criteria map layers.

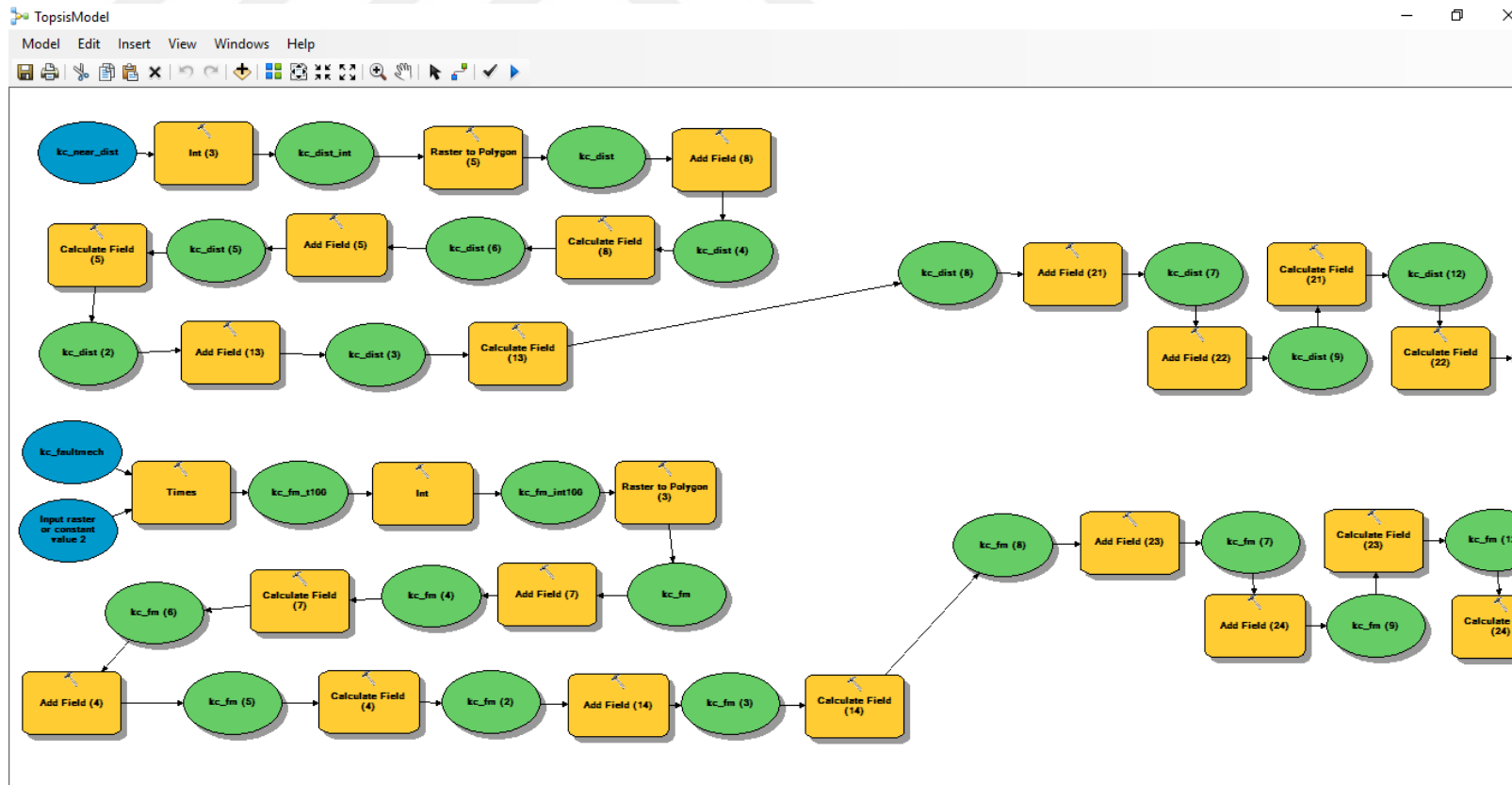


Figure A.2 : TOPSIS Model process flow for source-to-site distance (DS) and fault mechanism (FM) criteria map layers for EHM generation.



CURRICULUM VITAE



Name Surname : Penjani Hopkins Nyimbili

Place and Date of Birth : Zambia

E-Mail : nyimbili@itu.edu.tr/ penjahop@gmail.com

EDUCATION:

- **B.Eng.** : 2008, University of Zambia, Geomatic Engineering Department
- **Postgrad. IDPM (Project Management)** : 2011, University of Cambridge, Project Management

PROFESSIONAL EXPERIENCE AND REWARDS:

- 2008 *Best Graduating Final Year Project/Research*, Geomatic Engineering.
- 2009-2014 University of Zambia, Part-time Teaching Assistant/Staff Development Fellow at Geomatic Engineering Department.
- 2008 Geohydro Consulting Ltd, Consulting GIS Specialist.
- 2008 – 2011 Airtel Mobile Telecoms Ltd, Geo-marketing/Marketing Planning Executive (Asst.Manager – Research and Planning Section).
- 2011 – 2014 Rural Electrification Authority, Department of Energy, Ministry of Energy, Survey/Project Manager.
- 2013 Delegate, Energy Policy Consultation, UNDP Beijing China.
- 2014 CEC Liquid Telecommunication Ltd, Network Planning & Build Data Administrator/ Asst. Project Manager – Diversification Growth Projects.
- *Best Scientific Poster Presentation*: Nyimbili P H., Demirel H., Şeker D Z., Erden T., ‘*Structure-from-Motion (SFM) – Approaches and Applications*’, Selçuk International Scientific Conference on Applied Sciences, Antalya, Turkey; 2016

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- Nyimbili P H., Demirel H., Şeker D Z., Erden T 2016: *Structure-from-Motion (SFM) – Approaches and Applications*, September 30, 2016 Antalya, Turkey.