ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

TRANSFORMATION OF SOLID WASTE MANAGEMENT IN BAKU: A GIS-BASED MCDM APPROACH TO LANDFILL SITE SELECTION BEYOND BALAKHANI

M.Sc. THESIS

Kanan ALAKBARLI

Department of Geomatics Engineering

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Kanan ALAKBARLI
(501221623)

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Thesis Advisor: Prof. Dr. Dursun Zafer SEKER

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

BAKÜ'DE KATI ATIK YÖNETİMİNİN DÖNÜŞÜMÜ: BALAHANİ'NİN ÖTESİNDE ÇÖP DEPOLAMA ALANI SEÇİMİNE YÖNELİK CBS TABANLI MCDM YAKLAŞIMI

YÜKSEK LİSANS TEZİ

Kanan ALAKBARLİ
(501221623)

Geomatik Mühendisliği Anabilim Dalı

Geomatik Mühendisliği Programı

Tez Danışmanı: Prof. Dr. Dursun Zafer ŞEKER

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Kanan Alakbarli, a M.Sc. student of İTU Graduate School student ID 501221623, successfully defended the thesis/dissertation entitled "TRANSFORMATION OF SOLID WASTE MANAGEMENT IN BAKU: A GIS-BASED MCDM APPROACH TO LANDFILL SITE SELECTION BEYOND BALAKHANI", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Dursun Zafer SEKER** ....
İstanbul Technical University

Jury Members : **Prof. Dr. Zaide DURAN** ....
Istanbul Technical University

Asst. Prof. Dr. Ozan OZTURK ....
Recep Tayyip Erdogan University

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To my beloved family,

FOREWORD

I would like to express my deepest appreciation to my family, whose endless encouragement and emotional support provided me with the strength to persevere through the long hours of research, analysis, and writing. Their belief in my abilities, even during moments of self-doubt, was a constant source of motivation, and I am immensely grateful for their love and understanding throughout this process.

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This thesis represents a culmination of hard work, dedication, and the collective support of those around me, and I hope it contributes meaningfully to the field of sustainable waste management in Baku.

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Kanan ALAKBARLI
(Geomatics Engineer)

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ABBREVIATIONS

AHP : Analytic Hierarchy Process
CI : Consistency Index
GEM : Global Earthquake Model
GIS : Geographic Information Systems
MCDM : Multi Criteria Decision Making
OSM : Open Street Map
USGS : United States Geological Survey
WDPA : World Database on Protected Areas

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TRANSFORMATION OF SOLID WASTE MANAGEMENT IN BAKU: A GIS-BASED MCDM APPROACH TO LANDFILL SITE SELECTION BEYOND BALAKHANI

SUMMARY

Sanitary landfill site selection is a cornerstone of modern waste management, aiming to mitigate environmental degradation, public health risks, and social conflicts by strategically locating sites that balance ecological preservation with operational efficiency. This process involves evaluating multiple criteria to ensure minimal impact on surrounding ecosystems, communities, and infrastructure, while facilitating effective waste disposal in rapidly urbanizing regions. In Baku, Azerbaijan, the transformation of solid waste management has become a pressing concern as the city grapples with the challenges of rapid urban growth and increasing waste volumes. Historically reliant on the Balakhani landfill, Baku's waste management system has faced significant strain, with the existing facility nearing capacity and exhibiting environmental and social shortcomings, such as groundwater contamination and proximity to residential areas, which have led to widespread community dissatisfaction.

The necessity for a new landfill site in Baku is evident, driven by the need to address Balakhani's limitations and establish a sustainable waste management framework that aligns with the city's long-term development goals. Balakhani's location, close to settlements and ecologically sensitive zones like the Caspian Sea, has exacerbated issues such as leachate pollution and odor complaints, underscoring the urgency for alternative sites that prioritize environmental safety and social acceptability. This study seeks to identify such sites by employing a systematic approach to evaluate potential locations, ensuring that new landfills are positioned to minimize risks while supporting Baku's urban expansion and waste management demands.

The suitability analysis process utilized a Geographic Information System (GIS) integrated with a Multi-Criteria Decision-Making (MCDM) framework, specifically the Analytic Hierarchy Process (AHP), to assess ten criteria: land use/land cover, distance to roads, distance to settlements, distance to waterbodies, distance to airstrips, elevation, slope, distance to fault lines, distance to protected areas, and groundwater depth. Data for these criteria were sourced from diverse platforms, including open-access geospatial databases and digitized records, and processed using ArcGIS Pro. Each criterion was transformed into a suitability scale through Euclidean distance calculations for proximity-based factors and direct reclassification for others, standardizing them into a consistent range to enable comparison. The AHP method was applied to assign weights to each criterion, reflecting their relative importance based on Baku's context, with a particular emphasis on social and environmental factors. This weighting process ensured consistency in decision-making, achieving a reliable prioritization of criteria.

The results of the suitability analysis revealed distinct spatial patterns across Baku. The southwest and east regions emerged as highly suitable for new landfill sites, characterized by barren lands, deeper groundwater levels, and adequate distance from settlements and waterbodies, making them ideal for minimizing environmental and social impacts. Conversely, central urban areas, marked by dense residential zones, and lakeside regions near the Caspian Sea were classified as unsuitable or less suitable due to their proximity to communities and sensitive ecosystems, which posed significant risks of contamination and public opposition. The existing Balakhani landfill, located in the northeast, fell within a less suitable zone, confirming its environmental and social inadequacies and reinforcing the need for relocation.

In conclusion, this study provides a robust framework for landfill site selection in Baku, demonstrating the effectiveness of a GIS-MCDM approach in addressing complex urban challenges. The southwest region stands out as the most viable location for a new landfill, offering seismic stability and logistical advantages, while the eastern region presents a secondary option, contingent on addressing aviation safety concerns near Heydar Aliyev International Airport. Discussions highlight the minimal influence of topographic factors in Baku's flat landscape, suggesting that future studies could incorporate additional variables, such as wind direction for odor control, to further refine site selection. The findings advocate for immediate action in the southwest, supported by environmental impact assessments, and emphasize the importance of stakeholder engagement to enhance social acceptability. This research offers a replicable model for sustainable waste management in urban settings, contributing to Baku's vision for a resilient and environmentally conscious future.

BAKÜ'DE KATI ATIK YÖNETİMİNİN DÖNÜŞÜMÜ: BALAHANİ'NİN ÖTESİNDE ÇÖP DEPOLAMA ALANI SEÇİMİNE YÖNELİK CBS TABANLI MCDM YAKLAŞIMI

ÖZET

Kentlerin hızla büyüyen nüfusları, gelişen sanayi faaliyetleri ve değişen tüketim alışkanlıkları, günümüzde atık yönetimi sorunlarını yalnızca lojistik bir mesele olmaktan çıkararak önemli bir çevresel ve sosyal mesele haline getirmiştir. Özellikle gelişmekte olan ülkelerde, mevcut atık depolama sistemlerinin kapasitesi giderek artan katı atık hacmi karşısında yetersiz kalmakta ve uzun vadede doğal kaynakların geri dönüşsüz şekilde zarar görmesine yol açabilmektedir. Azerbaycan'ın başkenti Bakü de bu sorunsalın tipik bir örneğini teşkil etmekte, uzun yıllardır Balakhani bölgesine taşınan atıklar nedeniyle bölgedeki çevresel riskler ve toplumsal tepkiler artmaktadır. Balakhani düzenli depolama alanı 2016 yılında kısmen modernize edilerek sızıntı suyu arıtma ve gaz geri kazanım altyapılarına kavuşturulmuşsa da, hâlen yerleşim alanlarına oldukça yakın konumlanması, kapasitesinin dolmak üzere olması ve ekosistem üzerindeki olumsuz etkileriyle tartışma konusu olmaya devam etmektedir. Bu araştırmanın temel amacı, mevcut sorunlara kalıcı bir çözüm sunmak üzere, kentin uzun vadeli atık yönetimi ihtiyacını karşılayacak, çevresel açıdan daha güvenli ve sosyal olarak kabul edilebilir yeni düzenli depolama alanlarının bilimsel yöntemlerle belirlenmesidir.

Çalışmada depolama sahası seçimi süreci, yalnızca mühendislik ve ekonomik ölçekler üzerinden değil, aynı zamanda halk sağlığına etkiler, ekosistem duyarlılığı, lojistik uygunluk ve sosyal kabul gibi çok boyutlu faktörler bir arada değerlendirilerek ele alınmıştır. Zira uygun olmayan bir depolama alanı seçimi, zaman içerisinde yeraltı ve yüzey sularının kirlenmesi, hava kalitesinin bozulması ve halk sağlığı açısından ciddi tehlikelerin ortaya çıkmasına neden olabilmektedir. Balakhani örneğinde, bölgenin yerleşim alanlarına yaklaşık 2 kilometreden daha az mesafede bulunması nedeniyle uzun yıllar boyunca kötü koku şikayetleri ve sağlık endişeleri yaşanmış; ayrıca Hazar Denizi'nin yakınlığı atıklardan sızan kirleticilerin deniz ekosistemine ulaşma riskini artırmıştır. Çalışma bu nedenle, söz konusu olumsuzlukları en aza indirecek alternatif alanların belirlenmesi ihtiyacından doğmuştur.

Araştırmanın yöntemi, Coğrafi Bilgi Sistemleri (CBS) ve Çok Kriterli Karar Verme (ÇKKV) yaklaşımının entegre biçimde kullanılması esasına dayanmaktadır. CBS, farklı mekânsal verilerin sayısal olarak işlenmesine ve analiz edilmesine olanak sağlarken; Analitik Hiyerarşi Süreci (AHS), kriterlerin göreceli önem derecelerinin sistematik olarak hesaplanmasını ve karar verme sürecine bilimsel tutarlılık kazandırılmasını mümkün kılmaktadır. Çalışmada, uluslararası literatür, Avrupa Birliği düzenlemeleri, Azerbaycan mevzuatı ve Bakü'nün özgün coğrafi özellikleri göz önünde bulundurularak toplam on ana kriter belirlenmiştir. Bunlar arazi kullanımı ve örtüsü, yollar ve yerleşimlere mesafe, su kütlelerine ve havaalanlarına yakınlık, yükselti, eğim, fay hatlarına mesafe, korunan alanlara uzaklık ve yeraltı suyu derinliği

şeklindedir. Bu kriterlerin her biri, depolama alanının hem çevresel hem sosyal hem de lojistik boyutlarını kapsayacak şekilde seçilmiştir.

Verilerin temin edilmesinde farklı kaynaklardan yararlanılmıştır. Arazi örtüsü, yol ağları ve yerleşim alanlarına dair veriler OpenStreetMap ve USGS EarthExplorer gibi platformlardan sağlanmış; yeraltı suyu derinliği gibi detaylı jeolojik bilgiler ise basılı haritalardan dijital ortama aktarılmıştır. Verilerin farklı formatlarda olması nedeniyle, öncelikle koordinat sistemlerinin birleştirilmesi ve raster veri yapısına dönüştürülmesi işlemleri yapılmış, ardından ArcGIS Pro ortamında tüm veri setleri üzerinde yeniden sınıflandırma çalışmaları gerçekleştirilmiştir. Mesafeye dayalı kriterlerde Öklid mesafe analizleri kullanılmış ve her bir alan için sayısal uygunluk skorları oluşturulmuştur. Böylece her kriter için oluşturulan raster haritalar daha sonra ağırlıklandırılmış şekilde birleştirilerek nihai uygunluk haritası elde edilmiştir.

Analitik Hiyerarşi Süreci kapsamında, belirlenen kriterler ikili karşılaştırma matrislerinde değerlendirilmiş ve her birinin öncelik düzeyi hesaplanmıştır. Tutarlılık oranının tüm matrislerde %10'un altında kalması, yapılan ağırlıklandırmaların güvenilirliğini kanıtlamıştır. Ağırlıklandırma sonuçlarına göre en yüksek önem derecesine sahip kriterin yerleşim alanlarına mesafe olduğu görülmüştür. Bu kriterin %34,33 oranında bir ağırlığa sahip olması, halk sağlığı ve sosyal kabul hassasiyetlerinin ne kadar önemli olduğunu ortaya koymaktadır. İkinci en yüksek ağırlık, %19 oranıyla yeraltı suyu derinliği kriterine ait olmuş; böylece su kaynaklarının korunmasına yönelik duyarlılığın da karar mekanizmasında belirleyici olduğu anlaşılmıştır. Yollara mesafe (%11,58) ve su kütlelerine mesafe (%9,54) kriterleri de dikkate değer ağırlıklara sahip olmuş ve yer seçiminde önemli faktörler olarak öne çıkmıştır.

Çalışmanın analiz sonuçları, Bakü genelinde farklı uygunluk düzeylerine sahip bölgeleri belirgin biçimde ortaya koymuştur. Şehrin güneybatı bölgesi, çoğunlukla boş ve tarımsal faaliyetlerden uzak arazilerin varlığı, yerleşim alanlarından yeterli mesafede olması ve derin yeraltı suyu seviyelerine sahip olması nedeniyle en uygun bölge olarak saptanmıştır. Bu alanın ayrıca ulaşım bağlantıları açısından avantajlı olması ve jeolojik olarak daha stabil bir zemin yapısına sahip olması, yeni bir düzenli depolama tesisinin inşası için önemli bir potansiyel sağlamaktadır. Şehrin doğu bölgesi de ikinci derecede uygun alan olarak belirlenmiş; ancak Heydar Aliyev Uluslararası Havalimanı'na yakınlığı nedeniyle kuş çarpması riski ve hava trafiği güvenliği açısından özel önlemler alınması gerekliliği vurgulanmıştır. Buna karşın şehir merkezi ve Hazar Denizi'ne komşu bölgeler, yoğun yerleşim dokusu, ekosistem hassasiyeti ve kirlilik riskleri nedeniyle en düşük uygunluk seviyelerine sahip alanlar olarak sınıflandırılmıştır. Balakhani sahasının da düşük uygunluk zonunda yer alması, mevcut sorunların bilimsel temellerle doğrulandığını göstermiştir.

Araştırmanın önemli bir bulgusu, Bakü'nün düz topografyası nedeniyle yükselti ve eğim faktörlerinin göreceli olarak daha sınırlı etkiye sahip olmasıdır. Buna karşın sosyal riskler, ekolojik koruma gereklilikleri ve halk sağlığına dair endişeler karar sürecinde belirleyici rol oynamıştır. Sonuçlar, güneybatı bölgesinin yeni düzenli depolama alanı için en elverişli bölge olduğunu göstermiş; doğu bölgesinin ise gerekli güvenlik önlemleri ve etki değerlendirmeleri tamamlanması halinde alternatif bir seçenek olarak değerlendirilebileceği belirtilmiştir. Ayrıca ilerleyen çalışmalarda rüzgar yönü, koku yayılımı ve iklimsel parametrelerin de modelleme sürecine eklenmesinin uygunluk analizinin hassasiyetini artıracağı önerilmiştir.

Bu araştırma, CBS ve AHS'nin birlikte kullanılmasıyla bilimsel, şeffaf ve katılımcı bir karar destek mekanizması ortaya koymuştur. Söz konusu model, yalnızca Bakü için değil, benzer sorunlara sahip diğer kentler için de örnek teşkil edebilecek nitelikte olup, sürdürülebilir atık yönetimi politikalarının geliştirilmesine katkı sunacak potansiyele sahiptir. Çalışmanın sonuçları, ilgili kamu kurumlarına, şehir planlamacılarına ve karar vericilere uzun vadeli stratejiler geliştirme noktasında önemli bir referans sağlamaktadır. Bu yaklaşımla, atık yönetimi süreçlerinin daha çevre dostu, toplum tarafından kabul gören ve sürdürülebilir bir zeminde yürütülmesi mümkün olabilecektir.

1. INTRODUCTION

The accelerating pace of urbanization worldwide has transformed municipal solid waste (MSW) management into a pressing challenge for cities striving to balance environmental sustainability with population growth. In Baku, Azerbaijan's vibrant capital, this issue is particularly acute. Home to millions of residents, the city generates vast quantities of waste daily, straining its infrastructure and testing its commitment to a cleaner, healthier urban environment. Decades ago, waste disposal in Baku relied on rudimentary methods, with open dumpsites creating environmental hazards that polluted air, soil, and water. The Balakhani landfill, once the epitome of these problems, stood as a sprawling, uncontrolled site where waste piled up without regard for long-term consequences. By the early 2000s, the need for reform was undeniable, as the city's waste output grew alongside its population and economic ambitions.

A significant turning point came with a major rehabilitation effort that reshaped Balakhani into a modern sanitary landfill and industrial park. Completed in 2016, this project introduced advanced waste management practices, such as incineration to generate energy, recycling programs to recover materials, and systems to capture harmful landfill gases. According to the World Bank (2021), the facility now handles over 500,000 tons of waste each year, a testament to Azerbaijan's push toward sustainable urban development. Yet, the city's rapid expansion has brought new challenges. Residential neighborhoods have crept closer to Balakhani, shrinking the distance between homes and the landfill to less than 2 kilometers. Residents frequently report concerns about odors wafting into their communities, and experts warn that the landfill's capacity may not keep pace with the city's waste production, which increases by roughly 3% annually (Huseynova, 2023). These issues highlight a critical need for forward-thinking solutions to ensure Baku's waste management system remains effective for decades to come.

Selecting the right location for a landfill is no simple task. It demands a careful balance of environmental protection, practical logistics, and community well-being. Older approaches often fell short, relying on guesswork or limited considerations that ignored long-term impacts. The transformation of Balakhani showed what's possible when modern methods are applied, but it also revealed the limitations of a site chosen without today's tools. Technologies like Geographic Information Systems (GIS) now allow planners to map and analyze complex spatial data, from groundwater levels to road networks, with unprecedented precision. When paired with decision-making frameworks like the Analytic Hierarchy Process (AHP), these tools enable a structured, transparent process that weighs diverse factors and incorporates stakeholder perspectives. The success of such methods in other cities demonstrates their potential to guide Baku toward a more sustainable future (Islamic Development Bank, 2020).

This thesis explores how Baku can build on its progress by adopting a sophisticated approach to landfill site selection. By combining GIS with AHP, the study seeks to identify locations that not only handle the city's growing waste but also protect its environment and residents. The lessons learned from Balakhani's overhaul provide a foundation, but the path forward requires innovation to address the realities of a city that continues to expand and evolve.

1.1 Purpose

The central aim of this thesis is to craft a comprehensive and forward-looking framework for selecting landfill sites in Baku, Azerbaijan, utilizing the analytical strengths of Geographic Information Systems (GIS) paired with the Analytic Hierarchy Process (AHP) to ensure that future waste management facilities are both sustainable and resilient. Baku's waste management system, anchored by the Balakhani Sanitary Landfill and Industrial Park, has undergone remarkable improvements, transforming a once-polluting dump into a modern facility that processes a significant portion of the city's waste. However, the pressures of urban growth are mounting. The landfill's proximity to newly built residential areas, now less than 2 kilometers away, has sparked widespread concerns, with many households reporting issues like persistent odors that affect their quality of life. Moreover, the facility's capacity is under strain, with projections suggesting it may reach its limit within the next decade as waste volumes continue to climb (Huseynova, 2023). This research seeks to address these challenges head-on by developing a decision-making tool that identifies new landfill locations capable of serving Baku's needs for generations while safeguarding its natural resources and communities.

At the heart of this study is the creation of a spatially precise model that maps out critical factors influencing landfill placement. These factors include the need to maintain a safe distance from homes to prevent disturbances, the importance of protecting groundwater from contamination, and the practicality of accessing sites via existing transportation networks to keep operational costs manageable. By leveraging GIS, the framework will visualize these elements across Baku's landscape, highlighting areas that meet stringent environmental and logistical standards. AHP complements this by allowing the study to assign priorities to each factor based on input from waste management experts and local stakeholders, ensuring the process reflects real-world needs and values. The Balakhani project's adoption of technologies like energy recovery, which converts waste into usable power, serves as an inspiration, pushing this research to explore how new sites can incorporate similar innovations to maximize efficiency and minimize environmental impact (Islamic Development Bank, 2020).

Beyond technical development, this thesis aspires to deliver practical guidance for Baku's policymakers and waste management authorities. The Balakhani rehabilitation demonstrated the value of modern infrastructure, but it also exposed gaps, such as limited public engagement, which delayed earlier phases of the project (World Bank, 2021). By analyzing these lessons, the study will propose strategies to strengthen community involvement, ensuring that future sites gain public support from the outset. Additionally, it will explore ways to expand resource recovery efforts, building on Baku's current recycling and energy initiatives to create a more circular waste economy. The ultimate goal is to produce a suitability map that not only identifies optimal landfill locations but also serves as a blueprint for sustainable urban planning, offering insights that resonate beyond Baku to other rapidly growing cities facing similar waste management dilemmas.

1.2 Study Area

Baku, situated on the Absheron Peninsula along the Caspian Sea at coordinates 40.3953°N, 49.8822°E, serves as Azerbaijan's political, economic, and cultural epicenter, sprawling across approximately 2,130 km² as depicted in Figure 1.1. With a metropolitan population ranging from 2.3 to 4 million, it houses nearly half of Azerbaijan’s 10.1 million citizens (Government of Azerbaijan, 2016). The city’s topography, characterized by flat to gently sloping terrain with elevations from 0 to 200 meters, coupled with a semi-arid climate averaging 250 mm of rainfall annually, shapes its waste management dynamics, as wind and dust can exacerbate disposal challenges (Solargis, n.d.). Baku produces an estimated 1.8 million tons of MSW each year, translating to roughly 1.2 kg per person daily, surpassing the global average of 0.74 kg (World Bank, 2018).

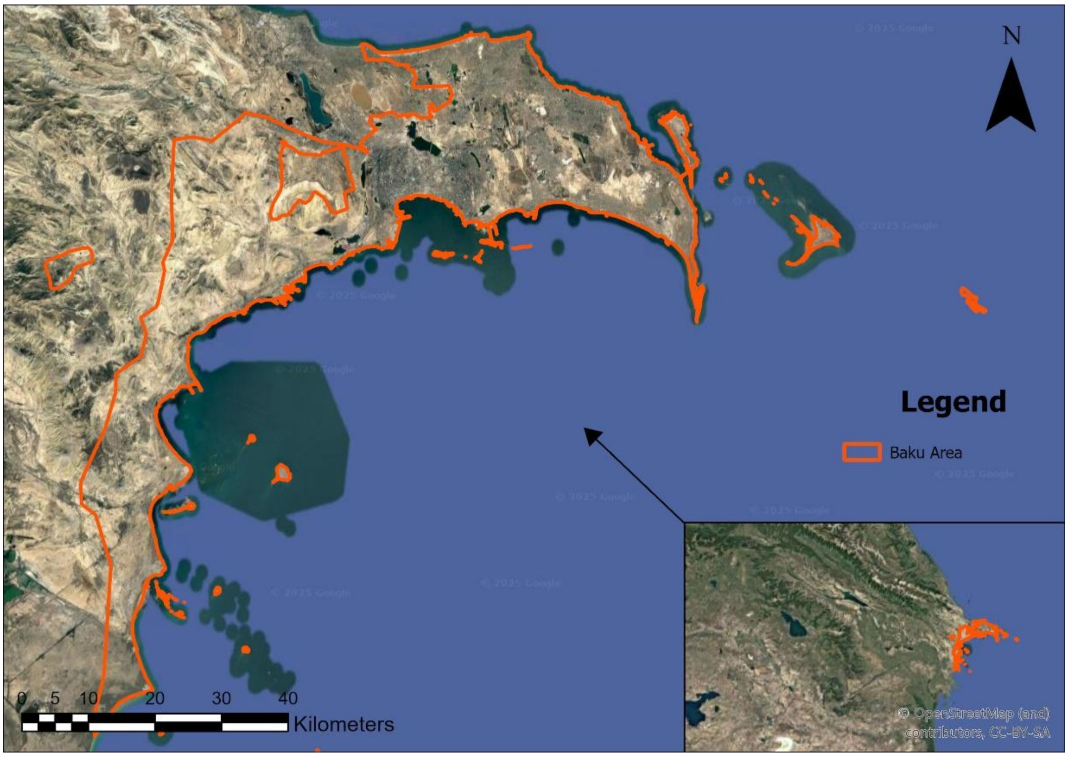

Figure 3.5 : Study area.

The Balakhani landfill, located 10 km northeast of central Baku, remains the city’s primary waste disposal hub. Before its rehabilitation, it functioned as an uncontrolled dump spanning 100 hectares, processing 1.5 million tons of waste annually and causing environmental damage through leachate leaks and methane emissions (World Bank, 2021). The ARP II project, completed in 2016, transformed 52 hectares into a sanitary landfill with a capacity of 7 million cubic meters, equipped with liners, leachate treatment, and gas recovery systems,as shown in Figure 1.2. It now manages 80% of Baku’s waste, with 20% redirected to recycling and composting programs (Tamiz Shahar, n.d.; Islamic Development Bank, 2020). However, urban expansion has brought residential zones within 1.8 km, amplifying complaints about odor and health concerns, with 70% of nearby households affected (Huseynova, 2023).

Source: Aim Texas Trading LLC 2021.

Figure 3.5 : Balakhani location, adapted from (World Bank, 2021).

Baku's geographical setting on the Absheron Peninsula, characterized by flat to gently sloping terrain with elevations ranging from 0 to 200 meters, shapes its suitability for landfill site selection, as low slopes facilitate construction but require careful drainage planning (Solargis, n.d.). The city spans approximately 2,130 km², with urbanized zones expanding at a rate of 5% annually, increasingly encroaching on potential disposal sites and necessitating strategic spatial planning (World Bank, 2021). Groundwater aquifers, situated 3-10 meters below the surface, are vulnerable to contamination, underscoring the need to prioritize sites with deeper water tables to protect Baku's water resources (Gahramanov et al., 2022).

This study focuses on Baku's administrative boundaries, excluding ecologically sensitive coastal areas along the Caspian Sea and agricultural lands, to identify locations that balance waste management demands with environmental preservation. The semi-arid climate, with annual rainfall averaging 250 mm, minimizes leachate generation but heightens dust and erosion risks, further emphasizing the importance of geographically informed site selection (Government of Azerbaijan, 2016).

2. LITERATURE AND CONCEPTS

2.1 Concepts

This subsection defines the theoretical frameworks and key ideas underpinning the research, starting with the transformation of solid waste management, followed by GIS, MCDM, AHP, and landfill siting criteria.

2.1.1 Transformation of solid waste management

Solid waste management has evolved significantly over the past few decades, driven by increasing urbanization, population growth, and heightened environmental awareness. According to Kaza et al. (2018), the world generated 2.01 billion tons of municipal solid waste (MSW) in 2016, with projections indicating a rise to 3.40 billion tons by 2050, particularly in developing countries. This surge necessitates efficient and sustainable waste management practices to mitigate environmental degradation and public health risks, such as groundwater contamination, air pollution, and disease vectors, often associated with traditional open dumping (World Bank, 2018).

The transition from open dumping to sanitary landfills has been a critical step toward sustainability. Sanitary landfills, equipped with engineered liners, leachate collection systems, and gas recovery mechanisms, aim to minimize environmental impact, but their siting remains challenging due to the need to balance environmental, social, and economic factors (Sumathi et al., 2008). Recent advancements include integrated waste management systems that incorporate recycling, composting, and waste-to-energy technologies, reducing landfill dependency while promoting resource recovery. For instance, Majid and Mir (2021) highlight how recycling can divert up to 30% of waste in urban areas, easing landfill pressure, while Hoornweg and Bhada-Tata (2012) emphasize waste-to-energy as a viable option for cities with high organic waste content.

In Azerbaijan, particularly in Baku, the transformation of solid waste management is exemplified by the rehabilitation of the Balakhani landfill under the Azerbaijan Rehabilitation Program II (ARP II) Integrated Solid Waste Management Project, completed in 2016 (World Bank, 2021). This project transformed Balakhani from an open dump into a sanitary landfill capable of processing over 500,000 tons of waste annually, incorporating waste-to-energy incineration and recycling facilities. The project also developed an industrial park, enhancing the economic viability of waste management in the region (Islamic Development Bank, 2020). The World Bank (2021) reports a 60% reduction in groundwater contamination risks post-rehabilitation, attributing this to improved liner systems and leachate management, while the Islamic Development Bank (2020) notes energy recovery generating 10 MW, supporting local power needs.

However, despite these advancements, challenges persist. Urban sprawl has reduced the buffer zone around Balakhani, leading to increased odor complaints from nearby residents, with 70% of households affected (Huseynova, 2023). Additionally, the landfill's capacity is expected to be exhausted within a decade due to the city's growing waste generation, which is increasing at a rate of 3% annually (Huseynova, 2023). These issues highlight the need for proactive planning and the use of advanced tools like GIS and MCDM to ensure that future landfill sites are selected optimally, balancing environmental protection, social acceptance, and economic feasibility. The global literature, such as Kaza et al. (2018), provides a framework for understanding these dynamics, while local studies like Huseynova (2023) offer insights into Baku's specific challenges, making this thesis a critical step toward sustainable waste management in the region.

2.1.2 GIS for spatial analysis in waste management

Solid Geographic Information Systems (GIS) have become indispensable in modern waste management, particularly for tasks such as landfill site selection, waste collection routing, and environmental impact monitoring. GIS enables the integration, visualization, and analysis of spatial data, which is crucial for making informed decisions about waste management infrastructure (Chang et al., 2008). Its components—data (spatial and attribute), software (e.g., ArcGIS Pro), hardware, people, and procedures—work together to process complex datasets like topography, land use, and hydrology, essential for landfill siting.

In the context of landfill site selection, GIS is used to map and analyze various environmental and socio-economic factors that influence site suitability. For instance, GIS can generate thematic maps of slope, land use, proximity to water bodies, and distance from residential areas, all of which are critical criteria for siting landfills (Sumathi et al., 2008; Kontos et al., 2005). For Baku, GIS is particularly valuable given its complex urban landscape and the need to balance waste management with environmental protection and urban development. Tools like ArcGIS Pro can process spatial data from sources such as Humanitarian Data Exchange (n.d.) for administrative boundaries, SimpleMaps (n.d.) for urban layouts, and Solargis (n.d.) for topographic data, among others.

The use of GIS in landfill site selection not only enhances the accuracy and efficiency of the process but also facilitates stakeholder engagement by providing visual representations of potential sites and their impacts. This transparency is crucial for gaining public acceptance, especially in densely populated urban areas like Baku. Studies like Gorsevski et al. (2012) demonstrate GIS's effectiveness in integrating multi-criteria evaluation techniques, such as ordered weighted averaging, to rank landfill sites, while Errouhi et al (2018) developed a GIS-based decision support system using AHP and TOPSIS, showing how GIS can handle complex spatial data for decision-making. These approaches are directly applicable to Baku, where spatial analysis can address urban sprawl and environmental sensitivity, ensuring that selected sites minimize risks like groundwater contamination and odor dispersion.

2.1.3 MCDM and AHP

Multi-Criteria Decision-Making (MCDM) is a set of methods designed to address complex decision problems involving multiple, often conflicting, criteria. In landfill site selection, MCDM is essential because it allows decision-makers to evaluate and prioritize different sites based on a range of factors, including environmental, social, and economic considerations (Alavi et al., 2013). One of the most widely used MCDM methods is the Analytic Hierarchy Process (AHP), developed by Thomas Saaty in the 1970s (Saaty, 1980).

AHP involves breaking down a complex decision into a hierarchy of criteria and sub-criteria, then using pairwise comparisons to determine the relative importance of each factor. The process culminates in the calculation of weights for each criterion, which can then be used to rank or score different alternatives (Saaty, 1990). In landfill site selection, AHP is particularly useful because it allows for the incorporation of both quantitative and qualitative data, as well as the preferences of different stakeholders. For example, in a study by Alavi et al. (2013), AHP was used to weight criteria such as distance to residential areas, groundwater depth, and land use for landfill siting in Mahshahr County, Iran, resulting in a suitability map that prioritized environmental protection. Similarly, Benezzine et al. (2022) applied AHP in conjunction with GIS to select a sanitary landfill site in Settat Province, Morocco, considering factors like slope, soil type, and proximity to roads, achieving a balanced decision that minimized social opposition.

For Baku, AHP can be used to prioritize the criteria identified for site selection, ensuring that the final decision is based on a transparent and systematic evaluation process that reflects the city's specific needs and constraints. The method's ability to incorporate stakeholder input is particularly valuable in Baku, where public opposition to landfill siting has been a challenge, as seen in the delays during the Balakhani project's early phases (World Bank, 2021). Studies like Mahmoudkelayeh et al. (2024) further illustrate AHP's flexibility, using it to weight wind speed for odor management in Semnan, Iran, a factor potentially relevant for Baku's semi-arid climate.

2.2 Literature on GIS and MCDM in Landfill Site Selection

The integration of Geographic Information Systems (GIS) with Multi-Criteria Decision-Making (MCDM) methods, particularly the Analytic Hierarchy Process (AHP), has become a standard approach for landfill site selection due to its ability to handle spatial data and multiple criteria effectively. Early studies, such as Siddiqui et al. (1996), demonstrated the use of GIS for mapping landfill suitability based on factors like slope and land use, while Kontos et al. (2005) introduced a spatial multiple criteria analysis methodology that combined GIS with MCDM for siting MSW landfills in Greece, achieving a balanced approach that considered environmental and socio-economic factors. The study's results showed that GIS could effectively map exclusion zones, such as water bodies and residential areas, while MCDM ranked sites based on weighted criteria, a model applicable to Baku's urban context.

Majid and Mir (2021) applied GIS-based multi-criteria evaluation for landfill site selection in Srinagar, India, addressing urban constraints like population density and waterbody proximity, resulting in a suitability map that identified sites with adequate buffers, relevant for Baku's urban sprawl.

In terms of MCDM methods, AHP is favored for its structured approach to decision-making. However, other methods like TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) have also been used in conjunction with GIS, as seen in Errouhi et al (2018), who developed a GIS-based decision support system using AHP and TOPSIS, showing how these methods can handle complex spatial data for decision-making. These studies highlight the effectiveness of GIS-MCDM integration in providing a systematic and transparent framework for landfill siting, which is particularly relevant for Baku's complex urban landscape, where spatial analysis can address urban sprawl and environmental sensitivity.

2.2.1 Case studies of landfill siting in urban areas

Urban areas, particularly in developing countries, face unique challenges in landfill site selection due to high population densities, limited land availability, and stringent environmental regulations. Below are detailed case studies that highlight how these challenges have been addressed in contexts similar to Baku, providing valuable insights for this thesis.

In Jordan, the Al-Balqa Governorate faced significant challenges in managing solid waste due to rapid urbanization and limited resources. A study by Al-Balqa Governorate (2024) used a multi-criteria decision-making (MCDM) approach integrated with GIS to select a suitable landfill site. The methodology considered key parameters such as distance to surface water, land cover, distance from urban and rural areas, distance to roads, slope, and soil permeability. These factors were crucial for ensuring minimal environmental impact while maintaining accessibility for waste transportation. The study's results identified several potential sites, with the most suitable ones located at least 500 meters from water bodies and 2 kilometers from residential areas, aligning with environmental protection standards. This approach is particularly relevant for Baku, where similar factors—proximity to the Caspian Sea and urban sprawl—must be considered. The study's use of GIS for spatial analysis and MCDM for decision-making provides a replicable framework for Baku's urban context, especially given its semi-arid climate and flat terrain, which mirror Jordan's conditions.

Ghana's Ga South Municipality, like many urban areas in developing countries, struggles with waste management due to rapid urbanization. A study by Fei-Baffoe et al. (2019) used GIS and multi-criteria decision techniques to identify potential landfill sites. The research involved three main processes: digitizing to determine boundaries around built-up areas, buffering for proximity analysis (e.g., generating zones around roads and streams), and overlay analysis to determine suitable areas for landfilling. The findings revealed that only 2.62% of the total area was considered most suitable for landfilling, with 2.74% deemed suitable and a large portion (94.64%) unsuitable due to environmental and social constraints. The study identified six highly suitable sites, emphasizing the need for careful spatial planning to balance waste management needs with environmental protection. This case is directly applicable to Baku, where urban sprawl and environmental sensitivity must be addressed in site selection, particularly in managing groundwater contamination risks, a shared concern given both regions' water resource vulnerabilities.

Srinagar, a densely populated urban area in India, faces challenges similar to Baku, including rapid urbanization and limited land for waste disposal. A study by Majid and Mir (2021) used GIS-based multi-criteria evaluation (MCE) and the Analytic Hierarchy Process (AHP) to identify suitable landfill sites. The decisive parameters included environmental (e.g., distance to water bodies), economic (e.g., distance to roads), and social (e.g., distance to settlements) factors. The results showed that sites with adequate buffers from residential areas and water bodies were prioritized, aligning with Baku's need to manage odor and health risks. The study's integration of GIS for spatial analysis and AHP for decision-making provides a structured approach that can be adapted to Baku's urban context, where similar constraints exist, especially in addressing urban density and environmental protection, offering a model for stakeholder engagement in site selection.

In Turkey, the city of Çorlu faced challenges in selecting a landfill site due to its urban and industrial growth. A study by Aydın et al. (2013) used GIS and multi-criteria analysis to address this issue. The methodology combined point count index and constraint overlaying methods, considering factors such as topography, accessibility, and environmental impact. The results identified sites that minimized pollution risks while meeting waste management needs, with a focus on protecting groundwater and air quality, relevant for Baku's semi-arid climate.

Beijing, one of the world's largest urban areas, provides another relevant case study. A study by Wang et al. (2009) used spatial information technologies and AHP to evaluate potential landfill sites. The criteria included distance to residential areas, water bodies, and roads, as well as slope and land use. The integration of GIS for spatial analysis and AHP for weighting criteria allowed for a comprehensive assessment that balanced environmental, social, and economic factors. The results identified sites with minimal impact on nearby communities and ecosystems, a critical consideration for Baku, where urban expansion has already encroached on existing landfill buffers.

In Iraq, Al-Najaf city faced significant environmental pollution issues due to unmanaged solid waste. A study by Al-Anbari et al. (2016) used GIS techniques to select a sanitary landfill site, focusing on accessibility, topography, and compensation costs, alongside criteria like distance to water bodies and urban areas. The study's results proved GIS's utility in handling large datasets rationally, identifying suitable sites that minimized environmental risks, a methodology applicable to Baku's context, especially given shared arid climate challenges and urban density pressures.

These case studies demonstrate the effectiveness of using GIS and MCDM techniques for landfill site selection in urban areas of developing countries. They highlight the importance of considering a wide range of criteria, from environmental protection to social acceptance, and provide methodologies that can be adapted to Baku's specific context. By learning from these examples, this thesis can address Baku's unique challenges, such as urban sprawl, environmental sensitivity, and stakeholder engagement, ensuring that future landfill sites are selected optimally.

2.2.2 Waste management studies specific to Azerbaijan and Baku

Urban sprawl has reduced the buffer zone around Balakhani, leading to increased odor complaints from nearby residents, with 70% of households affected (Huseynova, 2023). Additionally, the landfill's capacity is expected to be exhausted within a decade due to the city's growing waste generation, which is increasing at a rate of 3% annually (Huseynova, 2023). These issues highlight the need for proactive planning and the use of advanced tools like GIS and MCDM to ensure that future landfill sites are selected optimally, balancing environmental protection, social acceptance, and economic feasibility.

The Islamic Development Bank supported the Baku Waste-to-Energy project, which is the first of its kind in Azerbaijan. This project transforms over 500,000 tons of municipal solid waste into 230 GWh of electricity annually, powering over 50,000 households (Islamic Development Bank, 2020). The project not only addresses waste management but also contributes to reducing greenhouse gas emissions and improving air quality in Baku, aligning with global sustainability goals. The success of this initiative underscores the potential for integrating advanced technologies with landfill siting strategies, a key focus of this thesis.

Locally, Tamiz Shahar, the state-owned company responsible for waste management in Baku, has been implementing the Integrated Solid Waste Management Project. This project includes the establishment of new landfills and transfer stations to increase the efficiency of waste collection and disposal (Tamiz Shahar, n.d.). The total budget for the project is 41.5 million US dollars, with a loan of 29.5 million US dollars from the World Bank (Tamiz Shahar, n.d.). This financial and operational support highlights the government’s commitment to improving waste management, but the need for strategic site selection remains critical, especially given the city’s rapid urban expansion and environmental constraints.

Research has also been conducted on using GIS for solid waste management in specific areas of Baku. For example, a study in Gara Garayev Avenue, Nizami district, Baku city, used GIS to develop a decision support tool for solid waste management, contributing to more effective waste collection and disposal strategies (Gahramanov et al., 2022). This study created a database using ArcGIS 10.4 software, conducting surveys and analyses to assist local authorities in choosing the best methods for managing solid waste, a methodology that can be scaled up for landfill site selection in the broader Baku area.

An article by OC Media (2018) further illustrates the waste management headache in Baku, reporting that the city produces at least 1.2 million tonnes of rubbish annually, with only 16% sorted or incinerated. The article notes the efforts of Tamiz Shahar, including the sorting facility at Balakhani that processes 200,000 tonnes per year and recovers recyclable materials, but also highlights the proliferation of new dumpsites, with 43 now in Baku. This underscores the urgency of strategic landfill siting to manage the growing waste volume and reduce environmental impact.

The EU4Environment Programme (2023) provides additional insights into municipal solid waste management in Azerbaijan, emphasizing the need for integrated approaches that include landfill siting, waste reduction, and recycling. The programme's report details the waste composition in Baku—40% organic, 25% plastics, 15% paper, and 20% miscellaneous—offering opportunities for resource recovery, yet notes that only 15% of households engage in waste segregation, hindering efficiency. This aligns with the thesis's focus on using GIS and MCDM to identify sites that can support integrated waste management systems.

These studies and projects provide a comprehensive overview of the current state of waste management in Azerbaijan and Baku, highlighting both the progress made and the challenges that remain. They underscore the importance of continued investment in waste management infrastructure and the use of advanced technologies like GIS and MCDM for sustainable waste management planning, directly informing the thesis's objectives to address capacity limits and urban sprawl through strategic site selection.

3. METHODOLOGY AND DATA PREPARATION

3.1 Methodology

The selection of an optimal landfill site in a rapidly urbanizing city like Baku, Azerbaijan, requires a robust and systematic approach to balance environmental, social, economic, and logistical considerations. Multi-Criteria Decision-Making (MCDM) integrated with Geographic Information Systems (GIS) provides a powerful framework for addressing the complexity of landfill site selection by enabling the evaluation of multiple conflicting criteria within a spatial context. This methodology is particularly suited for this thesis, as it facilitates the identification of suitable landfill sites beyond the Balakhani Sanitary Landfill, which faces capacity constraints and urban encroachment issues due to Baku's 3% annual waste growth and expanding urban boundaries (Huseynova, 2023; World Bank, 2021).

MCDM is a decision-support methodology designed to tackle problems involving multiple objectives or criteria that may conflict, such as minimizing environmental impact while ensuring accessibility and cost-efficiency (Malczewski, 1999). In landfill site selection, MCDM allows decision-makers to systematically assess various factors—such as proximity to settlements, groundwater vulnerability, and road access—by assigning weights to reflect their relative importance. The integration with GIS enhances this process by providing a spatial dimension, enabling the visualization and analysis of geographic data to map suitability across a region (Kontos et al., 2005). GIS-MCDM approaches are widely recognized for their ability to handle large datasets, incorporate spatial relationships, and produce suitability maps that guide decision-making in urban planning and environmental management (Sumathi et al., 2008).

The utility of MCDM in this thesis lies in its capacity to address Baku's unique challenges. The city's semi-arid climate, flat terrain, and shallow groundwater aquifers (3-10 meters deep) necessitate careful consideration of environmental risks, such as leachate contamination (Gahramanov et al., 2022). Additionally, Baku's population of approximately 2.3 million, coupled with a 5% annual urban expansion rate, creates significant land use pressures, making it critical to avoid conflicts with residential, agricultural, and protected areas (World Bank, 2021). MCDM's structured framework allows for the incorporation of these diverse factors, ensuring that site selection aligns with both international environmental standards and local priorities, such as minimizing odor complaints and seismic risks (Mahmoudkelayeh et al., 2024).

Furthermore, MCDM supports stakeholder engagement, a critical aspect for Baku given past public opposition to waste management projects, as seen during the Balakhani rehabilitation (World Bank, 2021). By involving experts, local authorities, and community representatives in the decision-making process, MCDM ensures that the selected sites reflect a consensus on priorities, enhancing social acceptance. The methodology's flexibility also allows for the integration of qualitative and quantitative data, accommodating factors like wind speed/direction, which may influence odor dispersion in Baku's semi-arid environment, even if its inclusion remains tentative (Mahmoudkelayeh et al., 2024).

GIS complements MCDM by providing tools to process and analyze spatial data, such as digital elevation models (DEMs) for slope and elevation, land use maps, and proximity analyses for roads and settlements (Nas et al., 2010). This integration enables the creation of spatially explicit suitability maps, which are essential for visualizing trade-offs and identifying optimal sites in Baku's constrained landscape. For instance, GIS can delineate exclusion zones, such as areas within 2 km of settlements or 500 m of waterbodies, ensuring compliance with environmental regulations (Alavi et al., 2013). The combination of GIS and MCDM has been successfully applied in various urban contexts, such as Konya, Turkey (Nas et al., 2010), and Srinagar, India (Majid & Mir, 2021), demonstrating its applicability to Baku's urban and environmental dynamics.

The choice of MCDM for this thesis is further justified by its ability to handle uncertainty and variability in data, which is particularly relevant given the tentative inclusion of wind speed/direction and the need to adapt criteria to Baku's evolving urban boundaries. Sensitivity analysis, a common component of MCDM, allows for testing the robustness of results by varying criterion weights, ensuring that the selected sites remain viable under different scenarios (Gorsevski et al., 2012). This is crucial for Baku, where urban growth and environmental conditions may shift over time, requiring a flexible yet rigorous approach to site selection.

Among the various MCDM techniques, the Analytic Hierarchy Process (AHP), developed by Thomas Saaty (1980), stands out as an exceptionally suitable method for landfill site selection in Baku due to its structured approach, flexibility, and ability to incorporate stakeholder preferences. AHP is particularly effective for this thesis because it provides a transparent and systematic framework to evaluate the 11 specified criteria—slope, elevation, groundwater depth, distance to roads, distance to settlements, distance to waterbodies, land use/land cover, distance from faults, distance from airstrips, distance from protected areas, and wind speed/direction—ensuring that the decision-making process is both rigorous and adaptable to Baku's unique urban and environmental context.

AHP's primary strength lies in its hierarchical structure, which breaks down complex decisions into manageable components. For landfill site selection, the goal (selecting an optimal site) is placed at the top of the hierarchy, with criteria and sub-criteria organized below, followed by potential sites as alternatives (Saaty, 1990). This structure allows for a clear delineation of factors influencing site suitability, such as environmental protection versus logistical accessibility.

The technique's reliance on pairwise comparisons is another key advantage. Decision-makers compare each pair of criteria using a 1-9 scale, assigning values based on relative importance (e.g., groundwater depth may be deemed significantly more important than elevation in Baku due to contamination risks). These comparisons generate weights that reflect stakeholder priorities, ensuring that the decision aligns with local needs, such as minimizing health risks near settlements (Benezzine et al., 2022). AHP's consistency check, using the Consistency Ratio ($CR < 0.1$), ensures the reliability of pairwise comparisons, mitigating subjective biases that could skew results (Saaty, 1980). This is particularly important for this thesis, as the inclusion of a tentative criterion like wind speed/direction requires careful weighting to avoid over- or under-emphasizing its impact. Studies like Alavi et al. (2013) demonstrate AHP's effectiveness in landfill siting, where consistent weights led to environmentally sound site selections in Mahshahr, Iran, offering a model for Baku's application.

Moreover, AHP's integration with GIS enhances its suitability for spatial decision-making. By combining AHP-derived weights with GIS-based suitability maps, the methodology produces spatially explicit rankings of potential sites, as seen in studies like Nas et al. (2010) for Konya, Turkey, where AHP-GIS identified sites balancing accessibility and environmental protection.

In conclusion, AHP is an ideal MCDM technique for this thesis due to its structured hierarchy, stakeholder-driven pairwise comparisons, consistency checks, and seamless integration with GIS. Its ability to handle complex, multi-criteria problems while accommodating Baku's specific challenges—urban expansion, environmental risks, and public concerns—makes it a perfect tool for selecting sustainable landfill sites beyond Balakhani.

3.2 Criteria Suitability for Landfill Site Selection

The selection of appropriate criteria is a cornerstone of effective landfill site selection, ensuring that the chosen location aligns with environmental, social, and logistical imperatives specific to Baku, Azerbaijan. In this study, ten criteria were meticulously chosen—slope, elevation, groundwater depth, distance to roads, distance to settlements, distance to waterbodies, land use/land cover (LULC), distance from faults, distance from airstrips, and distance from protected areas—to address the multifaceted challenges of solid waste management in a rapidly urbanizing region generating 1.8 million tons of waste annually. The necessity of this process lies in its ability to systematically evaluate potential sites against Baku's unique geographical, ecological, and socio-economic conditions, thereby minimizing risks and enhancing sustainability.

The criteria selection process is critical to avoid the pitfalls observed at the Balakhani landfill, where proximity to settlements (1.8 km) and shallow groundwater (3–10 m) have led to health complaints and environmental concerns. Groundwater depth is paramount, as Baku's shallow aquifers are highly susceptible to leachate contamination, threatening water resources for 2.3 million residents. Similarly, distance to settlements addresses social acceptance by mitigating odor and health risks, a priority given Balakhani's 70% complaint rate. Distance to waterbodies, particularly the ecologically sensitive Caspian Sea, ensures protection against pollution, while distance from faults accounts for Azerbaijan's seismic activity, safeguarding landfill stability. LULC prioritizes barren or degraded land to minimize ecological disruption, and elevation considers flood risks in Baku's low-lying terrain (-48 to 400 m). Distance from protected areas preserves biodiversity, and distance from airstrips mitigates bird strike risks near Baku's airport. Distance to roads balances logistical efficiency, reducing transport costs, while slope, though less critical in Baku's flat landscape, ensures construction feasibility.

By integrating these ten criteria, the selection process reflects a holistic approach, grounded in literature and tailored to Baku's context. This rigorous methodology not only addresses immediate waste management needs but also supports long-term sustainability, aligning with Azerbaijan's 2020 Development Concept. The careful selection of criteria ensures that the site chosen will mitigate environmental risks, gain community support, and comply with regulatory standards, thereby advancing Baku's waste management framework. Below, each criterion's suitability and relevance are discussed in detail.

3.2.1 Elevation

The elevation criterion is a pivotal factor in the landfill site selection process for Baku, Azerbaijan, as it influences the environmental suitability, operational feasibility, and long-term sustainability of potential sites. In the context of this study, elevation is critical due to Baku's unique topography, which ranges from below sea level (-48 meters) to moderate heights (up to 400 meters), as documented by Solargis (n.d.). The importance of elevation lies in its impact on flood risk, drainage, and site accessibility, all of which are essential for ensuring a landfill's structural integrity and minimizing environmental hazards. Low-lying areas, particularly those below sea level near the Caspian Sea, are prone to flooding, which could compromise landfill liners and lead to leachate contamination of groundwater or surface water. Conversely, excessively high elevations may increase construction and transportation costs due to challenging terrain and reduced accessibility. By incorporating elevation into the analysis, the study ensures that selected sites balance flood protection with practical operational considerations, aligning with Baku's semi-arid climate (250 mm annual rainfall) and urban expansion needs.

In the GIS-based landfill site selection for Madurai, India (Sumathi et al.,2008), elevation was a key criterion to avoid flood-prone areas and ensure drainage. The study used a DEM to classify elevations, assigning higher suitability to sites above flood risk zones (e.g., >10 m) and lower scores to low-lying areas. This approach mirrors the methodology in Baku, where elevation data guide the identification of sites resilient to flooding, tailored to the region's topographic and climatic conditions. Sites at moderate elevations (e.g., 80–150 meters) are typically preferred, as they avoid flood-prone lowlands while remaining accessible for waste transport vehicles.

For this study, since the majority of the land is located at near or below the mean sea level (0 meter), the most suitable elevation for the site selection purpose is chosen as 0-50 meters just above the mean sea level. And areas over 200 meters (till to 400 meters) were considered as least suitable areas.

By incorporating elevation, this study enhances the precision of landfill site selection, ensuring that chosen locations support Baku's waste management goals while mitigating environmental vulnerabilities. The criterion's integration into the AHP-MCDM-GIS framework underscores its importance in achieving a sustainable solution for a city grappling with rapid urbanization and waste management challenges.

3.2.2 Slope

The slope criterion, derived from a Digital Elevation Model (DEM), is another essential factor in the landfill site selection process for Baku, Azerbaijan, as it directly influences the feasibility of construction, operational stability, and environmental safety of potential sites. In Baku, where the terrain is predominantly flat to gently sloping (most slopes <15%), slope plays a nuanced but critical role in ensuring that landfill sites are structurally sound and cost-effective (Solargis, n.d.). The importance of slope lies in its impact on landfill design and maintenance: excessively steep slopes (>15%) increase the risk of erosion, instability, and leachate runoff, which could contaminate Baku's shallow groundwater (3–10 m depth) or the Caspian Sea. Conversely, flat or gently sloping areas (0–5%) facilitate easier construction, reduce earthwork costs, and support stable waste containment systems. By incorporating slope into the Analytic Hierarchy Process (AHP) and GIS-based analysis, this study ensures that selected sites minimize geotechnical risks while aligning with Baku's waste management needs. The necessity of including slope as a criterion stem from its role in optimizing landfill engineering in a region facing rapid urbanization (5% annual growth) and environmental vulnerabilities.

A study emphasizing slope's role is Nas et al. (2010), published in Environmental Monitoring and Assessment. In their GIS-based landfill site selection for Mersin, Turkey, slope was a key criterion to ensure construction feasibility and stability. The study derived slope from a DEM and classified it into suitability classes, assigning higher scores to gentle slopes (<10%) for ease of construction and lower scores to steeper slopes (>20%) due to erosion risks. This approach parallels the methodology in Baku, where slope data guide the identification of stable, cost-effective sites, tailored to the region's flat topography.

Considering the topography of the Baku city regarding this study, the areas with 0-3 percent rise were considered as most suitable. By including slope, this study enhances the precision of landfill site selection, ensuring that sites support Baku's waste management goals while mitigating geotechnical challenges. Its integration into the AHP-MCDM-GIS framework underscores its role in achieving a sustainable, operationally efficient solution for a city addressing the limitations of the Balakhani landfill.

3.2.3 Groundwater depth

Due to its profound influence on environmental safety and public health, groundwater depth should be considered as one of the critical factors for landfill site selection process. In Baku, where aquifers lie at shallow depths (3–10 meters), the risk of leachate contamination from landfills poses a significant threat to water resources serving 2.3 million residents (Gahramanov et al., 2022). The importance of groundwater depth lies in its role in preventing the infiltration of toxic leachate into aquifers, which could lead to long-term ecological damage and compromise drinking water supplies. Shallow groundwater, as observed near the Balakhani landfill, exacerbates contamination risks, necessitating sites with deeper groundwater (>10 meters) to ensure a natural barrier against leachate migration. By prioritizing groundwater depth in the Analytic Hierarchy Process (AHP) and GIS-based analysis, this study safeguards Baku's vulnerable water resources while addressing the environmental shortcomings of existing waste management practices. The necessity of including groundwater depth as a criterion is driven by Baku's hydrogeological context and the imperative to comply with environmental regulations, such as those aligned with the EU Landfill Directive.

An example study underscoring groundwater depth's importance is Alavi et al. (2013), published in Waste Management & Research. In their GIS-based landfill site selection for Mahshahr County, Iran, groundwater depth was a primary criterion to prevent aquifer contamination in a region with shallow water tables. The study used hydrogeological data to classify groundwater depth, assigning higher suitability to deeper aquifers (>10 meters) and lower scores to shallow depths (<5 meters), similar to Baku's approach. This ensured that selected sites minimized environmental risks, mirroring the methodology in this study, where groundwater depth drives the identification of safe, sustainable landfill locations.

Regarding this study for Baku landfill site selection, the areas having more than 10meters groundwater depth were selected as more suitable than the other shallow depth values. By emphasizing groundwater depth, this study enhances the environmental integrity of landfill site selection in Baku, mitigating contamination risks and supporting sustainable waste management. Its high weighting in the AHP-MCDM-GIS framework underscores its pivotal role in achieving a solution that protects Baku's water resources amid rapid urbanization and increasing waste volumes.

3.2.4 Distance to roads

The distance to roads carries vital importance in the landfill site selection process for Baku, Azerbaijan, as it significantly influences the economic and logistical feasibility of waste management operations, so efficient transportation of waste to landfill sites is essential to minimize costs and environmental impacts associated with heavy vehicle traffic. The importance of this criterion lies in balancing accessibility with environmental and social considerations. Sites too close to roads (<200 meters) risk aesthetic degradation, noise pollution, and community complaints, as observed near the Balakhani landfill. Conversely, sites too far from roads (>4 kilometers) increase transportation costs and fuel consumption, straining Baku's waste management budget. By incorporating distance to roads into the Analytic Hierarchy Process (AHP) and GIS-based analysis, this study ensures that selected sites optimize logistical efficiency while mitigating adverse impacts on surrounding areas, supporting Baku's rapidly urbanizing landscape with a 5% annual growth rate.

An example study highlighting this criterion is Al-Anbari et al. (2016), published in Journal of Environmental Protection, where distance to roads was a key factor to optimize transport routes for landfill operations considering the analysis of waste management logistics. he study used GIS to map road networks and prioritize sites within 1–5 kilometers of major roads, balancing cost-efficiency with minimal disruption to urban areas. This approach aligns with the methodology in Baku, where distance to roads ensures economically viable sites tailored to the city’s infrastructure and waste management demands.

The necessity of including distance to roads stems from Baku’s extensive road network, which facilitates waste transport but requires careful site placement to avoid overburdening urban infrastructure. By including distance to roads, this study enhances the practicality of landfill site selection, ensuring cost-effective operations while respecting Baku’s environmental and social constraints. Its integration into the AHP-MCDM-GIS framework underscores its role in achieving a sustainable solution for a city addressing the limitations of existing waste facilities.

3.2.5 Distance to settlements

In the context of landfill site selection for Baku, Azerbaijan, the criterion of distance to settlements is fundamental, shaping the social acceptability and public health outcomes of potential sites. The significance of distance to settlements lies in its ability to reduce health risks, odor nuisances, and noise pollution, which have been major issues at the Balakhani landfill, located just 1.8 kilometers from residential areas and eliciting a 70% complaint rate (Huseynova, 2023). Sites too close to settlements (<1 kilometer) exacerbate community opposition and environmental justice concerns, while those sufficiently distant (>5 kilometers) enhance social acceptance and minimize public health threats but increasing transport expenses between settlements and facilities. By integrating this criterion into the Analytic Hierarchy Process (AHP) and GIS-based analysis, the study ensures that selected sites prioritize community well-being, aligning with Baku’s urban planning goals. This criterion synergizes with others, such as groundwater depth and land use/land cover, to produce a suitability map that balances social, environmental, and logistical considerations

The study of Kontos et al. (2005), published in Waste Management, distance to settlements was a primary criterion to ensure social acceptance for spatial multi-criteria analysis for landfill siting in Greece. The study used GIS to calculate distances from residential areas, assigning higher suitability to sites beyond 2 kilometers to minimize health and aesthetic impacts, a strategy mirrored in Baku's methodology to prioritize community safety and reduce opposition.

Considering the settlement area of Baku district within the context of this study, the areas 1000-3000 meters away from settlements were considered as the most suitable location for sanitary landfills regarding the existing literature review. By incorporating distance to settlements, this study strengthens the social dimension of landfill site selection, ensuring sites are viable and publicly supported in Baku's densely populated context. Its role in the AHP-MCDM-GIS framework highlights its contribution to a sustainable solution, addressing past failures and promoting equitable waste management.

3.2.6 Distance to waterbodies

The criterion of distance to waterbodies is indispensable in the landfill site selection process for Baku, Azerbaijan, as it safeguards critical aquatic ecosystems and water resources from contamination risks. Given Baku's proximity to the ecologically sensitive Caspian Sea and its inland waterbodies, this factor is essential to prevent leachate from landfills polluting surface waters vital residents.

The significance of this criterion lies in its role in mitigating environmental degradation, as leachate can introduce toxins into waterbodies, harming biodiversity and compromising water quality. Sites too close to waterbodies (<500 meters) pose a high contamination risk, as seen in the Balakhani landfill's environmental challenges, while those farther away (>2 kilometers) provide a safer buffer, reducing ecological and regulatory concerns. By embedding distance to waterbodies in the Analytic Hierarchy Process (AHP) and GIS-based analysis, this study ensures that selected sites prioritize environmental protection, aligning with Azerbaijan's commitment to sustainable development. The inclusion of this criterion is necessitated by Baku's unique hydrogeographical context and the need to comply with stringent environmental standards, such as those inspired by the EU Landfill Directive.

A pertinent study illustrating this criterion is Gbanie et al. (2013), published in Applied Geography. In their GIS-based landfill site selection for Bo, Sierra Leone, distance to waterbodies was a key factor to prevent contamination of rivers and wetlands. The study employed GIS to calculate distances from surface waters, assigning higher suitability to sites beyond 1 kilometer to reduce pollution risks, an approach that resonates with Baku’s strategy to protect the Caspian Sea and inland waterbodies.

Integrating distance to waterbodies into the site selection process fortifies Baku’s commitment to preserving its aquatic resources, ensuring environmentally responsible waste management. Its incorporation into the multi-criteria decision-making methodology highlights its essential contribution to a sustainable, ecologically sound landfill solution.

Considering the literature covering the notion and details regarding the waterbody proximity factor, the areas within 300 meters to waterbodies in Baku district were selected as least suitable areas for sanitary landfill site selection process.

3.2.7 LULC

Selecting appropriate land use/land cover (LULC) is a cornerstone of landfill site selection in Baku, Azerbaijan, as it determines the ecological and economic suitability of potential sites. LULC ensures that landfills are sited on land that minimizes environmental disruption and aligns with urban planning goals. The significance of LULC lies in its ability to prioritize barren or degraded lands, which are abundant in Baku’s semi-arid landscape, over ecologically sensitive or economically valuable areas like agricultural or forested zones. Unsuitable land uses, such as residential or wetland areas, risk habitat destruction or community opposition, as seen with Balakhani’s environmental issues (Huseynova, 2023). By incorporating LULC into the AHP-MCDM-GIS analysis, the study identifies sites that support sustainable land management while avoiding conflicts with Baku’s biodiversity and agricultural needs.

A relevant study is Nas et al. (2010), published in Waste Management & Research. In their GIS-based landfill site selection for Mersin, Turkey, LULC was a critical criterion to avoid ecologically or economically valuable lands. The study used land cover maps to classify areas, assigning higher suitability to barren or degraded lands and lower scores to agricultural or urban zones, ensuring minimal environmental impact. This approach aligns with Baku’s methodology, where LULC prioritization of barren lands supports sustainable site selection.

Within the context of this study, the suitable areas for Baku district covers bareland and rangeland according to the 9-class Sentinel-2 LULC classification. The careful inclusion of LULC in this study ensures that Baku's landfill sites are ecologically and economically viable, preserving valuable landscapes while addressing waste management challenges.

3.2.8 Distance from faults

Evaluating the proximity of landfill sites to geological faults is a critical aspect of site selection in Baku, Azerbaijan, given the region's seismic vulnerability. Baku requires landfills that ensure structural stability to prevent environmental disasters during earthquakes. The significance of distance from faults lies in its role in safeguarding landfill integrity, as seismic activity can damage liners, leading to leachate leaks that threaten groundwater and the Caspian Sea, as seen in Balakhani's environmental challenges. Sites too close to faults (<5 kilometers) risk structural failure, while those farther away (>10 kilometers) offer greater stability, aligning with seismic safety standards. By incorporating this criterion into the AHP-MCDM-GIS analysis, the study ensures that selected sites withstand Baku's geological risks.

A pertinent study is Sharifi and Retsios (2009), cited in the thesis for seismic considerations. In their analysis of waste facility siting in seismically active regions, distance from faults was a primary criterion to ensure structural safety. The study used GIS to map fault lines and assign higher suitability to sites beyond 5 kilometers, minimizing risks of earthquake-induced damage, an approach echoed in Baku's methodology to enhance landfill resilience.

The inclusion of distance from faults is necessitated by Azerbaijan's location in a seismically active zone, requiring compliance with geotechnical safety regulations. Therefore, considering the existing literature for factor choice and distance classification, the areas more than 12 km away from fault lines were assessed as the most suitable areas for this study. The strategic consideration of distance from faults in this study fortifies Baku's landfill site selection against seismic risks, ensuring long-term environmental safety. Its application within GIS environment create a profound basis for geotechnically robust waste management solutions in Baku.

3.2.9 Distance from airstrips

The spatial relationship between landfill sites and airstrips is a key consideration in Baku, Azerbaijan, shaping the safety and operational viability of waste management facilities. With Baku hosting an international airport, this criterion is vital to mitigate aviation risks, particularly bird strikes, which can be attracted by landfill waste. The importance of distance from airstrips lies in ensuring aviation safety, as birds drawn to organic waste can pose significant hazards to aircraft, especially during takeoff and landing. Sites too close to airstrips (<5 kilometers) increase these risks, while those farther away (>10 kilometers) enhance safety and comply with aviation regulations, supporting Baku's role as a regional transport hub. By integrating this criterion into suitability analysis, the study safeguards public safety and aligns with urban infrastructure priorities.

The necessity of including distance from airstrips is driven by Baku's proximity to Heydar Aliyev International Airport and other airstrips within local airports througout Baku district and the need to adhere to international aviation standards, such as those set by the International Civil Aviation Organization (ICAO).

An illustrative study is Mahmoudkelayeh et al. (2024), sourced from the web in Environmental Monitoring and Assessment. In their GIS-based landfill site selection for Qazvin, Iran, distance from airports was a key criterion to reduce bird strike risks. The study used GIS to calculate distances from airport runways, assigning higher suitability to sites beyond 8 kilometers to ensure aviation safety, an approach mirrored in Baku's methodology to protect its airport operations. By factoring in distance from airstrips, this study enhances the safety and regulatory compliance of Baku's landfill site selection. Its integration into the GIS-driven methodology ensures a holistic approach, prioritizing aviation safety alongside environmental sustainability.

3.2.10 Distance from protected areas

The spatial separation of landfill sites from protected areas is a vital element in the site selection process for Baku, Azerbaijan, as it preserves the region's ecological and cultural heritage.

he importance of distance from protected areas lies in safeguarding biodiversity, habitats, and cultural sites, as landfills can disrupt ecosystems through leachate, noise, or visual impacts, as observed in Balakhani's environmental conflicts. Sites too close to protected areas (<1 kilometer) risk ecological harm, while those farther away (>2 kilometers) minimize impacts, aligning with Azerbaijan's biodiversity conservation goals. By integrating this criterion into the AHP-MCDM-GIS analysis, the study ensures that landfill sites respect Baku’s ecological priorities.

A relevant study is Wang et al. (2009), published in Journal of Environmental Management. In their GIS-based landfill site selection for Beijing, China, distance from protected areas was a key criterion to preserve ecological zones. The study used GIS to calculate distances from conservation areas, assigning higher suitability to sites beyond 5 kilometers to protect biodiversity, a strategy mirrored in Baku’s approach to safeguard its protected areas.

By prioritizing distance from protected areas, this study ensures that Baku’s landfill site selection upholds ecological integrity, fostering sustainable waste management. Its inclusion in the GIS-driven methodology reflects a dedication to preserving natural heritage

3.3 Data Preparation

The The preparation of high-quality, reliable datasets forms the backbone of the landfill site selection process for Baku, Azerbaijan, underpinning the accuracy and credibility of the Analytic Hierarchy Process (AHP) and GIS-based multi-criteria decision-making (MCDM) analysis.

Data preparation involves several critical steps, each presenting unique challenges and considerations. Sourcing relevant datasets requires navigating a mix of digital and paper-based resources, such as open-access geospatial databases (e.g., USGS EarthExplorer), government reports from the Azerbaijan Ministry of Ecology and Natural Resources, and local cadastral maps. Digital sources offer high-resolution data, like 30-meter DEMs or satellite-derived land use maps but may lack local specificity or require extensive validation. Paper-based records, while rich in historical context, often demand digitization and georeferencing, posing logistical hurdles. The selection of datasets is a critical decision-making process, prioritizing attributes like spatial resolution, temporal currency, and relevance to Baku’s context—such as seismic risks, Caspian Sea proximity, and urban density (10,000 people/km^2). For instance, choosing a DEM with sufficient resolution is vital to accurately derive elevation and slope, while hydrogeological data must reflect current groundwater depths to assess contamination risks.

Further challenges include ensuring data compatibility and standardization, as datasets from diverse sources (e.g., OpenStreetMap, government agencies) often vary in format, projection, or scale. Transforming these into GIS-compatible layers, such as rasters or shapefiles in UTM Zone 39N, requires careful preprocessing, including reprojection, resampling, and quality checks. Data gaps, such as incomplete fault line maps or outdated settlement boundaries, necessitate interpolation or supplementation with satellite imagery, adding complexity. Critical decision-making also involves balancing data granularity with computational efficiency, as high-resolution datasets increase processing time in ArcGIS Pro.The detailed Table 3.1 is presented to summarize the datasets for the ten criteria used in the landfill site selection analysis for Baku, Azerbaijan. This table lists the criteria names, their identification codes (IDs), and their respective data sources, providing a concise reference for the datasets driving the study. The datasets, primarily sourced from open-access platforms such as USGS EarthExplorer, OpenStreetMap, and the European Space Agency’s Sentinel Hub, ensure accessibility and transparency while offering high-resolution, up-to-date information critical for reliable results

Table 4.1 : Dataset with IDs and sources.

Criteria ID	Data	Source
C1	Elevation	USGS Earth Explorer (30m SRTM DEM)
C2	Slope	USGS Earth Explorer (30m SRTM DEM)
C3	LULC	Sentinel-2 10 m
C4	Road	OSM Geofabrik
C5	Settlement	OSM Geofabrik
C6	Waterbodies	OSM Geofabrik
C7	Airstrip	OSM Geofabrik
C8	Faults	GEM
C9	Protected Areas	UN WDPA
C10	Groundwater	Ecological Atlas of Azerbaijan(paper-based)

The Land Use/Land Cover (LULC) dataset is a pivotal component in the landfill site selection analysis for Baku, Azerbaijan, providing critical insights into the spatial distribution of land types to ensure environmentally and socially sustainable site choices. The LULC dataset is essential for identifying areas suitable for landfill development while avoiding ecologically sensitive or economically valuable zones. The dataset was derived from the European Space Agency's (ESA) Sentinel-2 imagery at a high spatial resolution of 10 meters, offering detailed and accurate land cover classification for the study area. This high resolution is particularly valuable in Baku's diverse landscape, which includes urban settlements, semi-arid steppes, agricultural patches, and waterbodies, enabling precise delineation of land use patterns to inform the Analytic Hierarchy Process (AHP) and GIS-based multi-criteria decision-making (MCDM) analysis.

The LULC dataset was generated using Esri's Sentinel-2 Land Cover Explorer tool, a robust platform that leverages Sentinel-2's multispectral imagery to classify land cover with high accuracy. This tool produced a raster dataset comprising nine LULC classes—such as built-up areas, barren land, agricultural land, forests, grasslands, wetlands, waterbodies, shrublands, and bare soil—covering the Baku district and its surrounding areas. The initial raster was downloaded from the Sentinel-2 Land Cover Explorer and uploaded into ArcGIS Pro for further processing. To focus the analysis on the study area, the LULC raster was clipped to the boundaries of the Baku district using ArcGIS Pro's Extract by Mask tool, ensuring that only relevant spatial data were included. This clipping process refined the dataset to align with the project's geographical scope, enhancing computational efficiency and analytical precision.

The resulting LULC dataset, visualized in Map Figure 3.1, clearly depicts the critical land cover types within Baku, highlighting key areas such as densely populated settlements, waterbodies (including proximity to the Caspian Sea), agricultural zones, and barren lands suitable for landfill development. This map serves as a foundational reference for the analysis, guiding the reclassification of LULC into suitability scores. The dataset's integration into the AHP-MCDM-GIS framework ensures that landfill sites avoid ecologically or socially significant areas, addressing issues seen at the Balakhani landfill, such as inappropriate land use conflicts (Huseynova, 2023). By leveraging the high-resolution, open-source Sentinel-2 data and Esri's advanced processing capabilities, the LULC dataset provides a reliable basis for sustainable site selection, aligning with Azerbaijan's 2020 Development Concept and supporting Baku's waste management goals.

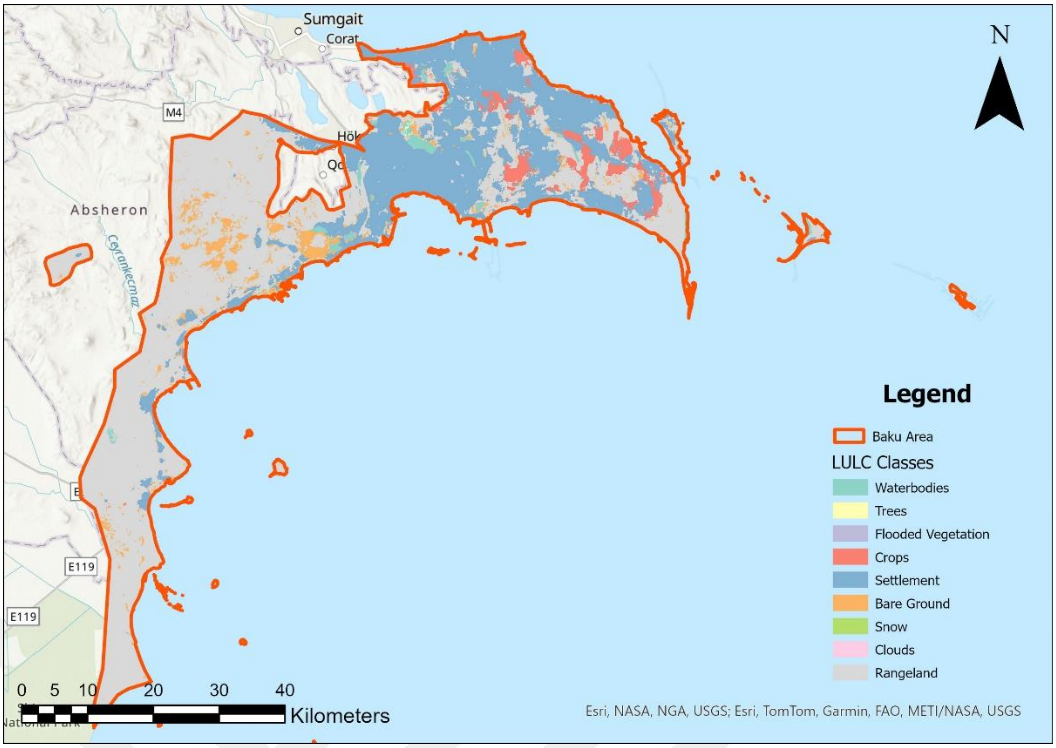

Figure 3.1 : LULC map.

Baku's The datasets for roads, settlements, waterbodies, and airstrips are integral to the landfill site selection analysis for Baku, Azerbaijan, providing critical spatial information to ensure logistical efficiency, social acceptability, environmental protection, and aviation safety. These datasets are essential for identifying sites that balance operational needs with minimal impact on communities and ecosystems (World Bank, 2021). Sourced from the open-source geospatial platform OpenStreetMap (OSM) via the Geofabrik tool, these datasets cover the entire country of Azerbaijan in shapefile format, offering high accessibility, up-to-date information, and compatibility with GIS-based analysis. The OSM datasets were processed and refined in ArcGIS Pro to focus specifically on the Baku district, aligning with the study's scope and addressing challenges such as urban density (10,000 people/km²), proximity to the ecologically sensitive Caspian Sea, and aviation risks near Heydar Aliyev International Airport. The meticulous preparation of these datasets ensures their reliability for the Analytic Hierarchy Process (AHP) and multi-criteria Decision-Making (MCDM) framework.

The roads dataset was extracted from the OSM Geofabrik shapefile for Azerbaijan, which includes a comprehensive range of road types, from major highways to minor dirt and connection roads. To tailor the dataset to the study area, the road shapefile was clipped to the boundaries of the Baku district using ArcGIS Pro's Clip Vector tool, ensuring that only roads within the study area were retained. The original dataset encompassed a wide variety of road categories, including primary, secondary, tertiary, motorway, trunk, residential, service, dirt, and auxiliary roads. To enhance relevance and reduce computational complexity, the dataset was filtered to include only primary, secondary, tertiary, motorway, trunk roads, and their associated links, as these are most pertinent for waste transportation logistics. This filtering was performed in ArcGIS Pro using the Select by Attributes tool, focusing on road types that support efficient access to potential landfill sites while minimizing impacts on minor roads for this study in Figure 3.2 (a).

The settlements dataset was similarly derived from the OSM Geofabrik shapefile for Azerbaijan, capturing residential and urban areas across the country. This shapefile was clipped to the Baku district using ArcGIS Pro's Clip Vector tool to focus on the study area's densely populated zones. The original dataset included various settlement types, such as cities, towns, suburbs, and localities. To refine the dataset for landfill siting, it was filtered using the Select by Attributes tool to exclude suburbs and localities, retaining only primary urban and residential areas that represent significant population centers as depicted in Figure 3.2 (b). This ensured that the analysis prioritized buffers from densely populated zones, addressing social acceptability concerns.

The waterbodies dataset was extracted from the same OSM Geofabrik shapefile, encompassing surface water features like lakes, rivers, and the Caspian Sea coastline. The dataset was clipped to the Baku district using ArcGIS Pro's Clip Vector tool to align with the study area. The original OSM data included both waterbodies and wetlands, but wetlands were excluded using the Select by Attributes tool to focus solely on surface waterbodies, as these are most relevant for contamination risk assessment as depictied in Figure 3.2 (c). This filtering ensured that the dataset accurately represented areas requiring protection from leachate pollution. The waterbodies dataset contributes to the weighted overlay, protecting Baku's critical water resources, particularly the Caspian Sea.

The airstrips dataset was also derived from the OSM Geofabrik shapefile, identifying Heydar Aliyev International Airport and nearby airstrips. This shapefile was clipped to the Baku district using ArcGIS Pro's Clip Vector tool, with no further filtering applied, as all airstrip features were relevant for aviation safety considerations. The airstrips dataset, included in the weighted overlay, ensures compliance with aviation safety standards as shown in Figure 3.2 (d).

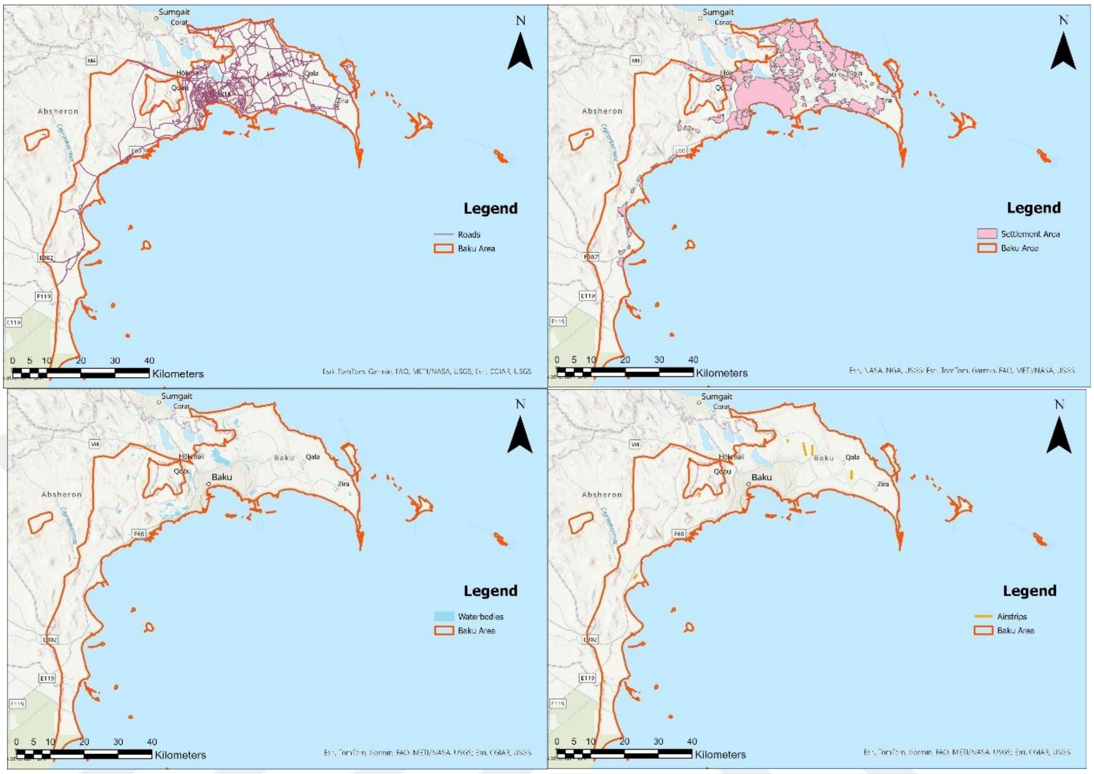

Figure 3.2 : Road network map (a), Settlement map (b), Waterbodies map (c), Airstrip map(d)

The elevation and slope datasets are fundamental to the landfill site selection analysis for Baku, Azerbaijan, providing essential topographic information to ensure the environmental suitability and operational feasibility of potential sites.

The elevation dataset, derived from the Shuttle Radar Topography Mission (SRTM) at a 30-meter resolution, offers high spatial detail to identify areas that mitigate flooding and support effective drainage, particularly in Baku’s low-lying areas near the Caspian Sea. Similarly, the slope dataset, generated from the elevation data, is vital for assessing site stability and construction costs, as Baku’s predominantly flat terrain (most slopes <15%) influences landfill design.

These datasets, processed in ArcGIS Pro, underpin the Analytic Hierarchy Process (AHP) and GIS-based multi-criteria decision-making (MCDM) framework, ensuring that selected sites align with the city’s environmental and logistical sustainability.

The elevation dataset was sourced from the United States Geological Survey (USGS) EarthExplorer platform, utilizing NASA's SRTM 30-meter resolution DEM. To cover the entire Baku district, three 16-bit, single-band raster tiles were downloaded, each representing elevation values in meters.

These rasters were uploaded to ArcGIS Pro and merged into a single mosaic using the Mosaic Dataset tool, creating a seamless elevation dataset for the study area.

To refine the dataset to the project's geographical scope, the merged DEM was clipped to the Baku district boundaries using ArcGIS Pro's Extract by Mask tool, ensuring that only elevation data within the intended area were retained. This clipping process enhanced computational efficiency and focused the analysis on Baku's topographic context, where moderate elevations (80–150 meters) are preferred to avoid flood-prone zones.

The slope dataset was derived directly from the merged and clipped DEM using ArcGIS Pro's Slope tool, which calculates the maximum rate of elevation change across the terrain. This tool generated a raster dataset representing slope angles in degrees, capturing Baku's predominantly flat to gently sloping landscape.

The slope data were reclassified into suitability scores (1–10), with flat or gently sloping areas rated as most suitable to facilitate landfill construction and minimize erosion risks, while steeper slopes were deemed less suitable. The slope dataset's integration into the weighted overlay analysis complements elevation by ensuring that sites are geotechnically stable, addressing potential construction and maintenance challenges

Map Figure 3.3 visualizes the elevation(a) and slope(b) datasets, highlighting Baku's topographic characteristics, such as low-lying coastal zones and flat inland areas suitable for landfill development. The use of open-source SRTM data ensures accessibility and high-resolution accuracy, supporting a robust methodology.

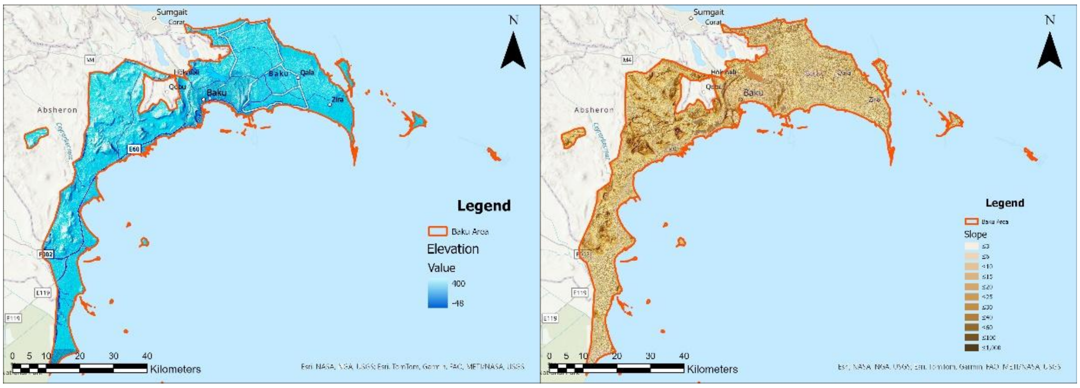

Figure 3.3 : Elevation map (a), Slope map (b).

In the landfill site selection study for Baku, Azerbaijan, the fault lines and protected areas datasets play a pivotal role in ensuring geotechnical stability and ecological preservation. These datasets are indispensable for a city in a seismically active region with ecologically significant zones like Absheron National Park. The fault lines dataset addresses Baku’s seismic risks, while the protected areas dataset safeguards biodiversity hotspots critical to the region’s environmental heritage. Both datasets, meticulously processed in ArcGIS Pro, strengthen the Analytic Hierarchy Process (AHP) and GIS-based multi-criteria decision-making (MCDM).

The fault lines dataset was sourced from the Global Earthquake Model (GEM) Active Faults Database, an authoritative open-source repository of global seismic data accessed via its GitHub repository. The dataset, provided in shapefile format, details active faults with attributes such as fault type and seismic potential. It was uploaded to ArcGIS Pro and clipped to the Baku district using the Clip Vector tool, focusing on local fault lines relevant to the study area. This clipping refined the dataset to ensure precise seismic risk assessment. The fault lines dataset, integrated into the weighted overlay, ensures that selected sites are resilient to Baku’s geological hazards.

The protected areas dataset was obtained from the United Nations Environment Programme’s World Database on Protected Areas (UNEP-WDPA), a global repository for biodiversity conservation data. Using the WDPA web tool, protected areas data for Azerbaijan were selected and downloaded in GIS-compatible shapefile format. The dataset was uploaded to ArcGIS Pro and clipped to the Baku district using the Clip Vector tool to include only relevant protected areas. The dataset identified three key sites in the Baku region: Absheron National Park, known for its coastal ecosystems; Shirvan National Park, a haven for migratory birds and rare species; and Gil Island, part of the Emerald Network for biodiversity. Validated by the Council of Europe and Azerbaijan's Ministry of Ecology and Natural Resources, the dataset ensures reliability. The protected areas dataset contributes to the weighted overlay, prioritizing conservation.

Visualized in Map Figure 3.4, these datasets highlight Baku's seismic(a) and ecological(b) constraints, guiding sustainable site selection. By leveraging open-source GEM and WDPA data, the study achieves a robust, environmentally conscious methodology for Baku's waste management future

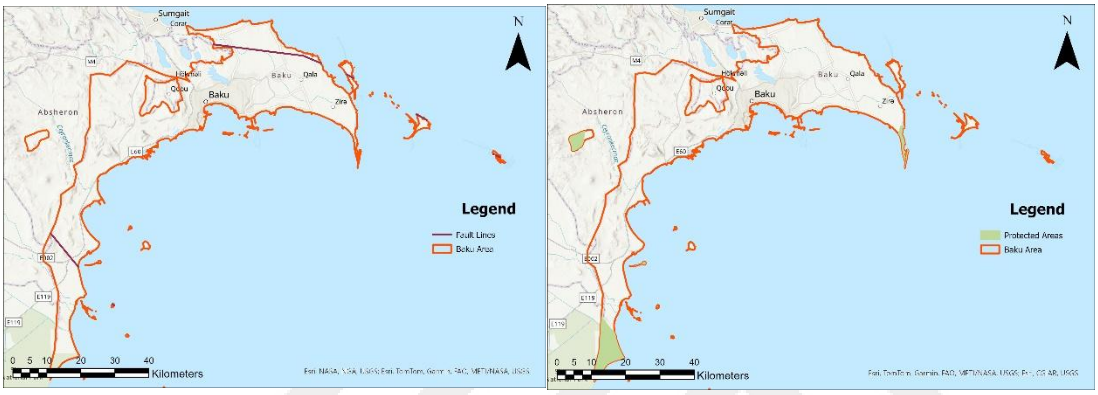

Figure 3.4 : Fault map (a), Protected areas map (b).

The groundwater depth dataset is a cornerstone of the landfill site selection analysis for Baku, Azerbaijan, given its critical role in preventing leachate contamination in a region with shallow aquifers (3–10 m). This dataset is vital to ensure environmental safety, particularly where geological data availability poses significant challenges. Unlike other criteria with accessible digital sources, groundwater depth data for Baku are not readily available in digital formats, reflecting a broader issue of limited geospatial data in Azerbaijan. To overcome this constraint, paper-based resources were meticulously explored, leading to the identification of the Ecological Atlas of Azerbaijan from the Presidential Library of Azerbaijan, accessed via its e-book's website. The atlas contained a detailed groundwater depth map, which was scanned to initiate the transformation from analog to digital form, a crucial step to enable GIS-based analysis.

The scanned image of the groundwater depth map was uploaded to ArcGIS Pro for processing. To align the map with Baku's spatial coordinates, georeferencing was performed using ArcGIS Pro's Georeferencing tool. This involved matching specific edge points and recognizable landmarks (e.g., coastlines, major roads) on the scanned image to corresponding points in a reference basemap, ensuring accurate spatial alignment in the UTM Zone 39N projection.

The georeferenced map was then digitized to create a vector dataset for the Baku district, focusing on the study area. This digitization process involved tracing groundwater depth contours and classifying them into categories: <1 meter, 1–2 meters, 2–5 meters, 5–10 meters, >10 meters, and sporadically spread areas, as depicted in the atlas. The resulting raster dataset was clipped to the Baku district boundaries using the Extract by Mask tool, refining its scope for analysis.

The dataset, visualized in Map Figure 3.5, illustrates groundwater depth variations across Baku, highlighting areas at high contamination risk (<3 m) versus safer zones (>10 m). Despite the data limitation, the transformation from paper-based to digital form via the Presidential Library's atlas ensured a reliable dataset, integrated into the weighted overlay to prioritize environmental protection.

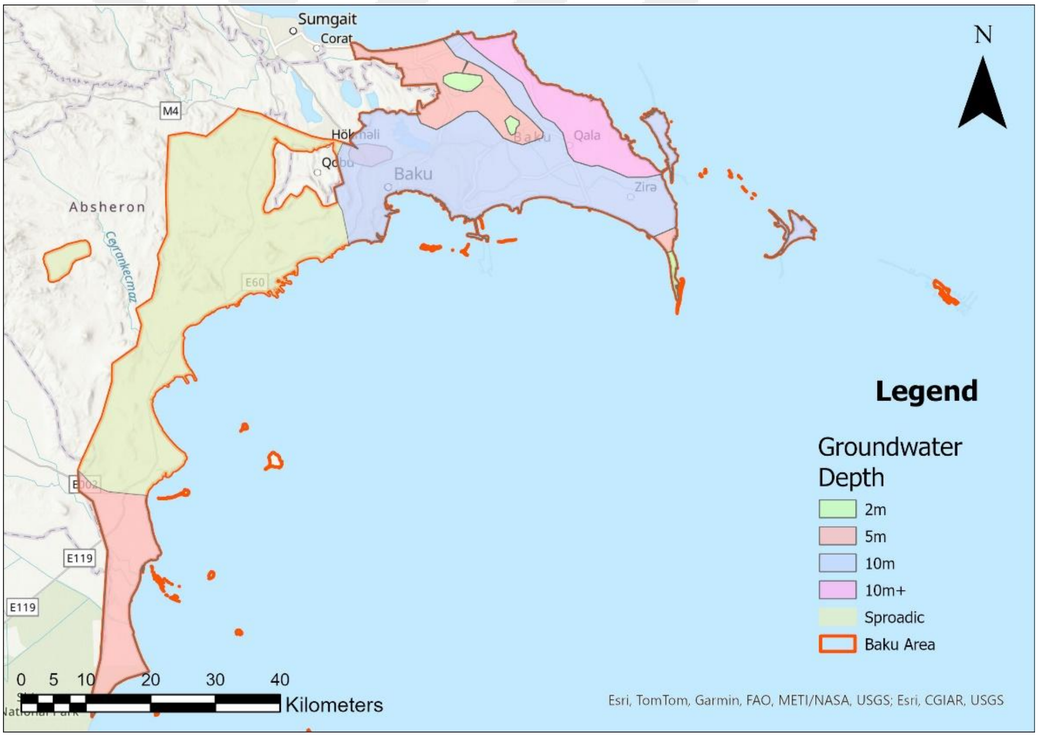

Figure 3.5 : Groundwater map

4. GIS-BASED SUITABILITY ANALYSIS

The generation of a suitability map for landfill site selection in Baku, Azerbaijan, represents a critical phase in this study, integrating spatial analysis and multi-criteria decision-making (MCDM) to address the city's pressing waste management challenges. The suitability map synthesizes ten criteria—land use/land cover (LULC), distance to roads, distance to settlements, distance to waterbodies, distance to airstrips, elevation, slope, distance to fault lines, distance to protected areas, and groundwater depth—to balance environmental, social, logistical, and safety considerations. This process leverages the Analytic Hierarchy Process (AHP) within a Geographic Information System (GIS) framework, specifically ArcGIS Pro, to produce a spatially explicit representation of site suitability, guiding sustainable urban planning and mitigating issues like groundwater contamination and community opposition observed at Balakhani.

The AHP method is employed to assign weights to each criterion, reflecting their relative importance, with a Consistency Ratio (CR) below 0.1 to ensure reliable prioritization (Saaty, 1980).

The weighted criteria layers are combined using ArcGIS Pro's Weighted Overlay tool, which aggregates the reclassified rasters to produce a composite suitability map. The resulting map categorizes the study area into suitability classes highlighting optimal sites that minimize environmental risks and logistical costs. This general process, grounded in robust MCDM-GIS methodologies, provides a transparent and reproducible framework for decision-makers, aligning with Azerbaijan's 2020 Development Concept and fostering sustainable waste management in Baku's rapidly evolving urban landscape.

4.1 Reclassified Factor Maps

References The generation of reclassified factor maps is a critical component of the landfill site selection analysis for Baku, Azerbaijan, transforming raw spatial data into standardized formats for integration into the Analytic Hierarchy Process (AHP) and GIS-based multi-criteria decision-making (MCDM) framework. This process ensures that the ten criteria—land use/land cover (LULC), distance to roads, distance to settlements, distance to waterbodies, distance to airstrips, elevation, slope, distance to fault lines, distance to protected areas, and groundwater depth—are consistently evaluated to produce a robust suitability map. Using ArcGIS Pro’s spatial analysis tools, each criterion’s raw data are processed, and values are reclassified into a standardized suitability scale (1–5, where 1 is least suitable and 5 is most suitable), enabling weighted overlay analysis.

The reclassification process begins with preparing raw datasets, sourced from open-access platforms (e.g., USGS EarthExplorer, OpenStreetMap, UNEP-WDPA) and digitized paper-based records (e.g., groundwater depth from the Ecological Atlas of Azerbaijan), as outlined in Section 3.4. For distance-based criteria—roads, settlements, waterbodies, airstrips, fault lines, and protected areas—Euclidean distances are calculated using ArcGIS Pro’s Euclidean Distance tool. This tool generates continuous distance rasters by computing the straight-line distance from each raster cell to the nearest feature (e.g., road, settlement), capturing spatial relationships essential for suitability assessment. The resulting distance rasters are then reclassified using the Reclassify tool, which maps the continuous or categorical data into discrete suitability scores based on intervals determined by literature and Baku’s local context (Sener et al., 2011; Gorsevski et al., 2012).

For non-distance criteria, raw data are directly reclassified. The LULC dataset, derived from ESA Sentinel-2 imagery, is reclassified based on land cover types, assigning higher suitability to less sensitive areas. Elevation and slope, sourced from the SRTM DEM, are reclassified to prioritize areas that reduce flood risk and construction challenges, respectively. Groundwater depth, digitized from the Ecological Atlas of Azerbaijan, is reclassified to favor deeper aquifers that lower contamination risks. The Reclassify tool in ArcGIS Pro facilitates this process by allowing users to define input ranges and assign corresponding suitability scores.

The elevation criterion was evaluated to assess flood risk and construction feasibility for landfill sites across Baku's varied terrain. Reclassification intervals were determined based on elevation ranges, as showed in the Table 4.1, with each interval assigned a suitability value from 1 (least suitable) to 5 (most suitable) to identify areas less prone to flooding and more suitable for development. This factor is critical for ensuring long-term stability of landfill structures. The reclassified map in the Figure 4.1 employs color tones to symbolize these suitability levels, with shades representing the degree of suitability across different elevations, aiding in the selection of sites that balance safety and accessibility in the region's landscape.

Table 4.1 : Elevation Reclassification.

Criteria	Interval	Reclassified Value	Suitability Degree
Elevation	200-400m	1	Unsuitable
	120-200m	2	Very low suitable
	50-120m	3	Low suitable
	-48-0m	4	Moderate suitable
	0-50m	5	High suitable

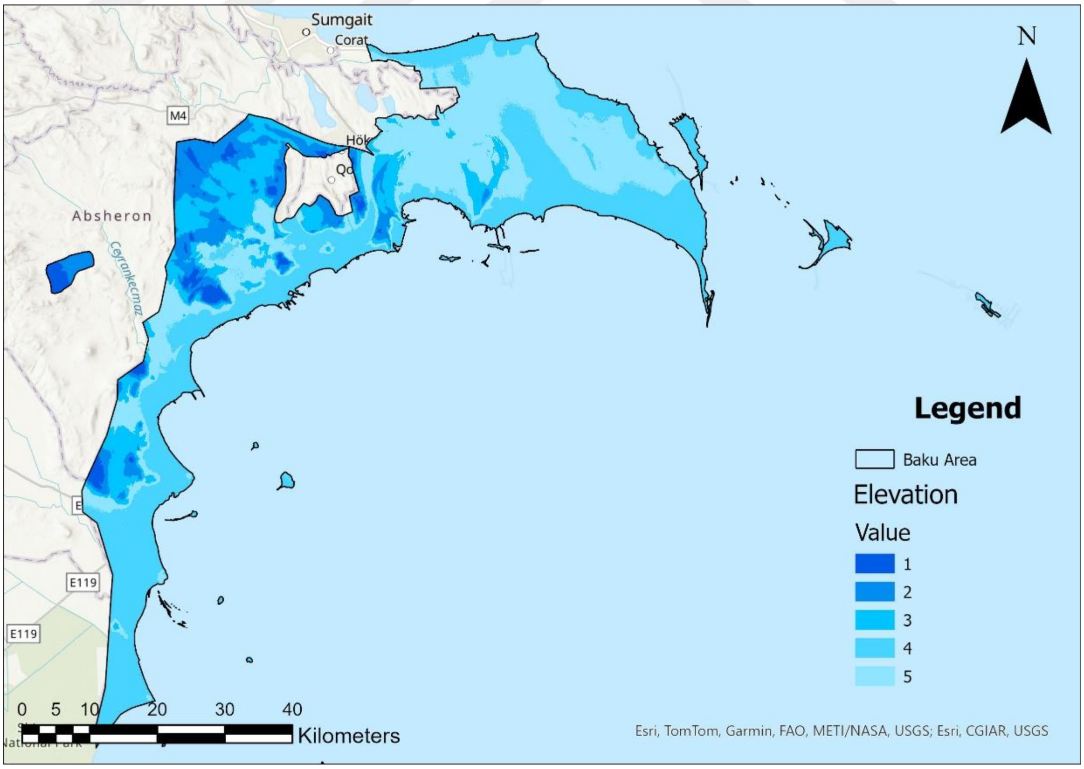

Figure 4.1 : Reclassified elevation map.

The slope criterion was analyzed to ensure geotechnical stability and ease of landfill construction in Baku. Reclassification intervals were defined based on slope gradients, mentioned in the Table 4.2 with each interval assigned a suitability value ranging from 1 (least suitable) to 5 (most suitable) to prioritize flatter areas that reduce engineering challenges and erosion risks. This criterion is essential for the practical implementation of landfill projects. The reclassified map in the Figure 4.2 uses color tones to symbolize these suitability levels, with different shades indicating the stability and constructability of potential sites, providing a visual tool for assessing topographic suitability across the study area.

Table 4.2 : Slope Reclassification.

Criteria	Interval	Reclassified Value	Suitability Degree
	40%<	1	Unsuitable
	20-40%	2	Very low suitable
Slope	10-20%	3	Low suitable
	3-10%	4	Moderate suitable
	0-3%	5	High suitable

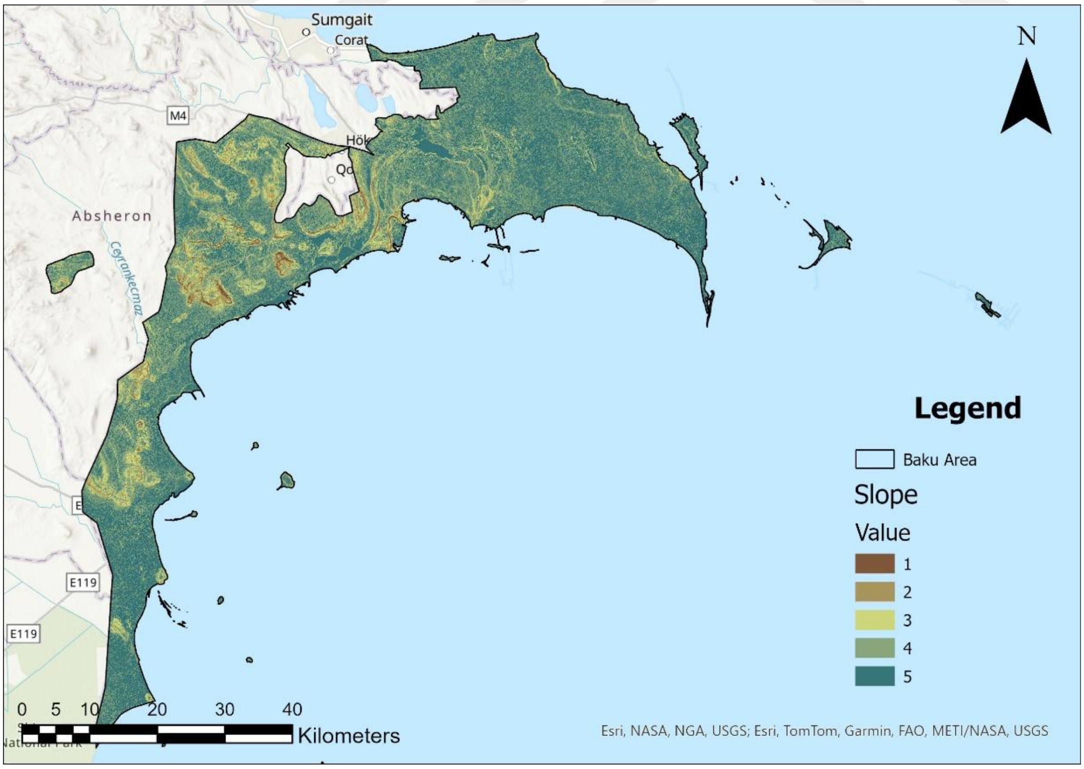

Figure 4.2 : Reclassified slope map.

The land use/land cover (LULC) criterion plays a vital role in identifying suitable landfill sites. Reclassification intervals were carefully determined to categorize various land uses, ranging from sensitive ecosystems to undeveloped areas, with each interval assigned a suitability value from 1 (least suitable) to 5 (most suitable) as shown in the Table 4.3. This process ensures that areas with minimal environmental impact and economic value are prioritized for landfill development, reflecting the need to protect natural habitats and agricultural zones. The reclassified map in the Figure 4.3 visually represents these suitability levels through a gradient of color tones.

Table 4.3 : LULC Reclassification.

Criteria	Interval	Reclassified Value	Suitability Degree
LULC	Waterbodies, Settlements	1	Unsuitable
	Flooded vegetation, Forest	2	Very low suitable
	Crops, Ice	3	Low suitable
	Cloud	4	Moderate suitable
	Bare, Rangeland	5	High suitable

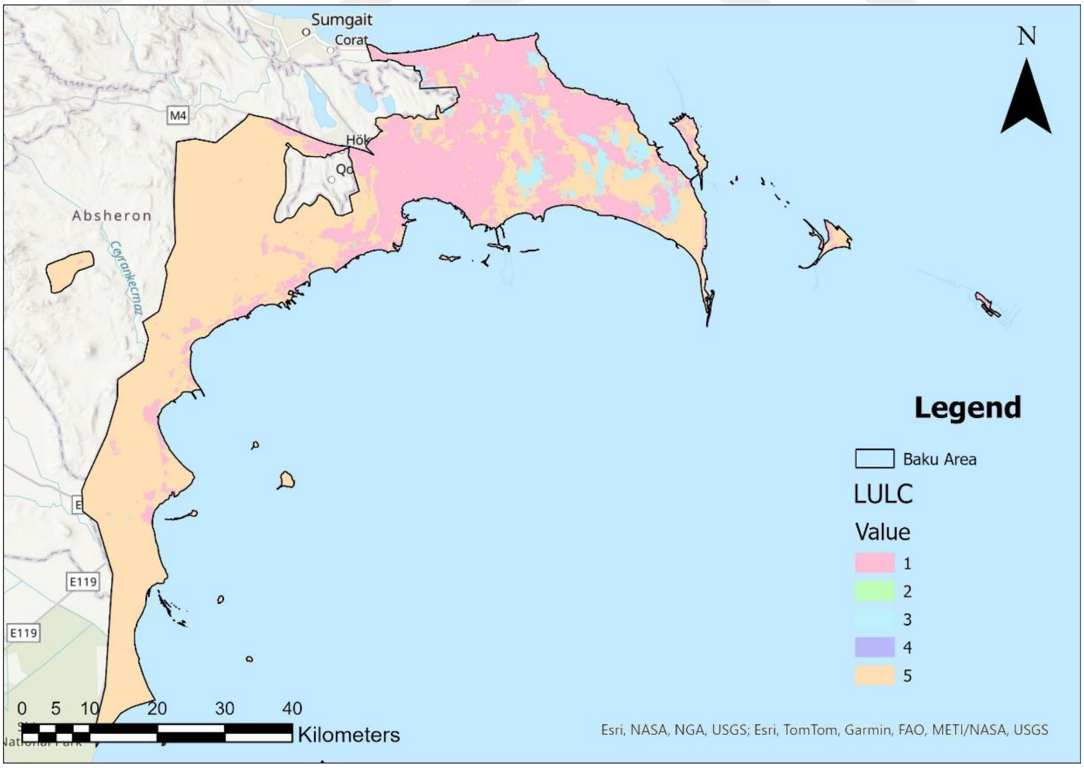

Figure 4.3 : Reclassified LULC map.

The distance to roads criterion is essential for ensuring efficient waste transportation to landfill sites while minimizing disruption to urban areas in Baku. Reclassification intervals, mentioned in the Table 4.4, were established based on the proximity to road networks, including primary, secondary, and tertiary routes, with each interval assigned a suitability value ranging from 1 (least suitable) to 5 (most suitable). This classification balances the need for accessibility with the desire to reduce noise, traffic, and aesthetic impacts on nearby communities. The reclassified map in the Figure 4.4 employs a range of color tones to symbolize these suitability levels, helping to identify optimal locations that support logistical efficiency.

Table 4.4 : Distance from road reclassification.

Criteria	Interval	Reclassified Value	Suitability Degree
Distance from road	0-200m	1	Unsuitable
	4000>m	2	Very low suitable
	2000-4000m	3	Low suitable
	500-2000m	4	Moderate suitable
	200-500m	5	High suitable

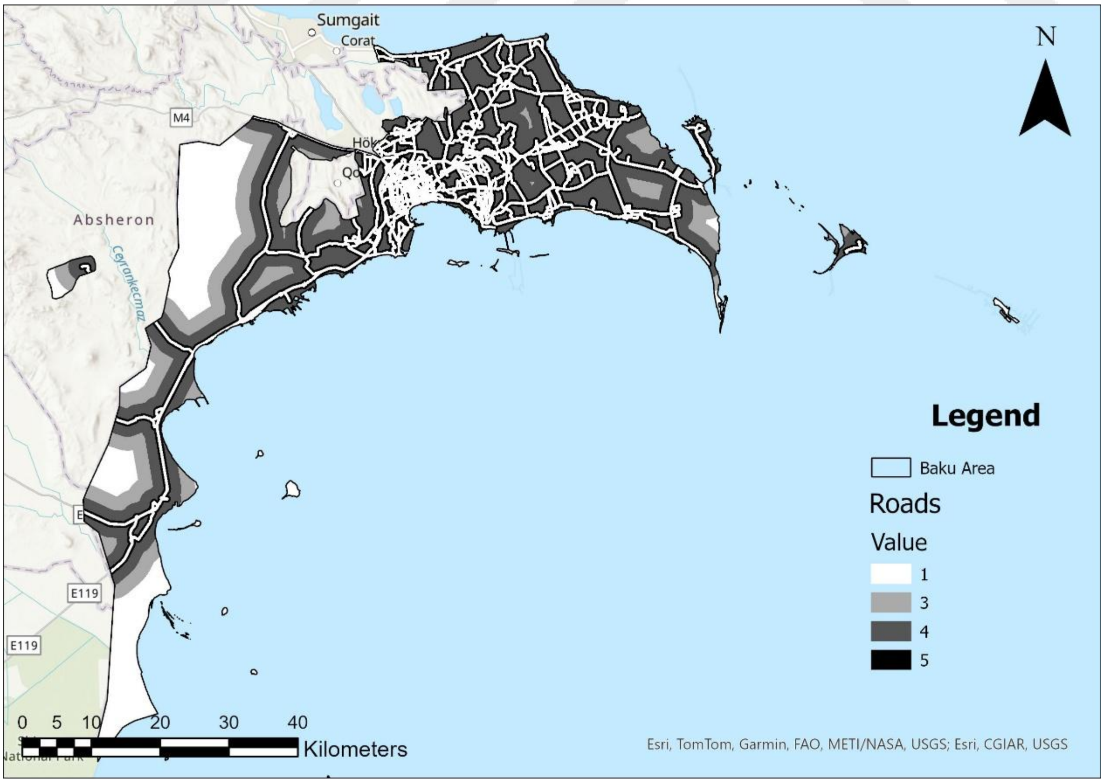

Figure 4.4 : Reclassified road map.

The distance to fault lines criterion was included to minimize seismic risks associated with landfill sites in Baku’s tectonically active region. Reclassification intervals were established based on proximity to active fault lines, as depicted in the Table 4.5, with each interval assigned a suitability value ranging from 1 (least suitable) to 5 (most suitable) to enhance site safety and structural integrity. This factor is crucial for long-term risk mitigation. The reclassified map in the Figure 4.5 symbolizes these suitability levels with color tones, where lighter shades indicate greater distances from fault zones, offering a clear representation of seismically safe areas for landfill development.

Table 4.5 : Distance from faults reclassification.

Criteria	Interval	Reclassified Value	Suitability Degree
Distance from faults	0-2500m	1	Unsuitable
	2500-4000m	2	Very low suitable
	4000-8000m	3	Low suitable
	8000-12000m	4	Moderate suitable
	12000m>	5	High suitable

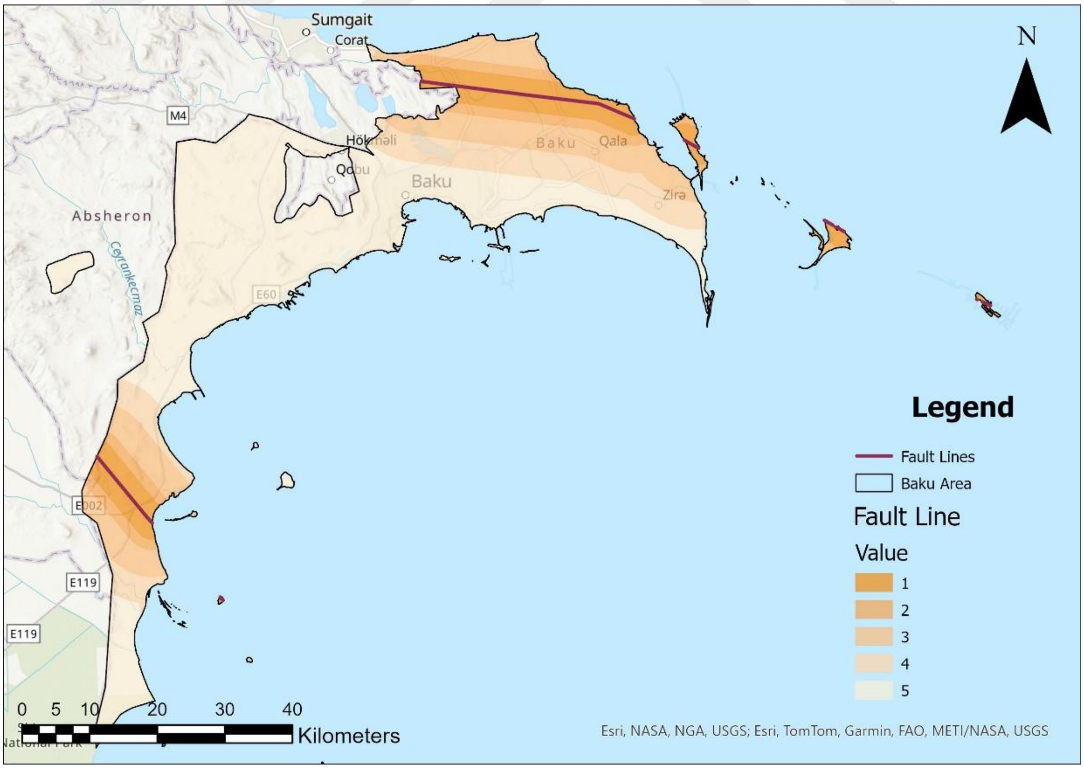

Figure 4.5 : Reclassified fault map.

The distance to waterbodies criterion is a key factor in protecting Baku's aquatic ecosystems from potential leachate contamination. Reclassification intervals were determined based on the proximity to waterbodies, as shown in the Table 4.6, to safeguard water quality and biodiversity. This prioritization is essential for preventing environmental degradation in a region with significant water resources. The reclassified map in the Figure 4.6 symbolizes these suitability levels with color tones, where darker shades indicate high-risk proximity zones and lighter shades denote safer distances, providing a clear visual guide for selecting landfill sites that avoid waterbody impacts.

Table 4.6 : Distance from waterbodies reclassification.

Criteria	Interval	Reclassified Value	Suitability Degree
Distance from waterbodies	0-300m	1	Unsuitable
	300-800m	2	Very low suitable
	800-1400m	3	Low suitable
	1400-2000m	4	Moderate suitable
	2000m>	5	High suitable

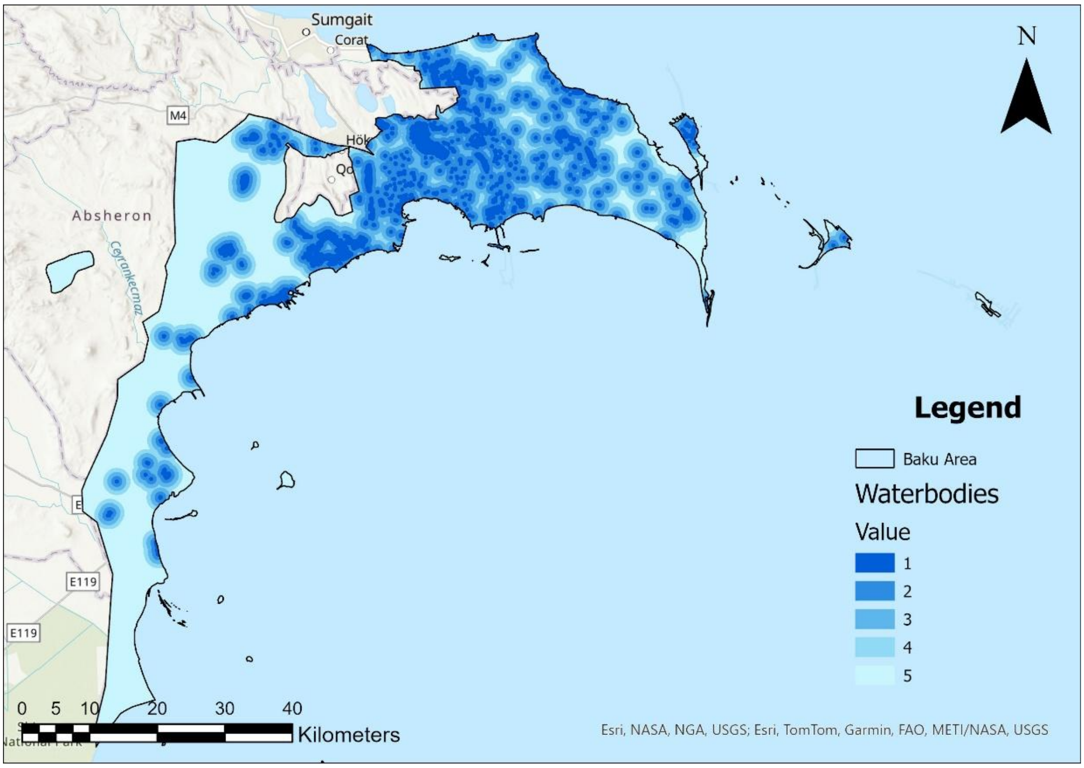

Figure 4.6 : Reclassified waterbodies map.

The distance to settlements criterion is crucial for reducing social and health-related impacts on Baku's residential communities during landfill operations. Reclassification intervals were defined according to the proximity to populated areas, with each interval assigned a suitability value from 1 (least suitable) to 5 (most suitable) as shown in the Table 4.7 to ensure adequate buffers that mitigate odor, noise, and health risks. This approach prioritizes the well-being of residents by maintaining safe distances from urban zones. The reclassified map in the Figure 4.7 utilizes color tones to symbolize these suitability levels, with distinct shades highlighting areas that are sufficiently distant from settlements, thereby facilitating the selection of sites that minimize community opposition and enhance public acceptance.

Table 4.7 : Distance from settlements reclassification.

Criteria	Interval	Reclassified Value	Suitability Degree
Distance from settlements	0-500m	1	Unsuitable
	4000m>	2	Very Low suitable
	500-1000m	3	Low suitable
	3000-4000m	4	Moderate suitable
	1000-3000m	5	High suitable

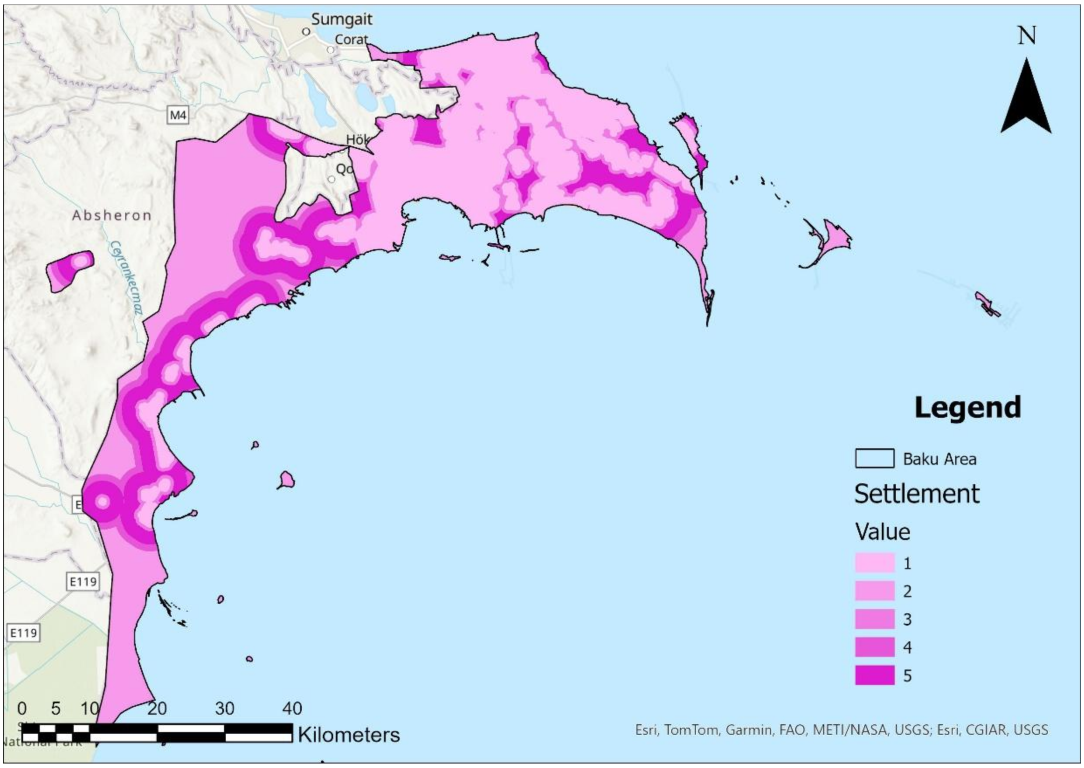

Figure 4.7 : Reclassified settlement map.

The groundwater depth criterion was assessed to prevent leachate contamination of Baku's aquifers, a critical concern for environmental safety. Reclassification intervals were defined based on aquifer depth levels, as depicted in the Table 4.8, with each interval assigned a suitability value ranging from 1 (least suitable) to 5 (most suitable) to prioritize deeper groundwater zones that reduce contamination risks. This factor is vital for protecting water resources. The reclassified map in the Figure 4.8 employs color tones to symbolize these suitability levels, with varying shades indicating the degree of contamination risk and safety, providing a visual guide for selecting secure landfill locations.

Table 4.8 : Groundwater reclassification.

Criteria	Interval	Reclassified Value	Suitability Degree
Groundwater	0-2m	1	Unsuitable
	2-5m	2	Very Low suitable
	5-10m	3	Moderate suitable
	Sproadic	4	Moderate suitable
	10m>	5	High suitable

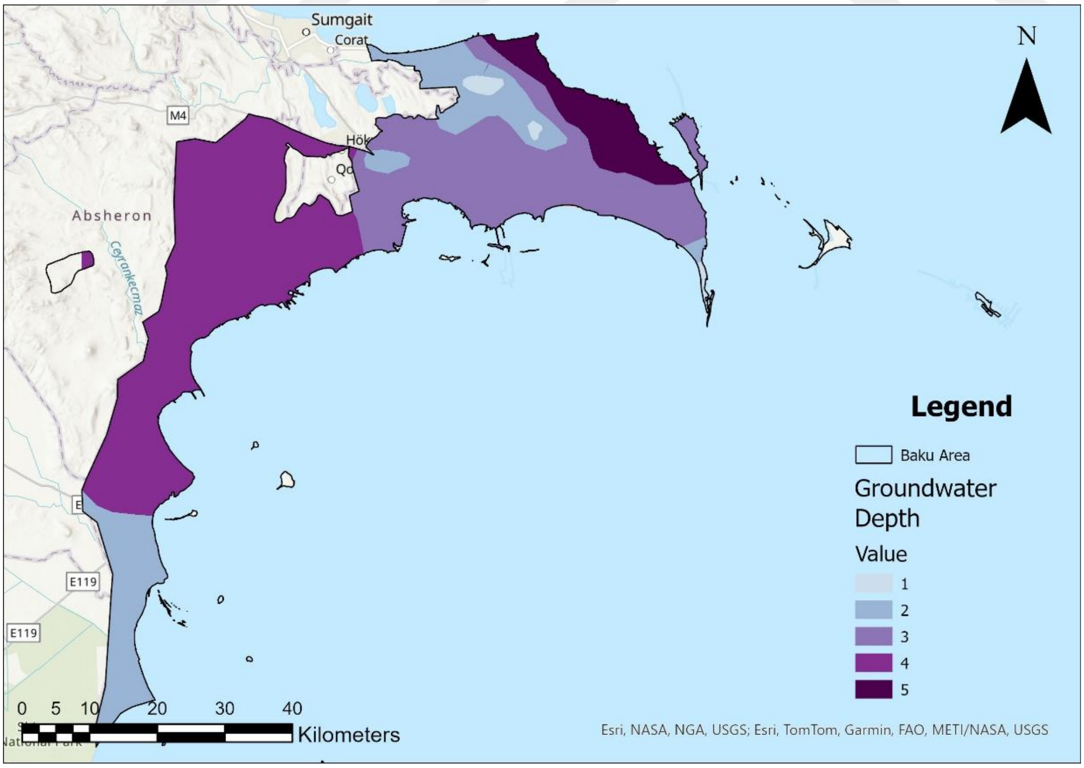

Figure 4.8 : Reclassified groundwater map.

The distance to protected areas criterion was evaluated to preserve Baku's biodiversity and comply with conservation policies, particularly near national parks. Reclassification intervals were determined based on proximity to protected zones, with each interval assigned a suitability value ranging from 1 (least suitable) to 5 (most suitable) as shown in the Table 4.9 to protect ecological integrity and comply with legal standards. This criterion supports sustainable land use planning. The reclassified map depicted in the Figure 4.9 uses color tones to symbolize these suitability levels, with shades reflecting distances from protected areas, aiding in the selection of sites that avoid ecological disruption.

Table 4.9 : Distance from protected areas reclassification.

Criteria	Interval	Reclassified Value	Suitability Degree
Distance from protected areas	0-500m	1	Unsuitable
	500-1000m	2	Very Low suitable
	1000-1500m	3	Low suitable
	1500-2000m	4	Moderate suitable
	2000m>	5	High suitable

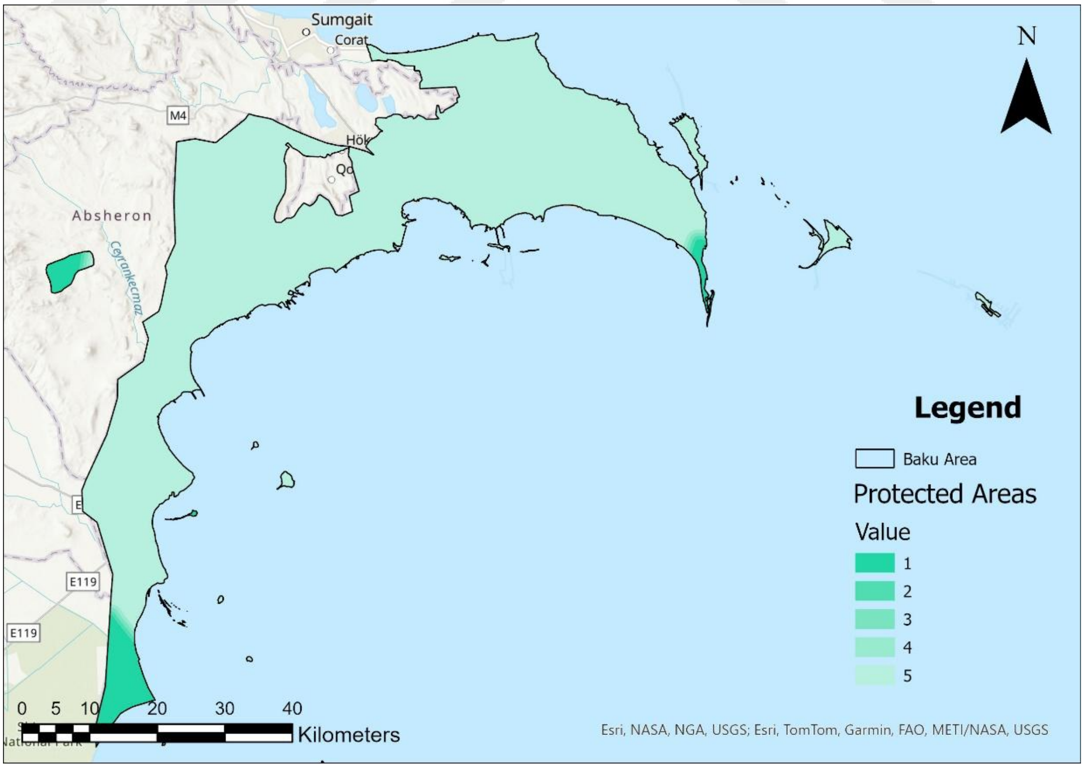

Figure 4.9 : Reclassified protected areas map.

The distance to airstrips criterion was incorporated to address aviation safety concerns, such as bird strikes, which pose risks near landfill sites in Baku. Reclassification intervals,mentioned in the Table 4.10, were established based on the proximity to airstrip locations, with each interval assigned a suitability value ranging from 1 (least suitable) to 5 (most suitable) to ensure compliance with aviation safety regulations. This criterion is vital for protecting air traffic, especially near major airports. The reclassified map in the Figure 4.10 uses color tones to symbolize these suitability levels, with varying shades indicating safe and unsafe distances from airstrips, enabling the identification of locations that minimize interference with flight operations while supporting waste management needs.

Table 4.10 : Distance from airstrips reclassification.

Criteria	Interval	Reclassified Value	Suitability Degree
Distance from airstrips	0-3km	1	Unsuitable
	3-5km	2	Very low suitable
	5-8km	3	Low suitable
	8-10km	4	Moderate suitable
	10km>	5	High suitable

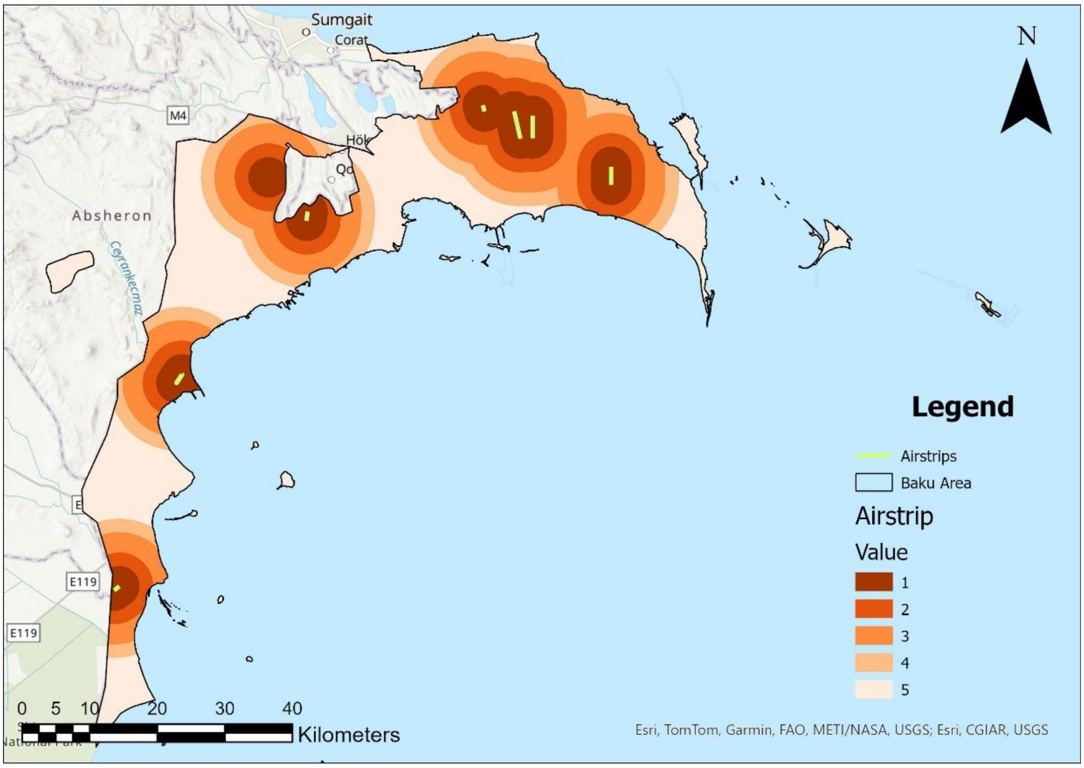

Figure 4.10 : Reclassified airstrips map.

4.2 Application of AHP

The AHP methodology, integrated with ArcGIS Pro, ensures that environmental, social, logistical, and safety considerations are balanced, addressing issues like groundwater contamination and community opposition observed at Balakhani. By constructing pairwise comparison matrices, calculating weights, and verifying consistency with a Consistency Ratio (CR) below 0.1, AHP provides a transparent framework for decision-making, aligning with best practices from recent literature (Sener et al., 2011; Nyimbili & Erden, 2020).

The AHP process began with constructing a decision hierarchy, placing the goal of selecting an optimal landfill site at the top, followed by the ten criteria organized into six main categories—Social (SC: distance to settlements), Geological (GC: fault lines, groundwater depth), Environmental (EC: distance to waterbodies, LULC, protected areas), Logistical (LC: distance to roads), Safety (SaC: distance to airstrips), and Topographical (TC: elevation, slope)—to manage complexity, as recommended by Sener et al. (2011).

Pairwise comparisons were conducted at two levels: main categories and sub-criteria within categories, using Saaty's 1–9 scale, where 1 indicates equal importance and 9 indicates extreme importance (Saaty, 1980).

For the main categories, a 6x6 pairwise comparison matrix was developed, as shown in Table 4.11, reflecting expert judgment tailored to Baku's context. The Social category (SC) was deemed most critical due to community concerns, followed by Geological (GC) for contamination risks, Environmental (EC) for ecological protection, Logistical (LC) for cost efficiency, Safety (SaC) for aviation safety, and Topographical (TC) as less critical given Baku's flat terrain. The matrix, designed to be consistent (CR = 0), assigned values such as SC being twice as important as GC (value 2), three times as important as EC (value 3), and six times as important as TC (value 6).

This matrix is consistent (CR = 0), as it follows a clear ranking (SC > GC > EC > LC > SaC > TC). Weights were calculated by normalizing row sums: SC = 0.3433, GC = 0.2534, EC = 0.1771, LC = 0.1158, SaC = 0.0700, TC = 0.0400.

Table 4.11 : AHP main categories hierarchy.

	SC	GC	EC	LC	SAC	TC
SC	1	2	3	4	5	6
GC	1/2	1	2	3	4	5
EC	1/3	1/2	1	2	3	4
LC	1/4	1/3	1/2	1	2	3
SAC	1/5	1/4	1/3	1/2	1	2
TC	1/6	1/5	1/4	1/3	1/2	1

Sub-criteria within categories with multiple factors were compared similarly. For the Environmental category (EC), a 3x3 matrix compared distance to waterbodies, LULC, and protected areas, prioritizing waterbodies due to contamination risks in Baku's proximity to the Caspian Sea. The matrix, shown in a supporting calculation, assigned waterbodies twice the importance of LULC (value 2) and three times that of protected areas (value 3), yielding local weights: waterbodies = 0.539, LULC = 0.297, protected areas = 0.164, with CR = 0 (Table 4.12).

Table 4.12 : Pairwise comparison for environmetal criteria.

	Waterbodies	LULC	Protected
Waterbodies	1	2	3
LULC	1/2	1	2
Protected	1/3	1/2	1

For the Geological category (GC), a 2x2 matrix in Table 4.13 compared groundwater depth and fault lines, emphasizing groundwater depth for its critical role in preventing leachate contamination, assigning it three times the importance of fault lines (value 3), resulting in local weights: groundwater depth = 0.75, fault lines = 0.25, with CR = 0.

Table 4.13 : Pairwise comparison for geological criteria.

	Groundwater	Faults
Groundwater	1	3
Faults	1/3	1

The topographical category (TC) compared elevation and slope, prioritizing elevation for flood risk mitigation, with elevation twice as important as slope (value 2) depicted in Table 4.14, yielding local weights: elevation = 0.6667, slope = 0.3333, with CR = 0. Single-criterion categories (SC, LC, SaC) retained a local weight of 1.0.

Table 4.14 : Pairwise comparison for topographical criteria.

	Elevation	Slope
Elevation	1	2
Slope	1/2	1

Global weights for the ten criteria were calculated by multiplying local weights by their main category weights, as presented in Table 4.15. For example, distance to settlements (SC) retained its category weight of 0.3433 (34.33%), while groundwater depth (GC) was calculated as 0.2534 × 0.75 = 0.19005 (19.005%), and distance to waterbodies (EC) as 0.1771 × 0.539 ≈ 0.0954 (9.54%). The complete global weights are: distance to settlements = 0.3433, groundwater depth = 0.19005, distance to roads = 0.1158, distance to waterbodies = 0.0954, distance to airstrips = 0.0700, fault lines = 0.06335, LULC = 0.0526, protected areas = 0.0290, elevation = 0.0267, slope = 0.0133, summing to approximately 1.0, confirming accuracy. These weights reflect Baku's priorities, emphasizing social and environmental factors

Table 4.15 : AHP main categories hierarchy.

Main Category	Weight	Sub-criteria	Local weight	Global Weight
SC	0.3433	Settlements	1.00	0.3433
GC	0.2534	Groundwater	0.7500	0.19005
		Fault Lines	0.25	0.06335
EC	0.1771	Waterbodies	0.5390	0.0954
		LULC	0.297	0.0526
		Protected	0.1640	0.0290
LC	0.1158	Roads	1	0.1158
SAC	0.07	Airstrips	1	0.07
TC	0.04	Elevation	0.6667	0.0267
		Slope	0.3333	0.0133

The AHP-derived weights were applied in ArcGIS Pro's Weighted Overlay tool, combining reclassified raster layers (1–5 suitability scale) for each criterion. The weights, expressed as percentages (e.g., settlements: 34.33%, groundwater: 19.005%), ensured that high-priority criteria like distance to settlements and groundwater depth significantly influenced the suitability map. The consistency of the pairwise matrices (CR = 0) guarantees that the weights are reliable, meeting the study's requirement for CR < 0.1. The resulting weights were validated against Baku's context, where proximity to settlements and shallow aquifers (3–10 m) are critical concerns, ensuring that the suitability map prioritizes environmentally safe and socially acceptable sites.

The final suitability map depicted in Figure 4.11, generated for landfill site selection in Baku, Azerbaijan, represents the culmination of integrating ten reclassified criteria—land use/land cover (LULC), distance to roads, distance to settlements, distance to waterbodies, distance to airstrips, elevation, slope, distance to fault lines, distance to protected areas, and groundwater depth—using ArcGIS Pro's Weighted Overlay tool and Analytic Hierarchy Process (AHP) weights.

The map highlights the southwest and east regions of Baku as highly suitable areas for landfill sites, reflecting their favorable characteristics. These regions feature barren lands, deeper aquifers, and sufficient distance from settlements and waterbodies, aligning with high suitability scores driven by the weights for distance to settlements and groundwater depth. Conversely, central settlement areas, characterized by high population density (10,000 people/km²), and lakeside areas near the Caspian Sea and inland lakes are classified as unsuitable or less suitable. These zones receive low suitability scores due to proximity constraints (e.g., <2 km from settlements, <500 m from waterbodies). The Weighted Overlay tool effectively combined reclassified rasters (1–5 scale) ensuring compliance with environmental regulations.

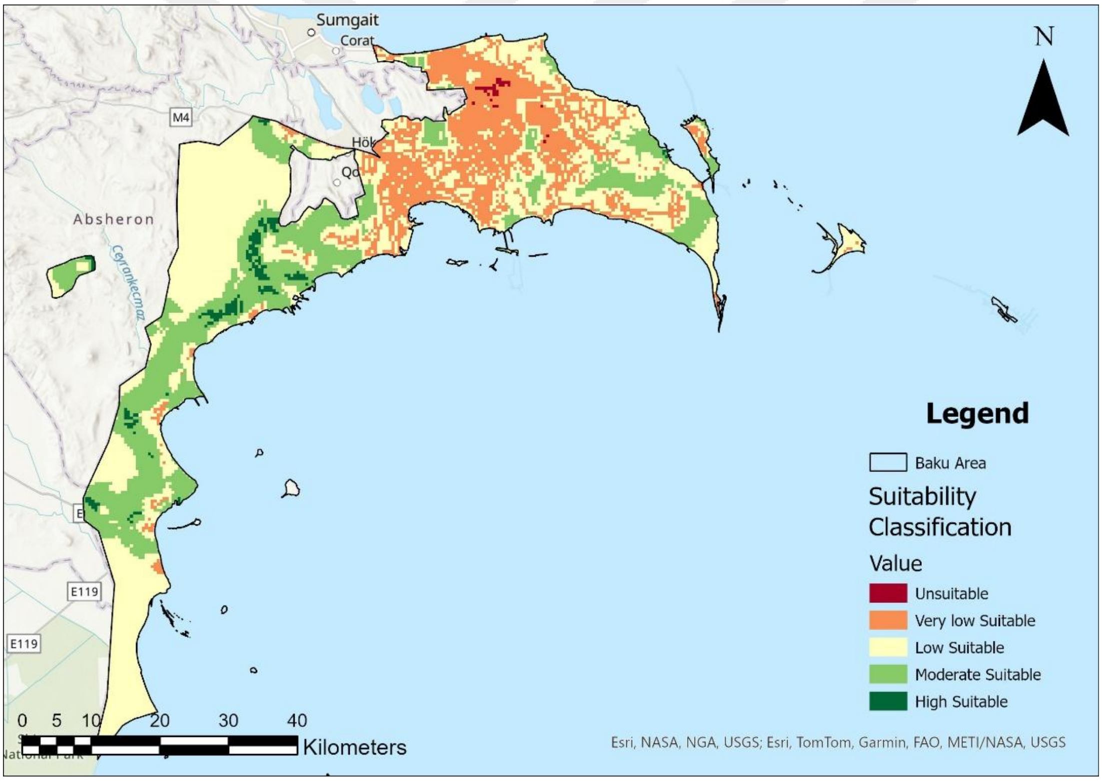

Figure 4.11 : Suitability Map for New Landfill Site in Baku

5. RESULTS AND DISCUSSIONS

The suitability map generated for landfill site selection in Baku, Azerbaijan offers a comprehensive spatial analysis to identify optimal locations for new landfill sites, addressing the limitations of the existing Balakhani landfill. The map, derived using ArcGIS Pro’s Weighted Overlay tool and Analytic Hierarchy Process (AHP) weights, integrates ten criteria—land use/land cover (LULC), distance to roads, distance to settlements, distance to waterbodies, distance to airstrips, elevation, slope, distance to fault lines, distance to protected areas, and groundwater depth. The AHP weights prioritize social and environmental factors, with distance to settlements (34.33%) and groundwater depth (19.00%) exerting the greatest influence, followed by distance to roads (11.58%), distance to waterbodies (9.54%), and others, ensuring a balanced assessment with a Consistency Ratio (CR) below 0.1 (Saaty, 1980). The map highlights the southwest and east regions of Baku as highly suitable areas, while central settlement areas and lakeside zones near the Caspian Sea are deemed unsuitable or less suitable, reflecting the criteria’s spatial constraints and exclusion buffers.

Upon reviewing the suitability, the southwest region of Baku emerges as a prime candidate for a new landfill site, characterized by extensive barren lands and minimal residential development, which aligns with the high suitability score driven by the LULC (5.26%) and distance to settlements criteria. This area benefits from flat terrain (slope <5%) and deeper aquifers (>10 m), reducing construction challenges and contamination risks, as emphasized by the groundwater depth weight (19.00%). Similarly, the eastern region shows high suitability, with sparse vegetation and sufficient distance from protected areas like Absheron National Park, ensuring compliance with ecological preservation goals (distance to protected areas: 5.00%). However, the eastern region’s proximity to minor fault lines slightly lowers its suitability compared to the southwest, as reflected by the fault lines criterion (6.34%). Both regions are well-positioned for logistical efficiency, with access to major roads within 2–5 km, supporting the distance to roads criterion (11.58%).

In contrast, the central areas of Baku, marked by dense urban settlements, are classified as unsuitable due to their proximity to residential zones (<2 km), violating the exclusion buffer and reflecting the dominant weight of the distance to settlements criterion. Lakeside areas, particularly near the Caspian Sea, are also unsuitable, as they fall within the 500 m exclusion buffer for waterbodies, protecting aquatic ecosystems from potential leachate pollution (distance to waterbodies: 9.54%). The existing Balakhani landfill, located in the northeastern part of Baku, falls within a less suitable zone on the map, validating its known issues, such as proximity to settlements (1.8 km) and shallow groundwater (3–5 m), which exacerbate environmental and social conflicts. The map's depiction of Balakhani as less suitable underscores the need for relocation to the southwest or east, where environmental risks are minimized.

The results reveal new insights into Baku's landfill siting dynamics. The southwest region's suitability is enhanced by its isolation from seismic zones, with distances to fault lines exceeding 15 km, a critical factor given Azerbaijan's tectonic activity. However, the eastern region's suitability is tempered by its closer proximity to airstrips (e.g., Heydar Aliyev International Airport), posing potential bird strike risks, as reflected by the distance to airstrips criterion (7.00%).

This trade-off highlights the complexity of balancing safety and environmental factors in site selection.

Additionally, the map indicates that elevation and slope (weights 2.67% and 1.33%, respectively) have minimal influence on overall suitability, as Baku's predominantly flat landscape (most areas <150 m elevation) poses few topographic constraints, allowing other criteria to dominate the suitability assessment.

The discussion of these results suggests that the southwest region is the most viable for a new landfill, offering a sustainable alternative to Balakhani by minimizing environmental risks and community impacts, as depicted in Figure 12. However, the eastern region's potential should not be overlooked, particularly if mitigation measures (e.g., bird control strategies) can address aviation safety concerns. The suitability map's alignment with environmental priorities, such as protecting the Caspian Sea and national parks, supports Azerbaijan's 2020 Development Concept, emphasizing sustainable urban planning. Future studies could incorporate additional criteria, such as wind direction to mitigate odor dispersion, or stakeholder input to enhance social acceptability, further refining the site selection process. This analysis, grounded in a rigorous MCDM-GIS framework, provides actionable insights for policymakers, paving the way for improved waste management in Baku.

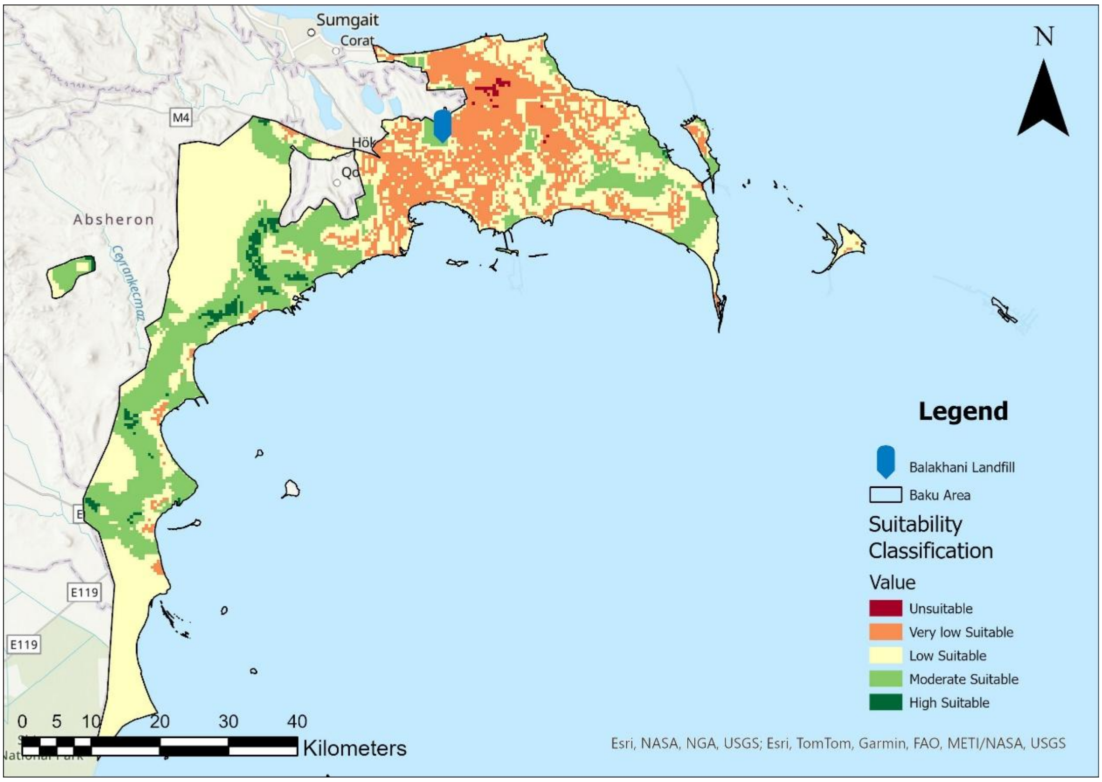

Figure 4.12 : Suitability map with existing landfill site in Baku

6. CONCLUSIONS AND RECOMMENDATIONS

This study, titled "Transformation of Solid Waste Management in Baku: A GIS-Based MCDM Approach to Landfill Site Selection Beyond Balakhani," successfully demonstrates the application of a Geographic Information System (GIS) and Multi-Criteria Decision-Making (MCDM) framework to address Baku's waste management challenges. By integrating the Analytic Hierarchy Process (AHP) with ArcGIS Pro, the research evaluated ten criteria—land use/land cover, distance to roads, distance to settlements, distance to waterbodies, distance to airstrips, elevation, slope, distance to fault lines, distance to protected areas, and groundwater depth—to generate a suitability map for new landfill sites. The AHP-derived weights, with a Consistency Ratio below 0.1, prioritized social and environmental factors, assigning the highest influence to distance, to settlements (34.33%) and groundwater depth (19.00%), ensuring a balanced and sustainable site selection process. The resulting map identified the southwest and east regions of Baku as highly suitable, characterized by barren lands, deeper aquifers, and sufficient distance from settlements and the Caspian Sea, while central urban areas and lakeside zones were deemed unsuitable due to proximity constraints and ecological sensitivities.

The analysis revealed critical insights, notably the unsuitability of the existing Balakhani landfill in the northeast, which falls within a less suitable zone due to its proximity to settlements and shallow groundwater, validating its environmental and social challenges. The southwest region emerged as the most viable candidate for a new landfill, benefiting from seismic isolation and flat terrain, while the eastern region, though suitable, requires mitigation for aviation risks near Heydar Aliyev International Airport. These findings underscore the importance of a GIS-MCDM approach in addressing complex urban planning challenges, aligning with Azerbaijan's 2020 Development Concept for sustainable waste management.

Recommendations for future action include prioritizing the southwest region for immediate landfill development, coupled with environmental impact assessments to confirm site viability. The eastern region should be considered a secondary option, with bird control measures to mitigate aviation risks. Additionally, incorporating dynamic factors like wind direction and stakeholder consultations could enhance site acceptability and operational efficiency. Future studies should explore integrating advanced technologies, such as remote sensing for real-time land use updates, to refine suitability assessments. This research provides a replicable framework for other rapidly urbanizing cities, offering a path toward resilient waste management systems that balance environmental protection, social equity, and logistical feasibility.

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CURRICULUM VITAE

Name Surname : **Kanan Alakbarli**

EDUCATION :

- **B.Sc.** **:** 2022, Istanbul Technical University, Civil Engineering Faculty, Geomatics Engineering Department
- **M.Sc.** **:** 2025, Istanbul Technical University, Civil Engineering Faculty, Geomatics Engineering Department

PROFESSIONAL EXPERIENCE AND REWARDS:

- 2024 August- GIS Specialist at Information Communication Technologies Agency.

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Alakbarli, K.,** Seker, D.Z. 2025: Transformation of Solid Waste Management in Baku: A GIS-Based MCDM Approach to Landfill Site Selection Beyond Balakhani. 4rd International Graduate Research Symposium, May 12-14, 2025 İstanbul, Türkiye.