

**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL**

**A DATA-DRIVEN APPROACH TO IDENTIFYING AND SELECTING  
TEMPORARY DISASTER DEBRIS MANAGEMENT SITES: THE CASE OF  
ISTANBUL**



**M.Sc. THESIS**

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**Department of Industrial Engineering**

**Engineering Management Programme**

**JANUARY 2025**



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**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ**

**GEÇİCİ AFET MOLOZ YÖNETİM ALANLARININ BELİRLENMESİ VE  
SEÇİMİ İÇİN VERİ ODAKLI BİR YAKLAŞIM: İSTANBUL ÖRNEĞİ**

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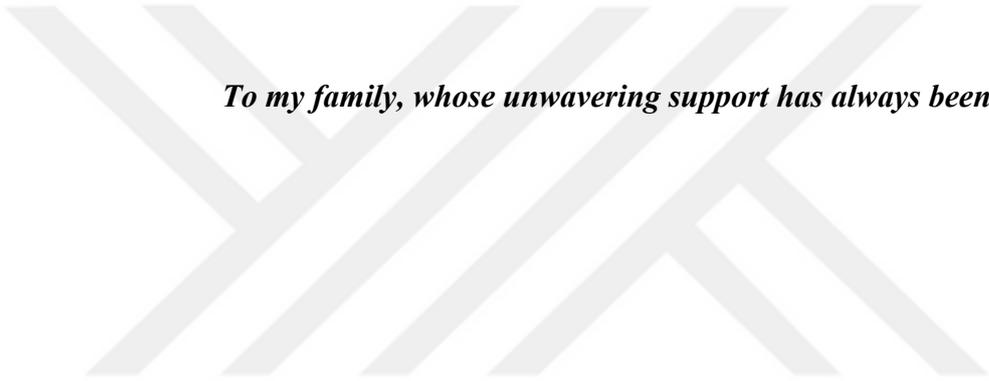
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*To my family, whose unwavering support has always been behind me*



## FOREWORD

This thesis marks the end of a difficult but rewarding journey in the subject of disaster management. Throughout this work, I focused on the essential issue of temporary disaster debris site selection and transportation optimization, with a particular emphasis on Istanbul, a city that is very vulnerable to seismic risks. The inspiration for this study derives from the growing need for better disaster management strategies in densely populated cities. Istanbul, with its distinct geographic, social, and economic characteristics, is a challenging scenario for optimizing post-disaster debris management. By combining Geographic Information Systems (GIS), clustering algorithms, and transportation models, this work intends to contribute to academic discourse while also providing practical insights for policymakers and disaster response teams.

The development of this thesis would not have been achievable without the advice, support, and encouragement of multiple individuals. My supervisor, Assoc. Prof. Dr. Şeyda Serdar Asan, provided significant experience, patience, and careful advice throughout my journey. I am deeply grateful. Her guidance has not only improved my academic comprehension, but it has also pushed me to set higher goals in my research. I am truly grateful to my friends for their discussions and feedback, which helped shape this work. I'd like to express my heartfelt gratitude to my family for their everlasting belief in me, even throughout the most difficult times. Their affection and encouragement have provided strength and motivation.

Finally, I hope that the findings of this study make a significant contribution to the field of disaster management and motivate further research in this area. It is my honest hope that this effort will help to construct communities with greater resilience and save lives in the aftermath of disasters.

With gratitude,

January 2025

Burak KABAKLI  
(Industrial Engineer)



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## **ABBREVIATIONS**

<b>GIS</b>	: Geographic Information Systems
<b>IFRC</b>	: The International Federation of Red Cross and Red Crescent
<b>MCDA</b>	: Multi-Criteria Decision Analysis
<b>MCDM</b>	: Multi-Criteria Decision Making
<b>ANP</b>	: Analytical Network Process
<b>FEMA</b>	: Federal Emergency Management Agency
<b>UNEP</b>	: United Nations Emergency Planning Agency
<b>PDNA</b>	: Post Disaster Needs Assessment
<b>DDM</b>	: Disaster Debris Management
<b>AHP</b>	: Analytical Hierarchy Process
<b>FAHP</b>	: Fuzzy Analytical Hierarchy Process
<b>TOPSIS</b>	: Technique for Order of Preference by Similarity to Ideal Solution
<b>SAW</b>	: Simple Additive Weighting
<b>MSW</b>	: Municipal Solid Waste
<b>TDDMS</b>	: Temporary Disaster Debris Management Sites
<b>NAFZ</b>	: North Anatolian Fault Zone
<b>MILP</b>	: Mix Integer Linear Programming
<b>C&amp;D</b>	: Construction and Demolition
<b>HSWLS</b>	: Hazardous Solid Waste Landfill Sites
<b>MSWLS</b>	: Municipal Solid Waste Landfill Sites



## SYMBOLS

<b><math>n</math></b>	: Total number of very heavy, heavy, and moderate damage buildings
<b><math>E</math></b>	: Estimated total debris volume
<b><math>N</math></b>	: Average number of housing units per building
<b><math>A</math></b>	: Floor area of each housing unit
<b><math>R</math></b>	: Debris generation rate per square meter
<b><math>D</math></b>	: The distance between two points
<b><math>r</math></b>	: The Earth's radius
<b><math>\phi_1, \phi_2</math></b>	: Latitudes of the two points in radians
<b><math>\lambda_1, \lambda_2</math></b>	: Longitudes of the two points in radians
<b><math>x_{ij}</math></b>	: The volume of debris transported from neighborhood $i$ to TDDMS $j$
<b><math>d_{ij}</math></b>	: The transportation cost from neighborhood $i$ to TDDMS $j$
<b><math>C_j</math></b>	: The capacity of TDDMS $j$
<b><math>y_j</math></b>	: A binary decision variable indicating whether TDDMS $j$ is used
<b><math>b_j</math></b>	: Suitability Index for a specific constraint criterion $j$
<b><math>n</math></b>	: Total number of constraint criteria
<b><math>w_j</math></b>	: Weight for a specific constraint criterion $j$
<b><math>v_j</math></b>	: Value of land for a specific constraint criterion $j$
<b><math>V</math></b>	: Total value of land



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**A DATA-DRIVEN APPROACH TO IDENTIFYING AND SELECTING  
TEMPORARY DISASTER DEBRIS MANAGEMENT SITES: THE CASE OF  
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SUMMARY**

Disasters manifest in various forms, encompassing both natural and human-induced events. They may arise suddenly, as in the case of earthquakes, fires, floods, tsunamis, hurricanes, and volcanic eruptions, or develop gradually, such as during civil conflicts or droughts. The impacts of these events can vary significantly in both their physical and social dimensions. The type and intensity of a disaster can result in the generation of substantial amount of debris, posing significant challenges for affected communities. To address such impacts, disaster management is typically divided into four key stages: mitigation, preparation, response, and recovery. During the recovery phase, debris management is essential, emphasizing the processes of collecting, reducing or recycling, and ultimately disposing of the remaining debris.

Disasters can generate debris volume that considerably surpass the yearly debris production of the impacted community often straining the resources of existing solid waste disposal systems and staff. Addressing such immense volume of debris requires substantial financial investment and significant time for its clearance, removal, and disposal. Despite its critical role in disaster recovery, disaster debris management has received relatively limited attention in the literature compared to other aspects of disaster management. By putting forth a combined structure designed to optimize disaster debris management procedures, this thesis seeks to close this gap, paying particular attention to the particular difficulties Istanbul presents.

This thesis's primary goal is to solve the difficulties associated with managing disaster debris, with a focus on enhancing the selection Temporary Disaster Debris Management Sites (TDDMS) and allocation debris to these sites. Through the integration of transportation optimization, clustering techniques, and spatial analysis, the thesis aims to:

- Establish identification criteria for TDDMS that consider the environment, engineering, and economy.
- Develop a clustering-based transportation model to optimize debris allocation to selected TDDMS.
- Develop a systematic and replicable approach to site evaluation and debris allocation.
- Validate the methodology by applying it to Istanbul's particular disaster debris management demands.

Introduction chapter discusses the important difficulties faced by disasters, focusing on their increasing frequency and intensity because of climate change, population increase, and unsustainable development. Communities are disrupted by natural and human-caused disasters like floods and earthquakes, which cause significant death tolls, economic losses, and environmental degradation. Turkey's geographical and geological circumstances cause it highly vulnerable to disasters caused by nature, particularly earthquakes. Historical disasters such as the 1999 Marmara earthquake

and the 2023 Kahramanmaraş-Hatay earthquakes are emphasized for their devastation, which included massive debris generation, fatalities, and community displacements. These instances demonstrate the critical necessity for effective disaster management strategies.

The chapter defines disaster management as a cyclical process that focuses on the recovery stage, when debris management becomes an important component, necessitating the removal, sorting, and disposal of debris to promote community reconstruction. Major research questions concentrate around the criteria for selecting TDDMS and optimizing the number and operation to save costs while increasing efficiency. The thesis seeks to solve two critical challenges in disaster recovery:

- Establishing the optimal number, locations, and service zones for TDDMS.
- Estimating and allocation debris volume to aid in effective resource planning.

Chapter 2 digs into disaster debris management, exploring its complexities and significance in the overall disaster management cycle. It starts by defining disaster debris and categorizing it according to its origin and features, stressing how different types of disasters result in distinct debris compositions. The volume of debris generated after disasters frequently exceeds typical waste production, posing problems to disposal systems and straining municipal waste disposal ability. The chapter emphasizes the significance of precisely calculating debris amount, as miscalculations can result in inefficiencies and financial losses. Various tools and methodologies, such as past record data analysis, mathematical models, and remote sensing techniques are highlighted as important means of forecasting debris amount.

TDDMS have been emphasized as critical components for disaster debris control. These facilities perform a variety of functions, including debris storage, processing, and recycling, as well as serving as logistical buffers. In order to balance economic effectiveness and environmental preservation, the selection of TDDMS requires a thorough evaluation of engineering, economical, and environmental considerations. The disaster debris supply chain is investigated, with a focus on the optimization of TDDMS locations and debris allocation. The chapter emphasizes the significance of reducing transportation costs, time, and hauling distances to provide an efficient response and recovery process. A review of the most recent literature demonstrates considerable advances in debris management approaches, including GIS-based analysis and optimization algorithms. However, it also highlights key shortcomings, such as the absence of integrated frameworks that combine site selection, transportation optimization, and multi-criteria decision-making. This chapter sets the stage for the thesis by identifying these shortcomings and suggesting novel techniques to improving disaster debris management systems, with a particular emphasis on tackling the unique challenges given by large-scale disasters.

Chapter 3 outlines the methodology employed to deal with disaster debris management challenges, with a particular emphasis on selecting TDDMS, estimating debris amount, and optimizing transportation. TDDMS selection begins with determining and prioritizing evaluation criteria based on a comprehensive literature study of 20 recently published national and international articles. These articles shed light on the environmental, engineering, and economic factors that influence the choice of TDDMS. The methodology strikes a balance between including different criteria, which typically range from 9 to 13 for reliability, practicality and meeting the dynamic and short-term demands of disaster recovery scenarios.

A crucial aspect of the methodology is the accurate sizing of TDDMS, which directly impacts the efficiency and capacity of disaster debris management systems. This involves using historical disaster data and estimation models to predict debris amount. In this regard, FEMA guidelines, which take into consideration storage requirements as well as operational areas such as safety zones, access roads, fire pits, and hazardous waste management zones, identify a minimum of 100 acres per million cubic yards (about 40 hectares per 0.76 million cubic meters) of debris. As part of the approach, the selected criteria are also given weights according to their significance in relation to others. The Equal Weight Method, Analytic Hierarchy Process (AHP), and Analytic Network Process (ANP) are three popular methods to criteria weighing. To ensure comparability, criteria are standardized into a single unit utilizing Boolean or Fuzzy Logic, which simplifies the assessment process.

Geographical Information Systems (GIS) are critical to the integration and analysis of spatial data. It includes comprehensive capabilities for correlating various data types, implementing zoning and buffering rules, and visualizing geographical relationships using criteria map overlays. This improves decision-making by providing a broader grasp of spatial dynamics. When integrated with Multi-Criteria Decision Analysis (MCDA), GIS allows for the integration of spatial and non-spatial data, resulting in a methodical and data-driven approach to site selection. This integration not only saves cost and time, but it also establishes a strong digital repository for continuing monitoring and adaption, guaranteeing that site selection processes are efficient and sustainable.

Chapter 3 presents a tailored approach to estimating disaster debris amount in Istanbul, based on lessons learned during the 1999 Marmara Earthquake, which produced 13.18 million tonnes of debris. The model fits to Istanbul's metropolitan characteristics by employing similar parameters, such as 4.2 housing units per building covering 100 m<sup>2</sup> and 1.3 tonnes per square meter of debris generation. Formulas are offered to estimate debris at the district and neighborhood levels, allowing for more precise design of TDDMS and logistical activities. This system ensures scalable and effective debris control that is specific to Istanbul's demands.

Chapter 3, additionally, explores cluster-based transportation optimization for disaster debris management, with a focus on efficient allocation of debris to TDDMS. To address unequal debris allocation and restricted site capacity, the system incorporates clustering algorithms and optimization models to reduce costs and environmental implications. Traditional optimization methods, such as Mixed Integer Linear Programming (MILP) and Multi-Objective Optimization (e.g., NSGA-II), are discussed for their ability to reduce costs and save time. Clustering approaches, such as K-medoids, provide more adaptability and precision for large-scale geographic and quantitative data sets. The K-medoids algorithm divides neighborhoods into clusters, then selects core spots (medoids) to optimize debris transportation while being robust to noise and outliers.

The Haversine formula is used to calculate precise distances, taking into account the Earth's spherical shape and ensuring spatial relationships are accurate. The transportation model's goal is to reduce the total costs associated with transporting debris from neighborhoods to TDDMS. Constraints include meeting the neighborhood debris levels, adhering to TDDMS capacity constraints, and ensuring sites are only used when activated. The model employs practical assumptions, such as fixed transportation costs, consistent site capacities, and adequate resources for debris

transports. By integrating clustering, spatial analysis, and optimization, the system assures effective and scalable disaster debris allocation, addressing logistical challenges while minimizing costs and environmental implications. This method offers a strong framework for managing debris allocation in disaster recovery scenarios.

Chapter 4 describes the practical application of the proposed methodology for opting for TDDMS in Istanbul, a city with high seismic risk due to its proximity to the North Anatolian Fault Zone (NAFZ). Applying GIS and land suitability analysis, the study assesses possible sites against a set of predetermined criteria customized to Istanbul's geographic, environmental, and urban characteristics. Istanbul, home to approximately 20 million people, has significant seismic dangers due to its proximity to the NAFZ. Historical statistics, including as the 1999 Marmara Earthquake, illustrate the city's vulnerability, with a 7.5 magnitude earthquake expected to yield almost 25 million tonnes of debris. This demands effective debris management systems, which include the identification and selection of TDDMS.

The study focuses on Istanbul's 38 districts, totaling 5,461 km<sup>2</sup>. The land suitability study includes nine important criteria derived from a thorough literature assessment. These include proximity to lakes and rivers, built areas, major roads, airports, land slope, aspect and wind direction, as well as ownership and land use. Data were gathered from reliable sources, including HydroSheds, ESRI, OpenStreetMap, and the General Directorate of Land Registry and Cadastre. The analysis used raster and vector data for spatial evaluations, with buffers and thresholds set for each criterion. The land suitability analysis evaluated TDDMS locations utilizing ArcGIS 10.8.2. Euclidean distances measured proximity to important characteristics, whereas Boolean logic reclassified land to be suitable (1) or unsuitable (0). Two overlay approaches were employed: Fuzzy Overlay ("AND") for tight binary outcomes and Weighted Sum for a flexible the suitability index that allows constraint relaxation as needed. This approach ensured a thorough assessment of potential sites. The Weighted Sum analysis was selected to identify TDDMS. Satellite imagery and property records confirmed the findings, excluding undesirable zones such as woods and overcrowded metropolitan regions. Reclassification maps indicated that proximity to built areas and land use were the most restrictive criteria, but distance from lakes and rivers posed fewer limits. Fuzzy Overlay produced limited results due to stringent constraints, whereas Weighted Sum allowed for more flexible categorization, identifying 46 eligible sites of varied sizes and ownership. Some industrial properties were allowed despite looser requirements to have adequate capability for managing the expected 25 million tonnes of debris.

After identifying potential TDDMS, the focus shifted to Istanbul's Asian side, enhancing the analysis by narrowing it to specific neighborhoods and utilizing neighborhood-level debris amounts estimates for greater precision. These estimations, computed using the debris estimation formulas outlined in the methodology section, are based on the Istanbul Earthquake Loss Estimation Update Project (2019) and consider a Mw 7.5 earthquake scenario. The projections include buildings classified as Very Heavy Damage, Heavy Damage, Moderate Damage, and Light Damage, along with the number of buildings categorized by story count (1-4, 5-8, 9-19 stories).

The final application in Chapter 4 compares clustering-based and non-clustering methods to optimize disaster debris transportation in Istanbul's Asian side. These methods were tested for their success in allocating debris amounts from neighborhoods

to TDDMS, emphasizing the importance of balancing cost efficiency, operational complexity, and site usage.

The clustering-based method applied the K-Medoids algorithm to group neighborhoods based on their geographical proximity. Among several cluster configurations, a 15-cluster scenario demonstrated a balanced trade-off between transportation cost and operational complexity. The method focused on allocations to seven active TDDMS, lowering transportation costs and simplifying logistics by concentrating on fewer, larger sites. Conversely, the non-clustering method assigned debris amounts from neighborhoods directly to TDDMS, leading in a modest increase in transportation costs. This method used a broader variety of TDDMS, including smaller sites, which provided greater flexibility but increased logistical constraints.

The comparative analysis revealed important trade-offs: clustering decreased costs and operational overhead by centralizing allocations, whereas non-clustering allowed greater flexibility and scattered allocations at the cost of increased complexity. These insights provide significant recommendations for disaster debris management, emphasizing the importance of tailoring methods to particular operational priorities and constraints.



## GEÇİCİ AFET MOLOZ YÖNETİM ALANLARININ BELİRLENMESİ VE SEÇİMİ İÇİN VERİ ODAKLI BİR YAKLAŞIM: İSTANBUL ÖRNEĞİ

### ÖZET

Afetler, hem doğal hem de insan kaynaklı olayları kapsayacak şekilde çeşitli biçimlerde ortaya çıkar. Depremler, yangınlar, seller, tsunamiler, kasırgalar ve volkanik patlamalarda olduğu gibi aniden ortaya çıkabilir veya iç çatışmalar veya kuraklıklar gibi kademeli olarak gelişebilirler. Bu olayların etkileri hem fiziksel hem de sosyal boyutları açısından önemli ölçüde farklılık gösterebilir. Bir afetin türü ve yoğunluğu, önemli miktarlarda enkazın ortaya çıkmasına neden olarak etkilenen topluluklar için önemli zorluklar yaratabilir. Bu tür etkileri ele almak için afet yönetimi tipik olarak dört temel aşamaya ayrılır: zarar azaltma, hazırlık, müdahale ve iyileştirme. İyileştirme aşamasında, enkaz yönetimi kritik bir rol oynar ve artık enkazın toplanmasına, azaltılmasına veya geri dönüştürülmesine ve nihai olarak bertaraf edilmesine odaklanır.

Afetler, etkilenen toplumun yıllık atık üretimini aşan ve genellikle mevcut katı atık yönetim tesislerinin ve personelinin kapasitesini zorlayan enkaz hacimleri oluşturabilir. Böylesine büyük miktarlardaki enkazın temizlenmesi, kaldırılması ve bertaraf edilmesi için önemli miktarda mali yatırım ve zaman gerekmektedir. Afet sonrası iyileştirmedeki kritik rolüne rağmen, afet enkaz yönetimi literatürde afet yönetiminin diğer yönlerine kıyasla nispeten daha az ilgi görmüştür. Bu tez, özellikle İstanbul'un sunduğu benzersiz zorluklara odaklanarak, afet enkaz yönetimi süreçlerini optimize etmek için uyarlanmış entegre bir çerçeve önererek bu boşluğu ele almayı amaçlamaktadır.

Bu tezin temel amacı, özellikle Geçici Afet Enkaz Yönetim Sahalarının seçimi ve enkaz tahsisinin iyileştirilmesine vurgu yaparak, afet enkaz yönetiminin zorluklarını ele almaktır. Mekânsal analiz, kümeleme teknikleri ve ulaşım optimizasyonunu entegre ederek tez şunları amaçlamaktadır:

- Çevresel, ekonomik ve sosyal faktörlere dayalı olarak Geçici Afet Enkaz Yönetim Sahalarının seçimi için kriterler belirlemek.
- Seçilen Geçici Afet Enkaz Yönetim Sahalarına enkaz tahsisini optimize etmek için kümeleme tabanlı bir ulaşım modeli geliştirmek.
- Saha değerlendirme ve enkaz tahsisi için sistematik ve tekrarlanabilir bir yaklaşım geliştirmek.
- Metodolojiyi İstanbul'un özel afet enkaz yönetimi taleplerine uygulayarak doğrulamak.

Giriş bölümü, iklim değişikliği, nüfus artışı ve sürdürülemez kalkınmanın bir sonucu olarak artan sıklık ve yoğunlukla ortaya çıkan afetlerin önemli zorluklarını ele almaktadır. Depremler ve seller gibi doğal ve insan kaynaklı afetler toplumları altüst ederek ciddi can kayıplarına, ekonomik zarara ve çevresel bozulmaya yol açmaktadır.

Türkiye'nin coğrafi ve jeolojik koşulları, başta depremler olmak üzere doğadan kaynaklanan afetlere karşı son derece savunmasız olmasına neden olmaktadır. Tarihsel olarak 1999 Marmara depremi ve 2023 Kahramanmaraş-Hatay depremleri gibi felaketler, büyük enkaz oluşumu, ölümler ve toplulukların yerlerinden edilmesini içeren yıkımlarıyla öne çıkmaktadır. Bu örnekler, etkili afet yönetimi tekniklerinin kritik gerekliliğini ortaya koymaktadır.

Bu bölümde afet yönetimi, enkaz yönetiminin önemli bir bileşen haline geldiği ve toplumun yeniden inşasını desteklemek için enkazın kaldırılması, ayrıştırılması ve bertaraf edilmesini gerektiren iyileştirme aşamasına odaklanan döngüsel bir süreç olarak tanımlanmaktadır. Başlıca araştırma soruları, Geçici Afet Enkaz Yönetim Sahalarının seçilmesi ve verimliliği artırırken maliyetlerden tasarruf etmek için miktar ve operasyonun optimize edilmesine yönelik kriterler etrafında yoğunlaşmaktadır. Tez, afet sonrası toparlanmada karşılaşılan iki kritik zorluğu çözmeyi amaçlamaktadır:

- Geçici Afet Enkaz Yönetim Sahaları için en uygun sayı, konum ve hizmet bölgelerini belirlemek.
- Etkin kaynak planlaması ve tahsisine yardımcı olmak için enkaz hacmini tahmin etmek ve tahsisini optimize etmek.

Bölüm 2, afet enkaz yönetiminin karmaşıklığını ve genel afet yönetimi döngüsündeki önemini araştırmaktadır. Afet enkazını tanımlayarak, kökenine ve özelliklerine göre kategorize ederek başlamakta ve farklı afet türlerinin nasıl farklı enkaz bileşimlerine yol açtığını vurgulamaktadır. Afetlerden sonra ortaya çıkan enkaz hacmi sıklıkla tipik atık üretimini aşmakta, bertaraf sistemlerinde sorunlara yol açmakta ve belediyelerin kapasitesini zorlamaktadır. Bu bölümde, yanlış hesaplamalar verimsizliklere ve mali kayıplara neden olabileceğinden, enkaz miktarlarının tam olarak hesaplanmasının önemi vurgulanmaktadır. Geçmiş veri analizi, matematiksel modeller ve uzaktan algılama teknikleri gibi çeşitli araç ve metodolojiler, enkaz miktarını tahmin etmenin önemli araçları olarak vurgulanmaktadır.

Geçici Afet Enkaz Yönetim Sahaları, afet enkaz yönetimi için kritik bileşenler olarak vurgulanmıştır. Bu tesisler enkaz depolama, işleme ve geri dönüşüm gibi çeşitli işlevleri yerine getirmenin yanı sıra lojistik tampon görevi de görmektedir. Geçici Afet Enkaz Yönetim Sahalarının seçimi, maliyet verimliliği ile çevrenin korunmasını dengelemek amacıyla çevresel, ekonomik ve sosyal kaygıların dikkatli bir şekilde değerlendirilmesini gerektirir. Afet enkazı tedarik zinciri, Geçici Afet Enkaz Yönetim Sahaları konumlarının optimizasyonuna ve enkaz tahsisine odaklanılarak incelenmiştir. Bu bölümde, etkin bir müdahale ve kurtarma süreci sağlamak için nakliye maliyetlerinin, zamanın ve taşıma mesafelerinin azaltılmasının önemi vurgulanmaktadır. Güncel literatürün gözden geçirilmesi, Coğrafi Bilgi Sistemleri tabanlı analiz ve optimizasyon algoritmaları da dahil olmak üzere enkaz yönetimi yaklaşımlarında önemli ilerlemeler olduğunu göstermektedir. Bununla birlikte, saha seçimi, nakliye optimizasyonu ve çok kriterli karar verme süreçlerini birleştiren entegre çerçevelerin bulunmaması gibi önemli eksikliklerin de altı çizilmektedir. Bu bölüm, bu eksiklikleri belirleyerek ve afet enkaz yönetim sistemlerini iyileştirmek için yeni teknikler önererek, özellikle büyük ölçekli afetlerin getirdiği benzersiz zorlukların üstesinden gelmeye vurgu yaparak tez için zemin hazırlamaktadır.

Bölüm 3, Geçici Afet Enkaz Yönetim Sahalarının seçilmesi, enkaz miktarının tahmin edilmesi ve nakliyenin optimize edilmesine özellikle vurgu yaparak afet enkaz yönetimi zorluklarının üstesinden gelmek için kullanılan metodolojiyi özetlemektedir. Geçici Afet Enkaz Yönetim Sahaları seçimi, yakın zamanda yayınlanmış 20 ulusal ve

uluslararası makaleden oluşan kapsamlı bir literatür çalışmasına dayanan değerlendirme kriterlerinin belirlenmesi ve seçilmesi ile başlar. Bu makaleler, Geçici Afet Enkaz Yönetim Sahaları seçimini etkileyen çevresel, sosyal ve ekonomik faktörlere ışık tutmaktadır. Metodoloji, güvenilirlik ve pratiklik için tipik olarak 9 ila 13 arasında değişen farklı kriterleri dahil etmek ile afet kurtarma senaryolarının dinamik ve kısa vadeli taleplerini karşılamak arasında bir denge kurmaktadır.

Metodolojinin önemli bir yönü, afet enkaz yönetim sistemlerinin verimliliğini ve kapasitesini doğrudan etkileyen Geçici Afet Enkaz Yönetim Sahalarının doğru boyutlandırılmasıdır. Bu, enkaz miktarlarını tahmin etmek için geçmiş afet verilerinin ve tahmin modellerinin kullanılmasını içerir. Örneğin, FEMA kılavuzları, depolama ihtiyaçlarının yanı sıra güvenlik bölgeleri, erişim yolları, yangın çukurları ve tehlikeli atık yönetim bölgeleri gibi operasyonel alanları da hesaba katarak, milyon metre küp başına en az 100 dönüm enkaz önermektedir. Metodoloji ayrıca belirlenen kriterlere göreceli önemlerine göre ağırlık verilmesini de içermektedir. Eşit Ağırlık Yöntemi, Analitik Hiyerarşi Süreci (AHP) ve Analitik Ağ Süreci (ANP) kriterlerin ağırlıklandırılması için kullanılan üç popüler tekniktir. Karşılaştırılabilirliği sağlamak için kriterler, değerlendirme sürecini basitleştiren İkili (Boolean) Mantık veya Bulanık Mantık kullanılarak tek bir birim halinde standartlaştırılır.

Coğrafi Bilgi Sistemleri, mekansal verilerin entegrasyonu ve analizi için kritik öneme sahiptir. Çeşitli veri türlerini ilişkilendirmek, bölgeleme ve tamponlama kurallarını uygulamak ve ölçüt harita katmanlarını kullanarak coğrafi ilişkileri görselleştirmek için kapsamlı yetenekler içerir. Bu, mekansal dinamiklerin daha geniş bir şekilde kavranmasını sağlayarak karar verme sürecini iyileştirir. Coğrafi Bilgi Sistemleri, Çok Kriterli Karar Analizi ile entegre edildiğinde, mekansal ve mekansal olmayan verilerin entegrasyonuna olanak tanıyarak yer seçiminde metodik ve veri odaklı bir yaklaşım sağlar. Bu entegrasyon sadece maliyet ve zaman tasarrufu sağlamakla kalmaz, aynı zamanda sürekli izleme ve uyarılma için güçlü bir dijital havuz oluşturarak yer seçimi süreçlerinin verimli ve sürdürülebilir olmasını garanti eder.

Bölüm 3, 13,18 milyon ton enkaz üreten 1999 Marmara Depremi sırasında edinilen derslere dayanarak İstanbul'daki afet enkazının tahmin edilmesine yönelik özel bir yaklaşım sunmaktadır. Model, 100 m<sup>2</sup>'lik bina başına 4,2 konut birimi ve metrekare başına 1,3-ton atık üretimi gibi parametreler kullanarak İstanbul'un metropol özelliklerine uyum sağlamaktadır. İlçe ve mahalle düzeyinde enkaz tahmini için formüller sunularak Geçici Afet Enkaz Yönetim Sahalarının ve lojistik faaliyetlerin daha hassas bir şekilde tasarlanmasına olanak sağlanmaktadır. Bu sistem, İstanbul'un taleplerine özel, ölçeklenebilir ve etkili bir enkaz kontrolü sağlamaktadır.

Bölüm 3, ek olarak, Geçici Afet Enkaz Yönetim Sahalarına verimli enkaz tahsisine odaklanarak afet enkaz yönetimi için küme tabanlı ulaşım optimizasyonunu ele almaktadır. Eşit olmayan enkaz tahsisi ve kısıtlı saha kapasitesini ele almak için sistem, maliyetleri ve çevresel etkileri azaltmak için kümeleme algoritmaları ve optimizasyon modelleri içermektedir. Karışık Tamsayı Doğrusal Programlama (MILP) ve Çok Amaçlı Optimizasyon (örn. NSGA-II) gibi geleneksel optimizasyon yöntemleri, maliyetleri azaltma ve zamandan tasarruf etme yetenekleri nedeniyle tartışılmaktadır. K-medoids gibi kümeleme yaklaşımları, büyük ölçekli coğrafi ve nicel veri setleri için daha fazla uyarlanabilirlik ve hassasiyet sağlar. K-medoids algoritması mahalleleri kümelere ayırır, ardından gürültü ve aykırı değerlere karşı dayanıklı olurken enkaz taşımayı optimize etmek için çekirdek noktaları (medoidler) seçer.

Haversine formülü, Dünya'nın küresel şeklini dikkate alarak ve uzamsal ilişkilerin doğru olmasını sağlayarak kesin mesafeleri hesaplamak için kullanılır. Ulaşım modelinin amacı, enkazın mahallelerden Geçici Afet Enkaz Yönetim Sahalarına taşınmasıyla ilgili toplam maliyetleri azaltmaktır. Kısıtlamalar arasında mahalle enkaz seviyelerinin karşılanması, Geçici Afet Enkaz Yönetim Sahaları kapasite kısıtlamalarına uyulması ve sahaların yalnızca etkinleştirildiğinde kullanılmasının sağlanması yer almaktadır. Model, sabit nakliye maliyetleri, tutarlı saha kapasiteleri ve enkaz nakliyecileri için yeterli kaynaklar gibi pratik varsayımlar kullanmaktadır. Kümeleme, mekânsal analiz ve optimizasyonu entegre eden sistem, maliyetleri ve çevresel etkileri en aza indirirken lojistik zorlukları ele alarak etkili ve ölçeklenebilir afet enkazı tahsisi sağlar. Bu yöntem, afet kurtarma senaryolarında enkaz tahsisini yönetmek için güçlü bir çerçeve sunmaktadır.

Bölüm 4, Kuzey Anadolu Fay Zonu'na (KAFZ) yakınlığı nedeniyle sismik riski yüksek bir şehir olan İstanbul'da Geçici Afet Enkaz Yönetim Sahalarının belirlenmesi için önerilen metodolojinin pratik uygulamasını anlatmaktadır. Coğrafi Bilgi Sistemleri ve arazi uygunluk analizinin uygulandığı çalışmada, İstanbul'un coğrafi, çevresel ve kentsel özelliklerine göre özelleştirilmiş, önceden belirlenmiş bir dizi kritere göre olası sahalar değerlendirilmektedir. Yaklaşık 20 milyon kişiye ev sahipliği yapan İstanbul, KAFZ'ye yakınlığı nedeniyle önemli sismik tehlikelere sahiptir. Aralarında 1999 Marmara Depremi'nin de bulunduğu tarihsel istatistikler, 7,5 büyüklüğündeki bir depremin yaklaşık 25 milyon ton enkaz üretmesinin beklendiği şehrin kırılganlığını göstermektedir. Bu durum, Geçici Afet Enkaz Yönetim Sahalarının tanımlanmasını da içeren etkili enkaz yönetim sistemleri gerektirmektedir.

Çalışma, İstanbul'un toplam 5.461 km<sup>2</sup>'lik 38 ilçesine odaklanmaktadır. Arazi uygunluk çalışması, kapsamlı bir literatür değerlendirmesinden elde edilen dokuz önemli kriteri içermektedir. Bunlar arasında göllere ve nehirlere yakınlık, yerleşme alanları, ana yollara ve havaalanlarına yakınlık, arazi eğimi, bakı ve rüzgar yönü, bunların yanı sıra arazi mülkiyeti ve arazi kullanımını da yer almaktadır. Veriler HydroSheds, ESRI, OpenStreetMap ve Tapu ve Kadastro Genel Müdürlüğü gibi güvenilir kaynaklardan toplanmıştır. Analizde mekânsal değerlendirmeler için raster ve vektör verileri kullanılmış, her kriter için tamponlar ve eşikler belirlenmiştir. Arazi uygunluk analizi, Geçici Afet Enkaz Yönetim Sahaları konumlarını ArcGIS 10.8.2 kullanarak değerlendirmiştir. Öklid mesafeleri önemli özelliklere yakınlığı ölçerken, Boolean mantığı araziye uygun (1) veya uygun olmayan (0) olarak yeniden sınıflandırmıştır. İki bindirme yaklaşımı kullanılmıştır: Sıkı ikili sonuçlar için Bulanık Kaplama (Fuzzy Overlay) ve gerektiğinde kısıtlamaların gevşetilmesine izin veren esnek bir uygunluk endeksi için Ağırlıklı Toplam (Weighted Sum). Bu yaklaşım, potansiyel sahaların kapsamlı bir şekilde değerlendirilmesini sağlamıştır.

Geçici Afet Enkaz Yönetim Sahalarını belirlemek için Ağırlıklı Toplam (Weighted Sum) analizi seçilmiştir. Uydu görüntüleri ve tapu kayıtları, ormanlık alanlar ve aşırı kalabalık metropol bölgeleri gibi istenmeyen bölgeleri hariç tutarak bulguları doğrulamıştır. Yeniden sınıflandırma haritaları, yapılaşmış alanlara yakınlık ve arazi kullanımının en kısıtlayıcı kriterler olduğunu, ancak göllere ve nehirlere olan uzaklığın daha az sınır oluşturduğunu göstermiştir. Bulanık Kaplama (Fuzzy Overlay), katı kısıtlamalar nedeniyle sınırlı sonuçlar verirken, Ağırlıklı Toplam (Weighted Sum) daha esnek bir sınıflandırmaya izin vermiş ve çeşitli büyüklük ve mülkiyete sahip 46 uygun alan belirlemiştir. Bazı endüstriyel mülklere, beklenen 25 milyon ton enkazı yönetmek için yeterli kapasiteye sahip olmaları için daha gevşek şartlara rağmen izin verilmiştir.

Geçici Afet Enkaz Yönetim Saha adayları belirlendikten sonra, odak İstanbul'un Asya yakasına kaydırılmış, analiz Asya yakasında yer alan mahallelere daraltılarak ve daha fazla hassasiyet için mahalle düzeyinde enkaz tahminleri kullanılarak geliştirilmiştir. Metodoloji bölümünde özetlenen enkaz tahmin formülleri kullanılarak hesaplanan bu enkaz miktarları, İstanbul Deprem Kayıp Tahmini Güncelleme Projesi'ne (2019) dayanmaktadır ve 7.5 büyüklüğünde deprem senaryosunu dikkate almaktadır. Projeksiyonlar, Çok Ağır Hasar, Ağır Hasar, Orta Hasar ve Hafif Hasar olarak sınıflandırılan binaların yanı sıra kat sayısına göre (1-4, 5-8, 9-19 kat) kategorize edilen bina sayısını da içermektedir.

Bölüm 4'teki son uygulama, İstanbul'un Asya yakasındaki afet enkazlarının taşınmasını optimize etmek için kümeleme tabanlı ve kümeleme dışı yöntemleri karşılaştırmaktadır. Bu yöntemler, mahallelerdeki enkazın Geçici Afet Enkaz Yönetim Sahalarına tahsis edilmesindeki başarıları açısından test edilmiş ve maliyet verimliliği, operasyonel karmaşıklık ve alan kullanımının dengelenmesinin önemi vurgulanmıştır.

Kümeleme tabanlı yöntem, mahalleleri coğrafi yakınlıklarına ve enkaz miktarına göre gruplandırmak için K-Medoids algoritmasını uygulamıştır. Çeşitli küme konfigürasyonları arasında 15 kümeli bir senaryo, nakliye maliyeti ve operasyonel karmaşıklık arasında bir denge olduğunu göstermiştir. Yöntem, yedi aktif Geçici Afet Enkaz Yönetim Sahasına enkaz tahsisine odaklanarak nakliye maliyetlerini düşürmüş ve daha az sayıda, daha büyük sahalarla odaklanarak lojistiği basitleştirmiştir. Buna karşılık, kümeleme yapmayan yöntem, mahallelerdeki enkazı doğrudan Geçici Afet Enkaz Yönetim Sahasına atayarak nakliye maliyetlerinde mütevazı bir artışa yol açmıştır. Bu yöntem, daha fazla esneklik sağlayan ancak lojistik kısıtlamaları artıran daha küçük sahalar da dahil olmak üzere daha geniş bir Geçici Afet Enkaz Yönetim Sahası yelpazesi kullanmıştır.

Karşılaştırmalı analiz önemli ödüneşimleri ortaya çıkarmıştır: kümeleme, tahsisleri merkezileştirerek maliyetleri ve operasyonel ek yükü azaltırken, kümelemesizlik daha fazla esnekliğe ve artan karmaşıklık pahasına dağınık tahsislere izin vermiştir. Bu görüşler, afet enkaz yönetimi için önemli tavsiyeler sunmakta ve yöntemlerin belirli operasyonel önceliklere ve kısıtlamalara göre uyarlanmasının önemini vurgulamaktadır.



## 1. INTRODUCTION

Disasters are among the most dramatic and tragic events in history, causing widespread damage, loss of life, and economic setbacks. The International Federation of Red Cross and Red Crescent Societies (IFRC) [1] defines disasters as serious interruptions to a community's ability to cope using its own resources. Over the past decades, the frequency and severity of disasters have escalated due to climate change, population growth, and unsustainable development practices.

Major disasters of the 21st century, including the Indian Ocean tsunami (2004), Hurricane Katrina (2005), the earthquake in Haiti (2010), and the Japanese tsunami (2011), have resulted in the loss of thousands of lives and inflicted billions of dollars in damages [2].

Türkiye, with the majority of its landmass in Asia and acting as a bridge between Europe and Asia, spans a total area of 780,000 square kilometers [3]. This geographic positioning exposes Türkiye to frequent natural disasters due to its geological, meteorological, and topographic characteristics. Türkiye makes up just 0.5 percent of the world's total land area. However, it ranks fourth globally for the number of major earthquakes, with 77 significant events recorded between 1900 and 2016 [4]. In the Global Risk Index for Risk Management, designed to assess the risks of humanitarian crises and disasters, Turkey is ranked 45th out of 191 countries [5]. With a score of 5.0, Turkey falls into the "high risk" category. As a result, the country regularly faces a variety of disasters, including earthquakes (pictured in Figure 1.1), landslides, floods, rock falls, and avalanches. The major disasters [6] that have impacted Turkey since 1990 are enumerated in Table 1.1. A comprehensive analysis of this table reveals the diverse range of disasters affecting the country and the substantial fatalities they cause.

**Table 1.1:** Major disasters witnessed in Türkiye between 1990 and 2023[6].

Type of Incident	Province/Region	Date	Loss of Life	Injury
Avalanche	Southeastern Anatolia	1992	328	53
Avalanche	Eastern and Southeastern Anatolia	1993	135	95
Earthquake	Erzincan	13 March 1992	653	3.850
Mudslide	Isparta (Senirkent)	13 July 1995	74	46
Earthquake	Afyon (Dinar)	1 October 1995	94	240
Flood	İzmir	4 November 1995	63	117
Earthquake	Çorum /Amasya	14 August 1996	0	6
Flood	Western Blacksea	21 May 1998	10	47
Earthquake	Adana (Ceyhan)	27 June 1998	145	1600
Earthquake	İzmit Bay	17 August 1999	17.480	43.953
Earthquake	Düzce	12 November 1999	763	4.948
Earthquake	Ayfon (Sultandağı)	3 February 2002	42	327
Earthquake	Bingöl	1 May 2003	177	520
Flood/Landslide	Rize	26 August 2010	14	-
Earthquake	Van (2 incidents)	23 October 2011	644	1966
Flood	Samsun	3 July 2012	13	21
Landslide	Siirt	17 November 2016	16	-
Earthquake	Kahramanmaraş- Hatay	6-20 February 2023	53.537	107.213

On August 17, 1999, a powerful earthquake struck the Marmara Region in northwestern Turkey, resulting in catastrophic consequences. Over 15,000 people lost their lives, and nearly 44,000 sustained injuries. The fault, extending over 500 kilometers, caused extensive damage to buildings, leaving more than 120,000 people homeless. The destruction of these buildings generated vast amounts of debris, particularly in the provinces of Kocaeli, Sakarya, Bolu, and Yalova. The earthquake's impact was felt across an area extending up to 500 kilometers from the fault, including industrial zones. The management of demolition waste began once the search and rescue phase were completed. The debris was disposed of at 17 designated dumpsites across the region, along with several unauthorized dumping locations [7].

In February 2023, Türkiye experienced a series of devastating earthquakes named Kahramanmaraş and Hatay earthquakes that surpassed previous records in scope and destruction. To date, the disaster has resulted in 48,448 fatalities, displaced 3.3 million people, and left nearly two million individuals residing in tent camps and container settlements. The devastation extends across a vast area of 110,000 square kilometers, where apartment towers and village houses lie in ruins in the provinces of Adana, Adıyaman, Diyarbakır, Elazığ, Gaziantep, Hatay, Malatya, Kahramanmaraş, Şanlıurfa, Kilis, Osmaniye. The total construction and debris waste is estimated to be between 100 and 120 million cubic meters [8]. Given in Figure 1.1 below an aerial photograph taken in Hatay after the earthquakes vividly illustrate the extensive impact of the Kahramanmaraş and Hatay earthquakes [9]. These recurring disasters result in

substantial loss of life, economic damage, and significant debris, underscoring the need for robust disaster management systems.



**Figure 1.1:** Kahramanmaraş and Hatay earthquakes, 2023[9].

Consequently, comprehensive planning and systematic improvements in pre-disaster and post-disaster activities are crucial. From this viewpoint, disaster prevention and mitigation strategies should be integrated into all stages of disaster management. Disaster managers conceptualize disasters as recurring events that unfold across four distinct phases: Mitigation, Preparedness, Response, and Recovery [10]. The pre-disaster phase of disaster management is segmented into two stages: mitigation and preparedness, while the post-disaster phase comprises the recovery and response stages. Preparedness phase encompasses planning, training, and educational activities geared towards events that cannot be mitigated. Mitigation phase involves implementing actions aimed at preventing or minimizing the causes, impacts, and consequences of disasters. The response phase occurs immediately after a disaster strikes. During this phase, normal business and operations are disrupted. Personal safety and well-being are paramount during an emergency, and the duration of the response phase is influenced by the level of preparedness. During the recovery period, restoration efforts proceed alongside regular operations and activities. The recovery period following a disaster can be protracted. Waste clean-up is addressed during the

latter two stages. Road cleaning is part of the response phase, aimed at facilitating evacuation and relief efforts. Debris removal from other affected areas occurs during the recovery phase.

## **1.1 Problem Statement**

Effective disaster debris management (DDM) is critical for the recovery stage, a period when decision-makers have more time to design an efficient system compared to the urgent waste clean-up required in the response stage and thereby minimizing environmental and economic impacts. A key component of DDM is the establishment of Temporary Disaster Debris Management Sites (TDDMS), which serve as intermediary locations for sorting, recycling, and temporary storage of debris before final disposal [11]. However, the design and optimization of TDDMS face two primary challenges:

- Accurately predicting the volume, distribution, and composition of debris to allocate resources efficiently.
- Determining the optimal number, location, and service areas of TDDMS to balance costs and environmental benefits.

TDDMS can accelerate debris removal and enable recycling initiatives, but they also increase costs due to double handling of materials [11]. Thus, optimizing TDDMS placement and allocation is critical to achieving cost-efficient and sustainable disaster recovery.

## **1.2 Purpose of Thesis**

This study aims to develop a comprehensive framework for the selection and management of TDDMS to enhance disaster debris removal systems. By addressing critical challenges such as predicting debris amount and selecting TDDMS locations by considering environmental, economic, and engineering criteria, the framework seeks to optimize the efficiency of debris removal processes, improve resource allocation, and ensure sustainability in post-disaster scenarios. It also aims to provide decision-makers with a structured methodology for evaluating and prioritizing TDDMS sites, ultimately leading to more effective disaster response and recovery

operations. This thesis addresses the challenges of disaster debris management by focusing on the recovery phase. Specifically, it aims to:

- (i) Determine the primary and sub-criteria for selecting appropriate TDDMS locations.
- (ii) Develop a clustering-based transportation model to locate the TDDMS and optimizes disaster debris allocation to selected sites.
- (iii) Develop a systematic methodology for identifying the most suitable candidate TDDMS by evaluating environmental, economic, and engineering criteria.
- (iv) Validate the proposed methodology and framework through their application to Istanbul's disaster debris management system.

### **1.3 Contributions of Thesis**

The followings are this thesis's main contributions of this thesis:

- Identification and prioritization of environmental, economical, and engineering criteria for TDDMS selection, allowing for a more systematic approach to site evaluation.
- Development of a new approach that combines spatial analysis with Boolean logic and K-Medoids cluster-based transportation optimization for the selection and allocation of TDDMS.
- Building cost-efficient models to reduce the total cost of debris transportation and allocation while maintaining environmental and engineering constraints.
- Application of the proposed methods to the case of Istanbul to demonstrate their applicability and effectiveness in real-world disaster debris management scenarios.

### **1.4 Outline of the Thesis**

The thesis consists of five chapters as follows:

*Chapter 1* presents the problem, outlining the objectives, and establishing the purpose of the research. It highlights the thesis's contributions to disaster debris management practices and provides an overview of its structure.

*Chapter 2* provides a comprehensive overview of disaster debris management, delving into the complexity of debris categorization, estimation approaches, and the function of TDDMS in disaster recovery. It reveals inadequacies in existing literature and operations, particularly in the integration of site selection, transportation optimization, and multi-criteria decision-making.

*Chapter 3* outlines the methodology, with an emphasis on TDDMS selection, debris volume estimation, and transportation optimization. The selection procedure incorporates GIS and Multi-Criteria Decision Analysis (MCDA), which apply criteria. Debris estimation is modeled using parameters adopted from the 1999 Marmara Earthquake, while transportation optimization employs clustering and algorithmic methods to maximize efficiency.

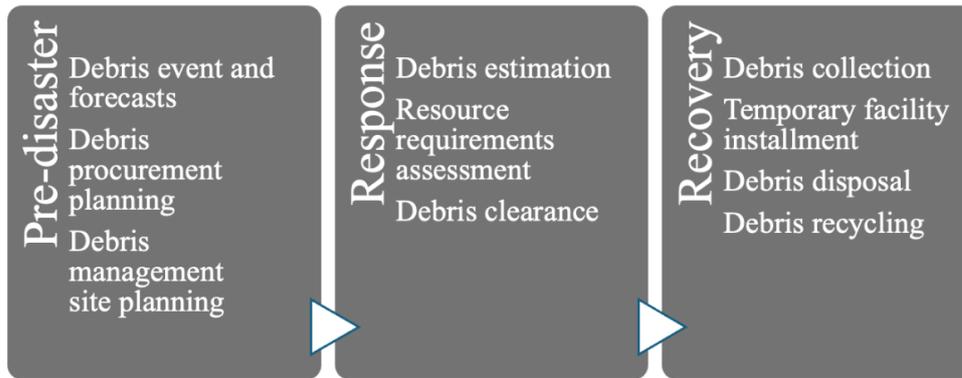
*Chapter 4* applies the methodology to Istanbul, highlighting the city's high seismic risk due to its proximity to the North Anatolian Fault Zone (NAFZ). The GIS-based land suitability study identifies 46 possible TDDMS, which are validated using satellite images and property data. The application focuses on Istanbul's Asian side, utilizing neighborhood-level debris estimations to improve accuracy.

*Chapter 5* highlights the results of implementing the proposed framework in Istanbul, with an emphasis on the comparison of cluster-based and non-cluster-based debris allocation approaches. This chapter also discusses the practical consequences of these findings, highlighting the significance of customizing debris management strategies to particular disaster scenarios. It concludes by reflecting on the study's contributions to disaster debris management while highlighting limitations that propose opportunities for future research.

## **2. DISASTER DEBRIS MANAGEMENT**

### **2.1 Disaster Debris Management**

Debris refers to the remains of anything broken down or destroyed, such as ruins or rubble [24]. Disasters can produce substantial debris, posing significant challenges, especially while in the response and recovery phases of the disaster management cycle. The type of waste produced is largely determined by the nature of the disaster and the characteristics of the affected built environment. Debris clearance, removal, and disposal following disasters pose significant challenges due to their difficulty, time-consuming nature, and expense. In the wake of major disasters, handling the resulting debris places a substantial burden on the infrastructure, economy, and workforce of the impacted area. To illustrate, the overall expenses incurred for managing debris following Hurricane Katrina in 2005, a catastrophe that generated over 100 million cubic yards of debris, are believed to have surpassed 4 billion USD [11]. This accounts for more than a quarter of the total expenditure associated with responding to and recovering from the disaster. The handling of post-disaster debris in the aftermath of the cascading disasters in Japan in March 2011 was made more challenging by the fact that a significant volume of debris was displaced from its original locations by the tsunami. This event also led to the mixing of various types of debris, which further complicated the task of removing over 25 million tons of debris [11]. In the Fukushima region, the inclusion of radioactive debris presented complexities for regional authorities. Three months post-disaster, officials remained undecided on the appropriate course of action for its removal due to the absence of established protocols or guidelines governing its management [11]. The scarcity of available space for debris disposal poses significant challenges, as illustrated by the consecutive disasters in Japan and the earthquake in Haiti in 2010.



**Figure 2.1:** Flow of debris management operations throughout the disaster timeline[12].

Derived from FEMA [12], Figure 2.1 depicts the sequence of debris management events across the duration of a disaster. Preceding the onset of the disaster, each local community is tasked with identifying various potential disaster scenarios, which subsequently inform projections regarding probable debris quantities and compositions. Utilizing these projections, plans are devised for workforce and equipment deployment, alongside the identification of potential debris management facilities such as processing sites, recycling plants, and disposal areas. Shortly after a disaster occurs, an initial evaluation of the affected area is conducted, during which estimations are made regarding the quantity and types of debris present. Additionally, an assessment is made regarding the necessary workforce and equipment needed to address the situation. At this phase, efforts are focused on removing debris from roads to ease the execution of response operations, including search-and-rescue missions and the transportation of relief supplies.

During the disaster recovery phase, debris collection takes place, which involves transporting debris from roadsides and curbsides to temporary processing sites (i.e. TDDMS). At these sites, the debris may undergo various processes including sorting, separation, grinding, incineration, wood chipping, and concrete crushing. Once these procedures are finalized, the processed debris, whether entirely or partially, could be discarded in landfills. Alternatively, specific sections of the debris might undergo additional processing to be recycled, subsequently repurposed, or sold.

### **2.1.1 Temporary disaster debris management sites**

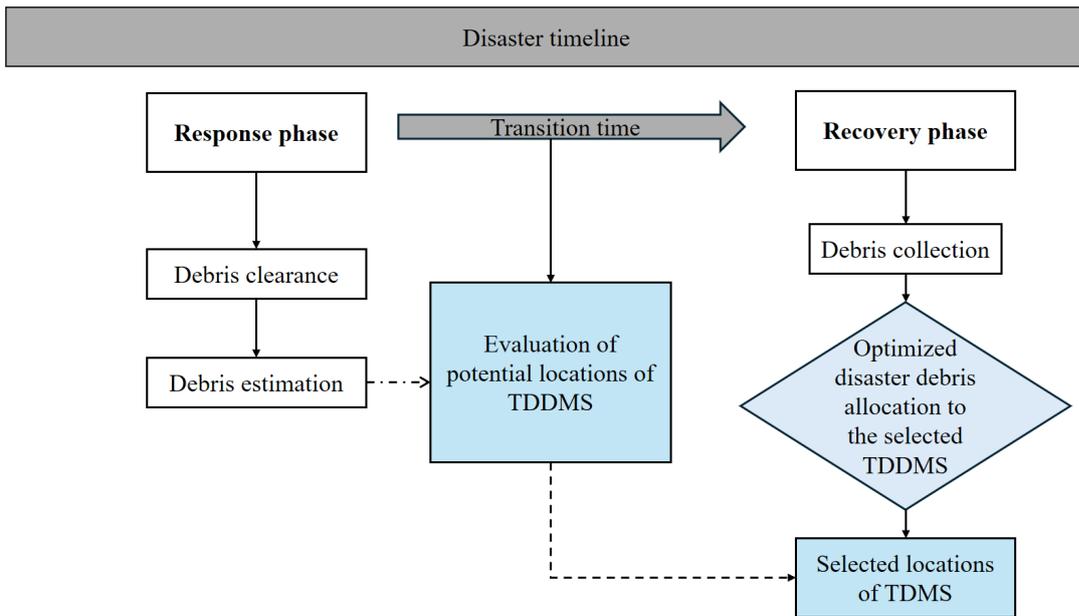
TDDMS play a crucial role in the disaster recovery process, as they help manage debris removal, which is vital for restoring access to affected areas and enabling relief operations. Disaster debris, if not promptly addressed, can disrupt emergency response efforts by blocking roads [13] hindering building access, consequently impeding rescuers, emergency services, and lifeline support from reaching survivors.

During the initial response phase, debris clearance is critical for restoring access to vital infrastructure, followed by debris removal which involves the systematic collection and transport of debris from roadsides and curbsides from disaster-affected regions to designated TDDMS [12], [14]. These sites serve as intermediary locations for sorting, recycling, and temporary storage before final disposal. According to FEMA [12], TDDMS should be positioned between waste generation sites and final disposal locations to facilitate effective waste processing. However, selecting appropriate TDDMS involve significant challenges due to the uncertainty surrounding debris volume and composition, which can vary greatly depending on the nature and scale of the disaster. Additionally, the site selection process must account for factors such as accessibility, environmental protection, and logistical efficiency. Key considerations include ensuring sufficient space for debris processing, accommodating heavy machinery, and minimizing potential environmental impacts while optimizing the overall cost and effectiveness of debris management [14].

TDDMS fulfill several functions within the overall system. The primary roles are as follows [15]:

- TDDMS serve as a buffer by providing space for waste temporarily, facilitating the transportation of debris from disaster-affected areas to these sites.
- At the TDDMS, various processes such as chipping, burning, and sorting are conducted to reduce waste volume and promote recycling and reuse.
- TDDMS serve as interim storage facilities prior to the ultimate disposal of waste.

The function of TDDMS in debris management is illustrated while in the disaster response phase in Figure 2.2.



**Figure 2.2:** Role of TDDMS in disaster debris management.

Following the identification of a range of potential TDDMS, the subsequent phase involves optimizing the disaster debris logistics operations. This endeavor encompasses determining the optimal quantity and locations of TDDMS, as well as allocating the debris efficiently [16].

Operational data pertaining to the dimensions, handling capacity, and resource availability of every potential TDDMS guide the assessment of the overall debris volume that can feasibly undergo storage, sorting, processing, and readying for recycling or landfill disposal. Alongside the projected overall debris volume, this data is utilized to ascertain the requisite quantity of TDDMS. Afterward, the most suitable TDDMS are determined from the potential locations, and the distribution of debris to these chosen TDDMS is accomplished using different linear programming methodologies. The selection of optimal TDDMS and the development of a disaster debris supply chain strategy primarily focused on minimizing the costs associated with debris removal [17], [18], [19], reducing collection time [17], [19], and minimizing the total hauling distance [20]. The cost and time of transporting debris are predominantly influenced by the hauling distance. Hence, information about debris sources, potential TDDMS locations, and the presence of existing waste management facilities are commonly utilized as entry variables in optimization models to ascertain the distance over which debris needs to be transported [20], [21].

## 2.2 Literature Review

Numerous prior studies on disaster debris management provide a comprehensive theoretical analysis of disaster waste management strategies, primarily based on guidelines established by expert organizations such as UNEP and FEMA of the United States.

The principles for disaster waste management in emerging economies were put forward by Asari et al. [22]. The researchers of this study qualitatively examined several disaster waste separation techniques, including categorical sorting (e.g., rubble, waste wood, home appliances, hazardous materials, valuables and items of sentimental value), recycling-oriented separation, incineration, separation of hazardous waste, management of tsunami sediment and provided a thorough description of the available alternatives for waste treatment for each category of debris.

Brown et al. [13] conducted a thorough examination of five past disasters: the 2009 Victoria bushfires in Australia; the 2009 L'Aquila earthquake in Italy; the 2005 Hurricane Katrina in the United States; the 2010 and 2011 Canterbury earthquakes in New Zealand; and the 2011 Great East Japan earthquake. Based on this analysis, seven disaster-specific elements were identified that impact the viability and efficacy of disaster waste recycling. These elements include waste composition and characteristics, waste volume, logistical challenges such as transportation and storage, time sensitivity in waste management to mitigate risks to the environment and public health, local infrastructure capacity, regulatory and legal frameworks, and social and community factors influencing recycling efforts. Together, these elements form a complete framework for comprehending and enhancing disaster waste recycling methods.

Quantitative studies on disaster debris management might aim to select TDDMS, to transport debris to these sites, and to allocate debris to TDDMS. Due to the fact that this paper is focused on selecting TDDMS, and to allocate debris to TDDMS, the following literature review is accordingly.

Onan et al. [21] aimed to create a framework for locating temporary storage sites and managing disaster waste sustainably. This work uses an evolutionary elitist algorithm (NSGA-II) to address a multi-objective optimization model. Istanbul, a city with severe earthquake damage, was chosen to illustrate the suggested framework. The

model's aims are to reduce costs and risks associated with hazardous waste exposure. This study combines disaster loss estimating techniques with post-disaster waste management. However, this study includes TDDMS selection by disregarding geographical conditions. Additionally, the number of TDDMS is determined based on the optimization model result, without precisely describing the criteria for TDDMS. However, based on standard disaster management principles and related literature, such criteria usually include proximity to debris generation points, environmental suitability, accessibility, capacity and space requirements etc. While these criteria are not specifically laid out in this study, their inclusion may improve the robustness and practicality of TDDMS selection in future frameworks. The study is confined to a single side of Istanbul, Türkiye.

Hu and Sheu [23] presented a reverse logistics system for disaster debris management encompassing a temporary storage facility. The notion of temporary storage quite resembled that of TDDMS. The study aimed to reduce overall logistical costs, risk penalties, and psychological costs.

Cheng and Thompson [24] carried out the land suitability analysis for selection of TDDMS using ArcGIS, and the analysis model was built using the Modelbuilder function. Additionally, Boolean logic was employed to standardize the criterion map layers and ten criteria were considered in the analysis. These criteria included the distance from surface water, land use, distance from protected areas, distance from residential areas, land slope, proximity to major roads, road accessibility, distance from waste generating sources, land ownership, and site size. A total of 45 prospective sites were chosen from the case study region, Victoria, Australia. The research found that the most critical variables are the distance from groundwater, drinking water resources, and public water supply.

Grzeda et al.[25] constructed a comparable mechanism for selecting TDDMS. They began by providing a detailed explanation of the environmental, social, technical, and legal assessment requirements for opting for debris management sites, and then they used their results to identify potential TDDMS in Hamilton County, Indiana. At the initial step, GIS was utilized to document the characteristics of potential debris management sites, and in the following step, binomial cluster analysis was used to identify the best debris management sites. However, this suitability evaluation was carried only to help in the pre-disaster planning of potential TDDMS, not to determine

the actual number of TDDMS and where they'll be placed during debris removal activities. Conversely, this study emphasizes enhancing the final selection process for TDDMS from among the potential sites.

Kim et al. [15] proposed a two-phase TDDMS selection process. The study combines data from a HAZUS-MH loss assessment report, Post Disaster Needs Assessment (PDNA), and GIS into a dynamic simulation model. During the first step, the GIS was used to extract the features of possibly accessible alternatives and select eligible locations for debris management sites. In the second phase, transportation distances from waste pickup stations to the chosen temporary debris management sites were lowered.

Lorca et al. [26] introduced a decision-support tool to help disaster and waste management professionals collect, transport, reduce, recycle, and dispose of debris. The tool optimizes and balances both financial and environmental expenses, disposal time, landfill utilization, and levels of recycling. The proposed approach incorporates several objectives, including reducing expenses and impact on the environment, shortening operational times, and increasing revenue from recycled materials. Furthermore, the tool facilitates both pre-disaster strategic planning—such as identifying viable processing sites and conducting what-if analyses—and post-disaster operational decision-making, such as determining transport paths and processing capabilities. The tool's user-friendly design and visualization capabilities make it accessible to experts who lack extensive optimization knowledge, bridging the gap between theoretical models and practical applications in disaster debris management.

Fetter and Rakes [27] devised a MILP model for choosing a DDM location with the goal of reducing total costs while taking into account recycling revenue. They explained how the model may be utilized for determining the number and location of TDDMS, as well as designate debris cleaning areas analyzing the area of Chesapeake, Virginia. Researchers utilized past records of debris cleaning activities after Hurricane Isabel's impact in 2003. The data encompasses quantities, locations, and expenses associated with collection operations and TDDMS activities.

Habib and Sarkar [28] presented a combined approach for selecting TDDMS and allocating debris during the disaster response phase that takes into account all regional and local restrictions. They introduced a MCDM process for the selection of TDDMS.

The MCDM process integrates ANP with the fuzzy TOPSIS. ANP is applied to determine the weights of evaluation criteria, while fuzzy TOPSIS is applied to rank the available alternatives. To tackle the uncertainty of the environment following a natural disaster, they presented a fuzzy possibilistic debris allocation model, with all entry parameters deemed unknown.

Wang et al. [17] proposed a multi-objective MILP method for reverse logistics decision support. The study then specifically incorporates data on debris volume and distribution into an optimization for debris removal aiming to maximize environmental advantages while minimizing the overall removal expenses and the total duration of reverse logistics (encompassing the sorting, handling, hauling, recycling, and disposal of waste, etc.).

Dincer and Demir [29] conducted a research for a very recent disaster, which is Kahramanmaraş Earthquake (2023). The research points to eight TDDMS based on numerous environmental and technological criteria. The research considers emissions from debris transportation while determining TDDMS. An algorithm designed to calculate emissions for each map pixel based on the transportation network is created and integrated with GIS to determine the optimal TDDMS. The first section examines the use of AHP and GIS to determine the best TDDMS in Kahramanmaraş. To prioritize TDDMS, in the following section, the TOPSIS technique was utilized to evaluate options by proximity to the optimal solution.

While previous studies provided useful insights into DDM, considerable gaps remain. These include the lack of an integrated structure combining site selection and debris allocation, inadequate consideration of geographical and environmental constraints, and the necessity for improved optimization methods. Furthermore, comprehensive techniques that consider transportation costs, environmental effect, and real-world validation utilizing multidimensional criteria are frequently disregarded. My thesis fills these gaps by creating a strong, cluster-based transportation optimization model that incorporates MCDM and spatial analysis to improve disaster debris management efficiency.

A considerable body of research has utilized GIS in conjunction with various decision-making and optimization approaches to solve the issues of TDDMS. These procedures span from Boolean logic and binomial cluster analysis to advanced MCDM methods

like AHP, TOPSIS, and FAHP. Table 2.3 summarizes the most important studies in this subject, emphasizing the methods used and case study sites. The methods used in the reviewed studies can be categorized into three groups: AHP-based methods, which rely on the Analytic Hierarchy Process without modifications; AHP variants, which combine AHP with other techniques such as TOPSIS, FAHP, MRSS-ANP, and ANP-SAW; and other methods, which include multi-objective optimization (NSGA-II), Boolean logic, binomial cluster analysis, and other MCDM techniques. This comparative evaluation provides a framework for addressing gaps and supporting the existing study methodology. Table 2.4 provides an overview comparison of the key methodologies, and locations of focus identified in the examined studies.

Overall, while the reviewed studies provide valuable insights into various aspects of TDDMS selection and debris allocation, there remains a significant gap in integrating these approaches into a unified framework that incorporates not only multi-criteria decision-making and optimization methods but also considers transportation costs, environmental impacts, and real-world validation in disaster management contexts. The current study aims to address these gaps by developing a cluster-based transportation optimization model that enhances the efficiency and sustainability of TDDMS selection and debris allocation, incorporating GIS to support decision-making in the selection process.

**Table 2.1:** Summary of research on gis-based waste disposal site selection.

Reference Number	Location	Methodology
[21]	Istanbul, Turkey	GIS – NSGA-II
[24]	Victoria Australia	GIS – Boolean logic
[25]	Indiana, USA	GIS - Binomial Cluster Analysis
[29]	Kahramanmaraş, Turkey	GIS – MCDM (AHP-TOPSIS)
[30]	Istanbul, Turkey	GIS – MCDM (FAHP)
[45]	Edirne, Turkey	GIS – MCDM
[31]	Javanrood County, Iran	GIS – MCDM (AHP-TOPSIS)
[32]	Istanbul, Turkey	GIS – MCDM (AHP)
[33]	Konya, Turkey	GIS – MCDM (AHP)
[34]	Selangor, Malaysia	GIS – MCDM (MRSS-ANP)
[35]	Northern Cyprus	GIS – MCDM (AHP)
[36]	Sanliurfa, Turkey	GIS – MCDM (SAW)
[37]	Qom City, Iran	GIS – MCDM (AHP)
[38]	Birjand, Iran	GIS – MCDM (ANP-SAW)
[39]	Konya, Turkey	GIS – MCDM (AHP)

**Table 2.2:** An overview of the selected studies in debris removal.

Reference Number	TDDMS Identification		TDDMS Selection Technique	Debris Allocation Optimization		Other Factors
	Multi-Criteria Based	Cost Based		Model Objective	Model Formulation	
[21]		√	Multi-objective optimization algorithm (NSGA-II), GIS	Selection of locations of temporary storage facilities, and planning for the collection and transportation of disaster waste	The bi-objective location–allocation model	Hazardous waste exposure risk
[15]	√		Post Disaster Needs Assessment (PDNA) and GIS	Minimize total hauling distance	Linear programming	
[26]		√	Mixed integer linear programming (MILP)	Minimizing the financial cost, environmental cost, debris, collection time, and disposal time	The analytical model	
[25]	√		Binomial cluster analysis			
[23]		√	Linear programming	Minimizing total reverse logistical costs	A multi-objective linear programming model	Environmental and operational risks psychological cost
[24]	√		Boolean logic			
[40]		√		Minimize the total cost of locating facilities	Mixed Integer Linear Programming (MILP)	Maximize recycling income

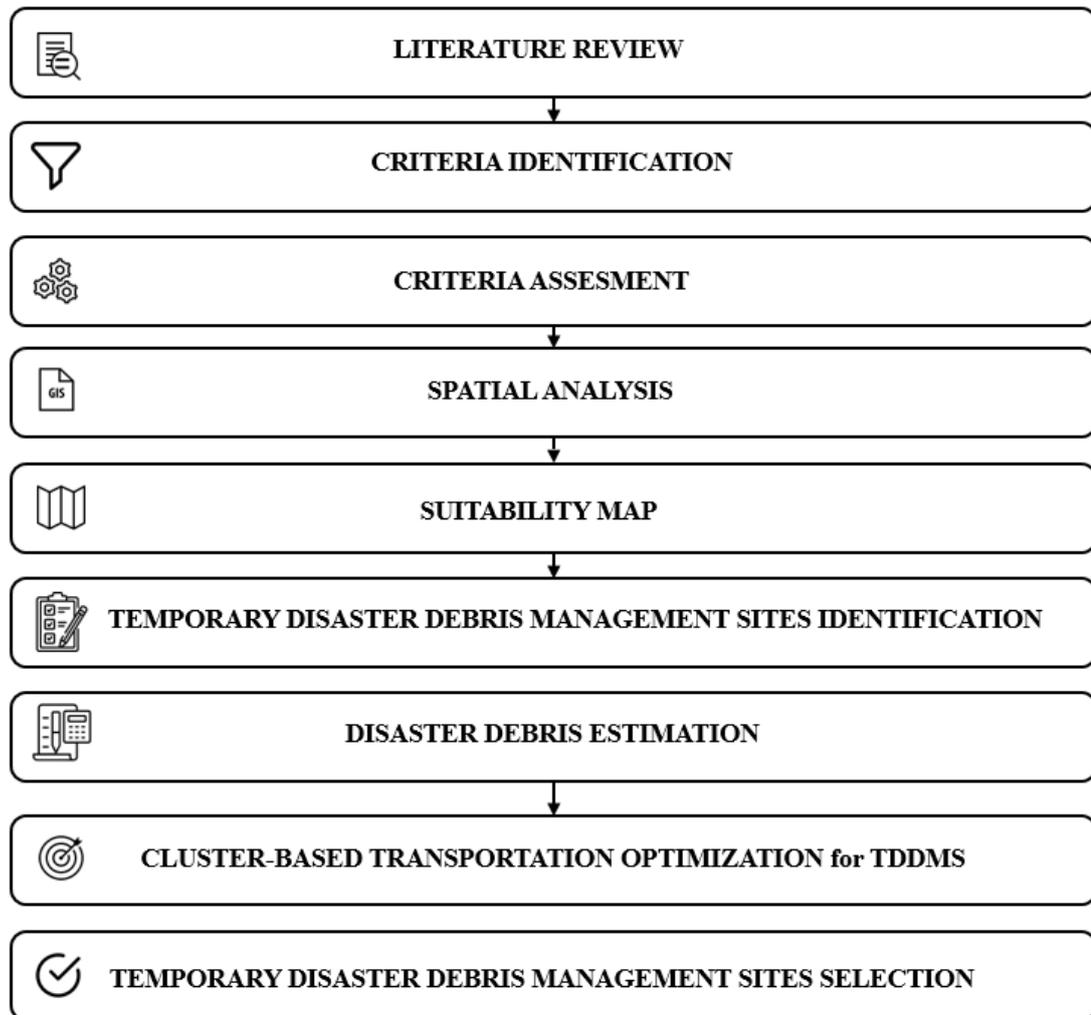
**Table 2.2 (continued):** An overview of the selected studies in debris removal.

Authors	TDDMS Identification		TDDMS Selection Technique	Debris Allocation Optimization		Other Factors
	Multi-Criteria Based	Cost Based		Model Objective	Model Formulation	
[28]	√		Analytical Network Process (ANP) and fuzzy TOPSIS	Minimize total transportation cost	Fuzzy possibilistic programming	Response phase uncertain environment
[17]				Minimize the aggregated removal cost and the total reverse logistical time	Mixed Integer Linear Programming (MILP)	Increasing the environmental benefits
[29]	√		Analytical Network Process (ANP) and TOPSIS			Emissions from waste transportation
Current Study	√		Equal Weight Method, Boolean Logic	Minimize total transportation cost	Mixed Integer Linear Programming (MILP), K-Medoids Algorithm	



### 3. METHODOLOGY

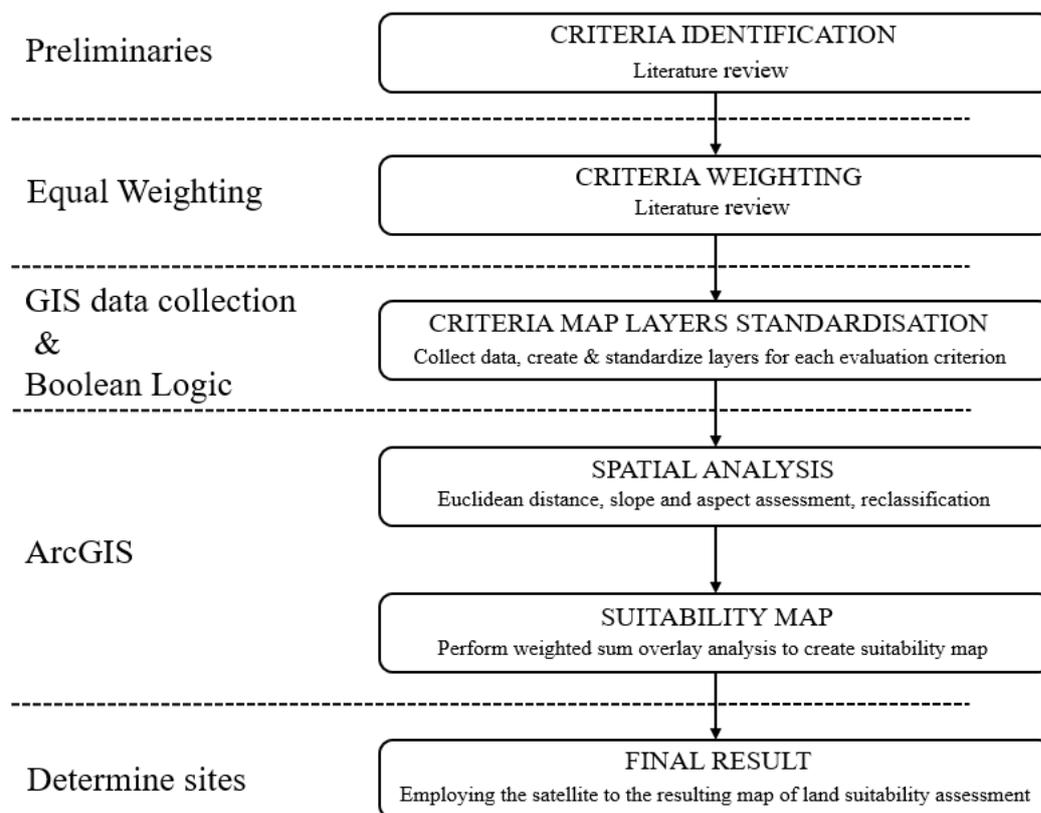
Disaster debris management entails an effective and methodical approach that addresses the complications of site selection, debris volume estimation, and transportation optimization. Figure 3.1 depicts the approach employed in this study, including the sequential processes taken to identify and manage TDDMS. The process starts with a literature review, which lays the theoretical and practical groundwork for the methodology. This is followed by the identification of possible TDDMS, which includes criterion assessment and spatial analysis to generate a suitability map. Once viable sites have been identified, the attention moves to disaster debris estimation and optimization models, which provide cost-effective and efficient debris allocation to the chosen sites.



**Figure 3.1:** Methodology overview of identifying the most suitable TDDMS.

### 3.1 Temporary Disaster Debris Management Sites Identification

The selection of candidate TDDMS can be viewed as a land suitability analysis problem. Figure 3.2 depicts the methodology applied in the present study, which involved a structured, multi-step approach. This procedure starts with identifying and weighing evaluation criteria based on literature research, then standardizing criteria map layers with GIS data and Boolean logic. Spatial analysis techniques, including Euclidean distance, slope, and aspect evaluation, are applied to create a suitability map through weighted sum overlay analysis. The final stage entails identifying candidate sites using satellite images to validate land suitability assessment map. This chapter mainly aims to to develop a methodology for identifying TDDMS candidates within the framework of land suitability analysis.



**Figure 3.2:** Methodology of land suitability analysis.

#### 3.1.1 Selection criteria for temporary disaster debris management sites

The suitability assessment module begins with delineating the criteria for including or excluding potential TDDMS [41]. The most important aspect in candidate selection of TDDMS is to identify the criteria to be considered. These criteria outline the necessary geographical attributes for the TDDMS. According to the EPA [42], TDDMS should

be located at a suitable distance from wells, rivers, lakes, floodplains, wetlands, environmentally sensitive areas, residential areas, and cultural properties. Additionally, they must possess adequate size and accessibility.

While Section 2.4 provided a thorough review of the methodologies and frameworks used in previous studies for TDDMS selection, this section focuses on consolidating the criteria outlined in widely accepted DDM guidelines [43] and Debris Management Guide [12].

DDM guidelines [43] presents a detailed set of criteria for selecting TDDMS. These criteria are intended to ensure that selected sites are environmentally suitable, operationally efficient, and safe for the public. The main concerns are as follows:

- Appropriately scaled relative to the volume of debris.
- Located on public land.
- Not located in floodplains, wetlands, agricultural areas.
- Located away from potable water sources, including wells, rivers, lakes, streams, and drainage channels.
- Free from obstructions.
- Have the capacity to accommodate rubble and natural debris.
- Ensure public health and safety is not compromised.
- Located near the affected area.
- Possess adequate size with suitable topography and soil composition.
- Include measures to mitigate stormwater runoff, erosion, fires, and dust if feasible.
- Access restricted to specific areas open to the public.

In addition to DDM guidelines [43], Debris Management Guide [12] outlines precise criteria for selecting and managing TDDMS. These criteria are intended to address ownership, size, location, and environmental concerns to promote effective and sustainable debris management. Ownership criteria prioritize public lands, followed by existing disposal or recycling facilities near disaster-affected areas, with potential consideration for private property if neither option is feasible. For size criteria, it is

essential to ensure sufficient space for waste treatment activities. Location criteria emphasize ample availability for TDDMS placement. Environmental and historic preservation concerns require evaluating pre-existing conditions, as sites must undergo restoration upon closure.

The summary below classifies the criteria into three main categories: ownership, size, and location.

1. **Ownership:** Public land is preferable due to lower rental costs. However, if public land is unavailable, private land can be considered under specific conditions.
2. **Size:** It's crucial to select sites large enough to accommodate debris treatment and storage requirements. Factors such as debris generation rates, site operations, and storage duration should be considered.
3. **Location:** Candidate TDDMS should not pose hazards in residential neighborhoods or near schools, disrupt local businesses, obstruct traffic flow on major transportation routes. Preferably, they should be situated away from residential areas, schools, churches, hospitals, and other sensitive locations. Additionally, sites should have good access and connectivity to major transportation routes.

Determining the TDDMS through land suitability assessment has been a focal point in research. Four primary steps are typically involved: criteria identification, criteria weighting, criteria map layer standardization, and criteria map layer overlaying, aimed at selecting suitable TDDMS. The initial step commonly involves identifying criteria for assessment, with a wide variety of criteria explored in prior studies. A search was carried out on Google Scholar using targeted keywords pertinent to the study, such as "*Temporary Disaster Debris /Waste Management Sites*", "*Waste Management Site*", "*Landfill Site*" along with "*GIS*" and "*MCDM*" 20 recently published national and international articles were reviewed using these keywords. Subsequently, the articles were filtered to identify potential evaluation criteria for selecting TDDMS and listed in Table 3.1. The table provides an overview of research articles focused on waste disposal site selection, with a particular emphasis on TDDMS and other landfill types, using GIS and MCDM methods. The studies span a range of years, from 2006 to 2024, and involve various criteria for site selection. Common criteria include land use,

proximity to water bodies (e.g., rivers, lakes, groundwater), distance from residential areas and protected zones, slope, soil and geological conditions, accessibility, and environmental and historical considerations. Several studies also examine the integration of remote sensing, GIS, and MCDM techniques to enhance the effectiveness of site selection for TDDMS and landfill facilities, while addressing environmental, operational, and social/safety concerns.



**Table 3.1:** Overview of research on waste disposal site selection that employ GIS.

Research Category	Reference Number	Year	Criteria
TDDMS	[29]	2023	Land use, distance to heavily demolished area, slope, elevation, distance to the populated area, distance to the roads, distance to the rivers, land ownership.
TDDMS	[24]	2016	Distance from surface water, land use, distance from protected areas, distance from residential areas, slope, distance from main roads, road accessibility, distance from waste generation source, ownership, size.
TDDMS	[25]	2014	Land use and land cover, topography, drainage networks, wetlands, floodplain boundaries, water reservoirs and public wellfields, threatened flora and fauna along with associated habitats, lithology, soil types, seismic fault zones, geologically unstable areas, coastal zone boundaries; as well as cultural features, transportation networks, utilities, medical facilities, religious complexes, cemeteries, schools, parks, historic sites and populated places.
HSWLS	[30]	2024	Land cover, soil and rock structure, surface and ground waters, slope, aspect, fault line, roadways, wind speed, land value.
HSWLS	[44]	2019	Distance to hazardous waste sources, available infrastructure, distance to residential development, distance to cultivated land and recreational parks, distance from airports, distance to transportation routes, groundwater, surface water boundary, soil hydraulic conductivity, wetlands, drainage system and flood plain, topography, depth to bedrock, main geological structure: fold, faults, fissures, and joints, slope, sand dune movement: direction and rate of movement.
MSWLS	[45]	2021	Distance from domestic water supply, distance from rivers, distance from lakes and ponds, distance from conservation and protected areas, forest lands, slope, soil erosion Geology, accessibility (distance from roads), agricultural lands, distance from urban and industrial areas, wind direction.
MSWLS	[31]	2019	Distance to surface water resources, distance to groundwater resources, land use/land cover, distance to faults, distance to residential areas, distance to protected areas, geology, aspect, distance to roads, slope.
MSWLS	[37]	2018	Distance from power line, network of access routs, distance from airport, distance form saline area, land use, distance from urban areas, distance from rural area, distance from historical sites, ground water protection, slope, distance from fault zone, distance from water wells.
MSWLS	[32]	2017	Land use, geology, settlement areas, surface waters, population density, airports, protected areas, slope, solid waste transfer stations, land values, roads.
MSWLS	[33]	2014	Distance from residential and industrial areas, distance from rivers, lakes, wetlands, coastal area and dam; distance from groundwater wells, distance from protection areas distance from infrastructure suitability (e.g. electrical supply lines, oil ducts and water pipelines), land use, slope, geology, distance from roads and railway, elevation, distance from tourism and historical sites, distance from airport.

**Table 3.1 (continued):** Overview of research on waste disposal site selection that employ GIS.

Research Category	Reference Number	Year	Criteria
MSWLS	[46]	2013	Aquifer vulnerability, distance from fault zones, exclusion of the verified geothermal fields., mineral exploitation industries and water reserve facilities, seismic hazard assessment, soil permeability, slopes, elevation, soils texture, environmentally protected areas, surface water protection, forests protection, pluviometry, wetlands protection, temperature, distance from permanently irrigated areas, protection from strong winds, distance from national borders/coastline, land use evaluation, distance from residential areas, distance from industrial and commercial units, distance from historical/cultural sites, distance from the transportation network, source of waste consumption, road network discriminations, distance from airports, public utilities (power lines, pipelines, gas lines), salinization zones.
MSWLS	[47]	2014	Groundwater depth from surface, lithology, permeability of the overlying layer, topographic slope, land use, proximity to streams, airports and industrial areas, proximity settlements, roads and highways as well as power lines.
MSWLS	[48]	2013	Distance to water surfaces, sensitive ecosystems, land cover, distance to urban and rural areas, land uses, distance to roads, slope, distance to waste generation places.
MSWLS	[35]	2012	Distance from waste generation centres, distance from roads, slope, distance from surface waters, distance from ground waters, distance from environmentally sensitive areas, vegetation, soil productivity, soil permeability, distance from settlements, distance from cultural heritage, distance from quarry areas.
MSWLS	[36]	2012	Settlement areas, land use, aquifer, geology, surface water, elevation, slope, airport, power lines, roads, industrial sites.
MSWLS	[49]	2012	Distance from pounds, lakes, swamps, wetlands, coastal areas, dams and rivers; distance from residential areas, distance from seismic areas, distance from environmental protection areas, distance from historical monuments, distance from infrastructure (electrical supply lines, oil ducts and water pipelines), distance from international airports and 3 km from local airports, distance from highways, main roads and freeways.
MSWLS	[39]	2010	Distance from settlements, distance from surface waters, distance from protected areas (ecologic, scientific or historic), geology/ hydrogeology, land use, distance from, roads, slope, height, aspect.
MSWLS	[50]	2009	Residential areas, surface water bodies, ground water, airport areas, land uses, slope, price of land, roads, proximity to waste production centers.
MSWLS	[51]	2007	Lake and ponds, rivers, water supply sources, groundwater table, groundwater quality, infiltration, air quality index, geology, fault line, elevation, land use, habitation, highways, sensitive sites.
MSWLS	[52]	2006	Residential areas, land uses, highways and railways, environmentally protected areas, important aquifers, surface water bodies, springs and wells, exceptional geological conditions, distance from country borders and the coastline.

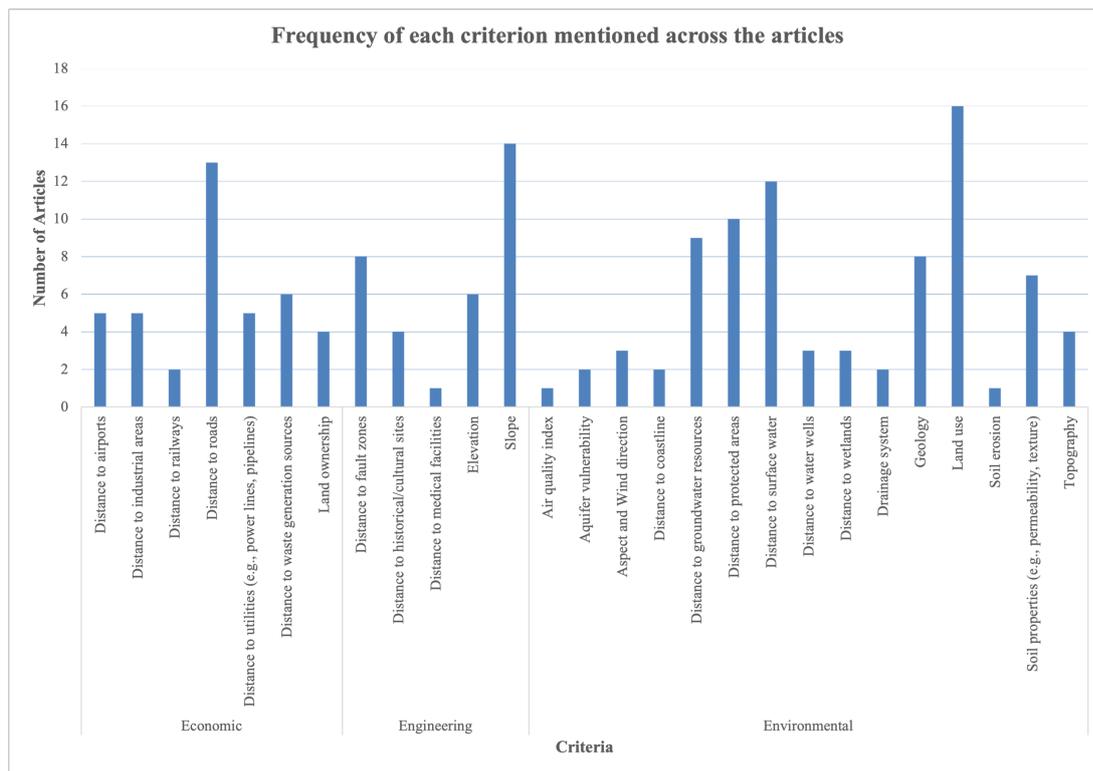
After identifying all the criteria evaluated in the articles, they were categorized into a higher-level hierarchy. Previous studies commonly classified criteria into three categories: environmental factors, social factors, and economic engineering factors.

To ensure environmental sustainability, logistical feasibility and minimal social disruption, the identification of TDDMS encompasses a multi-faceted approach. Land use plays a critical role, covering areas such as forests and agricultural land, which are assessed for their environmental and regulatory significance. Distance from built areas, consolidating both residential and industrial zones, is also a key consideration, ensuring that TDDMS are positioned at an appropriate distance to minimise disruption to urban and industrial activities. Geology and topography are crucial considerations in assessing soil stability and drainage suitability, while distance from water resources, including surface water, groundwater, wetlands and wells, is carefully assessed to avoid contamination risks. In addition, to reduce environmental, cultural and health impacts, sites are avoided near protected areas, historical or cultural sites and medical facilities. Infrastructure considerations include distance from roads, railways, industrial areas and utilities such as power lines and pipelines. These factors promote efficient transportation and operations while ensuring that critical infrastructure remains undisturbed. To ensure the stability and practicality of potential sites, slope, elevation and soil characteristics (such as permeability and texture) are assessed. To minimise the spread of dust and odours, particularly near built-up areas, aspect and wind direction are assessed. In order to maintain long-term environmental integrity, environmental factors such as the vulnerability of aquifers, drainage systems, soil erosion and air quality are taken into account. Distance to the coastline is also considered. This is to avoid risks associated with erosion or sea level rise. In addition, criteria such as the movement of sand dunes and the distance to fault zones are included to improve the safety of the site and its resilience to natural hazards.

Table 3.2 provides a classification of criteria employed in the identification of TDDMS based on high-level categories such as environmental, economic-engineering, and social factors. These criteria, sourced from various articles, encompass a wide range of considerations.

**Table 3.2:** Class definitions.

High-Level	Criteria	Article Numbers
Environmental	Land use	16
	Geology	8
	Distance to surface water	12
	Distance to groundwater resources	9
	Distance to protected areas	10
	Distance to wetlands	3
	Distance to water wells	3
	Topography	4
	Aquifer vulnerability	2
	Drainage system	2
	Sand dune movement	1
Economic - engineering	Slope	14
	Elevation	6
	Land ownership	4
	Distance to railways	2
	Distance to waste generation sources	6
	Distance to airports	5
	Distance to industrial areas	5
	Distance to fault zones	8
	Distance to utilities (e.g., power lines, pipelines)	5
	Distance to coastline	2
	Soil properties (e.g., permeability, texture)	7
Social	Aspect and Wind direction	3
	Distance to roads	13
	Distance to residential areas	12
	Distance to historical/cultural sites	4
	Distance to medical facilities	1
	Soil erosion	1
	Air quality index	1



**Figure 3.3:** Frequency of each criterion mentioned across the articles.

The range of criteria covered in the articles varies as depicted in Figure 3.3. Certainly, including more criteria typically enhances the reliability of analysis results. However, a higher number of criteria can also increase the complexity of analysis. Additionally, the importance of each criterion can vary depending on the decision-maker and specific circumstances. For instance, in landfill siting, assessing potential impacts on groundwater is crucial due to the generation of leachate. However, this criterion may not be relevant for TDDMS siting, given their temporary nature. TDDMS are utilized only for a short duration following disasters. Therefore, the likelihood of leachate generation is minimal. In summary, a range of 9 to 13 selection criteria is typically deemed sufficient for identifying suitable TDDMS [24].

### 3.1.2 Sizing for temporary disaster debris management sites

The acreage requirements for TDDMS are primarily influenced by predictions made before a disaster or estimates generated after a disaster regarding the amount of debris [25]. Though predicting precise debris amounts may prove difficult [53], FEMA suggests a minimum of 100 acres per million cubic yards (40 hectares per 0.76 million cubic meters) of debris, drawing from historical disaster data, experience, and

operational insights [12], considering that around 60% of this land space is designated for roads, safety zones, burn pits, and areas for hazardous household waste.

### **3.1.3 Assessing criteria for temporary disaster debris management sites**

Identifying TDDMS can be regarded as a type of land use suitability assessment, requiring an inventory of land parcels followed by prioritization according to defined constraints to support decision-making. In the context of TDDMS, however, this decision-making process is frequently deferred until a disaster event takes place. Various disciplines have conducted land use suitability assessments, covering areas such as locational theory, industrial site selection, habitat analysis, environmental evaluation, and land use planning [25]. These consist of wildlife management, operations research urban planning, geography, resource conservation.

Once the criteria are defined, the subsequent step is to determine the importance of each by assigning appropriate weights. Three widely used methods for addressing the varying importance of each criterion are Equal Weight, AHP, and ANP. In the Equal Weight method, each criterion is treated with equal importance. AHP provides a structured framework for analyzing and addressing complex decisions. Developed by Saaty [54], it draws on principles from mathematics and psychology to facilitate decision-making processes. Criteria are ranked according to their significance in achieving the overall objective of the evaluation. This is usually achieved by constructing pairwise comparison matrices to assess the relative importance of the criteria. In the AHP, each criterion is considered independent of the others. On the other hand, the ANP is a more comprehensive version of AHP used in MCDA, taking into account the interdependencies among the criteria [55]. Based on the provided summary in Table 3.3, AHP emerged as the most commonly employed method and has seen growing popularity over the past few years. Additionally, numerous articles employed the equal weight method.

**Table 3.3:** Methods used for weighting criteria.

Criteria weighting method	Reference
AHP	[29], [30], [31], [32], [33], [35], [37], [39]
ANP	[34], [38]
Equal Weight	[24], [25]

While suitability assessments are typically conducted with a focus on long-term land use planning, the suitability of TDDMS is based upon short-term and fluctuating demands driven by factors such as the type, location, extent, and severity of the disaster event.

To make various criteria comparable, each criterion's units must be standardized to ensure consistency. Common methods for achieving this include boolean logic and fuzzy logic. Boolean logic simplifies all values in algebra to either TRUE (1) or FALSE (0). This implies that each criterion determines whether the land is suitable or unsuitable for a waste management facility. Cheng and Thompson [24], Nickdoost and Chois [41], Eskandari et al. [56] and [57] utilized Boolean logic in their studies.

Fuzzy logic operates as a multi-valued logic system, allowing truth values to range anywhere between 0 and 1. Furthermore, the application of linguistic variables enables the use of specific functions to handle these degrees. In articles concerning the site selection of waste management facilities, two distinct methods of employing fuzzy logic have been utilized. For example, Sadek et al [58], Demir and Dincer [29], Ghobadi et al. [59] assessed land into categories of suitable, unsuitable and moderately suitable or marginally suitable. In other cases, land was evaluated using a continuous value based on fuzzy membership [38], [60], [61], [62].

MCDA combines and transforms spatial and non-spatial data to arrive at a final decision [63]. To incorporate both data and subjective evaluations, MCDA methods can be integrated with GIS such as studies given in Table 2.3.

GIS demonstrates the capacity to identify, correlate, and analyze spatial relationships among mapped phenomena, facilitating policymakers in integrating disparate information sources, conducting sophisticated analyses, visualizing trends, and overlaying diverse criteria and approaches for strategic planning objectives [64]. Additionally, GIS is widely regarded as its significant role in the field of TDDMS selection, which has been addressed through MCDA. In the majority of articles

focusing on criteria analysis tools, GIS were employed extensively [64]. The merit of utilizing a GIS-driven method for selecting sites lies in its capacity to decrease both time and costs, while also furnishing a digital database for the ongoing site monitoring [51]. Additional merits of utilizing GIS, while siting TDDMS encompasses:

- Applying objective zone exclusion processes guided by a specified set of evaluation criteria,
- Buffering and zoning capabilities,
- Management and correlation of extensive and intricate spatial datasets,
- Presentation of outcomes through mapping and graphical representation techniques.

### **3.2 Disaster Debris Volume Estimation Disaster Debris Composition**

The characteristics of disaster debris largely depend on the type of disaster that generates the waste. The diverse array of events that generate debris results in a wide range of debris types [65]. The debris originating from disasters can be classified into three primary categories: those directly attributable to the disaster event (e.g., green waste, rubble, and white goods), those arising indirectly (e.g., spoiled food due to power outage), and those emerging as a consequence of lifestyle adjustments (e.g., batteries and plastic water containers) [66].

The nature of the disaster significantly influences both the characteristics and volume of debris produced. For instance, fires typically leave behind ash, vegetation, smoke-damaged furniture, metal remnants from burned structures or vehicles, charred lumber, along with concrete, soil, and foundations. Floods, on the other hand, generate debris such as household items, plastic sheeting, mud, vegetation, sandbags, and demolition remnants. Hurricanes and tornadoes typically result in demolition debris, plastic bottles, sheeting, and batteries, as well as green waste. The debris types and corresponding examples [67] are given in Table 3.4.

**Table 3.4:** Debris types and relevant examples[67].

Type	Example
Construction and Demolition (C&D)	The damaged components of buildings and structures encompass a variety of materials, including wood, glass, metal, roofing material, tile, carpeting, concrete, and equipment.
Vegetative	Tree limbs and branches stacked in large piles on public rights-of-way.
Chemical, Biological, Radiological, and Nuclear-Contaminated Debris	Debris contaminated with hazardous materials resulting from an explosive event involving chemical, biological, radiological, or nuclear threat agents.
Putrescent Debris	Decomposed animal remains or other organic components, such as plant wastes. Identified by a bad odor and microbiological activity.
Vehicles and Vessels	Abandoned vehicles or vessels obstructing entry and exit points in public-use areas.
Soil, Mud, Sand	Deposits on improved public property and rights-of-way resulting from floods, landslides, and storm surges.
White Goods	Electrical or mechanical devices used in homes
Infectious Waste	Contaminated animal waste, human blood, pathological waste, and discarded medical instruments.
Hazardous Waste	Waste possessing properties that render it potentially harmful to human health or the environment.

### 3.3 Disaster Debris Generation

The volume and composition of debris, often greatly exceeding the regular solid waste generated under normal conditions, can quickly overwhelm traditional disposal systems [13]. A single event can generate debris volumes that are 5 to 15 times greater than the yearly waste produced by the affected community [19]. Table 3.5 sums up the debris produced during previous disasters, confirming that the volume of debris produced by these events is substantial.

**Table 3.5:** Debris generation of past disasters.

Disaster	Country	Date	Debris Generation	Reference
Hurricane Hugo	USA	1989	2 million	[66]
Erzincan earthquake	Türkiye	1992	500,000 million tons	[68]
Hanshin-Awaji earthquake	USA	1995	20 million tons	[68]
Hyogo-ken-Nambu	Japan	1995	20 million tons	[66]
Marmara Earthquake	Türkiye	1999	13.18 million tons	[7]
Hurricane Katrina	USA	2005	over 100 million CY	[69]
India Ocean Tsunami	Sri Lanka	2004	0.5 million	[70]
Haiti earthquake	USA	2010	30 million to 78 million CY	[71]
Black Saturday Bushfires	Australia	2009	380,000 tons	[72]
Great East Japan earthquake	Japan	2011	28 million m <sup>3</sup>	[73]

### 3.4 Disaster Debris Estimation

Estimating the volume and types of debris produced by different disasters is vital for effective disaster recovery. However, accurately estimating the debris generated by a disaster is a difficult task due to the numerous factors like the building's purpose, structural types, sizes of dwellings, or a combination of these elements [74] that must be considered. Moreover, inaccurate debris amount estimates can result in substantial financial costs [75]. Therefore, the accuracy in predicting the volume of disaster debris is significant for cost mitigation, as well as determining the size needed for disaster waste management sites [76]. Various tools have been developed to assist in

predicting, modeling, and estimating disaster debris volumes. Forecasting and estimating debris volume can be achieved through various methods, including:

- Utilizing historical disaster data [77], [78],
- General formulas [12]
- Employing modeling tools such as,
  - FEMA's Hazards U.S. Multi-Hazard software [80],
  - The Broward County Hurricane Debris Estimation [81],
  - The US Army Corps of Engineers Hurricane Debris Estimating Model [82],
  - ShakeMap to aid in generating shaking and intensity maps. These maps are utilized in earthquake planning, post-earthquake engineering and scientific analyses, emergency response, and loss estimation [83].
- Statistical/mathematical models [77], [84], [85], [86], [87],
- Remote sensing methods [88], [89], [90], [91], [92].

In the absence of historical disaster data, debris per unit generation can be estimated from prior events [93] or local inventories of household items [94], [95] or types of buildings [96], [97]. For instance from one of recent studies conducted in Türkiye, Demir and Dincer [87] employed a blend of mathematical models, on-site surveys, and formally released documents to estimate the volume of disaster debris. By assuming a unit density of 1.00 t/m<sup>2</sup> and an average residential unit size of 150 m<sup>2</sup> in Türkiye, they estimated that the total quantity of construction and demolition (C&D) debris generated in Kahramanmaraş from the 2023 earthquakes would be roughly 15 million tons in weight and approximately 9.1 million cubic meters in volume. They incorporated household item debris in their analysis, which adds to the overall debris and need to be incorporated into the recycling process, in addition to C&D debris. Following an on-site investigation, the total weight of household items was adjusted to 414 kg per household for Türkiye. As a result, it was projected that Kahramanmaraş earthquakes would generate approximately 41,000 tonnes of debris from household items.

Following the general discussion of debris volume estimation methods in Section 2.3, this section discusses an approach tailored to estimating disaster debris volume in Istanbul. Using insights from the 1999 Marmara earthquake, this model expands on established frameworks and tailors them to Istanbul's unique urban characteristics. Drawing from the experience of the 1999 Marmara Earthquake, Baycan [7] estimated that 13.18 million tonnes of debris were generated during that disaster. This estimation was fundamentally based on a damage assessment conducted by a Damage Assessment Committee. The damage evaluation categorized buildings into three groups:

1. Destroyed or heavily damaged buildings, which were demolished and removed to TDDMS.
2. Moderately damaged buildings, contributing an estimated 20% of the total debris generated, as they were assumed to be demolished and transported to TDDMS.
3. Lightly damaged buildings, which were considered with minimal contributions to overall debris.

This categorization provided a structured methodology for estimating the generated debris volume and planning the logistics for its disposal. This model provides a foundation for estimating potential debris volume in a comparable disaster scenario in Istanbul. Given that the urban structure of Istanbul resembles many of the affected areas during the Marmara Earthquake, using similar parameters allows for a preliminary estimation of debris volumes, which is crucial for planning TDDMS and logistical operations post-disaster. The characteristics of Istanbul's buildings, including their types, sizes, and densities, will be considered to adapt the volume estimation model for local application.

Building on Baycan's study [7], it was also assumed that each building, on average, contains 4.2 housing units, with each unit covering an area of 100 m<sup>2</sup>. Furthermore, the volume of debris generated per square meter of housing unit area was estimated at 1.3 tonnes. These specific assumptions help to provide a more granular understanding of how the total debris volume were estimated, allowing for a more refined application of the model in Istanbul.

The formula for estimating debris volume for a district is as follows:

Debris Estimate for a District (tonnes) = Number of Buildings in the District × Average Number of Housing Units Per Building × Floor Area per Unit (m<sup>2</sup>) × Debris Generation per m<sup>2</sup> (tonnes/m<sup>2</sup>)

In mathematical terms, it can be represented as:

$$E_{district} = n * N * A * R \quad (3.1)$$

Where:

$E_{district}$  : Estimated total debris volume for the district (tonnes)

$n$  : Total number of very heavy, heavy, and moderate damage buildings in the district

$N$ : Average number of housing units per building (e.g., 4.2)

$A$  : Floor area of each housing unit (e.g., 100 m<sup>2</sup>)

$R$  : Debris generation rate per square meter (e.g., 1.3 tonnes/m<sup>2</sup>)

Notably, the district-level formula presented earlier can be modified for use in neighborhood-based analysis. By considering data at a more localized level, such as the neighborhood, the same fundamental approach can be applied with higher granularity, allowing for more precise disaster debris management and logistical planning leading to a more refined estimation of debris volume following a disaster. To estimate the total volume of disaster debris for an entire neighborhood, the debris from all buildings in the neighborhood is aggregated. The formula for estimating debris volume for a neighborhood is as follows:

Debris Estimate for a Neighborhood (tonnes) =  $\Sigma$  (Number of Housing Units Per Building × Floor Area per Unit (m<sup>2</sup>) × Debris Generation per m<sup>2</sup> (tonnes/m<sup>2</sup>)) for all Buildings in the Neighborhood

Mathematically, this can be expressed as:

$$E_{neighborhood} = \sum_{i=1}^n (N_i * A * R) \quad (3.2)$$

Where:

$E_{neighborhood}$  : Estimated total debris volume for the neighborhood (tonnes)

$n$  : Total number of very heavy, heavy, and moderate damage buildings in the neighborhood

$N_i$  : Number of housing units in the  $i$ -th building

$A$  : Floor area of each housing unit (100 m<sup>2</sup>)

$R$  : Debris generation rate per square meter (1.3 tonnes/m<sup>2</sup>)

This formula provides an estimate of the total debris volume generated by summing up the debris from each building in the neighborhood. If all buildings in the neighborhood have similar characteristics, the formula simplifies to the following form:

$$E_{neighborhood} = n * N * A * R \quad (3.3)$$

In which,  $n$  is the total quantity of buildings in the neighborhood, and other parameters ( $N$ ,  $A$ , and  $R$ ) are consistent across buildings. This approach helps in planning debris management and logistical operations following a disaster.

### **3.5 Cluster-Based Transportation Optimization for Temporary Disaster Debris Management Sites**

Following an immense disaster, distributing disaster debris to TDDMS poses substantial logistical issues. The unequal distribution of debris among neighborhoods, as well as the restricted capacity of TDDMS, require an effective transportation approach to reduce costs and environmental implications.

The existing studies in DDM has primarily focused on high-level optimization models, as shown in Table 2.4 of Chapter 2. These models frequently address objectives such as cost reduction, transportation times, and environmental effect, but they do so without incorporating cutting-edge machine learning techniques. For example, approaches such as MILP and Multi-Objective Optimization (e.g., NSGA-II) have been used to handle debris management issues [25], [54]. While these approaches are

excellent at tackling certain optimization goals, they lack the adaptability and precision that clustering algorithms can provide, especially when working with large-scale geographic and quantitative data.

### **3.5.1 Machine learning applications in waste management**

Machine learning techniques are currently being employed in waste management applications, with a focus on Decision Trees, Support Vector Machines, and Linear Regression. These methods have been employed in crucial areas such as generating waste forecasts, collection routing, sorting, and treatment. One notable application is the use of Decision Trees to design decision support frameworks for MSW management [98] and to predict the compression ratio of MSW [99]. Similarly, Support Vector Machines has demonstrated its utility in tasks such as predicting urban waste generation [100], enhancing the safety of construction and demolition waste recycling [101], and optimizing packaging waste collection [102]. Linear Regression, on the other hand, has been employed in comparative studies to forecast hospital solid waste generation [103].

### **3.5.2 K-Medoids clustering for disaster debris management**

Clustering is one of the most significant unsupervised learning problems, aiming to identify a structure within unlabeled data, where a cluster represents a group of similar objects that are distinct from those in other clusters [104]. The literature offers a wide range of clustering algorithms, with the choice of technique based on the type of data, the specific objective, and the intended application.

K-medoids is a traditional partitioning-based clustering method that organizes a dataset of  $n$  objects into  $k$  clusters by selecting a medoid, the most central object within each cluster, which minimizes the overall dissimilarity to all other objects, making it more robust to noise and outliers [105].

The K-medoids clustering algorithm can be described as outlined below [104]:

- The algorithm starts by arbitrarily selecting  $k$  medoid points from a dataset containing  $n$  objects, where  $n > k$ .
- Each data point in the dataset is then assigned to the most similar medoid, with similarity typically measured using distance metrics such as Euclidean, Manhattan, or Minkowski distance.

- A non-medoid object  $O'$  is randomly selected.
- The total cost of swapping an existing medoid with  $O'$  is calculated.
- If the total cost  $S$  of the swap is negative (i.e.,  $S < 0$ ), the current medoid is replaced with  $O'$ , resulting in a new set of medoids.
- Steps 2 to 5 are repeated iteratively until the medoids remain unchanged, indicating convergence.

### 3.5.3 Haversine distance for disaster debris management

The Earth's shape is best described as an oblate spheroid, though no geometric model can entirely capture its exact dimensions [106]. However, the Haversine formula is well-suited for calculating distances on a spherical surface [107]. It determines the shortest path between two points on the Earth's surface or a sphere, measured along the surface, and is frequently visualized through Google Maps [106]. Assuming that the earth's radius is 6367,45 km and that two locations are located in spherical coordinates (latitude and longitude) at  $\phi_1, \lambda_1$ , and  $\phi_2, \lambda_2$ , the Haversine formula determines the great-circle distance between these points based on their latitude and longitude [108]. The Haversine formula [109] is expressed as follows in Equation 3.4:

$$D = 2r \arcsin \sqrt{\sin^2 \left( \frac{\phi_2 - \phi_1}{2} \right) + \cos \phi_1 \cdot \cos \phi_2 \cdot \sin^2 \left( \frac{\lambda_2 - \lambda_1}{2} \right)} \quad (3.4)$$

Where:

$D$ : The distance between two points (km).

$r$ : The Earth's radius (approximately 6,371 km).

$\phi_1, \phi_2$  : Latitudes of the two points in radians.

$\lambda_1, \lambda_2$  : Longitudes of the two points in radians.

The Haversine formula simplifies calculations by disregarding the Earth's surface irregularities, such as valleys and hills, thereby providing accurate distance measurements [110]. This precision is particularly important in DDM scenarios, where accurate spatial relationships are critical.

### 3.5.4 Transportation model of disaster debris allocation

The objective of this model is to optimize disaster debris management by minimizing the total transportation cost incurred in moving debris from neighborhoods to the selected TDDMS. The detailed mathematical formulation of the model, including its objective function and constraints, is provided below.

#### Sets

**i**: neighborhood index,  $i \in \{1, \dots, N\}$

**j**: TDDMS index,  $j \in \{1, \dots, M\}$

#### Parameters

$d_{ij}$ : The transportation cost from neighborhood  $i$  to TDDMS  $j$ .

$E_i$ : The total volume of debris generated in neighborhood  $i$ .

$C_j$ : The capacity of TDDMS  $j$ .

$K$ : Maximum number of TDDMS that can be utilized.

#### Decision variables

$x_{ij}$ : The volume of debris transported from neighborhood  $i$  to TDDMS  $j$ .

$y_j$ : The binary variable that determine whether TDDMS are used ( $y_j = 1$ ) or not ( $y_j = 0$ ) must be binary,  $y_j \in \{0,1\}$ .

#### Objective Function

Model aims to minimize the total transportation costs for moving debris from neighborhoods to TDDMS.

$$\text{Minimize } Z = \left( \sum_{i=1}^N \sum_{j=1}^M d_{ij} \cdot x_{ij} \right) \quad (3.5)$$

### **Total Debris Fulfillment Constraint**

This constraint ensures that the total debris generated in each neighborhood must be transported to one or more TDDMS.

$$\sum_{j=1}^M x_{ij} = E_i, \forall i \in \{1,2,\dots,N\} \quad (3.6)$$

### **TDDMS Capacity Constraint**

This constraint guarantees that the total volume of debris transported to a TDDMS does not exceed its capacity.

$$\sum_{i=1}^N x_{ij} \leq C_j \cdot y_j, \forall j \in \{1,2,\dots,M\} \quad (3.7)$$

### **TDDMS Utilization Constraint**

This constraint ensures that debris can only be transported to a TDDMS if the site is marked as usable.

$$x_{ij} \leq C_j \cdot y_j, \forall i \in \{1,2,\dots,N\}, \forall j \in \{1,2,\dots,M\} \quad (3.8)$$

### **Maximum Number of TDDMS Constraint**

This ensures that the number of active TDDMS does not exceed a predefined upper limit  $K$ .

$$\sum_{j=1}^M y_j \leq K \quad (3.9)$$

### **Non-Negativity Constraint**

These constraints ensure that all variables representing the volume of debris transported are non-negative, meaning they cannot take negative values.

$$x_{ij} \geq 0, \forall i \in \{1,2,\dots,N\}, \forall j \in \{1,2,\dots,M\} \quad (3.10)$$

## Transportation Model: Assumptions

- Fixed costs and capacity
  - Transportation costs per unit of debris  $d_{ij}$  are fixed and predetermined.
  - TDDMS capacities  $C_j$  remain constant throughout the planning horizon.
- All debris will be transported
  - The debris generated in each neighborhood  $E_i$  will be transported to one or more TDDMS.
- Medoid points represent cluster centers
  - The medoid of each cluster, as calculated by the K-medoids algorithm, is viewed as the central point for debris transportation, with all debris from the cluster assumed to originate from this medoid.
- Linear transportation cost
  - Transportation costs are directly related to the distance between neighborhoods and TDDMS as well as the volume of debris transported.
- Temporary disaster debris management site usage
  - A TDDMS can only accept debris when it is activated.
- Unlimited transportation resources.
  - It is expected that there are enough resources (vehicles and equipment) to transport debris from every area.
- Exclusion of environmental and transportation factors
  - The model does not take into consideration environmental conditions, traffic, or other logistical constraints that could affect transit efficiency.
- Exclusion of intra-cluster transportation costs
  - The medoid of each cluster is regarded as the new supply point during neighborhood clustering; however, the transportation costs within the cluster, i.e., transportation costs for transporting debris from other

neighborhoods in the cluster to the medoid, are not included in the model, which simplifies the analysis by concentrating only on inter-cluster transportation to TDDMS.

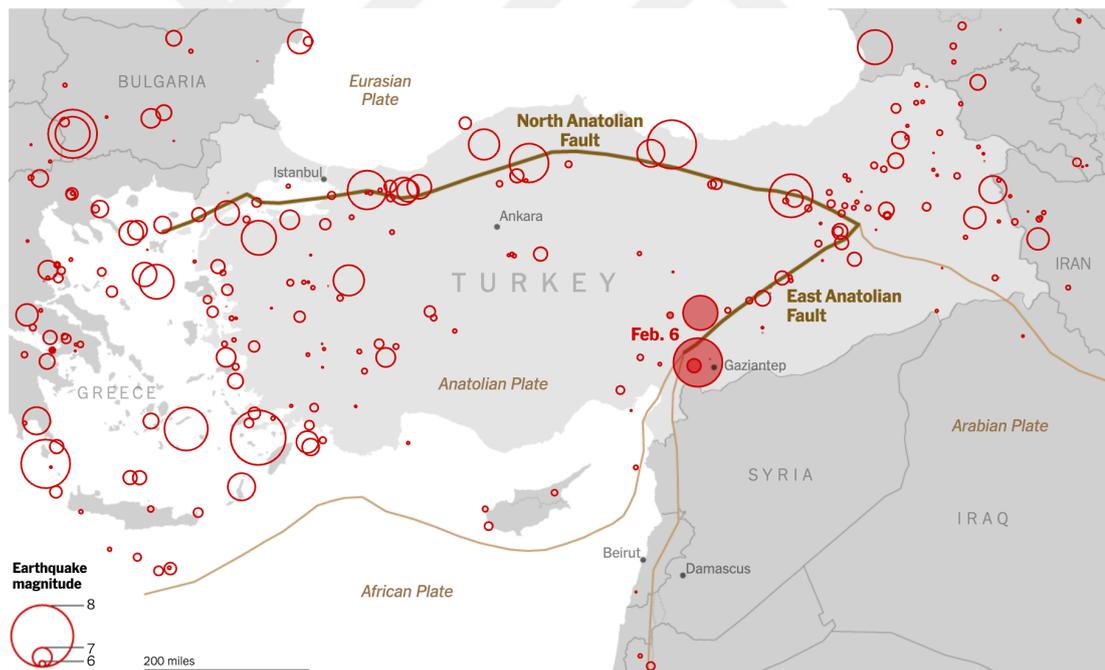




## 4. APPLICATION of PROPOSED METHODOLOGY for ISTANBUL

### 4.1 Temporary Disaster Debris Management Sites Identification

The case study focuses on earthquakes, as they are among the most frequent natural hazards in Türkiye. Earthquakes occur almost everywhere in Turkey. However, damaging earthquakes are primarily concentrated in three regions: NAFZ, which experiences the largest earthquakes; the East Anatolian Fault Zone, which is as active as NAFZ; and the Western Anatolian Graben System [111]. Türkiye has faced to several severe earthquakes over the last century. Since 1900, when instrumental measurement of earthquakes began, Türkiye and The surrounding regions have experienced 231 earthquakes with a magnitude of 6 or higher at different times [112]. The map in Figure 4.1 below shows earthquakes of magnitude 6 or greater that have occurred in Türkiye since 1900 [113]. The recent catastrophic earthquake in Kahramanmaraş on February 6th is marked on the map.



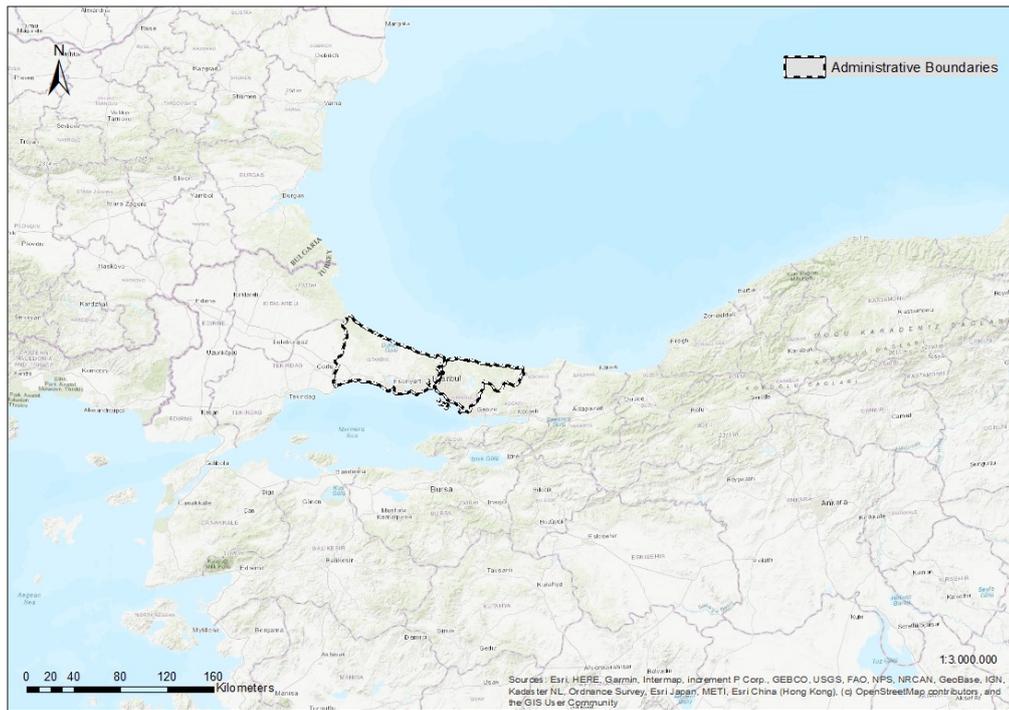
**Figure 4.1:** Magnitudes of major earthquakes since 1900[114].

Türkiye unfortunately endured two devastating earthquakes in 1999: the Gölcük-İzmit earthquake on August 17th (Mw 7.4), and the Düzce earthquake on November 12th (Mw 7.1) [114]. These were the most catastrophic earthquakes that the country has faced in the past ten years. These earthquakes occurred along segments of the renowned NAFZ, the most significant active fault zone in Türkiye. These earthquakes

are collectively remembered by the public as the Marmara earthquake. The Marmara Earthquake caused destruction in Kocaeli, Sakarya, Istanbul, Düzce, and Yalova [115]. The earthquake resulted in the deaths of 17,480 people and injured 43,953 others, approximately 200,000 people were left homeless, with 66,441 residences and 10,901 businesses destroyed. Nearly 16 million people were impacted to varying degrees by the earthquake [116]. The earthquake's occurrence in a region with Türkiye's major industrial centers, high urbanization, and dense population led to significant casualties and property damage. The earthquakes that occurred on August 17th and November 12th, 1999, have significantly stressed the Marmara segment of the fault, which has been closely monitored since the 1999 earthquakes. There is an approximate 50% probability of a major event with a magnitude of  $M \leq 7.6$  occurring on this segment in the next half-century [117]. The reality that Istanbul, with a population of around 15 million, historically renowned as an international hub for trade and culture, is now confronted with a substantial earthquake risk in the foreseeable future.

#### **4.1.1 Characteristics of the study region: Istanbul**

This section presents the procedures for identifying appropriate locations for establishing candidate TDDMS for expected earthquake in Istanbul, Türkiye. Istanbul's historical significance is unparalleled, having served as the epicenter of several empires, ranging from the Roman to the Ottoman. Its distinctive geographical location (Figure 4.2) along a 30 km strait, acting as a passage between the Black Sea and the Sea of Marmara, has been strategically significant for centuries. Istanbul portrayed in Figure 4.3 is located in the northwestern part of Türkiye, straddling the Bosphorus Strait, which separates Europe and Asia. Modern-day Istanbul spans an area of 5461 km<sup>2</sup> and had a population of 15,655,924 according to the 2023 Census. Currently, there are 39 districts in the province of Istanbul. Of these, 25 are located on the European side, while 14 are on the Asian side. On the European side, the districts are Arnavutköy, Avcılar, Bağcılar, Bahçelievler, Bakırköy, Başakşehir, Bayrampaşa, Beşiktaş, Beylikdüzü, Beyoğlu, Büyükçekmece, Çatalca, Esenler, Esenyurt, Eyüpsultan, Fatih, Gaziosmanpaşa, Güngören, Kağıthane, Küçükçekmece, Sarıyer, Silivri, Sultangazi, Şişli, Zeytinburnu. On the Asian side, the districts include Adalar, Ataşehir, Beykoz, Çekmeköy, Kadıköy, Kartal, Maltepe, Pendik, Sancaktepe, Sultanbeyli, Şile, Tuzla, Ümraniye, Üsküdar.



**Figure 4.2:** Geographical location of Istanbul.



**Figure 4.3:** Administrative boundaries of Istanbul.

Nevertheless, its remarkable history is overshadowed by a legacy of seismic volatility, stemming from its location within one of Eurasia’s most active seismic belts. The area's seismic activity, notably highlighted by the 1999 Kocaeli (M7.4) and Düzce

(M7.2) earthquakes along NAFZ, has significantly influenced the city's seismic risk profile. The western extension of the NAFZ, specifically the underwater fault system including the Islands, Çınarcık, Mid-Marmara, and Off-Tekirdağ fault segments, presents a significant seismic hazard to the Istanbul metropolitan region. These segments have the capacity to produce earthquakes with magnitudes of 7 or higher, posing a substantial risk to the city's infrastructure [118].

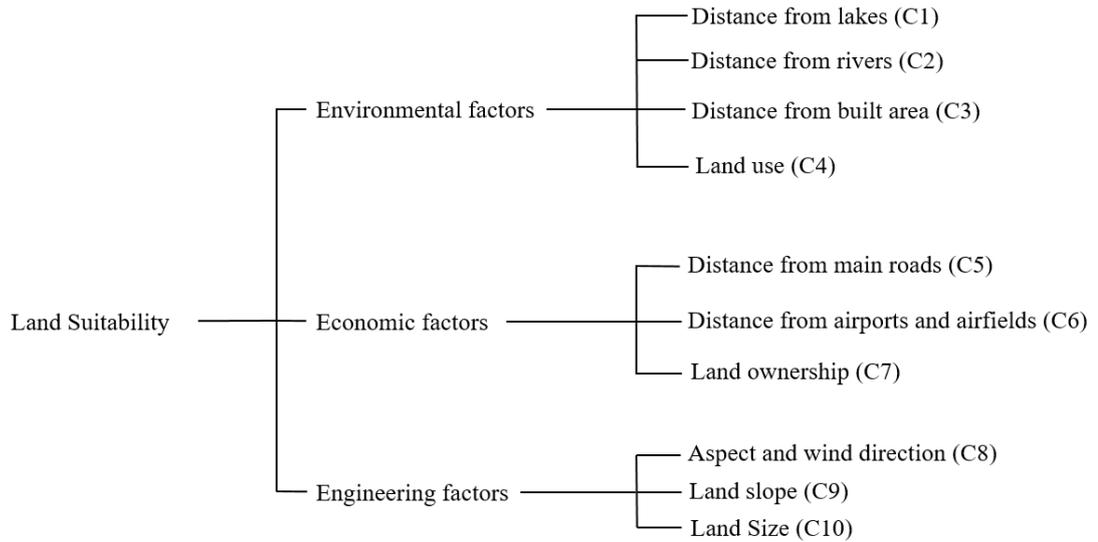
The earthquakes that occurred on August 17th and November 12th, 1999, caused 981 deaths and 7204 injuries. It was reported that 3073 houses and 532 businesses suffered severe damage, 13339 houses and 1999 businesses suffered moderate damage, and 12455 houses and 1239 businesses suffered minor damage. That indicated a substantial debris concern, even though the earthquakes' epicenters were not directly beneath Istanbul.

Although there are significant differences between debris estimates made using different approaches under current conditions (June, 2021), calculations based on average values suggest that approximately 25 million tons of debris could be generated in Istanbul following a projected scenario earthquake ( $M_w=7.5$ ) anticipated to take place in the Marmara Sea [119].

#### **4.1.2 Determining siting criteria for prospective temporary disaster debris management sites**

Cheng and Thompson [24] reviewed 55 criteria from articles pertaining to waste management facility siting. However, they concluded that including all these criteria in a study appeared unreasonable. Their findings suggest that 9–13 criteria are sufficient for performing land suitability analysis.

The hierarchy for TDDMS was established, and Figure 4.4 presents the decision hierarchy model for TDDMS in this instance.



**Figure 4.4:** Hierarchy model of land suitability of Istanbul.

The criteria for identifying TDDMS are based on a review of the literature, Istanbul's specific characteristics, and disaster debris management requirements [43][12]. The criteria also take into account the availability of reliable, up-to-date data to guarantee that analyses are accurate. Consequently, this study incorporated 9 criteria. These are Distance from lakes (C1) and rivers (C2), Distance from built area (C3), Land use (C4), Distance from main roads (C5), Distance from airports and airfields (C6), Land ownership (C7), Aspect and wind direction (C8), Land slope (C9), and Land size (C10).

This study seeks to identify suitable TDDMS in preparation for a potential earthquake anticipated along segments of the well-known North Anatolian Fault Zone (NAFZ), Türkiye's most significant active fault zone. Clearly, incorporating a criterion based on proximity to the fault zone would be highly beneficial. However, the segments of NAFZ expected to rupture are the Adalar and Kumburgaz faults. The Adalar fault is 10 km away, while the Kumburgaz fault is 15 km away from the city [120]. In other studies, a similar criterion has been included with a buffer of less than 1 km to the TDDMS. For instance, Lin and Kao [121] established a buffer of 80 meters from the potential sites, similarly, Eskandari et al. [56] stated that sites should have a minimum distance of 200 meters from seismic areas. Therefore, any site chosen in Istanbul for this study will be far from the nearest fault segments which are situated 10 to 15 km offshore from the city's southern coastline as indicated by Kalkan and Gülkan [118]. The following section provides a comprehensive rationale for each criterion.

#### 4.1.2.1 Distance from lakes (C1) and distance from rivers (C2)

TDDMS ought to be located at a sufficient distance from lakes and rivers to minimize the risk of environmental contamination. The buffer zone for surface waters varies depending on the specific circumstances of each case. The buffer distance from surface water sources can vary, with studies suggesting distances of 180 meters [121], 500 meters [46], [52], [122], and even 1000 meters [56] for all types of water bodies. The buffer distance may also vary based on the type of water body. For example, Sadek et al. [58] employed a 1000-meter buffer zone for lakes, 500 meters for major rivers, 250 meters for temporary rivers, and 150 meters for other rivers. Some researchers [123], [124] utilized guidelines for classifying buffer zones into different number of categories such as unsuitable, suitable, and most suitable etc. This study adopted a 500-meter buffer zone for all water sources depicted in Figure 4.5, as it is the most commonly used distance in previous studies. Increasing the distance from lakes and rivers is regarded positively since it decreases the potential environmental impact and guarantees compliance with water protection standards. This approach aligns with the classification criteria for suitability zones commonly used in the literature.



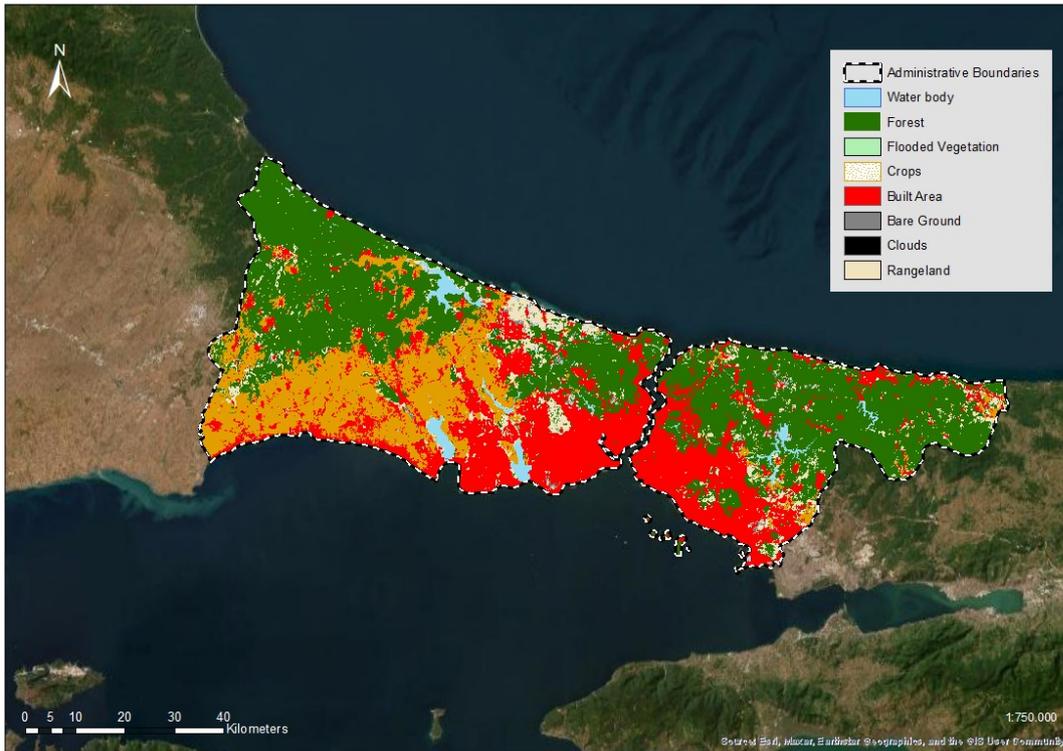
**Figure 4.5:** Lakes and rivers of Istanbul.

#### **4.1.2.2 Distance from built area (C3)**

The objective of this criterion is to situate TDDMS far from built area to minimize disruptions to reconstruction efforts and reduce potential impacts on the surrounding community. Previous research typically employed a buffer zone of 1,000 m [35], [47], [62], [125] or 500 m [51], [126], [127], [128] for this criterion. During severe earthquakes, TDDMS must handle the waste from many collapsed buildings. When evaluating potential TDDMS locations, buffers for built area are not required. The purpose of this study is to guarantee that TDDMS are not located in built areas, with a focus on less populated locations. Increasing the distance from constructed areas is regarded as a positive factor since it lowers interference with rebuilding activities, noise and dust disruptions, and ensures the safety and well-being of surrounding communities.

#### **4.1.2.3 Land use (C4)**

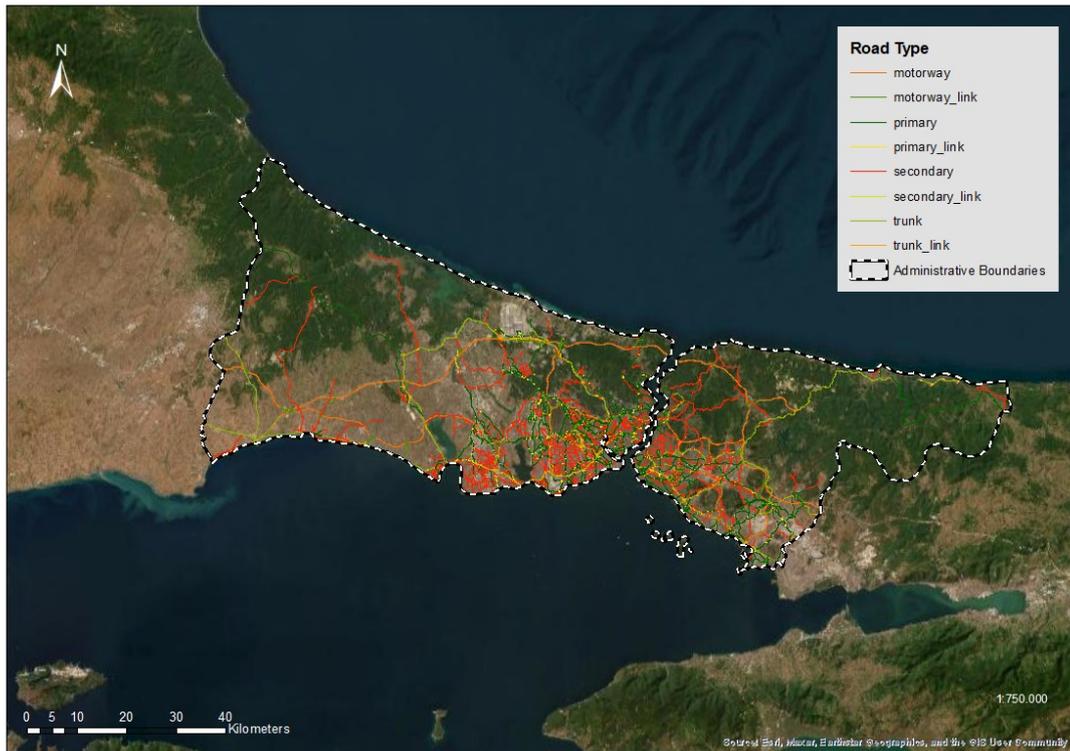
This criterion aims to ensure that TDDMS are neither located in productive regions nor in underdeveloped areas. In this context, previous studies demonstrate a broad range of consistency. Kara and Doratli [35] pointed out that forests and wetlands are unsuitable for landfill sites, whereas Demesouka et al. [128] determined that mountains are also inappropriate locations. Gemitzi et al. [129] excluded dense and sparse forests, along with agricultural and uncultivated land, from consideration for landfill siting. Ghobadi et al. [130] proposed that saline and rocky terrains are the most suitable locations for landfill sites. Sadek et al. [58] suggested that landfill sites ought to be located far from areas that may impact cattle and pasture management, high-quality grasslands, forests, parks, urban areas, military zones, and agricultural lands. Chatzouridis and Komilis [125] indicated that areas with minimal agricultural activity are suitable for landfill sites. Due to the diverse array of factors examined in the previous studies, not all can be encompassed in this study. Across most references, agricultural and forest lands were consistently deemed unsuitable for landfill sites. Therefore, avoiding agricultural and forest lands is a key criterion for land use. The land use map of Istanbul, shown in Figure 4.6, depicts the distribution of forests, agricultural areas, urbanized zones, and other land cover categories. This map helps to evaluate land use suitability requirements by indicating regions that are regarded unsuitable for TDDMS, such as forests and agricultural lands.



**Figure 4.6:** Istanbul land use map.

#### 4.1.2.4 Distance from main roads (C5)

A buffer zone was incorporated into the siting of landfills and TDDMS to protect the main road network from potential disruptions caused by waste management operations. When locating TDDMS, proximity to main roads is desirable since it allows for swift debris transportation and reduces logistical obstacles, especially after a disaster when relief and rescue activities are crucial. To balance accessibility with a minimal effect on road networks, this study employs a 200-meter buffer zone for highways, motorways, trunk roads, primary and secondary roads, and their connections, as shown in Figure 4.7. This approach makes sure TDDMS are easily accessible while minimizing the potential negative impacts on road infrastructure.



**Figure 4.7:** Main roads of Istanbul.

#### 4.1.2.5 Distance from airports and airfields (C6)

Given Istanbul's status as a large metropolitan city with significant geopolitical importance, it features numerous airports, aprons, and airfields as seen in Figure 4.8. During the disaster response phase, airports play a critical role in facilitating the rapid transportation of personnel, supplies, and equipment, ensuring the secure flow of information, and managing procurement and warehousing operations. Airpower is uniquely suited to respond to humanitarian logistical tasks with the urgency and speed required [131]. To minimize the potential disruptions to airport operations and maintain the efficiency of air logistics, establishing an appropriate buffer zone around airports is essential. In 1991, United States Environmental Protection Agency [132] established acceptable distances for airports at 3,000 and 1,500 meters. While selecting landfill sites, Alves et al. [133] and Wang et al. [50] determined 3 kilometer buffer whereas, Yesilnacar et al. [36] determined the buffer zone as 1,500 m. However, considering Istanbul's high population density and extensive urbanization, it is not always feasible to designate large buffer zones. Therefore, this study adopted a 1,500-meter buffer zone for airports and airfields, balancing the need to avoid interference

with aviation operations while acknowledging the constraints imposed by the city's land use and settlement patterns.



**Figure 4.8:** Airports and airfields of Istanbul.

**4.1.2.6 Land ownership (C7)**

The land ownership significantly influences the expense of TDDMS. According to FEMA [12], the ideal locations include public lands as the first priority, followed by nearby disposal or recycling facilities, and applicant-owned sites such as parks, vacant lots, and sports fields. If public lands are unavailable, alternative private properties ought to be investigated as TDDMS sites. Suitable instances involve recycling plants, current landfill sites, transfer stations, unused land, corporation sites, parks, driveways, rights-of-way, city/county-owned properties, and privately held lands [24]. Thus, while public lands are prioritized for TDDMS selection, private and industrial lands are also considered acceptable alternatives.

**4.1.2.7 Aspect and wind direction (C8)**

Aspect, the orientation of a slope, is a crucial topographic factor that significantly affects air temperature, wind speed, and wind direction. The geomorphological configuration of the environment, along with the aspect, dictates the direction and

speed of the wind. When selecting a TDDMS, the relative wind direction must be considered. Wind can transport harmful dust, scents, and litter, causing nuisance in surrounding populations [127]. Studies conducted by the Turkish State Meteorological Service between 1970 and 2023 have determined that the predominant wind direction in Istanbul is northeast [134].

#### **4.1.2.8 Land slope (C9)**

This criterion guarantees that TDDMS are situated on predominantly flat terrain. Previous studies have proposed different slope criteria for siting landfills, including less than 20% [124, 156], less than 40% [123], less than 10% [134], or alternatively, greater than 10% [137]. When selecting candidate TDDMS sites, it is crucial to prioritize relatively flat terrain, with the requirement typically set at a maximum slope of 20%.

#### **4.1.2.9 Size (C10)**

The size requirements of TDDMS are significantly influenced by predictions made before a disaster or estimates made afterward regarding the volume of debris generated. According to FEMA [12] drawing from past disaster record, practical experience, and operational considerations, a minimum of 40 hectares is recommended for every 0.76 million cubic meters of debris. According to the recent study conducted by Istanbul Metropolitan Municipality, in a scenario earthquake considered for Istanbul with a magnitude of Mw 7.5, the estimated total volume of construction and demolition debris that may occur is 25 million tons [119]. When considering 1 hectare is sufficient for 20,000 tons of debris, then for 25 million tons of debris, 1250 hectares of land in total would be necessary. In large metropolitan areas, identifying and securing extensive tracts of land for TDDMS presents significant challenges. This difficulty arises due to several interrelated factors such as space limitations, environmental and health concerns, economic factors, regulatory and planning issues. Thus, this criterion ensures that the total size of lands deemed optimal is sufficient to accommodate the total volume of debris likely to be generated.

**Table 4.1:** Overview of criteria and limitations.

Criteria	Constraints	
C1	Distance from lakes	500 m buffer zone
C2	Distance from rivers	500 m buffer zone
C3	Distance from built area	Not locate in built area
C4	Land use	Not locate in agricultural and forests area
C5	Distance from main roads	≥200 m
C6	Distance from airports and airfields	1500 m buffer zone
C7	Land ownership	Public land has priority
C8	Aspect and wind direction	Not Northeast
C9	Land slope	≤20%
C10	Land size	≥1250 ha

The criteria and limitations that were considered are compiled in Table 4.1. Since TDDMS are just temporary facilities for DDM, identical weightings were applied to all the criteria in this case because the advantages of weighting criteria do not outweigh the associated labor.

#### 4.1.3 Land suitability assessment

The GIS analysis for land suitability assessments is performed using ArcGIS 10.8.2, with each criterion represented as a distinct map layer within the software. In this context, criteria C1, C2, C3, C4, C5, C6, C8, C9 were analyzed in ArcGIS to evaluate land suitability, while criteria C7-C10 were employed to finalize the set of candidates TDDMS. The necessary data for evaluating each criterion is outlined in Table 4.2.

**Table 4.2:** Data sources for evaluation criteria.

Criteria	Source	Data Type	Analysis
C1	HydroSheds	Vector	Euclidean distance
C2	HydroSheds	Vector	Euclidean distance
C3	ESRI Land Cover (2023)	Raster	Reclassification
C4	ESRI Land Cover (2023)	Raster	Reclassification
C5	OpenStreetMap (2024)	Vector	Euclidean distance
C6	OpenStreetMap (2024)	Vector	Euclidean distance
C7	General Directorate of Land Registry and Cadastre		
C8	EarthExplorer USGS	Raster	Aspect
C9	EarthExplorer USGS	Raster	Slope

From a land use perspective, the city is categorized into eight classes according to the ESRI Land Use Land Cover map. These classes include water bodies, forests, flooded vegetation, crops, built areas, bare grounds, clouds, and rangelands. Detailed class definitions are provided in Table 4.3. According to the ESRI Land Use Land Cover map, crops are considered as agricultural areas. Thus, forest and crops classes are considered in Land use (C4) criterion. Class built area was assessed in Distance from built area (C3) criterion.

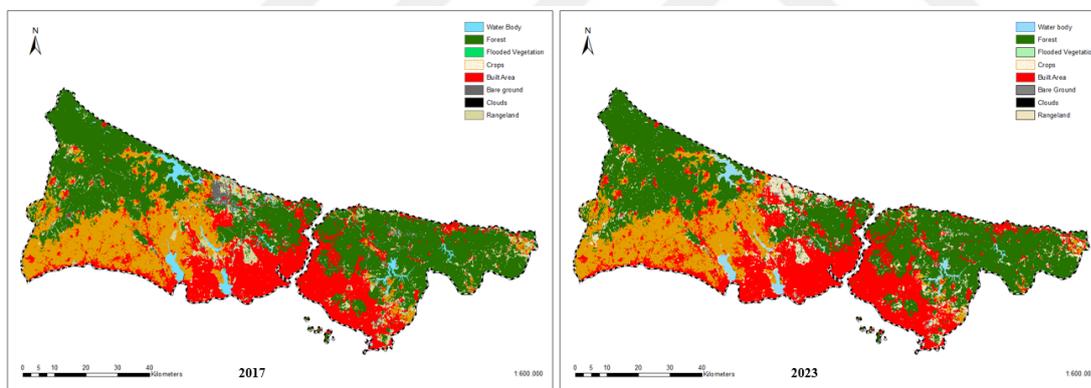
**Table 4.3:** Class definitions.

Class Name	Descriptions
Water body	Sites wherein water was largely present throughout the year; might exclude areas with sporadic or ephemeral water; includes little to no sparse vegetation, no rock outcrops, or built-up structures such as piers; examples: rivers, ponds, lakes, oceans, flooded salt plains.
Forest	Any notable collection of tall (~15 feet) dense vegetation, usually with a closed or dense canopy; instances include mangroves, wooded areas, and dense tall vegetation within plantations, savannas, swamps, or marshes (dense/tall vegetation with ephemeral water or canopy too thick to reveal water beneath).
Flooded vegetation	Areas of any form of vegetation with evident intermixing of water for the bulk of the year; seasonally flooded areas with a mix of grass/shrub/trees/bare ground; examples include flooded mangroves, emergent vegetation, rice paddies, and other extensively irrigated and inundated crops.
Crops	Mankind planted or plotted grasses, crops, and cereals that are not at tree height; instances are structured land's corn, wheat, soy, and fallow areas.
Built Area	Large homogenous impermeable surfaces, such as parking structures, office buildings, and residential housing; examples include homes, densely populated villages, towns, and cities; man-made structures; significant road and rail networks; and asphalt.
Bare ground	Examples of exposed rock or soil, deserts and sand dunes, dry salt flats and pans, dried lake beds, and mines are regions with very little to no vegetation throughout the year. Large expanses of sand and deserts are further examples.
Rangeland	Open terrain with uniform grass cover and a lack of taller vegetation; wild cereals and grasses without evident human plotting (not a plotted field); examples include open grasslands with few to no trees, parks, golf courses, lawns, and pastures; natural meadows and fields with little to not any tree cover. Scrub-filled clearings within dense forests that are obviously no taller than trees; examples: moderate to sparse cover of bushes, shrubs, and tufts of grass; grasslands with very sparse grasses, trees, or other plants; mixture of small clusters of plants or single plants dispersed on a landscape that indicates exposed soil or rock.
Clouds	Due to ongoing cloud cover, there is no information about land cover.

The initial geoprocessing tool used in the model was the Euclidean Distance tool, applied to determine the distance from each cell to the nearest source. Next, the Clip tool from Data Management Tools (Raster) was used to trim the map to match the

exact shape of the study area, as the Euclidean Distance results initially generated rectangular rasters.

The Reclass tool was then utilized to standardize the layers, enabling their comparability. This tool allowed the reclassification of layers using either Fuzzy logic or Boolean logic. Based on the literature review, the majority of prior studies have favored the use of Fuzzy logic for assessing the suitability of TDDMS, particularly for landfill locations. The goal was to prioritize land based on its suitability, leading to the classification of land into several categories within each criteria layer, thereby assigning a value to each piece of land following the specific requirements of the criteria. The suitability value of the land reflects its appropriateness for specific purposes. However, the conversion of barren and idle lands, and even forests, into development areas in Istanbul, along with the city's expansion both eastward and westward, has led to land scarcity. This conversion has been illustrated in Figure 4.9 and compared using ESRI Sentinel-2 10m Land Use/Land Cover Time Series data from 2017 and 2023, plotted in ArcMap 10.8.2.



**Figure 4.9:** Land Use/Land Cover Changes in Istanbul (2017-2023): Comparison Using ESRI Sentinel-2 Data.

The primary aim of the current study is to identify specific parcels of land that can function as potential candidate TDDMS; thus, Boolean logic was employed to eliminate unsuitable areas that are not viable for use as a TDDMS. Consequently, it is more pertinent to determine whether the land meets the necessary criteria for suitability as TDDMS rather than to rank the land across multiple levels of suitability.

In this context, it was deemed more appropriate to reclassify the criteria map layers using Boolean logic, categorizing the land as either suitable (1) or unsuitable (0). Land

can also be divided into multiple categories using various overlay rules in the final phase, as discussed in the following section. Consequently, criteria layers were reclassified using Boolean fuzzy. The raster's reclassification rules are detailed in Table 4.4.

**Table 4.4:** Criteria reclassification rules.

Criteria	Value	
	0	1
C1 Distance from lakes	$\leq 500\text{m}$	$> 500\text{m}$
C2 Distance from rivers	$\leq 500\text{m}$	$> 500\text{m}$
C3 Distance from built area	built area	Other zone
C4 Land use	crops and forest area	Another zone
C5 Distance from main roads	$\leq 200\text{ m}$	$> 200\text{m}$
C6 Distance from airports and airfields	$\leq 1500\text{ m}$	$> 1500\text{m}$
C8 Aspect and wind direction	Northeast	Other directions
C9 Land slope	Slope $> 20\%$	Slope $\leq 20\%$

The last stage of the model entails overlaying all the criterion layers to ascertain the land's general suitability for selecting potential TDDMS. In this step, two distinct approaches were used:

The first approach employed Fuzzy Overlay spatial analysis tool with "AND" overlay type. The "And" logic selects the minimum value from all the input evidence rasters to overlay all the layers, and the value of the output will always be in the range of 0 and 1. Thus, the Fuzzy Overlay with "AND" overlay type is intended for application to rasters with values ranging from 0 to 1. Using Boolean logic, the study area is divided into two categories: suitable areas assigned a value of 1 and unsuitable areas assigned a value of 0, as described in Equation 4.1:

$$\text{Boolean Suitablity Index} = \prod_{j=1}^n b_j \quad (4.1)$$

where Boolean Suitability Index takes a value of 0 or 1. Each  $b_j$  represents the Suitability Index for a specific constraint criterion  $j$ , which also has a value of 0 or 1, and  $n$  denotes the total number of constraint criteria [57]. This approach ensures that only the areas meeting all the criteria are identified as suitable for candidate TDDMS.

The second approach utilized the Weighted Sum spatial analysis tool to overlay all the layers, multiplying each by its assigned weight and then summing them together. This technique integrates the weighted influence of each criterion to produce a final suitability map for identifying candidate TDDMS thereby combining multiple rasters to input them and assign an equal weight of 1 to each. This approach utilized Equation 4.2-4.3 to calculate the total land value, enabling the classification of the land into various categories based on its assessed value.

$$v_j = w_j * b_j \quad (4.2)$$

$$V = \sum_{j=1}^n v_j \quad (4.3)$$

Where,  $b_j$  represents the Suitability Index for a specific constraint criterion  $j$ , which also has a value of 0 or 1, and  $n$  denotes the total number of constraint criteria,  $w_j$  represents the weight for a specific constraint criterion  $j$ , which also has a value of 0 for all criteria in the scope of this research,  $v_j$  represents the value of land for a specific constraint criterion  $j$ ,  $V$  represents the total value of land.

#### 4.1.4 Finalize candidate temporary disaster debris management sites

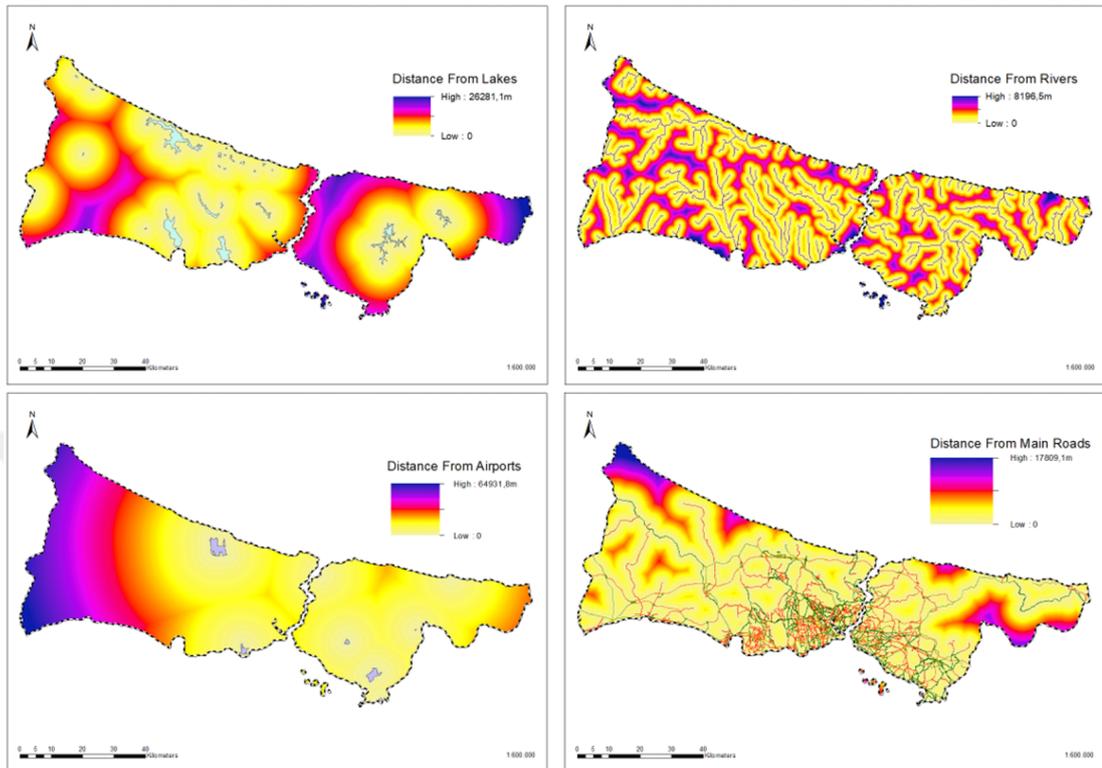
In this study, the primary objective of TDDMS initiative is to address debris generated from residential areas affected by an expected earthquake. The research identified potential TDDMS locations across 39 districts within Istanbul, where the land met the required size specifications. The land ownership of these potential sites was determined using information from the General Directorate of Land Registry and Cadastre. Furthermore, satellite imagery was incorporated into the land suitability assessment to ensure the exclusion of forested and agricultural areas as well as residential areas with a high housing density.

#### 4.1.5 Results and discussions

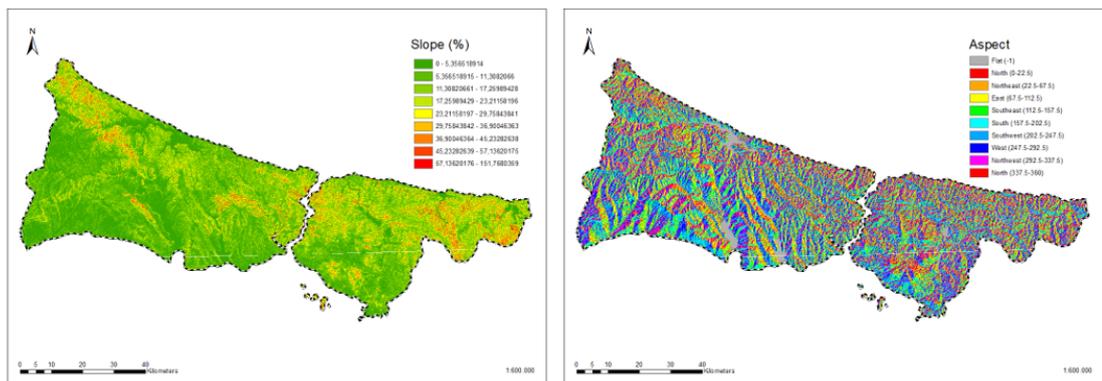
##### 4.1.5.1 Euclidean distance analysis

Figure 4.10 illustrates the criteria analysis map layers for criteria C1, C4, and C5 following the application of the Euclidean Distance and Raster Clip tools. In contrast,

Figure 4.11 shows the layers for criteria C7 and C8, which are based on the original data. These resultant layers can be used as inputs for factor standardization through either Fuzzy logic or Boolean logic.



**Figure 4.10:** Euclidean distance analysis.



**Figure 4.11:** Slope and aspect analysis.

#### 4.1.5.2 Reclassification analysis

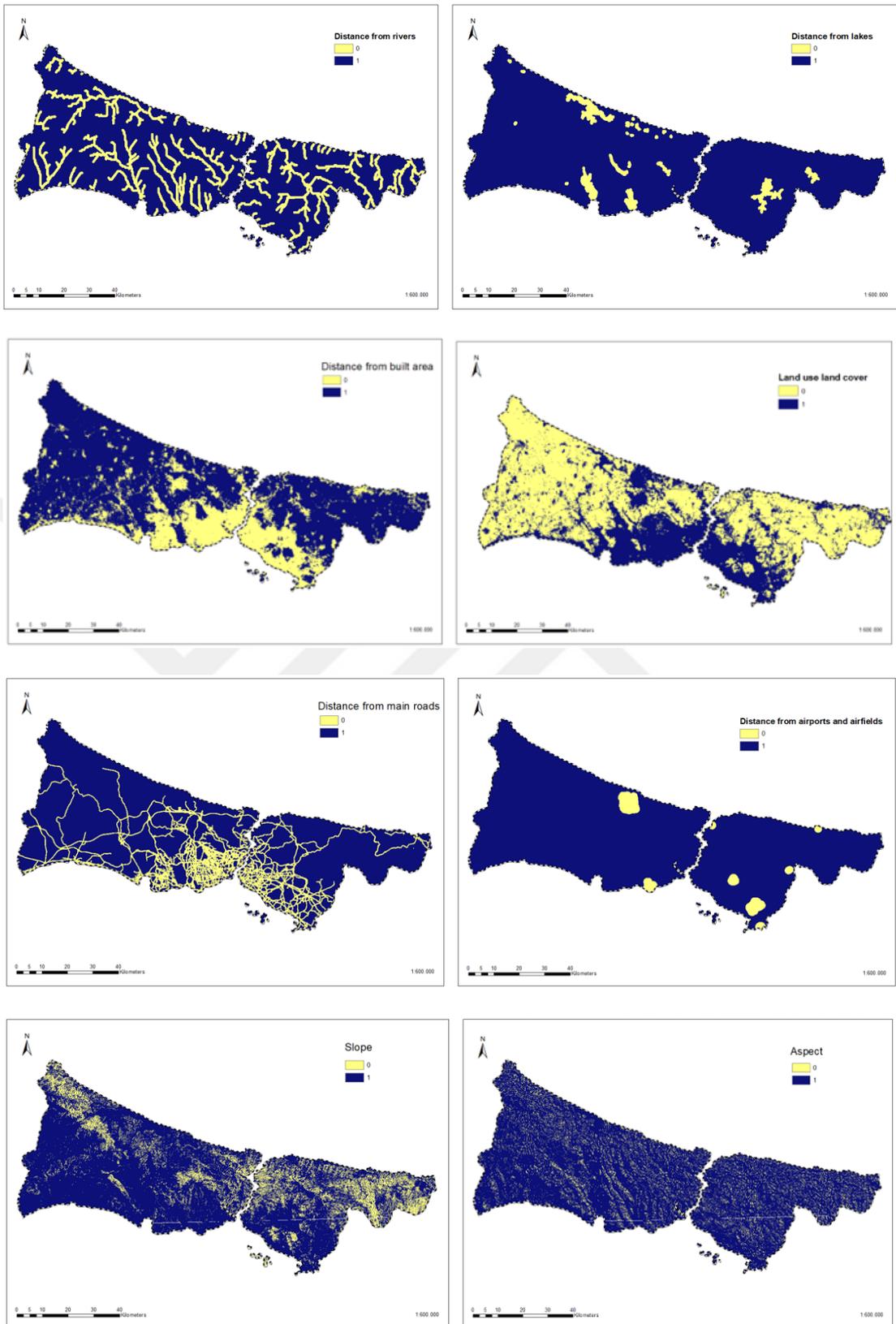
Figure 4.12 illustrates the outputs of the reclassification of various criteria, which reflect the land suitability for TDDMS based on each criterion. A value of 1 indicates that the land is considered suitable based on the specific criterion, while a value of 0 signifies that the land is deemed unsuitable. The map reveals that criteria C2 (Distance

from built area), C3 (Land use), and C4 (Distance from main roads) are more restrictive compared to criteria C1, C5, C7, and C8 as a larger proportion of the land is classified as unsuitable under the former criteria.

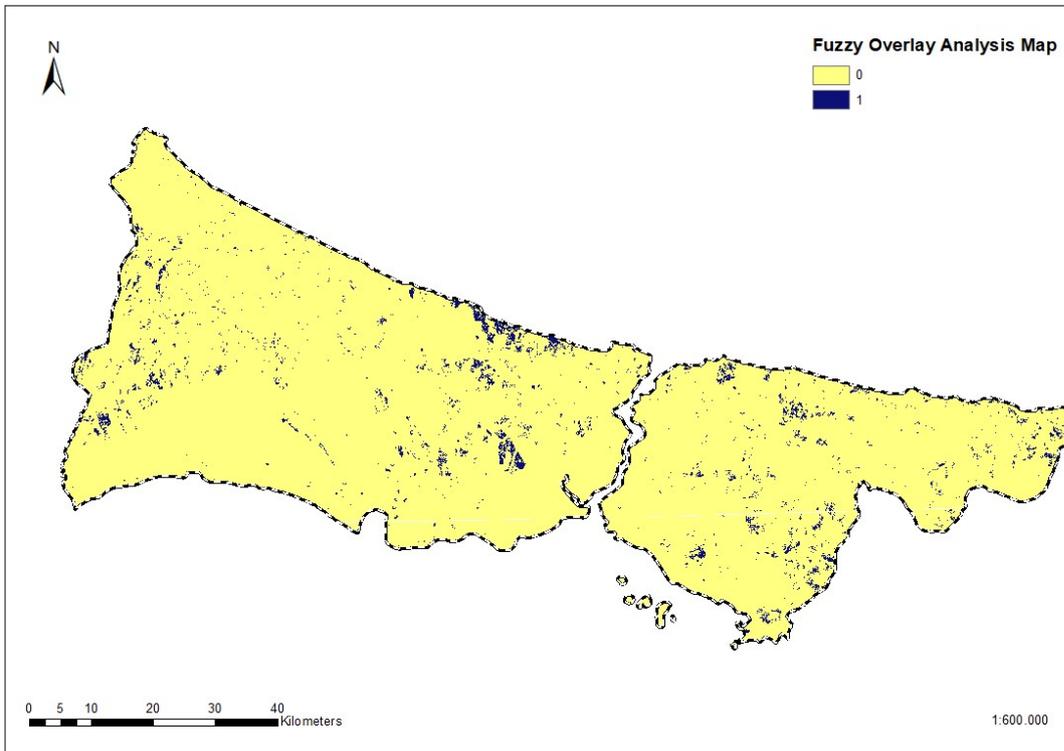
#### **4.1.5.3 Layers overlay analysis**

Figure 4.13 presents the outcomes derived from applying the Fuzzy Overlay spatial analysis tool with "AND" overlay type. According to the "AND" overlay type, the value of the output will always be in the range of 0 and 1. Thus, the Fuzzy Overlay tool is intended for application to rasters with values ranging from 0 to 1. Because Boolean logic was employed to standardize the units for each criterion to ensure different criteria are comparable, the Fuzzy Overlay tool with "AND" overlay type seems appropriate to obtain results either False (0) or True (1). In site selection case, land is assigned a value of 1 only if it satisfies all the specified criteria; otherwise, a value of 0 is given. Consequently, only land with a value of 1 in Fuzzy Overlay Analysis Map is deemed suitable for identifying TDDMS candidates.

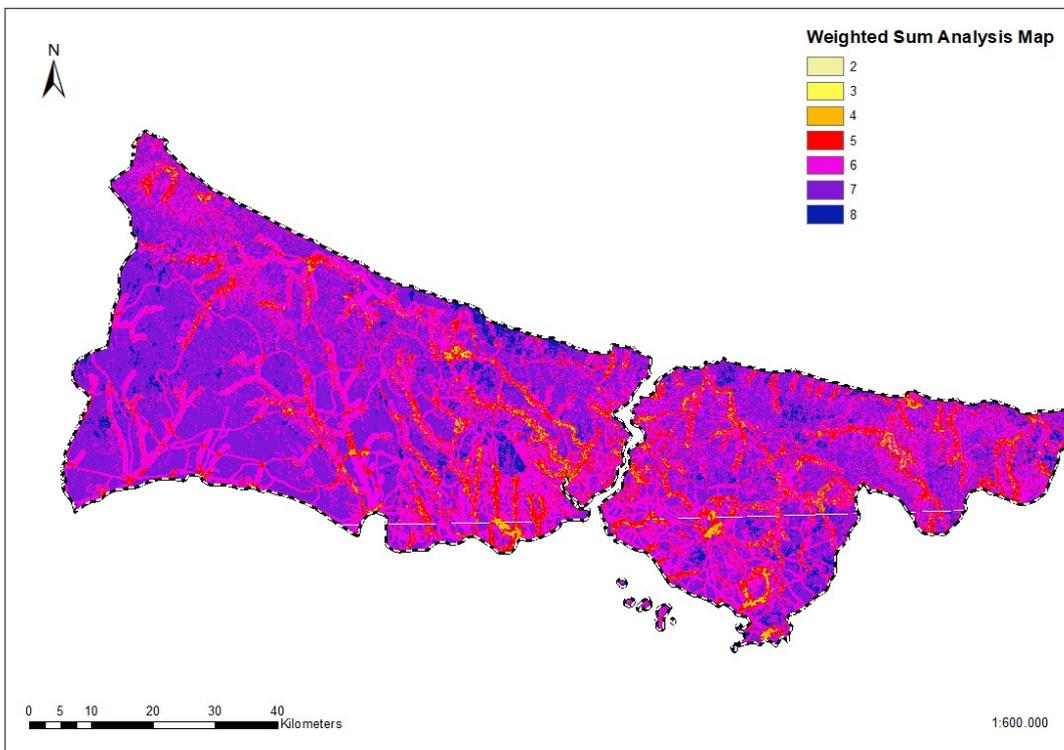
Nonetheless, this approach results in only a few small areas meeting the criteria. Conversely, under Weighted Sum spatial analysis tool, the land value in Weighted Sum Analysis Map depicted in Figure 4.14 represents the number of criteria the land satisfies as Equation 4.1 applied with equal weights of each criterion is 1. This allows for categorizing the land into more than two groups and provides the flexibility to relax certain criteria if suitable candidates cannot be identified in some regions.



**Figure 4.12:** Criteria layers reclass results.



**Figure 4.13:** Fuzzy overlay analysis reclassification results.

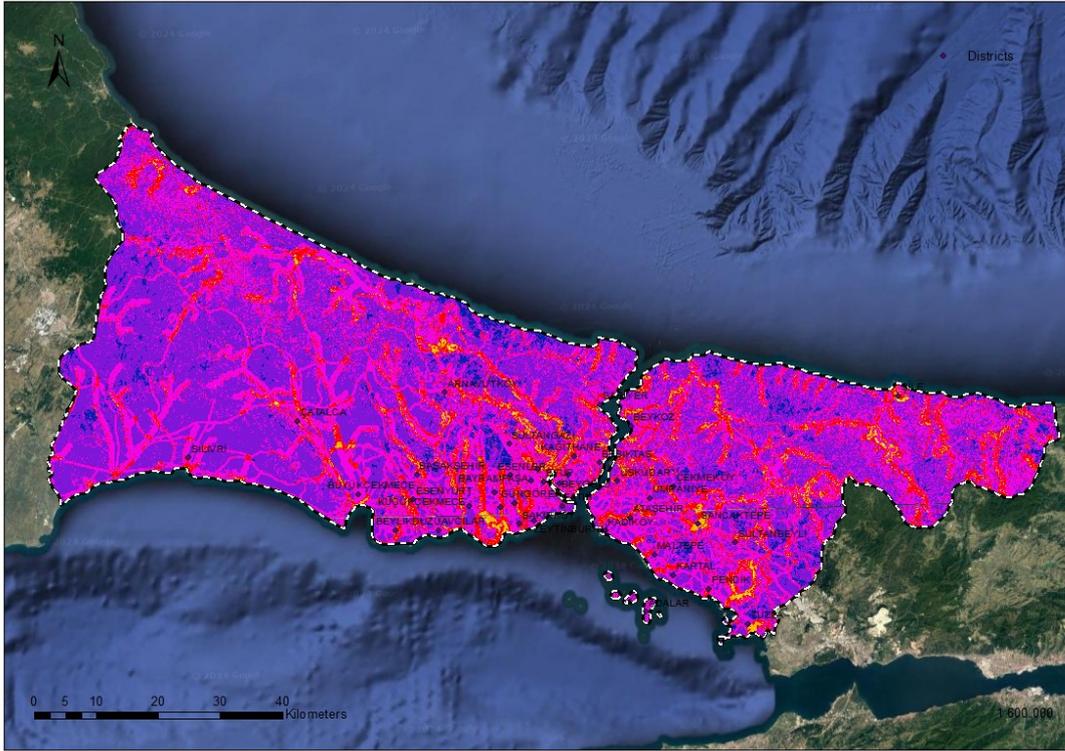


**Figure 4.14:** Weighted sum analysis reclassification results.

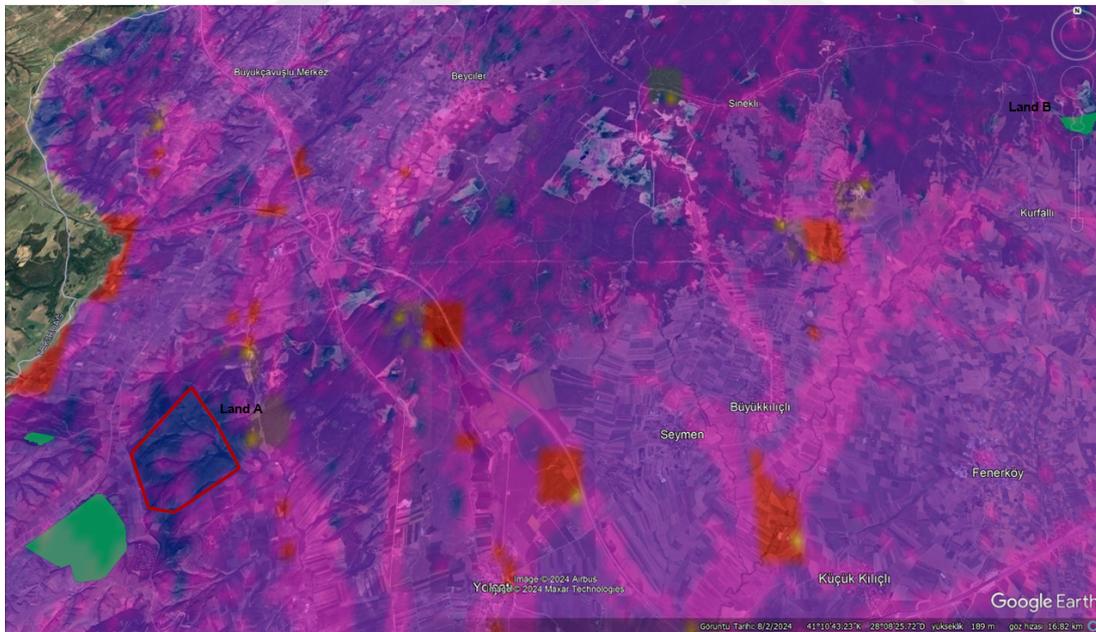
#### **4.1.5.4 Final temporary disaster debris management sites selections**

Weighted Sum Analysis Map depicted in Figure 4.14, was selected to conduct the analysis for identifying TDDMS candidates in Istanbul. For example, Figure 4.16 illustrates the results of selecting TDDMS for Silivri. Land marked in green represents the identified sites. Land A, shown in Figure 4.17, was excluded because it is classified as a forest area (“Orman” in Turkish) by the General Directorate of Land Registry and Cadastre. In some sites, relaxing certain criteria may be necessary to identify suitable candidates. For instance, in Davulcuhöyüğü Peak shown in Figure 4.18, Land B meets all the criteria but is classified as a forest area by the General Directorate of Land Registry and Cadastre, rendering it unsuitable for TDDMS selection. However, satellite imagery in Figure 4.18 indicates that the land features low-density tree areas. Consequently, criterion C4 was relaxed for Land B. The method to identify TDDMS included an extensive search utilizing Weighted Sum analysis illustrated in Figures 4.15-4.18. These data indicate how criteria such as land use and ownership influence the selection process. Following that, Table 4.5 offers a complete overview of the selected sites' properties, such as size, ownership, and the criteria relaxations employed during the study.

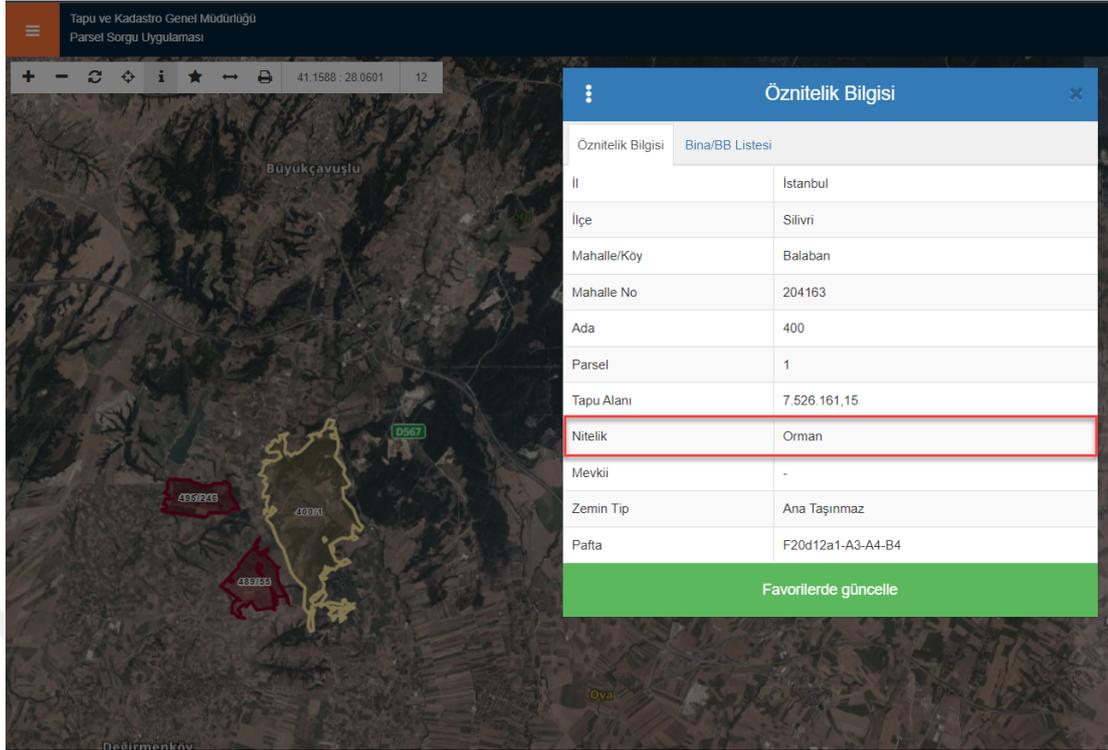
The identification of 46 candidate TDDMS was the result of a systematic analysis based on predefined criteria and methodologies. The total number of identified sites reflects the availability of suitable land within the constraints posed by Istanbul's dense urbanization, land ownership patterns, and environmental regulations. Some potential sites were excluded during the analysis because they failed to meet one or more critical criteria, such as being located in forest areas or exceeding buffer zone limits. Additionally, and perhaps most importantly, certain areas that met the criteria were excluded due to their insufficient size in hectares, which would render them ineffective for use as TDDMS. This highlights the importance of balancing compliance with criteria and practical functionality in the site selection process.



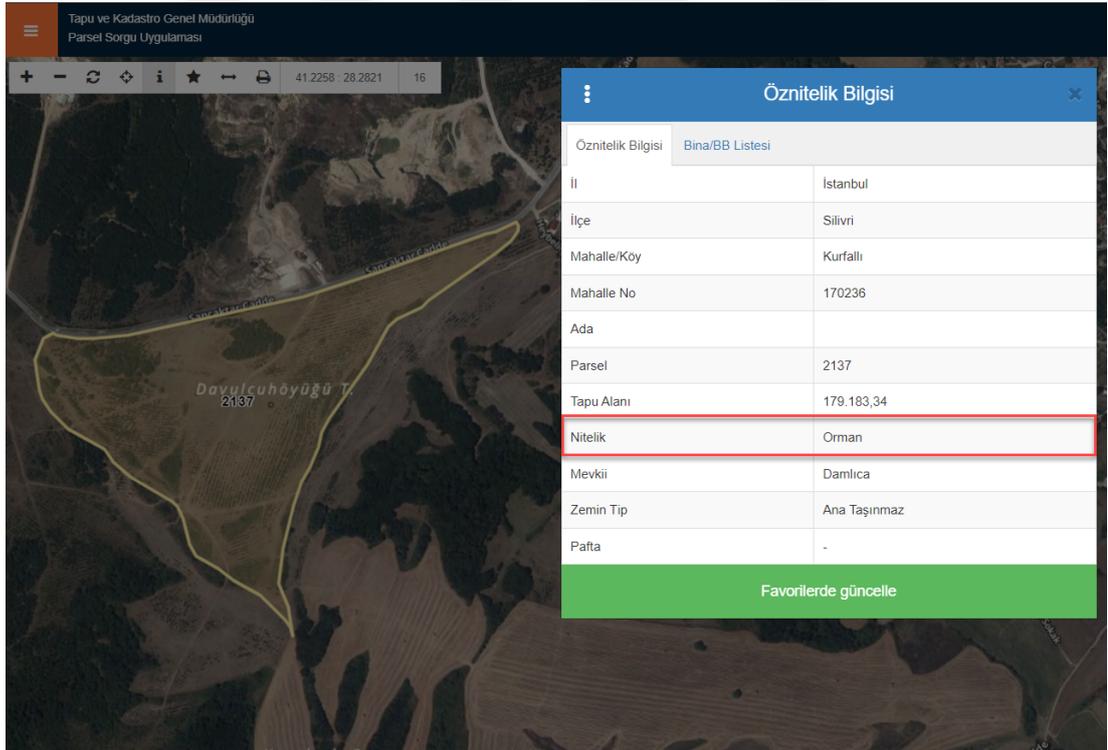
**Figure 4.15:** Districts location with satellite map.



**Figure 4.16:** Final candidate TDDMS in Silivri.



**Figure 4.17:** Land A as forest classification.



**Figure 4.18:** Land B in Davulcuhöyüğü Peak satellite image.

**Table 4.5:** Attributes of the selected sites.

Candidate	District	Size(ha)	Ownership	Criteria Relaxation
1	Arnavutköy	105	Public	No
2	Arnavutköy	19.1	Private	No
3	Çatalca	32	Public	No
4	Esenler	323	Private	No
5	Başakşehir	262	Private	No
6	Başakşehir	85	Industrial	C8, C4
7	Eyüpsultan	199	Industrial	C5, C8, C9
8	Sarıyer	21.5	Private	C3, C4, C9
9	Çatalca	27.6	Public	C9
10	Çatalca	18.8	Public	C8, C9
11	Eyüpsultan	16.3	Private	C8
12	Çatalca	3.21	Public	No
13	Sarıyer	7.70	Private	C8
14	Silivri	153	Public	C8
15	Silivri	6	Public	C4
16	Büyükçekmece	29.1	Private	C9
17	Avcılar	88.2	Private	C9
18	Başakşehir	299	Public	C8, C9
19	Arnavutköy	95.3	Public	C9, C5
20	Silivri	25.3	Public	C3, C4
21	Maltepe	671	Public + Private	C4, C8, C9
22	Maltepe	19.4	Public	C5
23	Beykoz	50.8	Private	No
24	Beykoz	23.3	Private	No
25	Şile	21.8	Public	No
26	Şile	6.46	Public	No
27	Şile	23.3	Public	C8
28	Şile	3.13	Public	C8
29	Beykoz	13.8	Public	C8
30	Beykoz	18.5	Public	No
31	Beykoz	19.3	Public	C4, C8
32	Şile	13	Industrial	C2, C8
33	Şile	20.4	Industrial	No
34	Şile	17.6	Industrial	No
35	Şile	10.1	Industrial	No
36	Şile	5.79	Industrial	No
37	Şile	6.28	Industrial	No
38	Şile	3.1	Industrial	No
39	Şile	17.6	Industrial	C8
40	Şile	12.5	Public	C8, C9
41	Şile	3.75	Public	No
42	Şile	19.3	Public	No
43	Şile	27.9	Industrial	C8, C9
44	Pendik	88.7	Public	C8
45	Arnavutköy	225	Public	C5
46	Arnavutköy	88.9	Private	C4

#### 4.1.6 Research limitations

This study recognizes various limitations that could influence the proposed model for selecting TDDMS:

- Dependence on GIS data and predefined criteria
  - The study is based on GIS data layers and predefined criteria, which may not respond well to real-time changes in emergency scenarios. As an instance, shifting debris sites or changing road conditions may limit the model's adaptability in dynamic post-disaster contexts.
- Data accuracy
  - The accuracy of GIS data, such as satellite images and property ownership records, is critical for selecting suitable TDDMS. Outdated, missing, or incorrect data may result in inefficient site selection, reducing the effectiveness of disaster management operations.
- Local infrastructure and constraints
  - Some sites identified as appropriate by the model may encounter unexpected local limits, such as legal or political concerns with land use or ownership. These limits may limit the practical application of the selected venues.
- Insufficient representation of social and cultural factors
  - Social and cultural criteria may be underrepresented or oversimplified in the model. Factors such as proximity to metropolitan centers, and culturally significant areas might have complicated societal consequences that are difficult to evaluate using a GIS framework.
- Community opposition
  - Technically suitable sites may face opposition from local residents due to proximity or environmental concerns. Such opposition could cause delays in the deployment of certain sites, impacting disaster response timetables.
- Sensitivity to disaster scenarios

- The study makes assumptions about the extent and nature of disaster. However, the volume and distribution of debris may differ greatly subject to the disaster type, its scale, and the impacted areas. The methodology may lack the flexibility to accommodate various disaster scenarios or concurrent events.
- Site-specific modifications
  - Relaxing criteria for specific sites, such as industrial zones, may result in the selection of fewer ideal places. If too many limits are violated, disaster management efficiency may suffer, and environmental problems may worsen.
- Challenges in real-time applications
  - While the model considers geographic and environmental factors, the real-time nature of disasters presents obstacles for static planning. The approach used in the study may fail to capture rapid changes in infrastructure, transportation networks, and trash patterns.
- Scalability and generalisability
  - This study's findings are specific to the Istanbul setting. Significant changes to the criteria and weighting would be required to apply the approach to other disaster-prone areas, limiting its scalability.

#### **4.2 Disaster Debris Volume Estimation**

The disaster debris estimation for Istanbul relies on data sourced from the Istanbul Earthquake Loss Estimation Update Project (2019) [135], published by the Istanbul Metropolitan Municipality Disaster Coordination Center. This dataset provides both district and neighborhood-level estimates for a Mw 7.5 earthquake scenario, including predictions for buildings classified as having Very Heavy Damage, Heavy Damage, Moderate Damage, and Light Damage, along with the number of buildings by story count (1-4, 5-8, 9-19 stories).

#### **4.2.1 District-based debris volume estimation**

To enhance the precision of disaster debris estimation for Istanbul, district-level data has been compiled, covering all districts except Adalar. The exclusion of Adalar, primarily due to its unique geographic characteristics and lower building density, allows for a focused analysis on the more urbanized and densely populated parts of the city.

Table 4.6 provides a summary of the estimated building damage and calculated debris quantities for each district of Istanbul, based on a Mw 7.5 earthquake scenario. The table includes the number of buildings classified as Very Heavy Damage, Heavy Damage, Moderate Damage, and Light Damage, and presents the corresponding estimated debris quantities for each district. The author computed the debris volumes in the final column using the methods and formula presented in Section 3.2. These estimates use data from the Istanbul Earthquake Loss Estimation Update Project [135] regarding building damage, as well as assumptions about debris generation rates per unit area and the average number of housing units per building. This method ensures consistency and accuracy in calculating debris quantities for disaster management planning.

#### **4.2.2 Neighborhood-based debris volume estimation**

Comprehensive neighborhood-specific data, encompassing a summary of projected building damage for each Istanbul neighborhood in the context of a Mw 7.5 earthquake scenario, is accessible in the Istanbul Earthquake Loss Estimation Update Project [135] for interested readers.

The debris volumes were computed using the formula outlined in Section 3.2, which considers the number of structures with significant structural damage, the average number of housing units per building, and the assumed debris generation rate per unit area. This assures compatibility with the district-level debris estimating approach described earlier in this work.

Given the scope of this debris estimation, the study exclusively examines the neighborhoods situated on the Asian side of Istanbul. This focus is driven by the logistical complexities encountered during the debris allocation process, particularly the challenges posed by the Bosphorus Strait, which hinders efficient transportation of

debris between the two sides of the city. Consequently, the allocation process has been confined to the Asian side. Future research could extend this methodology to neighborhoods on the European side, enabling a comprehensive analysis of the entire city.

**Table 4.6:** Estimated building damage and debris volumes for districts of istanbul under a mw 7.5 earthquake [135].

District	Very Heavy Damage	Heavy Damage	Moderate Damage	Light Damage	Estimated Debris (tonnes)
Arnavutköy	41	243	1704	4950	1,085,448
Ataşehir	123	471	2756	6833	1,829,100
Avcılar	233	1261	5545	9285	3,843,294
Bahçelievler	796	1490	5668	9686	4,342,884
Bakırköy	782	1306	3394	3939	2,993,172
Bayrampaşa	614	1182	4059	7415	3,196,830
Bağcılar	796	1825	8001	15397	5,799,612
Başakşehir	115	575	2977	6243	2,002,182
Beykoz	113	443	2756	7356	1,808,352
Beylikdüzü	321	950	3004	4331	2,334,150
Beyoğlu	410	841	3132	7158	2,393,118
Beşiktaş	64	187	1053	3241	711,984
Büyükkçekmece	439	1635	6622	9367	4,748,016
Esenler	391	813	3739	8302	2,698,878
Esenyurt	563	1768	7911	14672	5,592,132
Eyüpsultan	300	841	3794	8237	2,694,510
Fatih	2083	3496	9949	15758	8,478,288
Gaziosmanpaşa	129	403	2276	6969	1,533,168
Güngören	342	611	2407	4597	1,834,560
Kadıköy	209	505	2426	6717	1,714,440
Kartal	199	593	3282	8173	2,224,404
Kağıthane	94	275	1727	5816	1,144,416
Küçükçekmece	1240	2616	8978	13799	7,007,364
Maltepe	237	690	3388	8156	2,355,990
Pendik	274	1041	5625	13449	3,789,240
Sancaktepe	84	416	2539	6733	1,659,294
Sarıyer	102	365	2486	6977	1,612,338
Silivri	444	1707	7155	11997	5,081,076
Sultanbeyli	109	648	3949	8225	2,569,476
Sultangazi	61	245	1804	6884	1,152,060
Tuzla	446	1370	5310	8239	3,890,796
Zeytinburnu	510	1025	3799	6335	2,912,364
Çatalca	63	301	1656	4053	1,102,920
Çekmeköy	16	113	998	3392	615,342
Ümraniye	105	534	3626	10656	2,328,690
Üsküdar	146	493	3341	9610	2,173,080
Şile	21	106	774	2402	491,946
Şişli	68	207	1008	4333	700,518

## 4.3 Disaster Debris Transportation Optimization for Istanbul: A Cluster-Based Approach

### 4.3.1 Data preparation and exploration

This study's dataset includes information on both neighborhoods and TDDMS situated exclusively on the Asian side of Istanbul, reflecting the strategic decision to limit the analysis to this region in consideration of the logistical constraints imposed by the Bosphorus Strait. The data preparation method included several steps to assure accuracy and consistency with subsequent modeling. The following is a summary of the essential components and processes.

The dataset consists of the following columns:

#### For Neighborhoods:

- **District:** The district to which the neighborhood belongs.
- **Neighborhood:** The name of the neighborhood.
- **X\_Coordinate, Y\_Coordinate:** The centroid coordinates of the neighborhood.
- **Estimated Debris (tonnes):** The estimated volume of debris generated in each neighborhood.

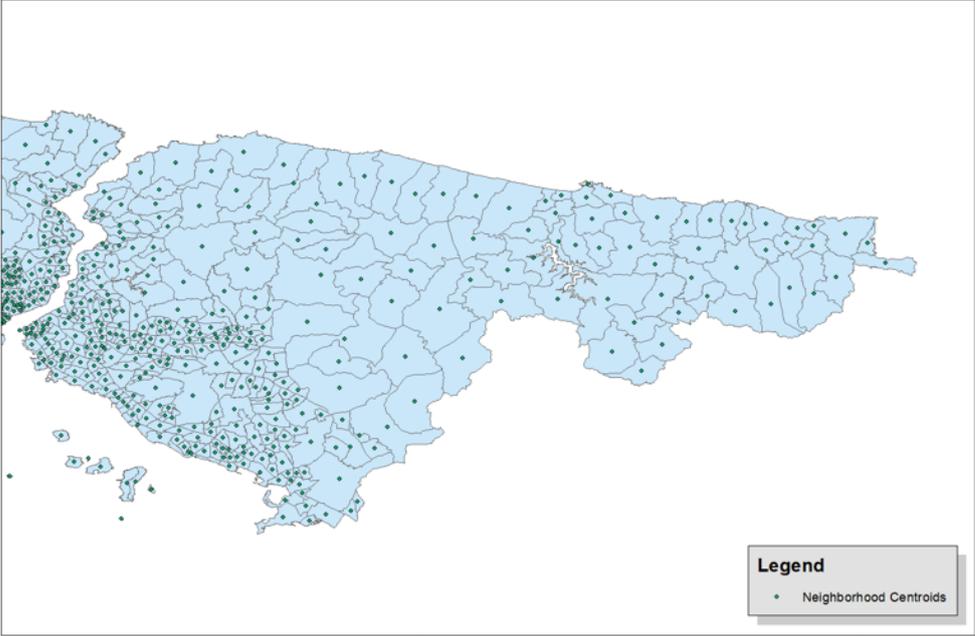
#### For TDDMS Candidates:

- **Name:** The name of the candidate TDDMS.
- **X\_Coordinate, Y\_Coordinate:** The centroid coordinates of the candidate site.
- **Total Area (hectares):** The total area of the candidate site, calculated using Google Earth Pro.
- **Capacity (tonnes):** The total debris capacity of the site, derived from its area.

#### 4.3.1.1 Neighborhood data preparation

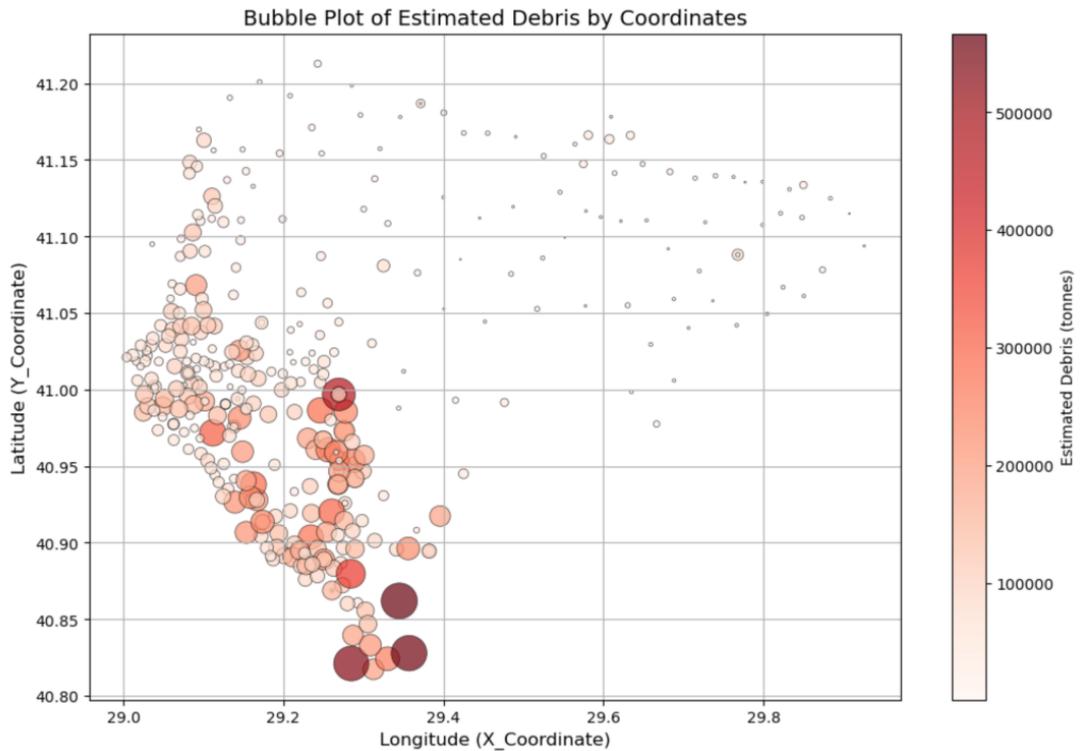
The polygonal boundaries of neighborhoods were extracted from OpenStreetMap by using the `admin_level = 8` filter, which ensures the selection of neighborhood-level administrative boundaries and rendered in KMZ format with ArcGIS. The centroids of these polygons were determined to get the X and Y coordinates for each neighborhood. Figure 4.18 depicts the retrieved neighborhood boundaries and

centroids, as displayed using OpenStreetMap data. The centroids, represented as dots on the map, indicate the X and Y coordinates for each neighborhood, which are critical inputs for the clustering and optimization methods outlined in the next sections.



**Figure 4.19:** Neighborhood polygons obtained from OpenStreetMap and their calculated centroids.

The estimated debris volumes for each neighborhood, received from the analysis in Section 4.2.2, were used as a crucial input to the model. The geographical distribution of neighborhoods and their estimated debris volumes are illustrated in Figure 4.19. The bubbles represent the centroid coordinates of each neighborhood, with size and color intensity proportional to the debris volume estimates.



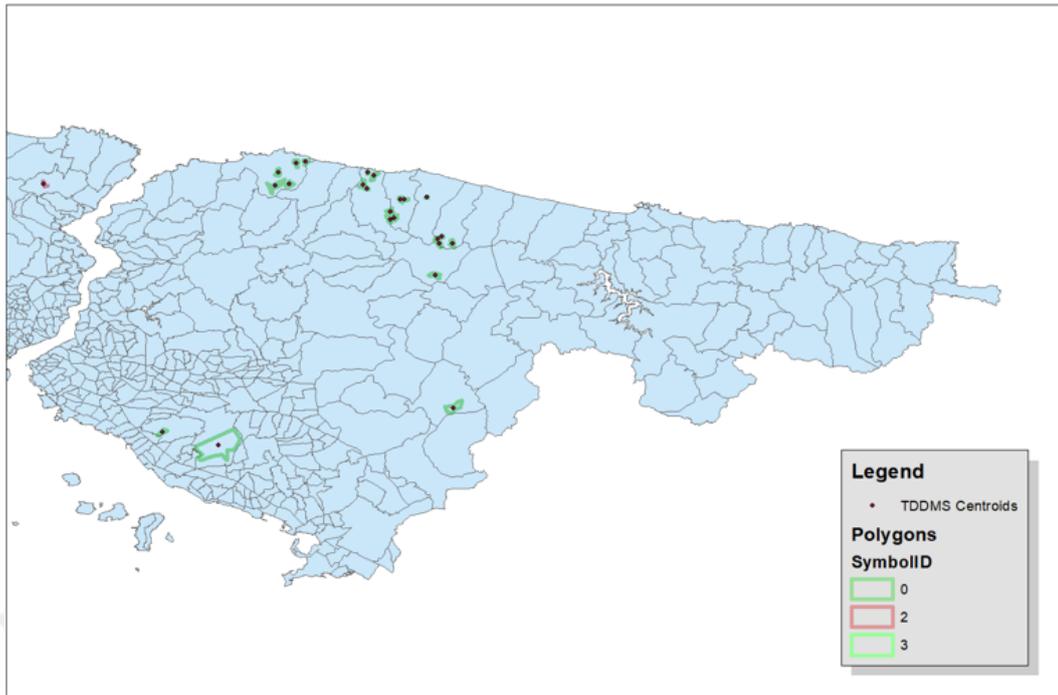
**Figure 4.20:** Bubble plot of estimated debris by coordinates.

#### 4.3.1.2 Temporary disaster debris management sites data preparation

Spatial analysis in ArcGIS in Section 4.1 was used to identify candidate TDDMS, which were then validated using Google Earth Pro. The process involved:

- Determine the total area of each candidate site in hectares.
- Calculating the centroids of each site polygon using X and Y coordinates.
- Determining each site's debris volume capacity depending on its area, as described in the next section.

Figure 4.20 depicts the candidate TDDMS found using spatial analysis in ArcGIS and validated with Google Earth Pro. The map shows the polygons representing candidate sites, as well as their determined centroids, which were used to compute each site's debris volume capacity based on its area, as explained in the sections that follow.



**Figure 4.21:** Candidate TDDMS identified through ArcGIS and verified with Google Earth Pro and their calculated centroids.

#### 4.3.1.3 Temporary disaster debris management sites debris volume capacity

The volume capacity of each TDDMS was calculated using its area, debris density, and FEMA requirements. To standardize the calculations, the following formulas were utilized:

$$\text{Capacity per Hectare (tonnes)} = (\text{Total Waste Capacity (m}^3\text{)} \times \text{Density (tonnes/m}^3\text{)}) / \text{Number of Hectares} \quad (4.4)$$

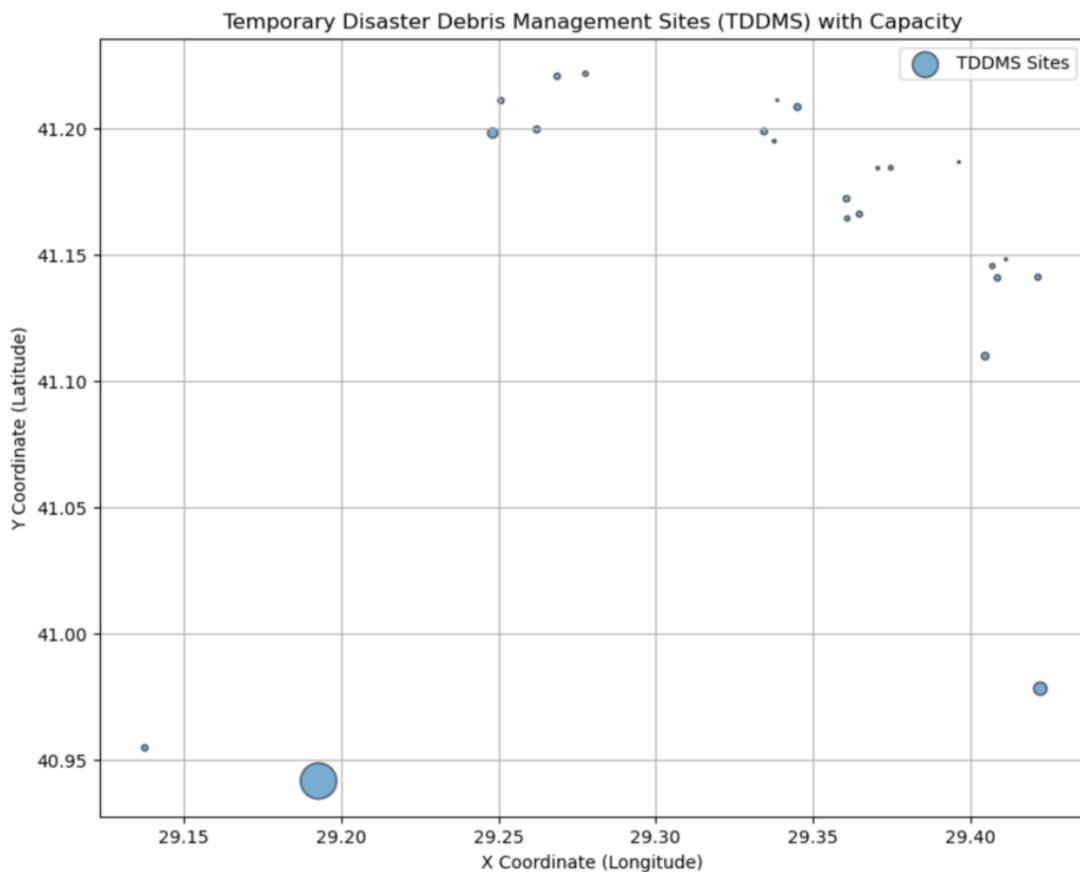
$$\text{Total Capacity (tonnes)} = \text{Capacity per Hectare (tonnes)} \times \text{Total Hectares} \quad (4.5)$$

In this study, the waste density was assumed to be 1.65 tonnes/m<sup>3</sup>, based on regional characteristics and similar studies [87], [136], [137]. This value was integrated into the capacity calculations for each candidate site. Additionally, according to FEMA's 2007 report [12], an analysis of past disasters indicates that approximately 0.52 square kilometers (52 hectares) of TDDMS is required for every 1 million cubic meters of debris. Using this ratio, the required area for debris storage was validated and cross-checked against the calculated capacities. For example:

- **FEMA Ratio:** Area per 1 million m<sup>3</sup>=52 hectares

- **Debris Volume (1 million m<sup>3</sup>) × Density (1.65 tonnes/m<sup>3</sup>):**  
 Estimated Capacity (tonnes per hectare) = 1,650,000 tonnes / 52 hectares  
 ≈31,730 tonnes/hectare.

This calculation was applied to validate the derived capacities of each candidate TDDMS. By integrating both FEMA guidelines and local debris density, the model ensures consistency and reliability in estimating the required storage capacity. The geographical distribution of candidate TDDMS along with their capacities are illustrated in Figure 4.21. The size of the markers is proportional to the debris storage capacity of each site, derived from their respective area and density calculations.



**Figure 4.22:** TDDMS with their capacities.

#### 4.3.1.4 Validation and finalization

To ensure geographic accuracy, all coordinates were confirmed according to the WGS84 format. Candidate sites were assessed to ensure their suitability for temporary debris management.

### **4.3.2 Transportation optimization with clustering**

This section describes the clustering and optimization approaches for allocating debris from neighborhoods to TDDMS. The goal is to minimize transportation costs while remaining within the TDDMS' capacity restrictions.

#### **4.3.2.1 Clustering with k-medoids**

The K-Medoids algorithm was used to cluster neighborhoods based on their geographical centroids and debris volumes. Various cluster configurations were tested (ranging from 5 to 20 clusters) to evaluate their impact on transportation costs.

##### **1. Clustering Process:**

- Initial medoids were selected randomly.
- Neighborhoods were assigned to the nearest medoid using the Haversine distance formula.
- Medoids were iteratively updated to minimize intra-cluster distances.
- The process was repeated until medoids stabilized.

##### **2. Cluster Outputs:**

- Centroids of the clusters were calculated, representing the average geographic location of each cluster.
- Total debris volumes for each cluster were aggregated.

#### **4.3.2.2 Cluster-based optimization**

The debris allocation problem was structured using a MILP model. The optimization aimed to allocate debris from clusters to candidate TDDMS with the aim of minimizing transportation costs while ensuring that no TDDMS exceeded its capacity.

##### **1. Decision Variables:**

- Continuous variables represented the volume of debris transported between clusters and TDDMS.
- Binary variables indicated whether a TDDMS was utilized or not.

##### **2. Constraints:**

- All debris from clusters was allocated to TDDMS.
- TDDMS capacities were not exceeded.

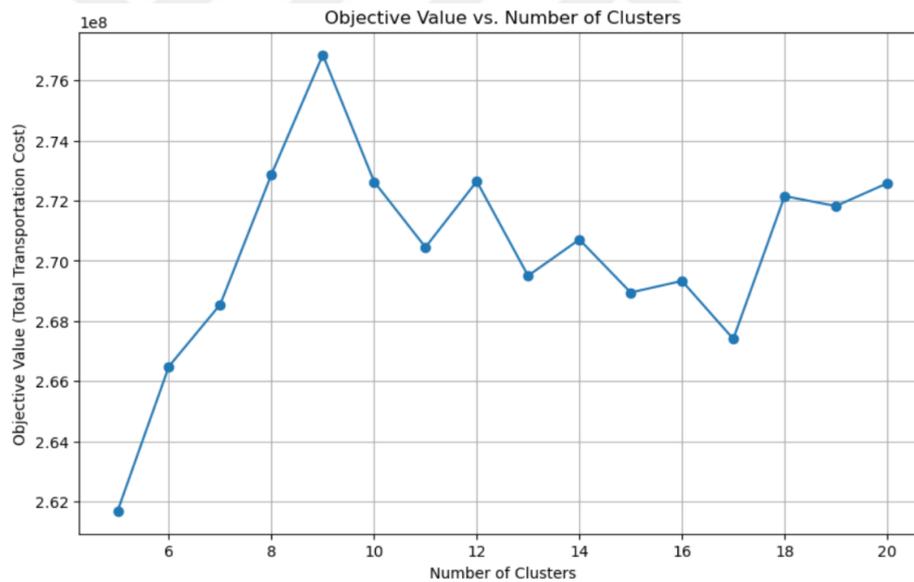
- A TDDMS could only be used if debris was assigned to it.
3. **Solver:** The MILP model was implemented and solved using the PuLP library.

#### 4.3.2.2.1 Cluster-based optimization general results

The optimization was performed for each cluster configuration (5 to 20 clusters). Key results included:

- The total transportation cost for each configuration.
- The optimal allocation of debris from clusters to TDDMS,

Figure 4.22 shows the variation in total transportation cost (objective value) with different cluster numbers, indicating a non-linear relationship and the presence of trade-offs between cost reduction and operational complexity. A detailed analysis of these trends is provided below.



**Figure 4.23:** Variation in total transportation cost with cluster numbers.

#### 4.3.2.2.2 Cluster-based optimization general trends

The graph demonstrates how the total transportation cost (objective value) fluctuates with the number of clusters:

- **Low Cluster Counts (5-8):** A rapid increase in transportation cost is observed.

- **Medium Cluster Counts (9-14):** Costs show a fluctuating pattern with partial reductions.
- **High Cluster Counts (15-20):** Costs stabilize with a slight upward trend.

This indicates that the relationship between the number of clusters and transportation cost is non-linear.

### **Impact of Low Cluster Counts (5-8)**

- **Rising Costs:** With fewer clusters, the cluster sizes become larger, increasing the distances between neighborhoods and cluster centroids. This results in higher transportation costs.
- **Operational Simplicity:** Fewer clusters require less coordination but are less efficient in terms of cost.

### **Fluctuation in Medium Cluster Counts (9-14)**

- **Fluctuating Decline:** During this range, transportation costs fluctuate as the clustering structure becomes more efficient in reducing transportation distances and better aligning with TDDMS capacities.
- **Optimal Points:** Some configurations in this range likely provide better balance between transportation efficiency and cluster compactness.

### **Impact of High Cluster Counts (15-20)**

- **Stabilization and Slight Increase:** As the number of clusters increases, the cost reduction slows and even reverses slightly. This could be due to:
  - **Increased Complexity:** More clusters create shorter distances but complicate TDDMS capacity allocation.
  - **System Limitations:** Higher cluster counts may exceed the capacity of nearby TDDMS, increasing logistical inefficiencies.

## Trade-Off

The graph highlights a trade-off between transportation costs and the number of clusters:

- **Low Cluster Counts:** Simpler logistics but higher transportation costs.
- **High Cluster Counts:** Shorter transportation distances but increased logistical complexity and capacity allocation inefficiencies.

An optimal cluster count would balance transportation cost minimization with manageable operational complexity.

## Key Insights

From the graph, several key conclusions can be drawn:

1. **Optimal Cluster Range:** The range of 9-14 clusters appears to offer a better balance between cost and operational feasibility.
2. **Cost Fluctuations:** Fluctuations in costs are likely influenced by the geographical distribution of neighborhoods and the proximity of TDDMS.
3. **Operational Recommendation:** Increasing clusters reduces transportation distances but requires careful consideration of logistical coordination and TDDMS capacities.

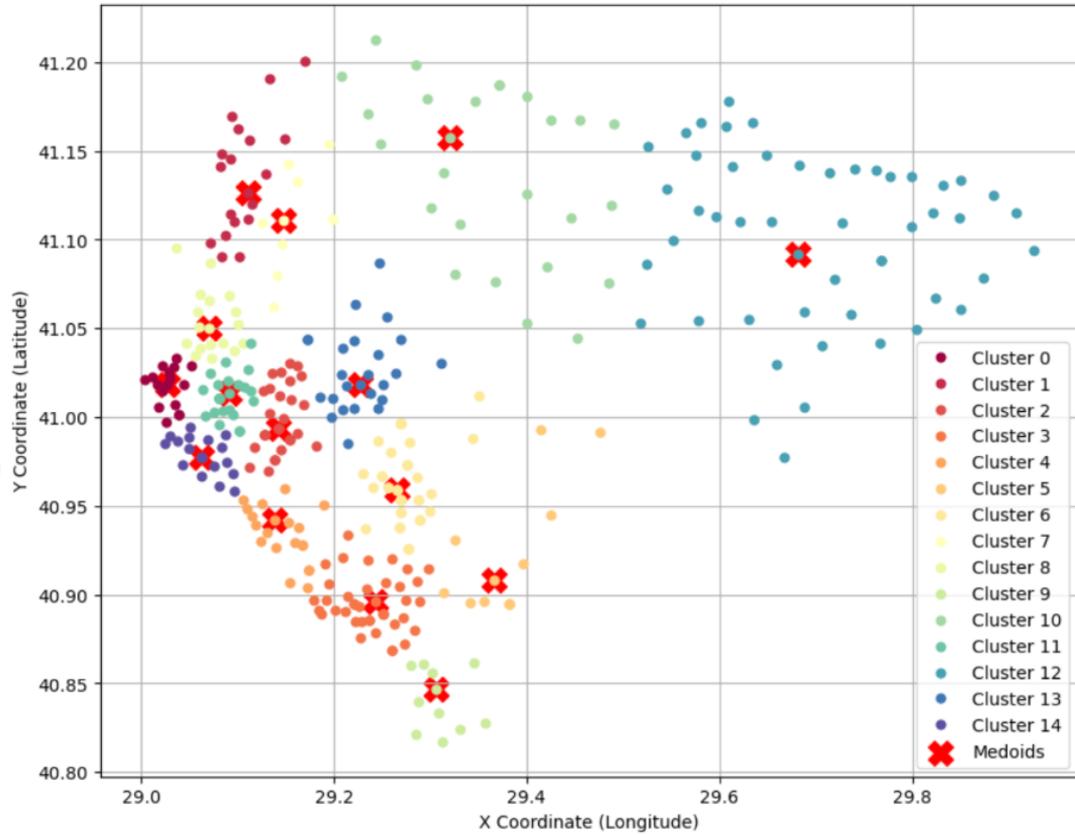
### 4.3.2.3 Optimization for n=15 cluster

The configuration with  $n = 15$  clusters was chosen as it represents a balanced trade-off between transportation cost reduction and manageable operational complexity, as observed above in Figure 4.22. This section provides detailed results for the clustering and optimization process under this specific setup. The clustering process grouped the neighborhoods into 15 distinct clusters. Each cluster represents a collection of geographically close neighborhoods with aggregated debris quantities.

- **Centroid Locations:** The centroids of these clusters were calculated as the average geographical coordinates of the neighborhoods within each cluster.
- **Debris Volumes:** The total debris volumes for each cluster were aggregated, providing an overview of the debris distribution across the study area.

As shown in Figure 4.23, the clustering algorithm grouped neighborhoods into 15 clusters based on their geographical locations. The red crosses represent the medoids, which serve as the central points for each cluster. This clustering

structure is used in the subsequent optimization process to allocate debris to TDDMS efficiently.



**Figure 4.24:** K-Medodoids clustering with haversine distance.

**Table 4.7** provides detailed information on the centroids' locations (latitude and longitude) and the total debris volumes allocated to each cluster.

**Table 4.7:** Summary of cluster centroids and debris distribution.

Cluster ID	Centroid Latitude	Centroid Longitude	Total Debris (tonnes)
0	41.017327	29.028585	972426.0
1	41.135428	29.106107	988806.0
2	40.999416	29.143827	2410044.0
3	40.895453	29.238048	4868136.0
4	40.934167	29.146338	2616432.0
5	40.921909	29.380146	948948.0
6	40.962320	29.272779	5199012.0
7	41.111107	29.156226	260988.0
8	41.053746	29.072924	1533714.0
9	40.840753	29.309631	2890524.0
10	41.139731	29.362537	315588.0
11	41.011985	29.090293	1521156.0
12	41.100642	29.701349	477204.0
13	41.026283	29.227323	1040130.0
14	40.978684	29.064056	1391754.0

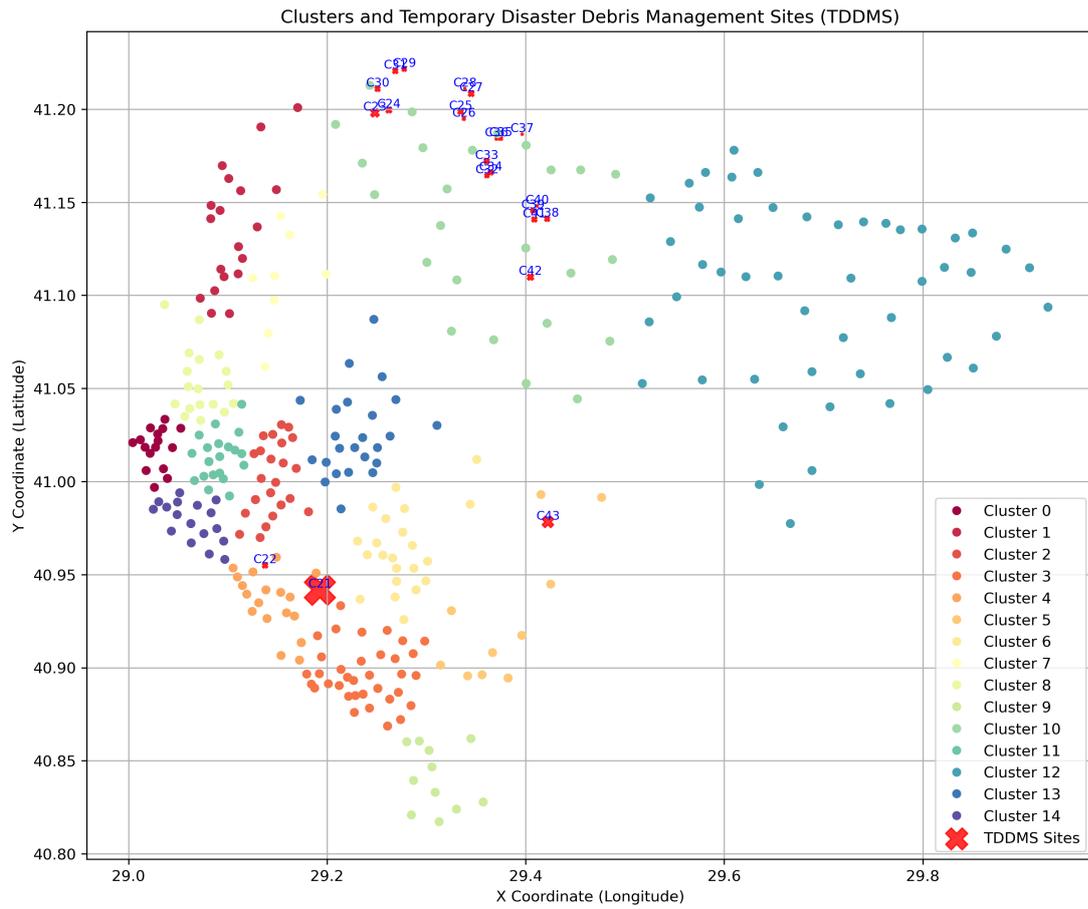
#### 4.3.2.3.1 Optimization results for n=15 cluster

The optimization model assigned debris from each cluster to the nearest TDDMS while minimizing transportation costs. The following Table 4.8 summarizes the allocation of debris from each cluster to the assigned TDDMS and the volume of debris transported.

Out of the available TDDMS, 7 sites were utilized, as shown in Table 4.9. All other TDDMS candidates were not utilized. Out of the available TDDMS candidates, the following sites were utilized, along with the number of clusters they served: C21, C22, C23, C24, C32, C38, C43. The constraint  $K$  ensures that the number of TDDMS selected is limited to a certain upper limit ( $K$ ). For the purposes of this study, the value of  $K$  was set to 7, thus controlling the maximum number of TDDMSs available. When analysing the model results, it can be seen that a total of 7 TDDMSs (C21, C22, C23, C24, C32, C38, C43) are actively used and this value is suitable for the constraint ( $K$ ). The addition of this constraint aims to protect the boundary in future optimisation studies and to provide flexibility to the model. The  $K$  constraint used in the model limits the number of TDDMS to 8. The effect of this constraint had no negative impact on the model's ability to minimise the total transport cost and was found to be compatible with existing optimisation results.

The total transportation cost for n=15 clusters was calculated to be 26,895,0571.63 units. This value represents the minimized total transportation cost for allocating debris from the 15 clusters to the selected TDDMS.

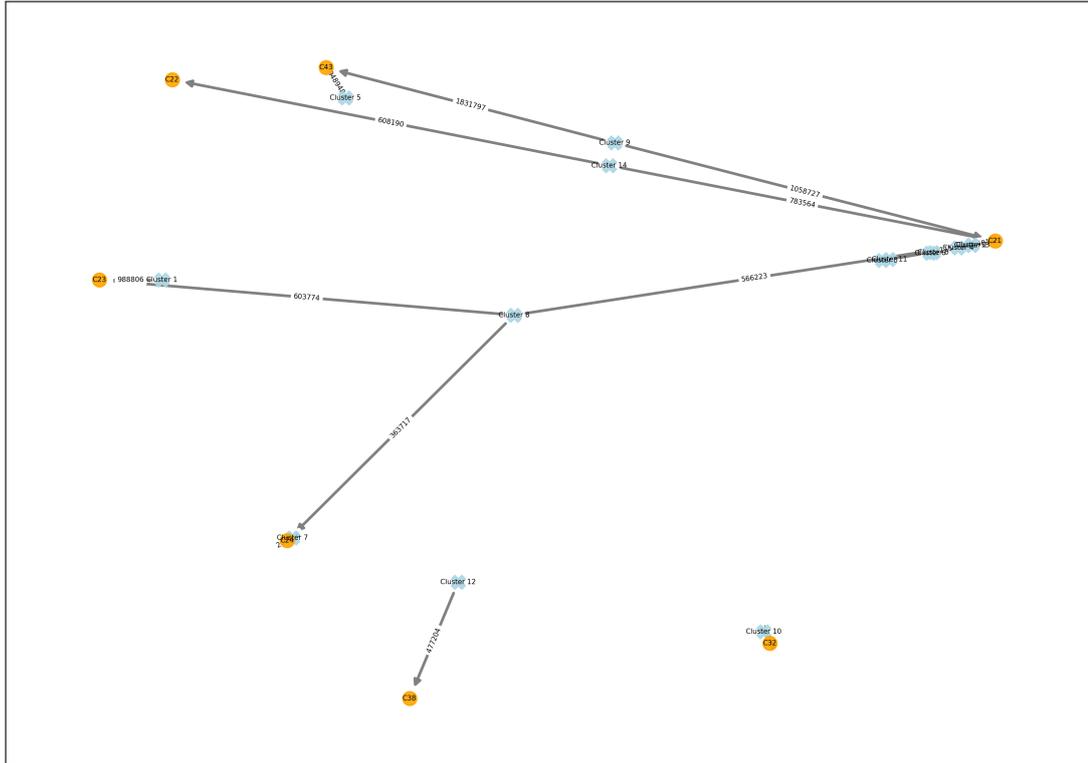
The spatial distribution of clusters and TDDMS is depicted in Figure 4.24. In this figure, each cluster is represented by a unique color, and the TDDMS locations are marked with red "X" symbols, with the size of each marker indicating the capacity of the respective site. Figure 4.25 also shows the relationships between the clusters and their assigned TDDMS as a directed graph. This graph highlights how debris is allocated from each cluster to its designated TDDMS, with the edges indicating the volumes of debris transported. The thickness and labels of the edges provide further insight into the amount of debris transported, while the node sizes distinguish between clusters and TDDMS capacities. Taken together, Figures 4.24-25 provide a comprehensive perspective on the debris allocation process and its spatial and operational dynamics.



**Figure 4.25:** Geographical distribution of clusters and TDDMS.

**Table 4.8:** TDDMS usage.

TDDMS ID	Number of Clusters Served
C21	11
C22	1
C23	2
C24	1
C32	1
C38	1
C43	2



**Figure 4.26:** Directed graph of clusters and TDDMS with debris allocation.

**Table 4.9:** Allocation results.

Cluster ID	TDDMS ID	Debris Transported (tonnes)
0	C21	972,426.0
1	C23	988,806.0
2	C21	2,410,044.0
3	C21	4,868,136.0
4	C21	2,616,432.0
5	C43	948,948.0
6	C21	5,199,012.0
7	C24	260,988.0
8	C21	566,223.0
8	C23	603,774.0
8	C24	363,717.0
9	C21	1,058,727.0
9	C43	1,831,797.0
10	C32	315,588.0
11	C21	1,521,156.0
12	C38	477,204.0
13	C21	1,040,130.0
14	C21	783,564.0
14	C22	608,190.0

### 4.3.3 Transportation optimization without clustering

This section discusses optimization approaches to allocating debris from neighborhoods to TDDMS. While Section 4.3.2 focuses on clustering-based optimization, this section uses non-clustering approaches to allow for a comparative examination. The goal remains to reduce transportation costs while complying to TDDMS capacity limits. The debris allocation problem was modeled as a MILP approach. The key components of the formulation and solution are outlined below:

The optimization aimed to allocate debris from clusters to candidate TDDMS in a way that minimizes transportation costs while ensuring that no TDDMS exceeded its capacity.

#### 1. **Decision Variables:**

- Continuous variables represented the volume of debris transported between clusters and TDDMS.
- Binary variables indicated whether a TDDMS was utilized or not.

#### 2. **Constraints:**

- All debris from clusters was allocated to TDDMS.
- TDDMS capacities were not exceeded.
- A TDDMS could only be used if debris was assigned to it.

3. **Solver:** The MILP model was implemented and solved using the PuLP library.

#### 4.3.3.1 Results of the optimization without clustering

MILP model provided the following results for allocating debris from neighborhoods to TDDMS without clustering:

#### 1. **Objective Value:**

The total transportation cost was minimized to 27,041,621.31 units.

#### 2. **TDDMS Usage:**

The allocation results, as summarized in Table 4.10, indicate that a significant proportion of debris was transported to a few key TDDMS, while others received relatively small volumes. Notably:

- **Major Contributors:**
  - **C21:** Received the largest volume of debris, totaling 21,035,850 tonnes, accounting for a significant majority of the total allocation.
  - **C43:** The second-highest contributor, with 2,780,745 tonnes of debris allocated.
  - **C23:** Played an important role, handling 1,592,580 tonnes of debris.
- **Small Numbers:**
  - The remaining TDDMS, such as C33 (4,368 tonnes), C37 (15,288 tonnes), and C40 (9,282 tonnes), handled considerably smaller volumes of debris.
  - These smaller allocations, as reflected in Table 4.10, suggest their use was optimized for specific neighborhood debris within their vicinity.

The optimization conducted without clustering resulted in the activation of a total of 13 TDDMS. Within the scope of this study, the  $K = 13$  constraint was applied to control the maximum number of TDDMS that could be utilized. The TDDMS selected in this scenario are as follows: C21, C22, C23, C24, C30, C32, C33, C36, C37, C38, C40, C42, C43. These results demonstrate that the model fully complies with the  $K = 13$  constraint while optimizing all debris allocations and minimizing transportation costs.

**Table 4.10:** Allocation results of the optimization without clustering.

TDDMS ID	Debris Volumes Transported (tonnes)
C21	21,035,850
C22	608,190
C23	1,592,580
C24	213,486
C30	257,793
C32	37,674
C33	4,368
C36	34,398
C37	15,288
C38	424,788
C40	9,282
C42	420,420
C43	2,780,745

#### 4.3.4 Clustering vs. non-clustering: a comparative analysis

This section compares clustering and non-clustering approaches for optimizing disaster debris allocation to TDDMS. The goal is to assess the impact of each approach on transportation costs and operational efficiency. The clustering-based optimization technique divides neighborhoods into clusters before distributing debris to TDDMS, while non-clustered technique allocate debris directly from each neighborhood.

Table 4.11 compares the results of non-clustered and clustered optimization techniques through demonstrating the differences in TDDMS assignments for selected neighborhoods under every technique. As shown in the table, the assignment varied due to the clustering process, which consolidates debris across different neighborhoods into a single cluster before assigning it to a TDDMS. Non-clustered technique, on the other hand, allocate debris directly from each neighborhood, resulting in more detailed assignments. To fully understand clustering and non-clustering optimisation approaches, Figure 4.22 (Objective Value vs. Number of Clusters) analyses transport costs against the number of clusters. This graphical representation reveals important trends and highlights the trade-offs associated with each method. The graph in Figure 4.22 (Objective Value vs. Number of Clusters) displays the following trends:

- Transportation costs rise initially as the number of clusters increases, peaking at 10 clusters and thereafter fluctuating.
- Transportation costs stabilize at increasing cluster numbers, but variances continue due to inefficiencies within individual cluster groupings.
- Conversely, non-clustering optimization approach considers each neighborhood independently, with no pre-grouping.
  - The general transportation cost was 27,041,621.31 units, establishing a constant baseline for comparison.

This approach directs debris from neighborhoods to TDDMS, eliminating inefficiencies induced by clustering.

**Table 4.11:** Neighborhood TDDMS assignments: clustering vs. non-clustering results.

Neighborhood	NonClustered	Clustered
Acarlar	C23	C24
Akbaba	C30	C23
Alibahadır	C30	C32
Anadolu Hisari	C23	C21
Anadolu Kavađı	C30	C23
Anadolufeneri	C30	C23
Bozhane	C24	C32
Çamlibağçe	C30	C23
Çengeldere	C23	C24
Göllü	C24	C32
Görelle	C23	C24
Göztepe	C22	C21
Mahmutşevketpaşa	C23	C24
Ortaçeşme	C30	C23
Öğümce	C24	C32
Örnekköy	C23	C24
Paşamandıra	C24	C32
Poyrazköy	C30	C23
Riva	C30	C32
Tokatköy	C30	C23
Yeni Mahalle	C23	C21
Zerzavatçı	C23	C24
Alemdağ	C24	C21
Çatalmeşe	C42	C21
Ekşiođlu	C42	C21
Koçullu	C42	C32
Nişantepe	C42	C21
Ömerli	C42	C32
Reşadiye	C24	C21
Sirapınar	C42	C32
Taşdelen	C42	C21
Caddebostan	C22	C21
Caferağa	C22	C21
Erenköy	C22	C21
Fenerbahçe	C22	C21
Feneryolu	C22	C21
Göztepe	C22	C21
Kozyatađı	C22	C21
Osmanağa	C22	C21
Zühtüpaşa	C22	C21
Emirli	C43	C21
Kurna	C36	C32
Kurtdođmuş	C43	C21
Hilal	C42	C21
Paşaköy	C42	C21

**Table 4.11 (continued):** Neighborhood TDDMS assignments: clustering vs. non-clustering results.

Neighborhood	NonClustered	Clustered
Yunus Emre	C42	C21
Akşemsettin	C43	C21
Mecidiye	C43	C21
Alacali	C38	C32
Avcikoru	C42	C32
Biçkidere	C42	C32
Çengilli	C42	C38
Darlık	C42	C38
Değirmençayırı	C43	C38
Doğancılı	C40	C32
Esenceli	C42	C32
Hasanlı	C42	C38
Karakiraz	C33	C32
Kervansaray	C42	C32
Kömürlük	C42	C32
Kurna	C36	C32
Oruçoğlu	C42	C38
Sahilköy	C37	C32
Sofular	C38	C32
Teke	C42	C38
Ulupelit	C42	C38
Üvezli	C42	C32
Yaka	C43	C38
Yeşilvadi	C38	C32
Aydinli	C43	C21
Cami	C43	C21
İstasyon	C43	C21
Şifa	C43	C21
Fatih Sultan Mehmet	C23	C21
Hekimbaşı	C23	C21
Topağaçı	C23	C21
Çengelköy	C23	C21
Güzeltepe	C23	C21
Kandilli	C23	C21
Kuleli	C23	C21
Küçüksu	C23	C21

#### 4.3.4.1 Clustering vs. non-clustering: key comparisons

- **Efficiency in costs**
  - Clustering lowers transportation costs compared to non-clustering for specified cluster numbers (e.g., 10-12 clusters).
  - Non-clustering ensures a consistent and predictable cost baseline.
- **Operating Complexity:**
  - Clustering decreases issue complexity by aggregating neighborhoods, but poor cluster design can result in economic inefficiencies.
  - Non-clustering treats each region separately, which increases computational requirements for huge datasets.
- **Flexibility:**
  - Clustering allows you to modify cluster sizes and numbers to optimize various scenarios.
  - Non-clustering eliminates clustering-related inefficiencies, but it may fail to capitalize on potential benefits across neighborhoods.

Differences in TDDMS utilization between clustering and non-clustering optimization approaches demonstrate how clustering influences debris allocation. Below is a comparison based on the data from Tables 4.9 (clustering) and 4.10 (non-clustering):

- **Number of active TDDMS:**
  - The approach of clustering activates fewer TDDMSs, concentrating allocation on primary sites such as C21.
  - The non-clustering approach makes use of a broader variety of TDDMS, including sites such as C33, C37, and C40, which received little debris.
- **Dominant TDDMS:**
  - Both approaches identified C21 and C43 as significant contributors. However, in the non-clustering scenario, these sites receive substantially more debris.

- **Allocation Distribution:**
  - Clustering produces a more concentrated allocation (for example, C21 serves 11 clusters), whereas non-clustering distributes debris more uniformly among numerous sites.
- **Operating Complexity:**
  - Clustering minimizes the number of TDDMS utilized, which could simplify processes.
  - Non-clustering increases complexity due to the participation of smaller TDDMS with limited allocations.

To conclude, the clustering approach is more efficient in allocating debris to fewer TDDMS, lowering operational overhead. However, the non-clustering approach allows for more scattered and flexible allocation, using a broader variety of TDDMS, albeit at the expense of additional complexity. The approach chosen is determined by operational priorities, such as reducing the number of active sites or increasing allocation flexibility.

## 5. CONCLUSION and FUTURE RECOMMENDATIONS

This study addressed a critical issue in disaster management: the identification and selection of TDDMS in Istanbul, a city with significant seismic risk. By integrating spatial analysis, clustering algorithms and transportation optimization, the research developed a systematic approach to debris management that balances environmental, economic and engineering criteria.

By combining geographical data with multi-criteria decision-making techniques, the GIS-based land suitability model employed in this study offers a systematic framework for assessing potential TDDMS. To ensure a thorough evaluation of site suitability, the model successfully integrates a variety of environmental, economic, and engineering factors, including slope analysis, major roads, built areas, and proximity to lakes and rivers. The model provides a balanced approach to site selection by employing weighted sum approach for flexibility and Boolean logic for strict binary classifications. The relationship between operational efficiency and environmental limits was highlighted by the GIS analysis, which showed how crucial certain factors—like Distance from major roads and Distance from built areas—are in limiting potential site alternatives.

Another essential part of the framework is the debris estimating methodology designed specifically for Istanbul. The study provides accurate neighborhood-level forecasts by utilizing historical data, such as debris volumes from previous earthquakes, and general formulas pertaining to building density, debris generation rates, and structure damage levels. The debris management plan will be in line with the specific requirements of Istanbul's diverse urban landscape thanks to this precise degree of estimation. However, depending solely on historical data has drawbacks because variables specific to disaster or changing urban features may not be adequately represented, which could compromise the estimates' accuracy.

A comparison of cluster-based against non-cluster-based debris allocation methods provides important novel insights about the trade-offs between logistical flexibility, cost effectiveness, and operational complexity. By centralizing debris allocation to fewer, larger TDDMS, the cluster-based approach—which made use of the K-Medoids algorithm—effectively clustered neighborhoods with comparable debris volumes and proximity, simplifying the transportation logistics. By directing debris from

neighborhoods to neighboring cluster medoids, this approach reduced transportation distances and consolidated processing activities, resulting in significant savings in transportation costs and operational overhead. The 15-cluster configuration performed optimally since it balanced cost-effectiveness and ease of operation.

On the other hand, a wider variety of smaller sites could be used with more flexibility owing to the non-cluster-based approach, which distributed debris directly from neighborhoods to TDDMS. This approach accommodated limitations like limited capacity or particular geographic issues of some TDDMS, allowing for a more distributed allocation even though it slightly increased transportation costs. In situations when site availability is severely limited or if a decentralized strategy is required due to the geographic dispersion of debris generation sources, this approach might be better.

The significance of aligning the debris management plan with particular operational priorities is highlighted by the comparison of different approaches. While the non-cluster-based approach allows flexibility and optimizes the use of available resources, the cluster-based approach performs particularly well in situations where cutting costs and logistical complexity is crucial. In the end, the results support a context-sensitive implementation of these approaches, customized to meet the particular requirements of every disaster situation, and utilizing the advantages of precise debris volume estimating and GIS analysis to guide decision-making.

Despite its benefits, the study has some limitations that ought to be acknowledged. The debris volume estimates were based on past records and basic formulas, which may not accurately reflect the diversity and complexity of various disaster scenarios. Furthermore, the model makes simple assumptions, such as fixed transportation costs and consistent site capacities, which may fail to capture the dynamic and unexpected nature of disaster logistics. In addition, the approach was uniquely adapted to Istanbul, limiting the findings' applicability to other geographic locations with distinct urban, environmental, and infrastructural characteristics.

Future studies might delve into several important areas to expand on this basis. Real-time data and dynamic variables can be incorporated into dynamic modeling to improve the model's responsiveness and adaptability during disaster occurrences. By applying the framework to a wider range of geographical areas, it would be possible

to validate and alter it while taking particular urban and environmental factors into consideration. Likewise, using cutting-edge methods like machine learning might boost the precision of site selection procedures and debris volume estimates. The optimization framework's incorporation of thorough environmental effect studies would further strike a balance between ecological protection and operational efficiency.





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