Analyzing and Selecting Key Indicators for Optimal Location of Disaster Logistic Centers in a Multi-Hazard and Risk Context: Case of Istanbul Mega-city, Turkey

TIONGE MUNTHALI
July, 2024

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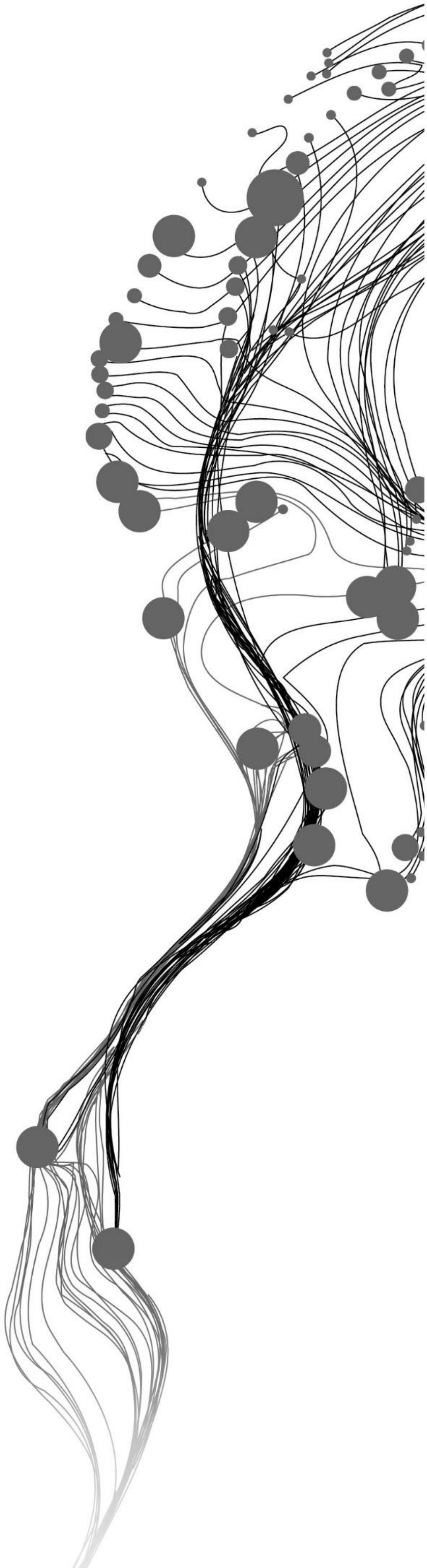

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Specialization: Urban Planning and Management

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ABSTRACT

Cities are growing at an alarming rate, with the recent decade witnessing the emergency of many megacities, which are often located in hazardous regions. High accumulation of people, infrastructure, assets and patterns of growth in cities, especially in megacities, translates into more hazard exposure and more vulnerable elements at risk. Consequently, it has been observed that communities are rarely prone to a single hazard, rather a multiplicity of hazards occur simultaneously, cascadingly or cumulatively over time, causing cascading impacts across different sectors and systems in a community. With the recognition that disasters cannot be completely prevented, effective and timely intervention is of utmost importance in all disasters; to reduce life, material and natural losses and accelerating the recovery process. This, on the other hand, depends on the availability and delivery of essential supplies, equipment and services to the affected areas within the shortest time possible. As almost 80% of disaster-related operations are related to logistics activities, finding strategic and optimal sites for locating such Disaster Logistics Centres (DLCs) is of utmost importance during the disaster preparedness phase.

DLCs are generally designed in several levels, ranging from small (3rd degree) to very large (1st degree). Where 3rd degree DLCs must be located in areas with high expected damage and should be based on the search and rescue needs upon disaster occurrence, 1st and 2nd degree DLCs are usually permanent and located in areas with little or no known hazards and good transportation connections. This study utilised a Spatial Multi-Criteria Decision Analysis approach to analyse and select indicators critical for the optimal location of DLCs in Istanbul. Three multi-criteria weighting methods of Entropy, Analytical Hierarchy Procedure and CRITIC were utilised.

The study revealed that a significant number of neighbourhoods, especially in the southern part of Istanbul are highly susceptible to multi-hazard impacts. Utilising the SMCA methodology, it was observed that emergency roads and geophysical hazards are critical factors for locating first degree DLCs while geophysical hazards and evacuation points were deemed essential for second degree DLCs. It can also be observed that geohazards have scored high in all the levels of DLCs stressing the fact of the significance of this in DLCs site selection especially in the changing environment of megacities. The study has also demonstrated the significance of integrating geospatial tools into DLCs location-allocation analysis, where the visual outputs generated can serve as a medium for stakeholder discussions, hence essential tools for achieving resilient urban futures. The suitability analysis has revealed that some most suitable locations for DLCs coincide with areas susceptible to multi-hazards. Therefore, future research could explore a cost-benefit analysis between two alternatives: (i) selecting DLC locations closer to urbanised and affected populations, which requires investing in constructing multi-hazard resilient buildings and facilities, or (ii) selecting locations further from urbanised areas, such as the north-western part, which are entirely safe from multi-hazard impacts, and focus on strategies that reduce increased travel and relief distribution travel time, brought by the absence of essential facilities and emergency roads.

Keywords: Disaster Logistic Centres, Megacity Istanbul, Multi-hazards, Location selection, Suitability analysis, Exposure.

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AHP	Analytical Hierarchy Process
CRITIC	Criteria Importance Though Intercriteria Correlation
DLCs	Disaster Logistic Centres
DM	Disaster Management
DRM	Disaster Risk Management
ERFs	Emergency Response Facilities
IMM	Istanbul Metropolitan Municipality
JICA	Japan International Cooperation Agency
MCDM	Multi-Criteria Decision Making
NAF	North Anatolian Fault
RLCs	Relief Logistic Centres or sites
SMCA	Spatial Multi-criteria Analysis
UNDRR	United Nations Office for Disaster Risk Reduction

1. INTRODUCTION

1.1. Background Information

Cities have been experiencing a tremendous increase in growth in recent decades. Zaheer (2020) postulates that in 2017, the rate of growth of some cities, such as Tokyo which had over 37 million people, was larger and faster than most individual nations in the world. The United Nations (UN) describes such cities with 10 million or more inhabitants as "*Mega-cities*" (UN, 2018). They originated in the mid-20th century, and the 21st century has seen a notable increase in the number of mega-cities across the world. Reports show that in 2010 there were 27 mega-cities (Kennedy et al. 2015), which increased to 33 by 2018 with estimations to reach 43 by 2030 (UN, 2018). However, current population statistics on world cities by *City Population* depicts underestimations in the projections as the number of megacities already reached 45 in 2023 (Brinkhoff, 2023).

Megacities, due to high population concentrations and rapid development dynamics, are at high risk of disasters associated with natural hazards. Gencer (2013) argues that most megacities are not just exposed to a single hazard, but rather to a wide range of geological, meteorological, and climatological hazards. To concur with this, Gu (2019) reported that megacities had higher levels of exposure to at least one of the following six types of natural hazards (earthquakes, cyclones, landslides, floods, droughts, and volcanic eruptions) as compared to other types of cities. The study revealed that in 2018, 73 per cent of the 33 megacities were exposed to multi-hazards. This translates to a total population of 401 million, representing 76 percent of the 509 million people residing in megacities as being exposed to multi-hazards that year. Additionally, Hochrainer & Mechler (2011), indicates that 8 out of 10 megacities in the world are located in coastlines, making them prone to storm surge and tsunami waves. They further state that a similar number of megacities worldwide have a moderate to high earthquake hazard. The increased number of elements at risk in megacities illustrates the urgent need for tackling such an urban mega-phenomenon.

Multi-hazards have been defined by the United Nations Office for Disaster Risk Reduction (UNDRR) as multiple major hazards that occur simultaneously, cascadingly, or cumulatively over time, causing cascading impacts across different sectors and systems in a community (UNDRR, 2016). Natural hazards in a given space usually interrelate with each other. According to van Westen & Kappes (2014) and Wang et al. (2020), hazards either trigger other hazards, leading to a series of hazards in a chain form or they affect the severity, process, and outcome of other hazards by changing the environmental conditions, which increases the area's susceptibility to the upcoming hazard. On the other hand, single independent hazards such as earthquakes and floods can spatially and temporally overlap without any hazard dependence or triggering effect. Significantly, multiple hazard events have been observed to evolve and coincide as a chain of disasters due to the initiation of a primary hazard, sometimes with unpredictable sequence of cascading events (Zhang et al., 2023).

Hazards with spatial and temporal correlations tend to have chain effects. Hochrainer-Stigler et al. (2023) and Kappes et al. (2012), postulates that multi-hazard interrelationships result into impacts that are usually greater than the impacts of multiple single hazards as effects of one hazard triggers or worsens the impacts of another hazard. Depietri et al. (2018) illustrated the chain impacts brought by Hurricane Sandy in New York City in 2012. As a post-tropical cyclone hazard, Hurricane Sandy caused a catastrophic storm surge along the city's coastlines, which was the primary cause of most damages and losses. Besides leading to deaths, the storm caused fire outbreaks and power outages, further inflicting damage in the city and flooding of essential facilities. This disruption affected communication systems and the delivery of essential services, such as healthcare, where critical equipment was damaged. These impacts increased the number of deaths and other damages beyond those directly caused by the primary event itself (Lane et al., 2013; Kemp and

Horton, 2013). Owing to the interconnections and complexity of urban systems, coupled with the dynamic socio-economic trends within megacities, it has proven challenging to comprehensively depict such hazard chain impacts (Menoni et al., 2017).

Consequently, hazard impacts are inevitable, and disasters cannot be completely prevented. This understanding necessitates the devising of effective disaster management (DM) strategies in all phases of DM: preparedness, response, recovery and mitigation. Additionally, this acknowledgement highlights the utmost importance of effective and timely intervention, especially during the response phase, so as to reduce life and material losses and accelerate the recovery process. Najafi et al. (2013) asserts that timely intervention depends on the availability and delivery of essential supplies and equipment to the affected areas within the shortest time possible after a disaster event. Kundu et al. (2022) argues that inefficient emergency logistics resource management can aggravate disaster fatalities in disaster-stricken areas. Since almost 80% of disaster-related operations are related to logistics activities (Maghsoudi & Moshtari, 2021), finding strategic and optimal sites for locating logistics centres is crucial during disaster preparedness phase in vulnerable communities.

Disaster Logistic Centres (DLCs) also known as Relief Logistic Centres or sites (RLCs), or Emergency Response Facilities (ERFs) are one of the essential aspects in humanitarian logistics and operations. DLCs are sites where relief commodities and essential services such as food, medical supplies, household equipment, transportation vehicles, fire stations, emergency shelters among others are positioned before a disaster. Additionally, upon a disaster occurrence, these sites provide support for evacuees and disaster response teams, as well as serve as supply points for distribution of items (Yılmaz & Kabak, 2020). According to Boonmee et al. (2017), pre-planned and positioned emergency supplies and services translate into better aid outreach, which directly helps reduce the suffering of affected people and speed up the recovery process. It is argued that pre-positioning supplies reduces time needed for aid to reach disaster victims, which in turn results into timely rescue and improved relief provision, which are critical for recovery from disaster impacts.

The recognition that disaster impacts can substantially be reduced with effective planning, response systems and emergency preparedness (Hannah & Max, 2019), has made that various entities (governments, organisations, and research community) focus on selecting strategic locations for DLCs. Abazari et al. (2021) postulates that locations for DLCs should enable relief chains to efficiently respond to emergencies. In this, Liu et al. (2021) indicates five principles as crucial in logistic planning: efficiency, effectiveness, equity, uncertainty, and robustness. Additionally, Trivedi (2018) and Yılmaz & Kabak (2020) argues for topographic conditions, transportation capacity, infrastructure, safety and security, cost, proximity, and type of ownership as major determinants for locating DLCs. However, it is important to note that different relief commodities and services differ in characteristics and missions, hence their level of urgency when disasters strike. Furthermore, in the context of multiple hazards, it is argued that hazards vary in nature and results from distinct processes, making that their analysis be confronted with high levels of uncertainties (van Westen & Kappes, 2014). This, on the other hand, infers that criteria for DLCs' site selection significantly differ among respective items, services and type of natural hazards.

1.2. Problem Definition

The risk of disasters associated with natural hazards is increasing in megacities, threatening their safety and sustainability. Due to their location *(mainly along waterways and coastal areas),* rapid population growth and rapid development dynamics *(which modify the environment),* megacities usually experience multiple natural hazards, leading to complex disaster risks and magnified impacts and fatalities as compared to other cities (Pelling and Blackburn, 2013; UNDESA, 2016). Depietri et al. (2018) concurs that the concentration of different hazards in densely populated areas, highly interconnected infrastructures and assets, and inadequate management have exacerbated the degree of fatalities and economic losses in these areas. Such complex hazard interrelationships and dynamic processes in megacities have proved to derail the decisions on optimal facility locations. As van Westen & Kappes (2014) and Gill and Malamud (2016) assert, different hazards require specific preparedness measures and resources, making it difficult to find a centralized location that caters to all eventualities.

Despite the recognition of complex hazard interrelationships and their influence on facility location, Disaster Risk Management (DRM) activities, such as logistic planning in the emergency preparedness phase, are still being addressed from a single hazard perspective, with little consideration on all hazards that are spatially relevant in a given region (Ward et al., 2022). As de Ruiter et al. (2021) noted, this lack of comprehensive analysis of hazard interactions in disaster preparedness results in *"asynergies"* in the devised and implemented measures. Therefore, it is against this background that this study analysed indicators that can be utilised to determine optimal locations for DLCs considering complex hazard interactions faced in contemporary megacities. Locating DLCs while considering multi-hazard and risk situations ensures sites are utilised and accessed for relief activities in worse case events without disruption in cases of secondary and unanticipated events. Furthermore, devising indicators that are specific to megacities is essential in ensuring effectiveness of preparedness and disaster management actions in such complex areas, which in turn is an integral process for achieving resilient communities (Cariolet et al., 2019).

1.3. Case Study Problem Overview: Megacity Istanbul

Istanbul is one of the megacities in the world and the largest city in Türkiye. In 2018, the city had 15 million inhabitants which accounted for 20% of the Turkish total population (World Bank, 2018). A recent report by the World Population Review (2024) indicates an increase in Istanbul's population to 16 million, with the city experiencing uncontrolled urban growth and expansion, and a high population density of 2523 people per square kilometre, 6530/sqm[1]. This high accumulation of people, infrastructure and patterns of growth (sprawled, informal and unplanned) coupled with its location at the crossroads between the Black Sea and Marmara Sea, and on one of the most active faults on earth, the North Anatolian (NAF), has increased multi-hazard exposure and susceptibility to multi-hazard impacts (Kundak, 2004; Ergintav et al., 2014).

According to Hussain et al. (2021), Istanbul megacity is prone to 22 natural hazards, with 73 potential hazard interactions where one hazard triggers the other hazard or changes the probability of occurrence of another hazard. The city is highly susceptible to earthquakes and their associated hazards of ground shaking, liquefaction, landslides, and tsunami. Historically, the city has been affected by earthquakes, with the recent event being the 1999 Kocaeli earthquake (7.6Mw in magnitude) which led to 18,000 deaths, 48,901 injuries and complete damages of 96,000 homes, 15,000 workplaces and infrastructure estimated at $5-$13 billion (World Bank, 2018). With the changing climate, cases and threats of hydrometeorological hazards such as extreme heat, wildfire and flooding are also increasing in Istanbul (GFDRR, 2020).

To ensure prompt response to emergencies, as well as the availability and accessibility of resources, and to achieve effective disaster risk management at large, a 3-scale logistics system has been set-up in the city. The Working group report on Istanbul Earthquake (2023) by the Istanbul Metropolitan Municipality (IMM) details this logistics system as consisting of first-, second- and third-level logistic centres; based on the types of services, spatial coverage and the urgency of the services to be provided by the centres (IMM, 2023). In this, the first-degree logistic centres have been planned to be in three positions within the megacity, with

[1] https://worldpopulationreview.com/world-cities/istanbul-population

other logistic points catering for search and rescue teams, health facilities, transportation vehicles among others potentially planned for and distributed across various sites within the city.

However, the fact that earthquakes are the most devastating and feared hazards in Türkiye, as they claim almost 80% of the total disaster costs, and based on the earthquake scenarios for Istanbul prepared by the Japan International Cooperation Agency[2] (JICA & IMM, 2002), this logistic system and other efforts against disasters in Istanbul have been seen to be earthquake-hazard-centric, with little consideration on other hazards that can be triggered or worsened in the aftermath of earthquakes. In their study Balcik & Beamon (2008) and Kilci et al. (2015) used mathematical and quantitative models to solve facility-location problems in the city, but these models did not incorporate uncertainty in demand and evacuation management. Feng et al. (2023) further criticized these models for failing to capture the complexity of facility location problems and the actual site constraints essential in site selection. Although Yilmaz & Kabak (2020) and Ozbay et al. (2019) addressed facility-location problems considering such site constraints, they did not consider the multi-hazard context of the city and the dynamics of Istanbul as a megacity. To the knowledge of the researcher, no disaster facility location study has incorporated other hazards, either those triggered by earthquakes or spatially coincides with earthquakes, in modelling of and devising criteria for optimal location of DLCs in Istanbul. This gap necessitated using Istanbul megacity as a case study area for this research, in order to update site selection indicators, accordingly, considering a multi-hazard perspective and dynamically changing risk drivers in the city.

1.3.1. Main Objective

The main objective of this study was to analyse and select relevant indicators to inform the optimal location of disaster logistic centres in a multi-hazard environment of Istanbul mega-city in Türkiye.

1.3.2. Specific Objectives and Research Questions

1. To analyse potential hazard interactions and their spatial extent in the aftermath of a Model A (*most-probable*) earthquake scenario in Istanbul mega-city.
    - *1.1. Which hazards are likely to occur during and after a Model A earthquake occurrence in the study area?*
    - *1.2. In what ways do these hazards interact with one another (trigger, worsen, increase probability of occurrence)?*
    - *1.3. What is the spatial coverage of these natural hazards in Istanbul?*

2. To examine the level of exposure of elements at risk (EaR) to multi-hazard in Istanbul mega-city.
    - *2.1. What is the percentage of buildings exposed to impacts of multi-hazard occurrences in Istanbul?*
    - *2.2. Which neighbourhoods in Istanbul mega-city have higher building exposure relative to other neighbourhoods?*
    - *2.3. What is the percentage of critical facilities, essential for effective emergency response, exposed to the impacts of multi-hazards in Istanbul?*

3. To determine the essential goods and services needed in for the 3-DLCs levels for responding to the expected multi-hazard impacts in Istanbul mega-city.
    - *3.1. What goods and services are needed for effective response to the expected disaster impacts?*
    - *3.2. On which level of DLCs will such commodities and services be located?*

4. To analyse and apply indicators for determining the spatial suitability of DLCs in Istanbul mega-city.
    - *4.1. What are the factors that influence the site selection decisions for DLCs location?*

[2] The four JICA earthquakes scenarios for Istanbul were modelled along the NAF in the Marmara Sea, with the length of their faults being the main distinguishing parameter. Model A assumes an approx. of 120km long section from west of the 1999 Izmit Earthquake fault to rupture, with an estimated magnitude of 7.5Mw. This is the most probable scenario, as the seismic activity is already progressing to the west. Model B considers an approx. of 110km section from the eastern end of the 1912 Murefte-Sarkoy Earthquake, with an estimated magnitude of 7.4Mw. Additionally, Model C which is the worst-case scenario estimates the rupture of the entire 174km section of the NAF, with a magnitude of 7.7Mw; while Model D presumes a rupture on the normal fault of 37km long and estimated with 6.9Mw magnitude.

4.2. Which factors are relevant for locating different levels of DLCs in Istanbul?
4.3. Which spatial locations are suitable for locating different levels of DLCs in Istanbul megacity?

1.4. Structure of the Thesis

This thesis consists of five main chapters. Chapter 1 highlights the background context and relevance of the study, research problem, the case-study problem overview, objectives and their respective research questions. Chapter 2 presents the review of literature on multi-hazards and DLCs location-allocation. Then, Chapter 3 describes the study area and datasets, followed by the methodological procedures used in the study to analyse multi-hazards and to determine key indicators for DLCs site suitability analysis. Chapter 4 presents main study findings respective to the research objectives and questions, followed by Chapter 5 which discusses and interprets significant research outcomes and highlights recommendations for future research and potential measures to be undertaken.

2. LITERATURE REVIEW

This chapter provides a review of relevant literature pertaining to multi-hazards, emergency preparedness, and disaster logistic planning. A detailed discussion of approaches employed to assess multi-hazards and determine the optimal location of DLCs have been presented. Furthermore, the chapter also presents factors commonly used in the location-selection of DLCs. Then, techniques utilised in a multi-criteria decision to determine suitable and optimal DLCs location has also been discussed.

2.1. Multi-Hazards and Risk

The concept of multi-hazard and risk gained its prominence in the early 1990s. One of the first significant agreements to call for a comprehensive multi-hazard research was Agenda 21 for Sustainable Development, in which the term was later transferred into the subsequent international agreements on sustainable development and disaster risk reduction(DRR) of Hyogo Framework for Action (2005-2015) and the Sendai Framework for Disaster Risk Reduction (2015-2030). These agreements recognised the need to shift from single to multi-risk assessments, detailing the effectiveness of DRR measures achieved when a comprehensive systemic risk approach is considered. As Kappes et al. (2012) and Wang et al. (2020b) concur, the notions of multi-hazards and multi-risks were advocated due to the shortcomings of single hazard approaches, which are considered as being inaccurate and incomplete in their risk analyses.

Considering the term's ambiguity, the scientific community has described multi-hazards to indicate multiple hazards or more than one hazard with potential to occur in a specific area. The United Nations Office for Disaster Risk Reduction (UNDRR) (2016) and Kappes et al. (2012) further describe multi-hazards as the selection of all relevant hazards *(regardless of their magnitude or frequency)* occurring in a given spatial region; either simultaneously, cascadingly or cumulatively over time. As Kappes et al. (2012) notes, the relevance aspect in this definition varies considerably and may include the hazard frequency, intensity, damage potential, or overall risk based on exposure and vulnerability. Several types of hazards exist, which are classified into distinct categories mainly based on primary physical characteristics, processes and nature of the hazard, the type of damage they produce, the speed of onset or their respective frequency among others (Gill & Malamud, 2014). Utilising the physical nature of the hazard, Gill & Malamud (2014) classified natural hazards into six categories of geophysical (5 hazards), hydrological (3 hazards), shallow earth processes (4 hazards), atmospheric (8 hazards), space/ celestial (2 hazards) and biophysical (1 hazard).

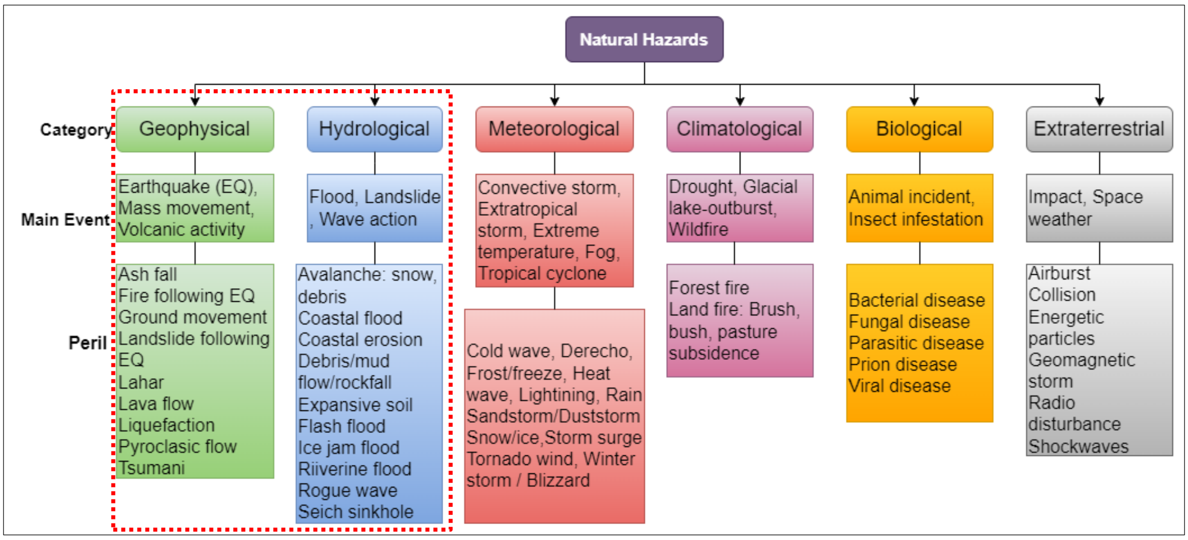

Figure 1: Classification of natural hazards by the IRDR (2014)

Furthermore, the Integrated Research on Disaster Risk (IRDR) also classified natural hazards into six main categories as shown in *Figure 1*, where shallow earth processes were integrated into the geophysical, while incorporating climatological hazards in the categories (IRDR, 2014). Additionally, the UNDRR, the International Science Council (ISC) and the Sendai Framework for DRR identified 302 hazards which are classified into 8 main hazard types of meteorological and hydrological (60 hazards), extraterrestrial (9 hazards), geohazards (35 hazards), environmental (24 hazards), chemical (25 hazards), biological (88 hazards), technological (53 hazards) and societal hazards (8 hazards) (UNDRR, 2020).

Based on the UNDRR (2020) Technical Report on hazards, such distinct hazard categories among entities and sectors mainly arise due to differences in the risk contexts and the objectives behind the classification. The report stipulates that meteorological, climatological, and hydrological hazards have been major causes of human and economic losses in decades, where between 1979 to 2019 they accounted for 50% of all recorded disasters, with 56% of deaths and 75% of economic losses attributed to them. On the other hand, geophysical hazards, especially earthquakes, have been observed to be one of the hazards with highest likelihood of leading to wide range of specific hazards such as ground shaking, subsidence, or ground rupture, and trigger secondary hazards of tsunami or rockfall. Bearing this in mind, this research considered geophysical hazards, as the main primary hazards of focus, and hydrological hazards.

Additionally, Nascimento & Alencar (2016) assert that hazards in the abovementioned categories, particularly earthquakes, floods, volcanic eruptions, and tsunamis, are major causes of technological accidents, which are on the increase in modern society. Whether induced from the failure of an existing or emerging technology (*technological hazards*) or as cascading impacts of natural hazards on critical infrastructure and industrial facilities (*referred to as NaTech hazards*), such events result in cascade effects that usually lead to catastrophic damages, which do not only affect industrial facilities, but also cause death and injuries to people, pollution, adverse environmental impacts, and significant economic losses. de Almeida et al. (2015) and Cozzani et al. (2014) concurs that during disaster events, a more critical situation arises when natural disasters occur and/or affect an industrial zone, leading to leakage of hazardous substances, which increase the likelihood of events with catastrophic consequences. Xiao et al. (2024) further illustrates the impacts the the Great East Japan Earthquake that occurred on 11th March 2011. The disaster led to the explosion at the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant (FDNPP), releasing various radioactive materials into the atmosphere and causing the displacement of people, with impacts still felt to date, 12 years later.

Risk is defined by the UNDRR (2016) as the probability of harmful consequences, or expected losses from interactions between hazards, exposure, and vulnerable conditions. Conversely, multi-(hazard) risk signifies risk arising from multiple hazards and the interrelationships among these hazards (Zschau, 2017). In a multi-hazard and risk context, where two or more consecutive hazard occur in close succession and overlap spatially (before the region recovers from the previous event completely), the impacts of one hazard on the other hazard is manifested through changes in exposure and/ or vulnerability levels (de Ruiter et al., 2020; Gill et al., 2022). These interrelations and progression through multi-hazard events, leading into simultaneous changes in risk factors, make disaster risks (in a multi-risk context) to be more complex as compared to single-risk analyses.

2.1.1. Spatial and Temporal Scale of Hazards

Hazards exhibit varying characteristics such as time of onset, duration, extent and the resulting impact on humans and EaR. Gill & Malamud (2014) assert that the spatial and temporal scale over which natural hazards impact upon the natural environment cover many orders of magnitude. As depicted in *Figure 2*, the spatial scale, which signifies the areas that hazard impacts are manifested, can range from only fractions of square kilometres (micro-scale) with localized impacts to hundreds of millions of square kilometres (global-scale) with widespread impacts. Additionally, the temporal scale, which refers to the time duration over which a hazard acts on the natural environment, can range from seconds to millennia, depending on the type of hazard. For instance, while ground collapses and earthquakes both occur on a temporal scale of seconds to minutes, their spatial scales differ. In this, ground collapses are more localised and micro in scale, whereas earthquakes can impact a broader area, from local to regional scales, while coinciding with other natural hazards

In a multi-hazard setting, spatial scale of hazards mainly depends on their spatial overlaps. Gill & Malamud (2014) postulate that spatial proportion of secondary hazard occurrences in locations where primary hazards manifest their impacts is examined to determine the spatial scale of hazards in a given region. In this, simple spatial overlays are utilized to determine the hazard spatial overlaps. The authors further state that, although spatial overlap alone does not guarantee that a hazard will be triggered, the temporal likelihood of primary and secondary hazards coinciding is difficult to approximate with precision. This is because it depends on the fulfillment of certain thresholds, supplemented by engineering judgment, to determine if the conditions are met for a secondary hazard to be triggered. With this in consideration, this study focuses only on the spatial scale of multi-hazards.

Understanding the spatial and temporal scales of natural hazards is an essential step for achieving effective disaster management (Coppola, 2015). It has been argued that the urgency for mobilising emergency services and coordinating response measures differs among disasters, in which rapid onset hazards and more localised hazards require immediate action and concentrated response respectively, as compared to slow-onset and widespread disasters.

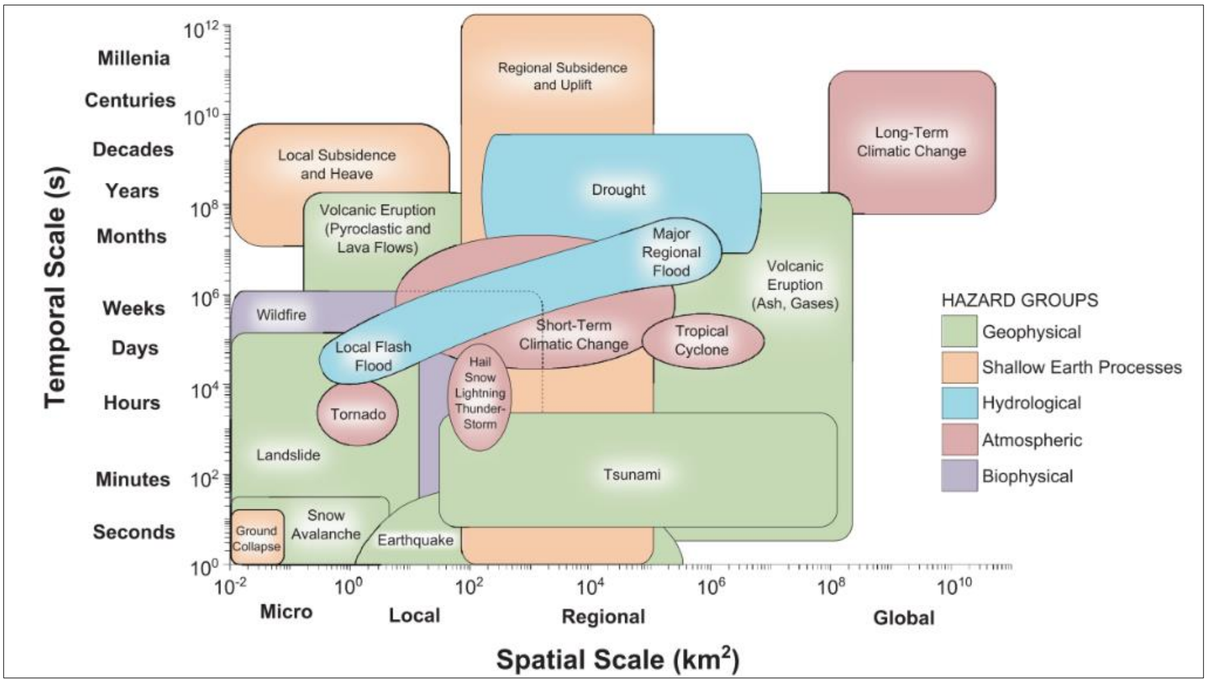

Figure 2: Spatial and Temporal scale of some types of hazards (Source: Gill & Malamud, 2014)

2.1.2. Multi-Hazard Interactions

Gill & Malamud (2016) define hazard interactions as the unidirectional or/and bidirectional effects between one hazard or process and another hazard or process. As *Table 1* depicts, there is a wide variety of hazard interaction types and different authors have identified and classified these possible hazard inter- and intra-relations differently (van Westen & Greiving, 2017; Gill & Malamud, 2014; Tilloy et. al., 2019; de Angeli et al., 2022). However, Ciurean et al. (2018) and de Angeli et al. (2022) argue that, despite variations in classification by diverse authors, commonalities can still be identified, leading to three main types of hazard interactions. In this, Ciurean et al. (2018) note triggering, amplifying and compound hazard interactions as the main classes depicted among various literature sources, while de Angeli et al. (2022) categorise these interactions into triggering, amplifying and independent/coincidence hazards. Hochrainer-Stigler et al. (2023) concurs with the three main interactions categorised by Ciurean et al (2018), where it is argued that independent hazards are part of the compound hazard interactions. In this, compound hazard interrelations may take forms that include interactions where different hazards originate from the same primary event, primary hazard simultaneously triggers multiple secondary hazards that occur at the same time or two independent hazards (without underlying relationship) impacts the same region and/or time period or in close succession. The types of hazard interrelationships described above can also overlap in real-life situations, creating complex scenarios (Gill & Malamud, 2016).

Table 1: Variations in the classification of hazard interactions by diverse authors

Authors	Hazard Interaction Type	Description
Gill & Malamud (2014)	Interactions where a hazard is triggered	One hazard triggers one (or more) other hazard(s), where the secondary natural hazard might be of the same type as the primary hazard or different.
	Interactions where the probability of a hazard is increased	One hazard changes environmental parameters that moves toward a change in the likelihood of another hazard; changes some aspect of the natural environment in order to changes that increase the probability that another hazard to occur.
	Interactions where the probability of a hazard is decreased	One hazard alters the frequency or magnitude of another; by changing one or more environmental parameters that result in the risk of a particular secondary hazard being reduced.
	Events involving the spatial and temporal coincidence of natural hazards	Two hazards are independent and occur simultaneously by coincidence, within a relevant timeframe and with appropriate spatial overlap
van Westen & Greiving (2017)	Independent events	Two hazards are independent and caused by different triggers
	Coupled events	Two hazards are triggered by the same triggering event
	One hazard changes the conditions for the next	The influence one hazard exerts on the disposition of a second hazard, though without triggering it. Highlights changes in conditions that make certain areas more susceptible to hazards
	Domino, or cascading hazard	Consists of hazards that occur in chains, where one hazard causes the next. These are also called domino effects, concatenated, or cascading hazards
Tilloy et al., (2019)	Independence	Implies a spatial and temporal overlapping of the impact of two hazards without any dependence or triggering relationship. The impacts of one hazard are exacerbated because of the impacts of the other
	Triggering (Cascading)	Implies a primary and a secondary hazard or any natural hazard that might trigger zero, one or more secondary natural hazards
	Change conditions	Relates to one hazard altering the disposition of a second hazard by changing environmental conditions.
	Compound hazard (association)	Two different natural hazards that impact the same time period and spatial area. These hazards are the result of the same primary event or large-scale processes which are not necessarily hazards.
	Mutual exclusion (negative dependence)	Two natural hazards that exhibit negative dependence or be mutually exclusive
de Angeli et al., (2022)	Parallel hazards	Refers to a series of hazards generated by the same trigger, named “primary event”.
	Cascading hazards	An adverse event triggers one or more sequential events
	Disposition alteration	One hazard that changes the general setting of another one and thus its disposition towards a possibly occurring trigger event. No direct triggering of one hazard by another or any simultaneous temporal occurrence.

	Additional hazard potential	Amplification effects due to a possible coincidence of different hazards in space and time. The primary hazard changes the scenario of the second hazard, possibly increasing the risk.
	Coincident triggering	Refers to the simultaneous occurrence of two hazards triggering a third hazard
	Cyclic triggering	The triggering of the second hazard exacerbates the first hazard, therefore triggering further episodes of the secondary hazard, creating positive feedback.

2.1.3. Approaches for Multi-Hazard Assessments

Kappes et al. (2012) and the European Commission (2010) describe multi-hazard assessments as processes or activities aimed to determine and map the potential occurrence of different types of hazards in a given area, considering the characteristics of single hazard events and their mutual interactions and interrelationships. Ward et al. (2022) emphasises on the significance of identifying all spatially relevant hazards, as failure to consider multi-hazard interrelationships can distort management priorities, increase vulnerability to other spatially relevant hazards or result in an under-estimation of risk. The overall objective of these assessments is to identify the spatial distribution of the effects of the different hazards over a range of respective intensities, with outputs presented as single or aggregated hazard maps or hazard curves (Liu et al., 2016).

De Angeli et al. (2022) and Liu et al. (2016) stipulate two approaches for multi-hazard assessment: (i) *"independent multi-hazards"* which aims at assessing different independent hazards that threaten a given area. According to Gill & Malamud (2014) this kind of approach entails methodologies that carry out independent analysis of multiple different hazards and overlay various hazard layers to identify areas that overlap. Van Westen & Greiving (2017) further argue that considering hazards as independent and caused by different triggers is the simplest approach to multi-hazard analyses, as the expected losses from one hazard type are independent from the losses expected from the other hazard type. (ii) *"interacting multi-hazards"* which identify and assess possible interactions and/or cascade effects among different possible hazardous events. According to van Westen & Greiving (2017), this approach can include methods that consider coupled events, where the analyses of hazards that occur in the same areas with overlapping hazard footprints are done simultaneously; or concatenated events, which depicts chains of hazard impacts having cascading or domino effects.

Hochrainer-Stigler et al. (2023) argue that even though the second approach leads into comprehensive analyses, as losses from such hazard interactions may be larger or smaller than the simple aggregation of individual losses, it is more demanding in computational efforts and data requirement than the independent hazard approach, with van Westen & Greiving (2017) stipulating that these analyses are difficult to quantify over certain areas. Additionally, Zschau (2017) asserts that progressing from single-independent hazard analyses to multi-hazards helps overcome the comparability challenges when aggregating different hazards with varying reference units, return periods and intensities. As van Westen & Grieving (2017), establishing a common timescale to consider how hazard interacts is essential in multi-hazard analyses, as static assumptions on the conditions of exposure and vulnerabilities can lead to inconsistencies.

2.1.4. Exposure Analysis

United Nations International Strategy for Disaster Reduction (UN-ISDR, 2004) defines exposure as the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas. Van Westen (2013) simplifies this by stating that exposure indicates the degree to which the elements at risk (EaR) are exposed to a particular hazard in a given area. The author further asserts that exposure of EaR can be quantified either in numbers (of buildings, people etc), in monetary value (replacement costs, market costs etc), area or perception (importance of EaR) and can be aggregated in various spatial units ranging from a global scale, administrative units (countries, provinces, municipalities, neighbourhoods, census tracts), or homogeneous units with similar characteristics in terms of type of EaR. Additionally, van Westen (2009) states that exposure analysis involves spatial interaction between the EaR and the hazard footprints, in which they are depicted in a GIS by map overlays of the hazard maps with the EaR maps.

2.2. Humanitarian Logistics and DLCs Planning

2.2.1. Description of Humanitarian Logistics

Humanitarian logistics (HLs) is a branch of logistics that encompass different operations aiding in preparedness and response to various catastrophes. The Fritz Institute (2005) defines HLs as the process of planning, implementing, and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of alleviating the suffering of the vulnerable people. During the pre- and post-disaster phases, HLs are required to procure and store supplies and equipment, which need to be rapidly transported to the victims and areas of emergencies, respectively. Van Wassenhove (2006) and Nikbakhsh & Zanjirani Farahani (2011) assert that HLs are crucial to the effectiveness and speed of relief operations and programs. When a disaster strikes, unavailability of supplies or slowness in mobilizing them may cause emergency responses to be ineffective, resulting in increased human suffering and loss of life. Kundu (2022) argues that sometimes fatalities are not directly caused by the disaster but by the inefficient emergency logistics resource management in the affected area. As Tuzkaya et al. (2015) note, with efficient HLs systems, casualties and property losses encountered during disasters can significantly be reduced.

Due to the nature of the disaster environment in which the HLs systems operate, humanitarian relief chains portray unique characteristics that differentiate them from traditional business logistics. Balcik & Beamon (2008) stipulate that compared to commercial logistics, HLs are characterised by the unpredictability of demand; suddenly-occurring demand in very large amounts and short lead times for a wide variety of supplies; high stakes associated with adequate and timely delivery and lack of resources (including supplies, personnel, technology, transportation capacity, and funding). Nikbakhsh & Zanjirani Farahani (2011) concur that the nature of demand in HLs is highly uncertain because disaster time, location, and intensity, hence the exact relief requirements, are not known until after a disaster occurs. Additionally, Zhang et al. (2013) state that while traditional business logistics aim at cost minimization, HLs focus on quick response to emergencies and urgent needs of the affected people. Understanding these distinct features is crucial for designing effective HLs systems.

2.2.2. Levels of Disaster Logistic Centres

The HLs systems consist of three main stages in its chain structure: supply acquisition and procurement, prepositioning and warehousing and transportation (*Figure 3)* (Tomasini et al., 2009). Each of these stages involve critical decisions and challenges that need to be addressed to achieve efficiency in emergency relief operations. Balcik et al. (2010) argue that while ensuring the availability of necessary supplies and reducing lead times are crucial decisions during the supply acquisition stage, Nikbakhsh & Zanjirani Farahani (2011) emphasise that facility prepositioning, and transportation are critical decisions to be made. The authors note that, amidst costs challenges, selecting suitable locations for DLCs is vital, as these facilities must be strategically planned to withstand disasters, given their high risk of being destroyed during disasters. Duran et al. (2011) further concur that structuring a pre-positioning network to support emergency response for sudden-onset disasters is challenging because the magnitude, timing, and location of disasters can be highly unpredictable. Balcik and Beamon (2008) stipulate that transportation, which encompass the movement of personnel, equipment, and necessary items to predefined central distribution centres (CDCs), distribution intermediary points, local distribution centres (LDCs), and finally regions affected by the disasters, is the most difficult stage of HLs even if different kinds of preventive measures and plans are considered, mainly due to the damage and poor condition of transportation infrastructures and equipment after a disaster.

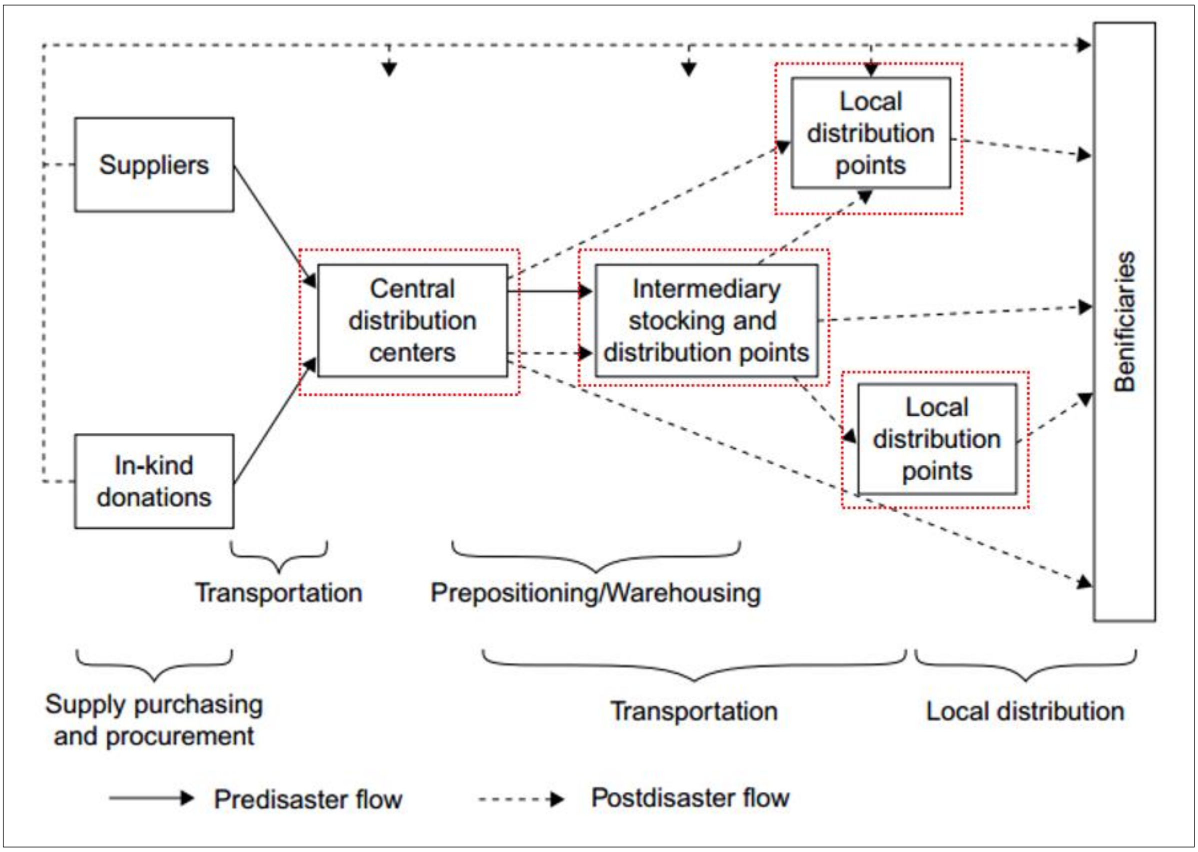

Figure 3: Humanitarian Logistic Chain Structure (Source: Balcik et al., 2010)

Balcik and Beamon (2008) state that recently emergency relief agencies aim to pre-position and warehouse critical relief supplies in strategic locations that are out potential disaster impact zones but close to affected areas. This strategy is taken to enhance their (agencies) capacity to deliver sufficient relief aid within a relatively short period of time. DLCs or emergency relief centres (ERCs), serve as hubs for coordinating the flow of resources from various sources and stockpile essential relief supplies and equipment (*Table 2*). Roh et al. (2015) further state that as the characteristics of disasters around the world vary from region to region it is likely that different combinations of aid stocks could be pre-positioned in different locations. As depicted in *Figure 3,* DLCs primarily exist in different levels, each level with different characteristics and mission depending on the scale and complexity of disasters (Balcik et al., 2010; Yilmaz & Kabak, 2020). Balcik et al. (2020) presents three levels of logistic centres comprising of central distribution centres (CDCs) which receive and stockpile all relief supplies and donations during the pre-disaster phase, which are then distributed to other centres; the distribution intermediary points (DIPs) and the local distribution points (LDPs) which are near to the beneficiary. Conversely, Yilmaz and Kabak (2020) categorise logistic centres into two main levels of main distribution centres (MDCs) and local distribution centres (LDCs). MDCs are permanent facilities for pre-positioning, storing, or sorting purposes and usually assumed that they are not affected by a disaster while LDCs deliver relief goods to victims directly and constructed temporarily in the hot zone after a disaster occurs.

Table 2: List of some of the essential supplies during emergency relief operations (Nikbakhsh & Zanjirani Farahani, 2011)

Supplies Category	Items
Goods and Materials	Food, water and hygiene products, baby and children's products, agricultural products and livestock, medicines, fuels such as coal, gas or oil, clothing, and blankets
Equipment	Field kitchen equipment, generator, environmental sanitation equipment and items, tents for shelter and temporary accommodation facilities, cleaning supplies specialized equipment for transport of dangerous goods, communication tools, fire extinguishing equipment, debris removal equipment and tools, health kits and supplies, field hospitals such as mobile health units

2.2.3. DLCs Facility Site Selection Problem

The Australian Council for International Development's Humanitarian Reference Group (ACFID) (2007) asserts that relief agencies often have difficulty finding secure, affordable, undamaged local warehousing and storage facilities. Consequently, research on the site selection of DLCs has attracted the attention of scholars and decision makers in many fields. Yilmaz and Kabak (2020) state that the facility location problem for DLCs in DM is studied mostly through two main approaches: (i) mathematical programming models such as the covering model and the P-median methods, and (ii) multi-criteria decision problems. They further state that, the first approach mostly concentrates on modelling and solving predefined problems, which are usually single-objective or bi-objective, considering either cost and time factors separately, or combining these factors in solving facility location problem. Feng et al. (2023) further observed that such models often fail to capture many actual site constraints, as an addition of objectives make the models complicated, hence difficult to execute, thereby limiting the problem description and solution devising.

Bayram et al. (2015), Kilci et al. (2015) and Balcik & Beamon (2008) utilize mathematical models in facility location problems in Istanbul and Turkey. Bayram et al. (2015) developed a second-order conic programming model capable of optimally solving combined location and evacuation route planning problems for real-sized scenarios in Istanbul. However, their study did not incorporate uncertainty in demand and evacuation management. Another important study addressing the case of Istanbul is by Kılcı et al. (2015), who considered the problem of selecting temporary shelter site locations and assigning demand nodes (affected people) to each open shelter area. They proposed a mathematical model aimed at maximizing the minimum weight of open shelter areas while ensuring a sufficient level of service and utilization of shelters. They validated their results for a base case scenario in the Kartal district of Istanbul against the Turkish Red Crescent's methodology on shelter site selection[3]. Their modelling approach uses deterministic data and assumes that the exact number of affected people for each demand node is known.

Additionally, Balcik and Beamon (2008) studied site location problem where relief items are classified based on their response time criticalities, and DLCs have capacity limits for holding each item type. They presented

[3] The Turkish Red Crescent 10-criteria for locating DLCs include: Accessibility, Proximity to disaster-prone regions, Transportation infrastructure, Adequate storage facilities, Safety and security, Availability of skilled personnel, Proximity to communication networks, Logistic and supply chain efficiency and Capacity for rapid deployment.

a scenario-based model that determines the number and locations of DLCs and their optimum inventory levels to maximize the satisfied demand for relief item types. The authors argue that upon the occurrence of disasters, the demand of aid supplies changes over time, where some items are needed in the earliest stages of relief operations (such as food items, medical supplies and telecommunication equipment among others), while others can be safely supplied during the later stages of disasters. Furthermore, Gomez et al. (2011) addressed the ERCs location problem in Istanbul by modelling a two-tier distribution system which utilised existing public facilities to determine the number of new facilities to be added. With the aim of minimizing both the number of new ERCs and the weighted average distance between demand points (casualty locations) and their closest ERCs, the study concluded for small number of new facilities needed in the metropolitan city.

Conversely, Feng et al. (2023) argue that mathematical and quantitative models fail to capture the complexity of facility location problems and the actual site constraints essential in site selection. The authors argue for multiple criteria decision-making (MCDM) approaches to effectively tackle the emergency relief site selection problems. The MCDM method can effectively solve multi-layered, complex and conflicting problems and has the advantage of being able to describe the problem comprehensively and computationally fast, which is suitable for providing ranking decision solutions for site selection studies. The authors further argue that MCDM methods based on qualitative research, such as the Analytical Hierarchy Procedure (AHP), Criteria Importance Though Intercriteria Correlation (CRITIC), Entropy, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), the Structural Equation Model (SEM) and the Preferential Ranking Organization of Rich Evaluation (PROMETHEE) when integrated with GIS technologies, which have capabilities of manipulating, analysing and mapping geographic information, can efficiently tackle emergency site selection problems.

Yılmaz & Kabak (2020) proposed a hybrid multi-criteria decision support model for locating main distribution centres (MDCs) and local distribution centres (LDCs), while taking into account the complexity and vagueness of the disaster environment and expert opinions in Istanbul. The study incorporated AHP and TOPSIS under interval type-2 fuzzy sets (IT2FSs) to overcome the uncertainty of experts` judgments and expressions in the evaluations of candidate distribution centres. With transportation, cost, infrastructure, and security being relevant criteria for MDCs, and cost warehouse facilities and security as determining criteria for LDCs, the study concluded that different facilities require different criterions, as location determining factors for LDCs rendered insignificance for MDCs. Additionally, Tuzkaya et al. (2015) integrated the Decision-Making Trial and Evaluation Laboratory (DEMATEL)[4] and Analytic Network Process (ANP)[5], MCDM methods, to determine convenient locations for ERCs for disaster-prone cities in Turkey. Utilising relationships among 11 criteria[6] and alternative locations, the study ranked optimal locations and cities for locating DLCs for larger emergency situations encompassing earthquake and landslide disasters.

[4]DEMATEL is a MCDM method developed by Science and Human Affairs Program of the Battelle Memorial Institute through Geneva Research Centre between 1972 and 1976. It is used to determine the interdependencies between decision criteria and visualise causal relationships among criteria (Tuzkaya et al., 2015).

[5] ANP is a MCDM method that evaluates the weight of criteria and alternative locations by making pairwise comparisons, with the goal of choosing the most convenient alternative. This method structures the decision problem into a network with a goal, decision criteria and alternatives (Tuzkaya et al., 2015)

[6] Route flexibility, Transportation mode opportunities, Damaging risks, International accessibility, Proximity to non-governmental organizations, Seasonal and environmental effects, Transportation vehicle reachability, Presence of the 3PL firms, Communication and coordination conditions, Shortest starting time, Proximity to Red Crescent depots.

Integrating MCDM and GIS, Feng et al. (2023) utilised nine criteria[7] to solve ERCs site selection problem in Xi'an, China. The authors advocated for the combination of data-driven weighting MCDM methods of Entropy and CRITIC, arguing that the approach eliminates the subjectiveness of criteria weights when decision-makers preferences are involved. They further argue that the complementarity of these two methods take into account the strengths of these methods: the variability of each criterion data and the correlation between the data, respectively. Furthermore, Sun et al. (2021) state that the combination of MCDM and GIS is considered as a successful way to solve site selection problems due to the capability of GIS to for handling geographic data and creating visual maps on such.

In summary, the reviewed literature has highlighted a research gap, particularly, pertaining to integrating MCDM with GIS and considering multi-hazard scenarios in the analysis. It has been observed that most studies, especially in Turkey, have focused on bi-objective mathematical and quantitative models, emphasizing either on allocating demand to service points or determining the capacity of DLCs based on perceived demand. Conversely, those studies that utilized qualitative methods, such as MCDM, aimed at weighting criteria and ranking alternative locations also show methodological limitations, as they are usually single-hazard centric. For instance, despite identifying relevant criteria for different levels of DLCs in Istanbul, Yilmaz & Kabak (2020) did not consider the multi-hazard context of the area and GIS was not integrated to aid the analysis of facility site selection problem in the megacity. It can, therefore, be concluded that current studies have overlooked the complexities introduced by multi-hazards and the changing urban environments, especially in megacities. Table 3 presents some of the criteria utilised in DLCs facility site selection by diverse authors.

Table 3: List of criteria for locating DLCs by distinct authors

Authors	Research Areas	Criteria used
Tuzkaya et al. (2015)	An integrated methodology for the ERCs location selection problem and its application for the Turkiye Case.	Route flexibility, transportation mode opportunities, damaging risks, international accessibility, proximity to non-governmental organizations, seasonal and environmental effects, transportation vehicle reachability, presence of the 3PL firms, communication and coordination conditions, shortest starting time, proximity to Red Crescent depots
Feng et al. (2023	Emergency logistics centres site selection by multi-criteria decision-making and GIS: Xi'an China	Hospital location, intersection location, expressway location, location of colleges and universities, infrastructure location, metro location, traffic jam, railway location and population density distribution
Yilmaz & Kabak (2020)	Prioritizing distribution centres in humanitarian logistics using type-2 fuzzy MCDM approach.	Transportation (land route, sea route, airways and accessibility), cost, security and infrastructure (office and warehouse facilities).
Ak & Acar (2021)	Selection of humanitarian supply chain warehouse location: A case study based on the MCDM methodology	Disaster free location, proximity to disaster prone area, closeness to other support services, transportation mode opportunities (seaport, airport, road, and railway), route flexibility, transport vehicle reachability, government and

[7] Hospital location, Intersection location, Expressway location, Location of colleges and universities, Infrastructure location, Metro location, Traffic jam, Railway location and Population density distribution.

		political stability, socio-political, cultural and social stability, labour cost, land cost, replenishment cost, storage cost, logistics cost, investment cost, cooperation with logistics agents, local and international NGOs, and IT/Communication
Roh et al. (2013)	Warehouse location decision factors in humanitarian relief logistic	Geographic location; proximity to beneficiaries; disaster free location; donor's opinion; climate; closeness to other warehouses; proximity to disaster prone area, airports, seaports, roads and warehouses; social, political and economic stability; cost of labour, land, storage, logistics and replenishment; cooperation which included host government, international NGOs, local NGOs, UN, neighbouring countries and logistics agents
He et al. (2017)	A decision model for emergency warehouse location based on a novel stochastic MCDM method: Evidence from China	Traffic condition, stock holding capacity, surrounding environment for reserving relief supplies, distance to disaster-prone area, cost.

3. RESEARCH METHODS

This chapter outlines the research methods utilised to achieve the objectives of this study. To begin with, the rationale for selecting megacity Istanbul as a case-study is presented. This is followed by the description of the research design and secondary datasets and their sources. The analysis was divided into two main methodological steps: (i) multi-hazard scenarios and exposure analysis, and (ii) DLCs location-allocation analysis. Detailed methodological procedures for each step have also been presented in this chapter.

3.1. Study Area: Megacity Istanbul

Megacity Istanbul is located in the Marmara region, of Türkiye. The Bosphorus Strait, in the middle of the city, connects the Black Sea in the North and the Marmara Sea in the South and it also acts as a bridge between Europe and Asia. The study aimed to identify relevant criteria and the optimal locations for DLCs at the megacity level, specifically focusing on megacity Istanbul. This comprehensive scope required and necessitated analysing the entire spatial extent of Istanbul city, including all 39 districts, without sampling some districts. Given the multi-hazard context, the study assumed that almost every part of the city could be exposed to at least one type of natural hazard. Although some districts, such as Beykoz, Çatalca, and Şile (*Figure 4*), are considered to have lower seismic risks, their inclusion in the study remains crucial for selecting DLC locations.

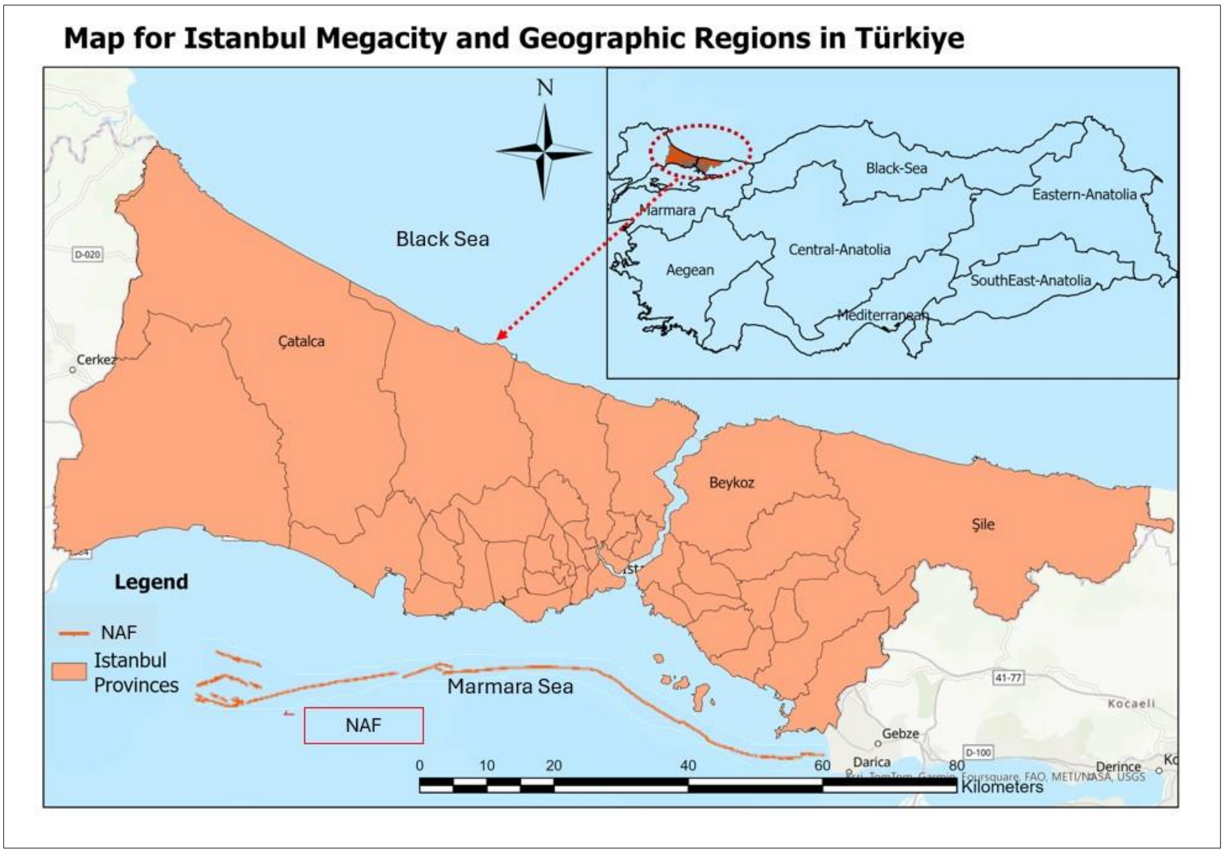

Figure 4: Location Map of the study area-Istanbul Megacity (Source: Author, 2024)

3.1.1. Multi-hazards and their interactions in Istanbul Megacity *(Objective 1: RQ 1 and 2)*

Table 4: Objective 1 and research questions that formed the basis of the multi-hazard methodological procedure

Objective	Research Question (RQ)
1. To analyse potential hazard interactions and their spatial extent in the aftermath of a Model A (*most-probable*) earthquake scenario in Istanbul mega-city.	1.1. Which hazards are likely to occur during and after a Model A earthquake occurrence in the study area?
	1.2. In what ways do these hazards interact with one another (trigger, worsen, increase probability of occurrence)?

A comprehensive overview of relevant single hazards is an essential step to understand the multi-hazard landscape as it enables analysis of what multi-hazard interrelationships may occur and how these connect into more complex multi-hazard scenarios. Gill et al. (2020) assert that spatial and temporal footprints of single hazards vary, and a single hazard does not have to occur in the city to have an impact and be considered relevant in a given spatial unit. For instance, volcanic eruptions have a spatial scale ranging from regional to global, implying that its eruption outside Istanbul can have impacts in the city (as depicted in *Figure 2*, see page 8).

a. Hazards in Megacity Istanbul

The dynamic nature of Istanbul, in terms of growth, migration, and spatial characteristics, coupled with its complex urban structure, has increased the city's exposure and susceptibility to a wide range of hazards (Masoumi et al. 2019). According to Terzi & Bölen (2009) and Terzi & Kaya (2011), due to enormous urban population growth driven by internal migration from rural areas, the city is experiencing both sprawled and compact (infill) development to meet the increasing demands for housing and infrastructure. The increasing pressure on resources coupled with lack of effective planning and effective enforcement of building codes, urban development in the city has encroached on hazardous locations. Masoumi et al. (2019) highlight that the main urban (built-up) area, which includes former informal settlements known as the "*Gecekondu*" in the southern part of the city, is situated near one of the most active fault: the North Anatolian Fault (NAF) (*Figure 4*). Such development patterns and the western progression of the NAF, predicted with 35%-75% chance of producing a major earthquake by 2030 (JICA, 2002; Kundak, 2004; Ergintav et al, 2014) significantly increase earthquake risk in the city. Historically, the city has been affected by earthquakes, with the recent event being the 1999 Kocaeli earthquake (7.6Mw in magnitude) which led to 18,000 deaths, 48,901 injuries and complete damages of 96,000 homes, 15,000 workplaces and infrastructure estimated at $5-$13 billion (World Bank, 2018). According to Breunig et al. (2009), these impacts were worsened by sub-standard construction practices in the former informal settlements, where buildings were densified and additional floors were added without adhering to sustainable and earthquake-resistant building regulations.

Furthermore, Şenol (2023) states that the pressure of rapid construction to keep pace with the growing population has led to irregular and unplanned urbanisation, transforming the environmentally sensitive areas, such a as water basins, agricultural ad forested lands, into built up areas. Masoumi et al. (2019) argue that poor planning decisions and large-scale urbanisation have led to development on liquefiable soils in Istanbul. Aslan et al. (2018) concurs by revealing that reclaimed lands along the coast of Istanbul underwent subsidence of up to 8±1.3 mm/year between 1992 and 2017, indicating the risk of subsidence and liquefaction in the megacity.

Additionally, Sulpizio et al. (2012) argue that the Istanbul is prone to impacts from large volcanic eruptions in the Mediterranean such as Vesuvius, with its ash deposits reaching as far as the city. Cruz et al. (2004) and Girgin (2011) highlight the risk of NaTech hazards triggered by the earthquakes which were also evident during the Kocaeli, Turkey Earthquake of August 17, 1999, due to the concentration of industrial facilities in the city. Hussain et al. (2021), through the analysis of peer-reviewed and grey literature (including government, NGO reports, research grant reports, and national and international hazard databases such as AFAD and EM-DAT), along with media and social media reports, identified the presence of 22 out of the 23 hazards categorized by Gill & Malamud (2014) in Istanbul. In contrast, Šakić Trogrlić et al. (2023) reported the presence of all 23 natural hazards, either occurring or with the potential to impact the megacity. These identified hazards and their interactions formed the basis for defining multi-hazard scenarios used in this study, while also addressing Objective 1 (RQ1 & 2) (*Table 4*). Table 5 details some of the major hazards that have occurred or have the potential to occur in Istanbul.

Table 5: single hazards evidenced to have occurred or have potential to occur in Istanbul megacity, Turkey (Source: Hussain et al., 2021; Cruz et al., 2004; Girgin, 2011)

Category	Hazard Type	Source
Geophysical	Tsunami	Hébert et al. (2005)
	Earthquakes	Disaster and Emergency Management Authority (AFAD, 2007)
	Landslides	Görüm and Fidan (2021)
	Volcanic eruption	Sulpizio et al. (2012)
	Subsidence / Liquefaction	Aslan et al. (2018); Akarvardaret al. (2009)
Hydrological	Floods	Kömüşcü & Çelik (2013)
	Droughts	Kurnaz(2014)
Atmospheric	Fog, snow or heavy rain	Bayar (2010)
NaTech	Industrial fires, chemical releases	Cruz et al. (2004); Girgin (2011)

3.1.2. Multi-hazard Scenario Definition

The analysis of the criteria for site selection for DLCs in Istanbul under scenarios of multi-hazard interactions and their subsequent impacts were based on 2 distinct scenarios (*Table 6*), defined by their physical nature and characteristics. As aforementioned, geophysical and hydrological hazards are among the most disastrous and recurrent hazards, with evidence of higher probabilities of impacting the Istanbul megacity. Therefore, the scenarios were based on these two categories of hazards, with compound hazard interactions being the main focus. Additionally, the assumptions for earthquake triggered multi-hazard scenarios were seasonal dependent (Summer and Winter), with assumption that post-seismic hazards differ between distinct seasons of the year, hence differences in the possible hazards to occur in the aftermath of earthquake occurrence.

Table 6: Multi-hazard scenarios utilised in the study.

Scenarios	Hazard Category	Hazard Types	Description/ Assumption
Scenario 1	Geophysical	Earthquake Liquefaction Tsunami	Assumes earthquakes occurs on during summer season, which triggers liquefaction and tsunamis, either in close succession or in distinct temporal scale
Scenario 2	Hydrological	Floods Landslides	Assumes heavy rains in winter which either triggers landslides and floods as independent hazards or only landslides which increases the probability of floods due to debris from failed slopes

3.2. Research Design

The study employed a mixed-research approach where both qualitative and quantitative methods were used in data collection and analysis processes. Literature review was used to identify hazards that are spatially relevant in Istanbul megacity, levels and purposes of DLCs and indicators relevant for DLC site selection. Hydrological hazards especially floods and landslides, which are on the rise due to climate change and urban growth patterns in the city, and geophysical hazards, the most feared and predicted to occur in the near future were selected to aid the definition of the two multi-hazard scenarios and the overall study analysis. The two multi-hazard scenarios can also be combined into a third one: an earthquake co-occurring with high rainfall. Spatial overlaps of these single natural hazards were computed using Raster Calculator tools in ArcGIS Pro software. Composite multi-hazard maps for all the two scenarios were produced as final results, detailing the spatial scale and area occupied by distinct hazards, with varying intensities within the city boundary. Building and critical facilities exposure analysis was then computed for these two scenarios, to determine the degree of exposure of these EaR to different geophysical and hydrological hazard intensities.

Then, a qualitative approach, based on semi-structured interviews with experts and literature review, was utilised to determine the varying purposes of and the goods and services to be stored in first-, second- and third- DLCs levels in Istanbul. A Spatial Multi-Criteria Analysis (SMCA) was utilised to analyse and select indicators / criteria relevant for determining suitable sites for these DLCs in Istanbul megacity. The lower level DLCs were also utilised as a separate criterion for its subsequent higher level DLCs, to ensure connectivity among these DLCs levels. ArcGIS Pro and QGIS tools, plugins and Python packages such as ArcPy were utilised for data preparation, processing, analysis and map production. Additionally, MS-Excel tools were used for conducting statistical analysis essential for understanding and revealing patterns in the analysed spatial data. *Figure 5* depicts a summarised overview of the study methodology

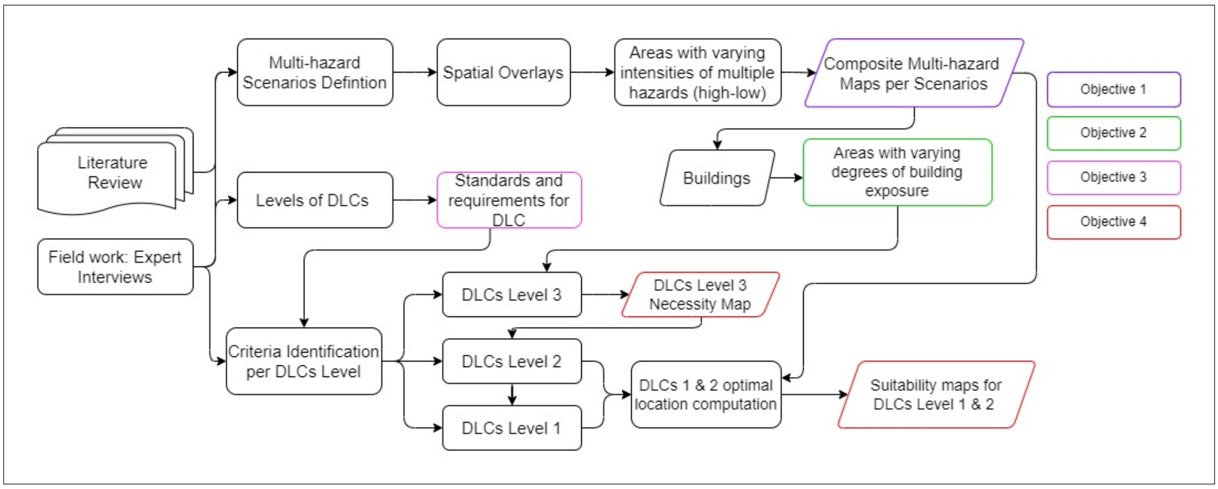

Figure 5: Summary of the study methodology (Source: Author, 2024)

3.3. Spatial Datasets

The main spatial data source utilised in this study was the Istanbul Metropolitan Municipality (IMM), provided either in GIS editable formats (shapefiles) or PDF reports, which were converted into GIS editable formats. Where data specifically produced for Istanbul megacity was scarce, open-source global datasets and studies were also utilised to aid the analysis of this study (*Table 7*).

Table 7: Description and sources of spatial datasets

Step	Dataset	Format	Year	Source
Multi-Hazard Assessments	Earthquake hazard (7.5Mw)	Shapefile (Vector)	2019	Istanbul Metropolitan Municipality
	Flood hazard	PDF	2017	Istanbul Metropolitan Municipality
	Landslide hazard	PDF	2017	Istanbul Metropolitan Municipality
	Tsunami hazard	PDF	2017	Istanbul Metropolitan Municipality
	Liquefaction	Image (Raster)	2017	Zhu et al. (2017): Global dataset *https://doi.org/10.1785/0120160198*
	Building footprints	Shapefile (Vector)	2018	Istanbul Metropolitan Municipality
DLCs Location-Allocation Analysis	Roads	Shapefile (Vector)	2015	Istanbul Metropolitan Municipality
	Emergency Roads	Shapefile (Vector)	2019	Istanbul Metropolitan Municipality
	Evacuation Sites	Shapefile (Vector)	2023	ESRI API
	Airports	Shapefile (Vector)	2024	OpenStreetMap *https://download.geofabrik.de/*
	Seaports	Shapefile (Vector)	2018	Istanbul Metropolitan Municipality
	Railway Lines	Shapefile (Vector)	2024	OpenStreetMap *https://download.geofabrik.de/*
	Health Facilities	Shapefile (Vector)	2024	Istanbul Metropolitan Municipality
	Water Bodies	Shapefile (Vector)	2024	OpenStreetMap *https://download.geofabrik.de/*
	Protected Areas	Shapefile (Vector)	2019	OpenStreetMap *https://download.geofabrik.de/*
	Land Parcels	Shapefile (Vector)	2018	Istanbul Metropolitan Municipality
	Corine Land Cover	Shapefile (Vector)	2018	*https://land.copernicus.eu/pan-european/corine-land-cover/clc2018*
	Elevation (DEM)	Image (Raster)	2024	SRTMGL1 (GEE)

Spatial data for the five multi-hazards analysed in the study were obtained from the Department of Earthquake Risk Management and Urban Improvement under the Earthquake and Ground Investigation Directorate of the IMM. The earthquake hazard map was produced with collaboration of the IMM and Boğaziçi University, Kandilli Observatory and Earthquake Research Institute, Department of Earthquake Engineering in 2019 under the Probable Earthquake Loss Estimates for Istanbul Province Updating project. This hazard map (*Figure 6*) was computed using the deterministic ground motion estimation approach, which, according to IMM (2019), is commonly utilised for evaluating urban earthquake risks. It is argued that deterministic method is more appropriate for evaluating and planning of urban disaster management processes as compared to the probabilistic approaches. In this, probabilistic approaches consider different earthquakes that may affect any two points of the city, hence the ground motions obtained with this approach are not values that reflect the probability of earthquakes occurring at the same time, but belong to different earthquakes that may occur at different times for each analysed point. Considering this, the study utilised a hazard map based on deterministic ground motion modelling of an earthquake with a magnitude of Mw 7.5, which may occur in the segments of the Main Marmara Fault that has not broken in the recent past. According to IMM (2019) the scenario is considered a worst-case scenario, that will rupture all fault segments close to Istanbul that have not experienced an earthquake recently.

Furthermore, flood, landslides and tsunami hazards were accessed in PDF format from the Geological Survey Report (2017) by the Earthquake Risk Management and Urban Improvement Department under the Earthquake and Ground Investigation Directorate of IMM. The flood hazard map consists of flood zones which were identified as the immediate surroundings, middle and lower parts of the streams that overflow out of the stream beds as a result of excessive rainfall; and areas that experience floods during rainy season due to inadequacy of bridges, culverts and infrastructure volume, clogging of stream beds with garbage or natural sedimentation, illegal and unplanned construction among others. It is important to note that, these floodplains were utilized in the study to indicate areas prone to flooding due to lack of comprehensively modelled flood hazard maps in the city. Additionally, through Micro-zonation project, the IMM simulated tsunami occurrence for any earthquake greater than 6.0Mw of magnitude and determined areas of active landslides across Istanbul megacity.

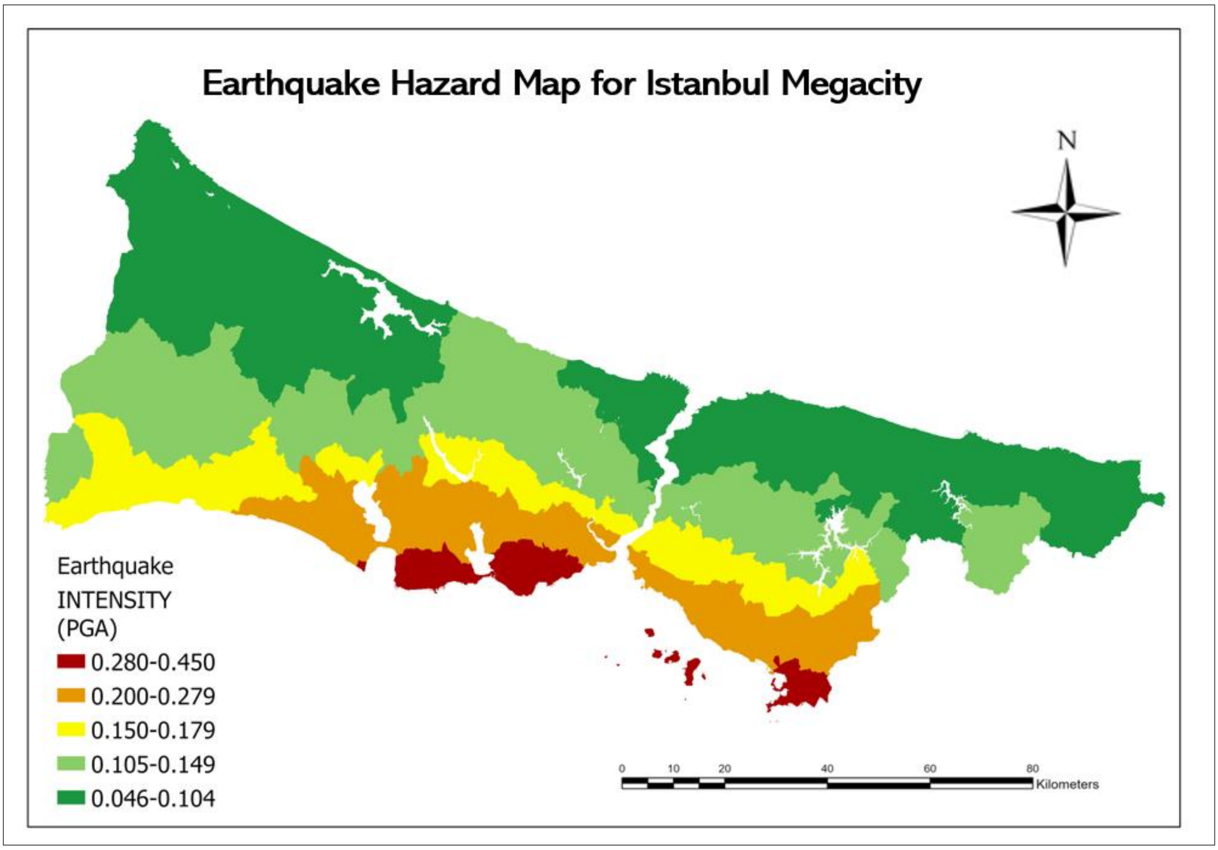

Figure 6: Map of earthquake hazard scenario Mw7.5 in Istanbul megacity (Source: IMM, 2019)

Due to lack of comprehensive spatial data on liquefaction in Istanbul, a global earthquake-induced liquefaction raster image was obtained from Zhu et al. (2017). To model liquefaction hazards, 27 earthquakes that occurred between 1943 to 2014, with magnitudes ranging from 4.0Mw to 9.1Mw from the United States, Japan, New Zealand, China, Taiwan, and India liquefaction database were utilised. The dataset was adopted and considered fit for utilisation in Istanbul because the model was deemed as best-fit for coastal regions. In this, the majority of earthquakes events (22 of 27) utilised in the model, occurred in the coastal areas with soil density, saturation and earthquake loading as main variables with 6 of 14 variables being water dependent. However, this saw the liquefaction map to be sensitive to water bodies, hence more liquefaction potential in areas in close proximity to water bodies.

As illustrated in *Table 7*, diverse data sources, including OpenStreetMap, were utilized to access datasets relevant to the analysis of this study. To differentiate between the "*Roads*" dataset and the "*Emergency Roads*" dataset: The road dataset comprises all roads in Istanbul megacity, while the emergency roads dataset consists of roads designated to specifically keep road transport functioning during emergencies. These roads were selected from regional, urban and district main roads and wider roads. The emergency roads consist of 371 km (45%) of roads wider than 15 meters, 137 km (17%) of roads between 12 and 15 meters wide, 278 km (34%) of roads between 7 and 11 meters wide, and 31 km (4%) of roads between 2 and 6 meters wide. These roads were designated to ensure proper emergency vehicle operation for the collection and exchange of disaster information, emergency response activities, emergency goods supply, and rehabilitation works. Therefore, the assumption adopted in this study is that these roads will remain operational during disaster events (JICA & IMM, 2002).

3.4. Data Preparation and Processing

3.4.1. Objective 1 & 2: Multi-hazard Scenarios and Exposure Analysis

3.4.1.1. Multi-hazard Scenarios and Composite Multi-hazard Maps

As aforementioned, hazard data were obtained in different formats, raster, vector and PDF. These datasets were processed and converted into similar raster format and resolution (20m), considered appropriate for the scenario analysis. PDF datasets for landslides, tsunami and floods were georeferenced to assign spatial coordinates and digitised into vector format, to make them usable in the GIS environment. All single hazard maps were converted into raster format. To create hazard datasets that can be comparable and overlayed to determine areas of distinct degrees of multi-hazard intensities in the city, single hazard maps were reclassified into three classes (geophysical) and two classes (hydrological) (*See Appendices 1 and 2*). The geophysical hazards, which had more than three classes of intensities, were reclassified into 3 main classes of high, medium, and low as shown in *Table 8*. Since hydrological hazard maps only contained 2 classes indicating the presence and absence of a given hazards, the classes were maintained as seen in *Table 8*.

Then composite multi-hazard susceptibility raster maps were computed by combining the reclassified single hazard maps for each scenario accordingly. This was to determine the spatial distribution and overlap of natural hazards in Istanbul megacity, hence possible hazard interactions in the area. Equations (eq) 1 and 2 were used to compute composite multi-hazard map for the geophysical and hydrological hazards, detailing the combination of distinct intensities of the hazard per each raster cell.

*Scenario 1: "Earthquake" * 100 + "Liquefaction" * 10 + "Tsunami"* [eq1]

*Scenario 2: "Floods" * 10 + "Landslides"* [eq2]

Table 8: Reclassification of hazard intensities per multi-hazard scenario.

Scenario	***Hazard type***	***Intensity***	***Old class***	***New class***
Scenario 1	Earthquake (PGA)	0.200-0.450	4,5	3 (High)
		0.105-0.199	2,3	2 (Medium)
		0.046-0.149	1	1 (Low)
	Tsunami (Metres)	6-10	5	3 (High)
		2-5	2,3,4	2 (Medium)
		0-1	0,1	1 (Low)
	Liquefaction		4,5	3 (High)
			3	2 (Medium)
			0,1,2	1 (Low)

Scenario 2	Floods	Safe areas	0	0
		Prone areas	1	1
	Landslides	Safe areas	0	0
		Prone areas	1	1

3.4.1.2. Exposure Analysis

Exposure analysis was computed from both the two multi-hazard scenarios and individual hazards, to compare the potential impacts of these single hazards in Istanbul. This analysis was performed for buildings and critical facilities for the response phase of DRM such as airports, health centres, fire stations among others. Additionally, to determine areas that might be prone to NaTech hazards in the event of natural hazard occurrences in the city, exposure of industries to the two multi-hazard scenarios was performed. To aid the analysis, all industries within the medium and high multi-hazard intensities were selected to be susceptible to damage, hence result to secondary disasters. In general, the process involved overlaying the hazard vectorised datasets with the respective EaR, using the Spatial Join tool in ArcGIS Pro, to extract hazard status values to each building in the study area.

To compute building exposure to varying degrees of geophysical hazards, the combined hazard intensities were reclassified into 3 classes, based on the mean values. Statistics were computed in ArcGIS Pro to reveal the means for each multi-hazard intensity combination, which were rounded to the nearest whole number of either 1 (low), 2 (medium) and 3 (high). For instance, in cases where hazard intensity combination values were 332 with 2.6 as mean value, high intensity was assumed. Conversely, for hydrological hazards, classes were determined based on the number of hazards present per each cell, as the hazard datasets did not have intensities. All cells with no hazard exposure well classified as 1 (low), those with the presence of at least 1 hazard (1,0; 0,1) were classified as 2 (medium) while with all the 2 hazards present (11) as 3 (high). These composite multi-hazard maps for each scenario *(See Appendices 3 and 4)* were then converted to vector format and overlaid with building footprint shapefile. Various building exposure characteristics such as construction type, number of floors were used to aid the analysis. As Mapelli & Prina Howald (2017) and Asadi et al. (2022) argues, these are some of the major determinants of the level of impacts hazards can exert on a given spatial unit. Neighbourhoods with the highest number of buildings exposed to varying degrees of multi-hazards were computed, in which percentage of buildings located in high intensity areas were also computed to determine neighbourhoods highly prone to geophysical and hydrological hazards. Figure 7 shows the methodological flowchart used for computing these two procedures.

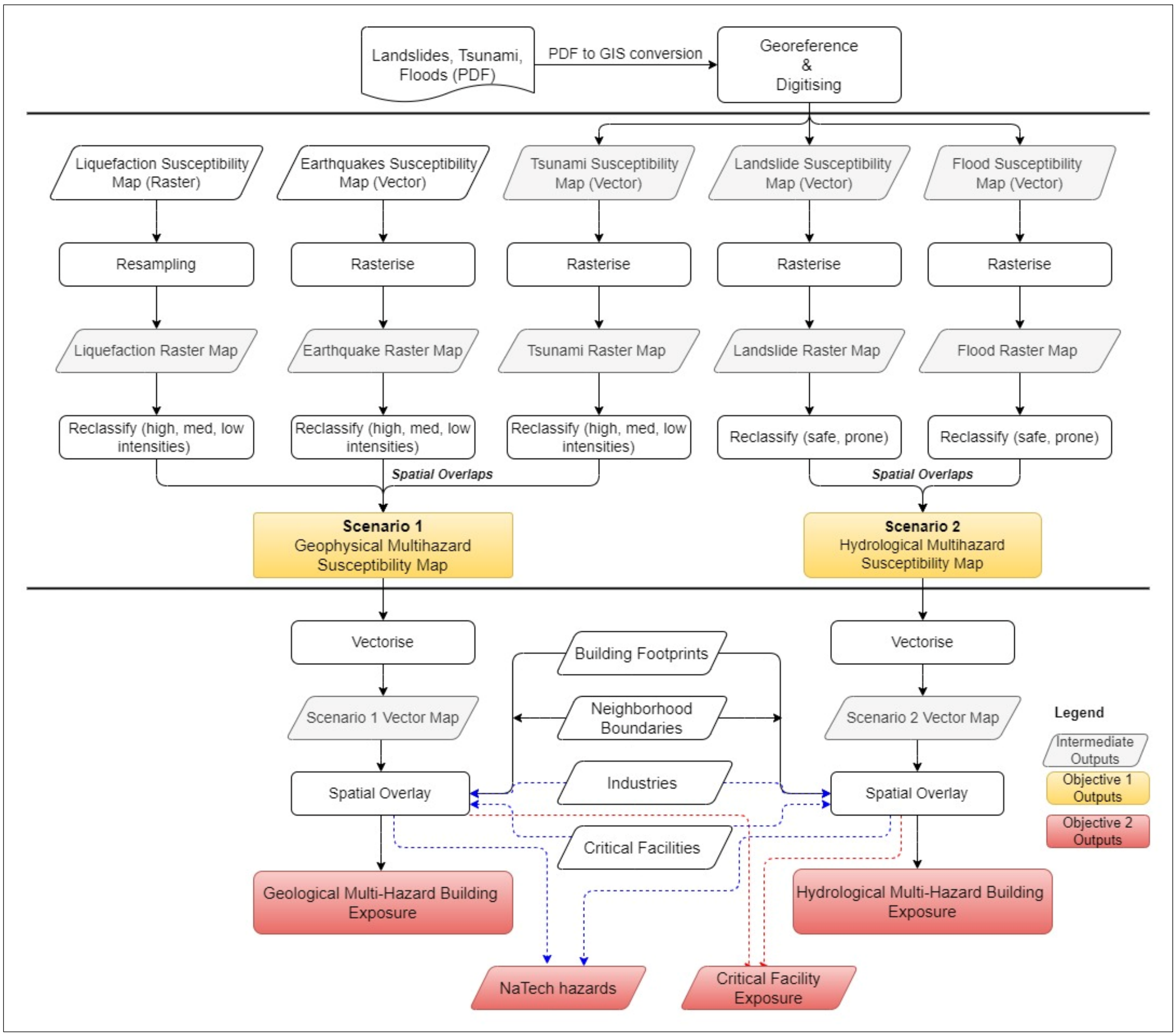

Figure 7: Flow chart showing the summary of the methodology for computing multi-hazards and exposure analysis in Istanbul megacity (Source: Author, 2024).

3.4.2. Objective 4: DLCs Location-Allocation Analysis

3.4.2.1. Spatial Multi-Criteria Analysis (SMCA)

The SMCA was utilised to analyse the criteria used for DLCs site selection and identify potential suitable sites for locating varying levels of DLCs in megacity Istanbul. This method was used because it allows for a systematic integration of different criteria with varying levels of importance to stakeholders, considers the spatial distribution and relationships among indicators, and helps to identify and prioritise indicators by weighting them based on their relative importance (Boggia et al., 2018). The fact that it integrates well the stakeholder input and data driven results, makes SMCA an effective tool in indicator identification and decision-making in spatial context. To gather stakeholder input and views on site selection and planning for DLCs in Istanbul, a questionnaire was sent to one of the Project Specialists at the Department of Earthquake Risk Management and Urban Improvement under the Earthquake and Ground Investigation Directorate of the Istanbul Metropolitan Municipality (IMM) (*see Appendices 5 and 6*). Due to unforeseen limitations, the researcher was unable to conduct the planned extensive interviews with various stakeholders involved in emergency response. However, a one-day field visit with experts from the Department of Earthquake Risk Management and Urban Improvement provided valuable insights into some of the crucial aspects considered in DLC site selection.

The main procedures taken included: (i) criteria selection for 3 levels of DLCs (ii) Standardisation and Normalisation of criteria (iii) determination of criteria weights, hence their relative importance and (iv) determination of potential suitable DLCs sites.

1. Determination of Criteria for DLCs Location

1.1. Criteria Selection

Literature was used to identify indicators that are widely used to locate centres for HLs. Since various terms have been used to describe such centres, *Table 9* shows some key words that were used to search for such indicators. Google scholar and Scopus were used as platforms to find peer-reviewed papers to extract criteria. From the list of reviewed criteria, 14 criteria were selected, based on the available spatial datasets and their relevance in the context of Istanbul. *Table 10* describe such criteria and their rationale behind their selection and utilisation in the study.

Table 9: Key words used to in literature search for criteria relevant for DLCs site selection.

"Humanitarian logistics"	*"Factors"*	*"Site Selection"*
"Disaster centres"	*"Criteria"*	*"Locating"*
"Warehouses"	*"Indicators"*	*"Location determination"*
"Emergency logistic centres"		*"Location selection"*
"Distribution centres"		*"Site suitability"*
"Humanitarian relief"		*"Location-allocation*
"Temporary Shelter"		

Table 10: Criteria for determining DLCs suitable sites.

Criteria	Rationale
Proximity to Emergency Transportation Roads	Transportation routes have a critical role in the post-earthquake emergency phase, where they constitute one of the main elements of the transportation system in storing rescue and first aid teams, disaster victims that need to be evacuated, emergency goods supply, and rehabilitation works (JICA, 2002; Gehl, et al., 2022). Land route is usually the most preferred transportation mode (Yilmaz & Kabak, 2020), therefore, *areas close to designated emergency transportation routes are more suitable for DLCs as compared to those far,* as they enable reliable transportation connectivity for emergency relief operations (Yilmaz & Kabak, 2020; Keser, 2019)
Proximity to Evacuation Sites	Disaster logistics warehouse location to be selected in close proximity to disaster affected population (Keser, 2019)
Proximity to Airports	Airports are crucial factors in ensuring that quick response is provided during disaster events because most emergency relief items provided in the initial phases of an emergency are delivered through air-chartered flights (Roh et al., 2015). Proximity to an airport facilitates faster arrival of disaster response teams mobilised from different parts of the country or from abroad, minimizing delays in essential relief and rescue operations (IBB, 2024) Therefore, Keser (2019) & Roh et al. (2015) asserts that *DLCs located closer to airports are preferred* as they allow goods and services reach beneficiaries in the shortest time possible.
Proximity to Seaports	Seaports are another important logistics infrastructure factor for pre-positioned warehouse selection. Seaports are normally used to receive large quantities of relief items from suppliers for replenishment purposes and to deliver relief to regional warehouses for long-term post-disaster relief operations. Seaports handle the large quantities of replenishment goods and

	they are used to deliver relief goods for post-disaster operations (Roh et al., 2015)
Proximity to Railways	In order to transport the materials to the desired location in a short time and with the lower cost, the location of the disaster logistics warehouse should be close to the railways (Keser, 2019)
Safety and Natural Hazards	DLCs need to be located in areas of no or little-known disaster prone. This entails that candidate emergency relief centers should avoid any potential risk areas such as fault lines, liquefaction risks and chemical warehouses. A site that has high priority should be far from risk buildings and facilities such as chemical factories and fault lines. (Xu et al, 2022; Wang et al., 2014; Witkowski et al., 2018)
Slope	Due to higher construction costs in high slope areas, the slope percentage of the area where the disaster logistics warehouse needs to be installed in low slope areas (Keser, 2019). According to the Turkish Red Crescent, the slope of the terrain of a candidate location cannot exceed 7 percent and it is better if the slope is between 2 percent and 4 percent (Kilci et al., 2019)
Current Development Status	It is assumed that open and recreational spaces, unconstructed lands, parks, gardens and villas, and parking lots are suitable for temporary relief centre, as they normally have more open space and less constructed parts (Xu et al., 2022)
Land Ownership: Public or Private	Land ownership determines the investment costs which is considered as land buying and/or construction cost for a distribution center. Candidate shelters should be selected from land parcels where their use rights are controlled by the government (Yilmaz & Kabak, 2020). It is easier to get construction permission if the proposed area is publicly owned than if privately owned.
Proximity to Protected Sites	Protected sites include areas such as environmentally sensitive areas, military bases among others, where development is usually not permitted. Therefore, DLCs should not to be located in environmentally protected areas (IMM, 2023).
Proximity to Health Facilities	DLCs need to be closer to hospitals for emergency response might be preferred because of strategic reasons (Yilmaz & Kabak, 2020)
Proximity to Industrial Sites	A DLC proposed site should be far from industrial centres and avoid potential risks that might come from chemical factories. The land-uses located in closer distances from the industrial centres got lower priority compared to other land uses (Xu et al., 2022; Shiraz, 2017).
Proximity to Waterbodies	DLC sites should be located away from water bodies, such as rivers, to avoid potential risks such as floods (Wang et al., 2014)
Proximity to Highly Vulnerable Sites	Disaster logistics warehouse location to be selected should be close to the disaster affected population or areas (Keser, 2019)

1.2. Criteria for the Three Levels of DLCs in Istanbul

There are three levels of DLCs being planned for by the by the Earthquake Risk Management and Urban Improvement Department Earthquake and Ground Investigation Directorate of IMM. *Figure 8* illustrates the relationships among these levels of DLCs.

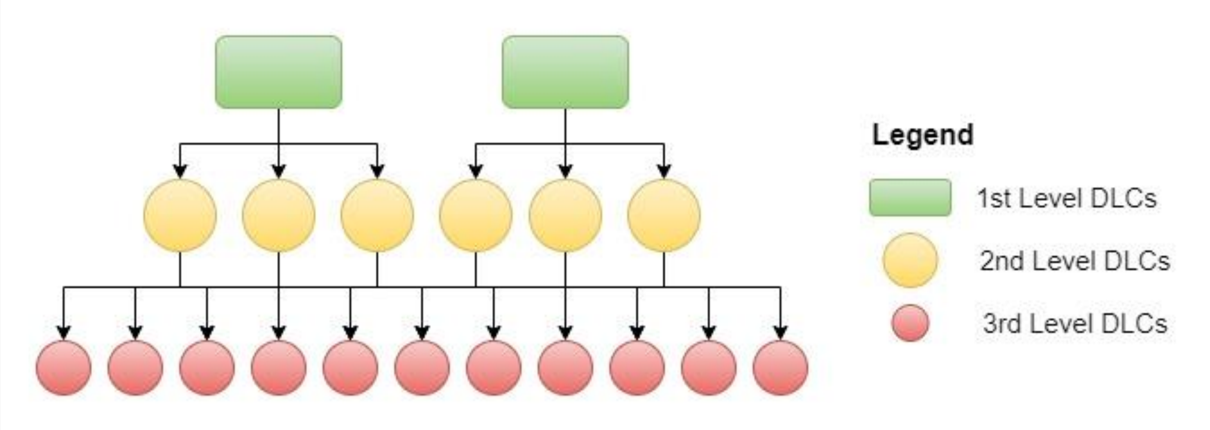

Figure 8: Three levels of DLCs in megacity Istanbul (Source: IMM, 2023; Author, 2024)

i. 1st Level Disaster Logistic Centres

The main purpose of the 1st level DLCs is to provide tents, materials, and equipment to the affected people in need of emergency shelter in case of a disaster in Istanbul. Yilmaz & Kabak (2020) describes these main distribution centres as permanent facilities for pre-positioning, storing, or sorting purposes and usually assumed that they are not affected by a disaster. Mostly these are planned to act as supply and coordination points from where relief items will be distributed to local distribution points in the affected areas. The evaluation for this level consisted of 13 sub-criteria which were categorised into main criteria of *accessibility, transportation, safety and natural hazards, and location. Figure 9* illustrates these categories and indicators under each category

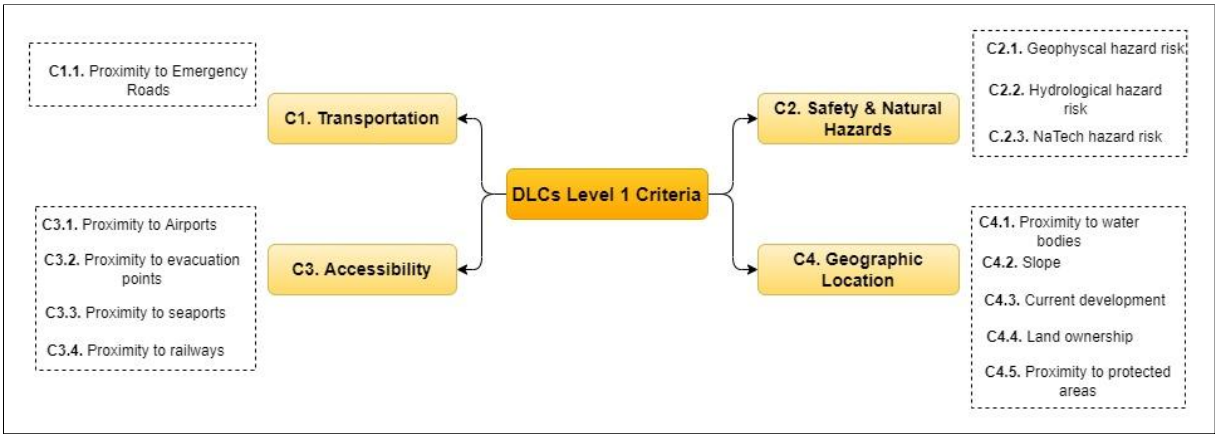

Figure 9: Criteria for 1st level DLCs location in Istanbul (Source: Author, 2024)

ii. 2nd Level Disaster Logistic Centres

The 2nd level DLCs are points where the materials coming from 1st level DLCs will be distributed to the city and 3rd level DLCs and where transfers will be made from large vehicles to small vehicles. These centres are planned to be specialised sites with distinct themes based on the surrounding settlements and needs (IMM, 2023). The evaluation includes 12 sub-criteria, also categorised into main four categories of *accessibility, transportation, safety and natural hazards, and location*, as depicted in *Figure 10*.

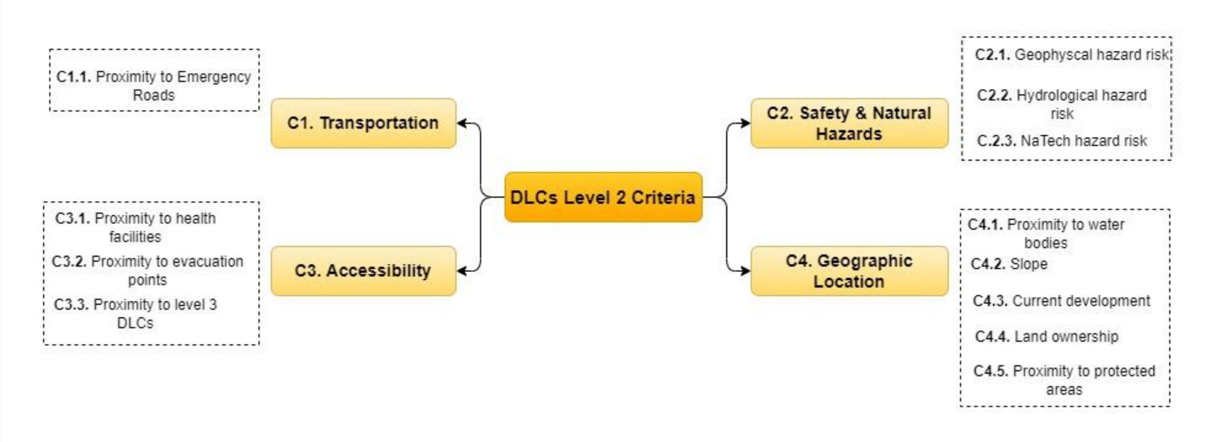

Figure 10: Criteria for 2nd level DLCs location in Istanbul (Source: Author, 2024)

iii. 3rd Level Disaster Logistic Centres

The 3rd level DLCs are for offering response to the affected areas and people. Yilmaz and Kabak (2020) terms these as local distribution centres (LDCs) which deliver relief goods to victims directly and constructed temporarily in the impacted areas after a disaster occurs. The main criterion for locating level 3 DLCs is their proximity to disaster-prone areas. As illustrated in Chapter 2, these local level DLCs need to be in disaster prone areas to ensure prompt response during emergencies. Therefore, the criteria for these DLCs included proximity to vulnerable neighbourhoods and the current development status, with emphasis on vacant or undeveloped areas within the vulnerable neighbourhoods.

2. Criteria Data Processing

To generate the input data for the *Accessibility* criteria, travel time for accessing such facilities was computed. Even though most studies utilise Euclidean distance for such computations, it was deemed appropriate to use fastest path or travel time in this study, as HLs and emergency relief aim at achieving the shortest time possible to reach the desired victims. The steps below were followed to prepare datasets with fastest path in QGIS.

2.1. Preparation of Road Network dataset

The 2015 roads dataset for Istanbul, obtained from Istanbul Technical University (ITU), under PARATUS project, was prepared to act as a network for preparing and processing a network dataset. This network dataset was used to compute the fastest path from facilities considered essential factors during DLCs site selection. The work is composed of three steps: input data layer preparation, preparation of facilities for the computation of travel time, and determination of maximum travel time for ideal DLC location.

The roads' layer coordinate system was converted to metric (projected system) TUREF/ TM30 as a prerequisite for a network dataset to work for fastest path computation. Geometry cleaning was done to ensure a well-connected network for the computation to be achieved. No invalid geometries (checked and corrected) disconnected islands and all Network group not equal to 0 were removed to ensure that the group for this computation was all that is present in the dataset. Then the attributes most crucial for the analysis (Speed and direction) were verified and populated accordingly. For all Null values, the value of the road that was either an extension of it or similar to it was assumed. Then direction attributes were repopulated where they had null values and reclassified to only have 0 (bi-directional) and 1 as one-way. Since the attributes contained 2 and 3 values were reclassified as 0, hence bi-directional. Then, geometry checker was re-used to validate the roads layer.

2.1.1. Preparation of facilities for the computation of travel time

QNEAT 3 plugin, a Network analysis toolbox in QGIS, was used for the computation and preparation of the criteria via the use of ISO-areas tool. This tool requires input datasets to be in lines and points and not polygons. Therefore, centroids were created for all facilities with polygon features to create points of origins. Travel time was put at 30km/hour, regardless the road's hierarchy, considering uncertainties that can slow the traffic flow.

2.1.2. Determination of Maximum travel time for ideal DLC

Literature was used to compute the travel time ideal to ensure prompt response during emergencies (*see Table 11 for distinct travel time for each criteria).* All areas within this maximum travel time were coded as suitable, and those outside the maximum travel time were considered unsuitable. All vector data sets were converted into raster layers for ease analysis and computation of the criteria. All global datasets were reprojected to local reference systems; from WGS to EPSG:5254-TUREF/TM30. *Table 11* shows the GIS analysis conducted for each criterion.

3. Standardization and Normalization of Criteria

To achieve an accurate comparison of the criteria, a Min-max standardization method was used to normalize the identified criteria for each DLC level. Equations 3 and 4 were used to normalize the criteria with distinct units into a comparable unit, ranging from 0 to 1, with value 0 entailing most suitable areas and 1 most unsuitable locations.

For criteria that had a positive contribution (benefit), meaning the more of the criteria the more the suitability of the potential new site, the formula was:

$$\frac{(Xi - Xmin)}{(Xmax - Xmin)} \quad \text{[eq3]}$$

Where Xi is the criteria value, Xmin is the minimum criteria value and Xmax is the criteria maximum value.

For cost criteria with negative contribution, meaning the more of the criteria the less the favourability of the sites, the formular was:

$$1 - \frac{(Xi - Xmin)}{(Xmax - Xmin)} \quad \text{[eq4]}$$

Where Xi is the criteria value, Xmin is the minimum criteria value and Xmax is the criteria maximum value.

Table 11: Methodological processes conducted for the criteria for DLCs location in Istanbul.

Criteria	Indicator	GIS Analysis	Normalization
Proximity to emergency transportation roads • Selected from regional, urban and district main road and wider road; with less probability of being completely blocked during earthquake occurrences (JICA, 2002)	Areas within 5km maximum travel distance from the emergency transportation roads (Uyan, 2013)	Euclidean Distance computation Areas 0-5km (Suitable) All areas above 5km (unsuitable)	Benefit
Proximity to evacuation sites	Areas within 60 minutes of distribution travel time to the evacuation sites (World Bank, 2019)	Iso-Areas-fastest path computation Areas within 60minutes travel time (suitable) 15 minutes more suitable 30 minutes medium suitable Areas outside 60 minutes (unsuitable)	Benefit
Proximity to airports	Areas within 60 minutes maximum travel time to the airports	Iso-Areas-fastest path computation Areas within 60minutes travel time (suitable) 15 minutes more suitable 30 minutes medium suitable Areas outside 60 minutes (unsuitable)	Benefit
Proximity to Seaports	Areas within 60 minutes maximum travel time from seaports	Iso-Areas-fastest path computation Areas within 60minutes travel time (suitable) 15 minutes more suitable 30 minutes medium suitable Areas outside 60 minutes (unsuitable)	Benefit
Railways	Areas within 5km from railways	Euclidean distance computation Areas within 5km (suitable) Areas above 5km (unsuitable)	Benefit
Safety and Natural Hazards	Areas located in low-multi-hazard disaster risks (Scenario 1 and 2)	1-Low multi-hazard risk (more suitable) 2-medium multi-hazard risk (moderate) 3-high multi-hazard risk (un-suitable)	Benefit
Slope	Areas with the terrain is flat which is the percent slope should not be greater than 7%	Percentile rise using DEM All areas below 7% (suitable) Above 7% to 1330 (unsuitable)	Benefit

Current development status	Areas that are non-built up or vacant	Corine land cover map (Label 1) All agricultural areas, forest, seminatural (suitable and coded 1) All water bodies, wetlands, artificial areas and urban fabric (unsuitable, Coded 2)	Benefit
Land ownership: public or private	Availability of public and private land in the area	Public land (suitable, coded 1) Private/Public (suitable; coded 2) Private land (unsuitable, coded 3)	Benefit
Proximity to protected sites	Areas not zoned for protected sites such as military, environmentally sensitive areas, national parks	All protected areas (not suitable, coded 1) Other areas (suitable, coded 2)	Cost
Proximity to health facilities	Areas within 60 minutes reach to the major health facilities in the city as maximum travel time Extract all major hospitals in the city	Iso-Areas-fastest path computation Areas within 60minutes travel time (suitable) 10 minutes more suitable 30 minutes medium suitable Areas outside 60 minutes (unsuitable)	Benefit
Proximity to industrial sites	Density of industries per 200 square meters	Kernel Density computation	Benefit
Proximity to waterbodies	Areas within 300 meters from the waterbodies	Euclidean distance computation Areas above 300m considered (suitable, coded 2) Areas below 300m and water bodies considered (unsuitable, coded 1)	Cost

4. Weighting of Criteria

Due to lack of extensive expert judgement on the criteria importance (as aforementioned), AHP was augmented with data-driven weighting methods of Entropy and CRITIC, to obtain meaningful weights for each criteria. Sari (2021) asserts that the usage of more than one MCDM technique is suggested to reveal more reliable results of a given decision problem. ArcPy in ArcGIS Pro was used to automate the process.

4.1. Analytical Hierarchy Process (AHP)

The indicators were divided into four main domains of Transportation, Safety or Disaster Risk, Location and Accessibility. This method provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions (Chaudhary et al., 2016). The weights were computed using the Pairwise Comparison Matrix (PWM). Firstly, based on the expert's and the researcher judgement the weights for each main criteria category were computed. These weights for the overall categories were then utilised to assign weights for their respective sub-criteria after a PWM. *Table 12 and 13* illustrate the weights assigned to the criteria and sub-criteria for first and second level DLCs; on a scale of 1-5; with 5 indicating high relative importance.

Table 12: Weights for DLCs level 1

Location (3)	**Transportation (5)**	**Accessibility (3)**	**Safety (5)**
Slope (3)	Emergency roads (5)	Seaports(3)	Geophysical hazards (5)
Water bodies (3)		Evacuation (5)	Hydrological hazards (3)
Land ownership(4)		Airports (4)	NaTech hazards (2)
Protected areas (3)		Railways (3)	
Current development (5)			

Table 13:weights for DLCs level 2

Location (3)	**Transportation (5)**	**Accessibility (3)**	**Safety (5)**
Slope (3)	Emergency roads (5)	Hospitals(4)	Geophysical hazards (5)
Water bodies (3)		Evacuation (5)	Hydrological hazards (3)
Land ownership(4)		DLC3 (5)	NaTech hazards (2)
Protected areas (3)			
Current development (5)			

4.2. Entropy

The entropy weighting method is one of the widely used MCDM methods for determining criteria weights because it does not rely on the judgements of decision makers. Feng et al. (2023) argue that due to the method's simplicity in its mathematical computations, entropy has been easily applied to different multi-criteria problems. The core principle of the entropy method is that a smaller entropy value indicates more dispersed data, which implies that the data contains more information, hence criteria with more dispersed data are assigned higher weights. Equations 5 to 8 depict steps followed to compute for criteria weights using entropy.

i. Calculate the proportion of criteria

$$p_{ij} = \frac{x'_{ij}}{\sum_{j=1}^{n} x'_{ij}} \quad \text{[eq5]}$$

where x'*ij* is the value of criterion *i* for alternative *j*.

p*ij* is the proportion of the *i-th* criterion for the *j-th* alternative

ii. Calculate entropy values

$$E_i = -k \sum_{j=1}^{n} p_{ij} \ln(p_{ij})$$ [eq6]

where Ei is the entropy for each criterion i

iii. Calculate degree of diversification

$$d_i = 1 - E_i$$ [eq7]

where di is he diversification for each criterion i

iv. Calculate and determine weights (importance) of the criteria

$$w_i = \frac{d_i}{\sum_{i=1}^{m} d_i}$$ [eq8]

where m is the number of criteria.

4.3. Criteria Importance Though Intercriteria Correlation method (CRITIC)

The CRITIC method is an objective weighting technique which comprehensively measures the weight of criteria based on the comparative strength of evaluation indicators and the conflict between indicators. This method accounts for the variations and correlations within the criteria data, utilizing the objective attributes of the data for scientific evaluation (Feng et al., 2023; Chen et al., 2022). Its basic concept is to determine the objective weights of the criterion based on the comparative strength of the evaluation scheme and the conflicting nature of the evaluation criterion. Equations 9 to 12 depict steps followed to compute for criteria weights using CRITIC.

i. Calculate the standard deviation

$$\sigma_i = \sqrt{\frac{1}{n} \sum_{j=1}^{n} (x'_{ij} - \bar{x}_i)^2}$$ [eq9]

where $\bar{x}_i$ is the mean value of the normalised criterion i

ii. Calculate the correlation coefficients

$$r_{ij} = \frac{\sum_{k=1}^{n} (x'_{ik} - \bar{x}_i)(x'_{jk} - \bar{x}_j)}{\sqrt{\sum_{k=1}^{n} (x'_{ik} - \bar{x}_i)^2 \sum_{k=1}^{n} (x'_{jk} - \bar{x}_j)^2}}$$ [eq10]

where rij is the correlation coefficient between each pair of criteria i and j

iii. Compute contrast intensity for each criterion i

$$C_i = \sigma_i \sum_{j=1}^{m} (1 - r_{ij})$$ [eq11]

iv. Calculate and determine the weights for each criterion i

$$w_i = \frac{C_i}{\sum_{i=1}^{m} C_i}$$ [eq12]

4.4. Suitability Analysis and Index

The composite weight approach, as employed by Feng et al. (2023) was then used to combine the AHP, CRITIC and Entropy weights to obtain the final comprehensive weights for each criterion. These final weights were used for the computation of the DLCs suitability maps for first and second level DLCs in Istanbul. Equation 13 was used to compute for composite weights which were then normalised to aggregate to 1.

Combined weights = A * E * C [eq13]

where A is weights for AHP, E for Entropy and C for CRITIC

Then, a weighted sum through spatial overlays of the normalised criteria was used to create a suitability analysis to represent potential sites for DLCs in the area. Based on the aggregated scoring of spatial points on the criteria, suitability indices for DLC level 1 and 2 were derived. Through this, areas were categorised as being highly suitable to low suitable for the location of DLCs in Istanbul. Equation 14 was utilised for this computation.

assuming they were 3 criteria, the suitability index was calculated using equation 14:

*Suitability Index =(Criterion weight * criterion1 raster values) +(Criterion weight * criterion2 raster values) + (Criterion weight * criterion3 raster values)*

[eq14]

3.4.2.2. DLC Level 3 Location Evaluation through Necessity Analysis

As aforementioned, level 3 DLCs offer response directly to the victims and affected areas, hence located either temporarily or permanently in disaster prone areas to ensure prompt response during emergencies. To determine suitable locations for this DLC level, buildings exposed to high-intensity geophysical and hydrological multi-hazards were analysed. Kernel density estimation was applied to compute the density of buildings within a 200-square meter grid. The resulting building density layer was then overlaid with a land cover map to identify non-built-up areas with lower densities of highly exposed buildings. These areas were proposed as potential suitable locations for level 3 DLCs in the city. Figure 11 details the methodological summary used to compute DLCs location-allocation analysis for the study.

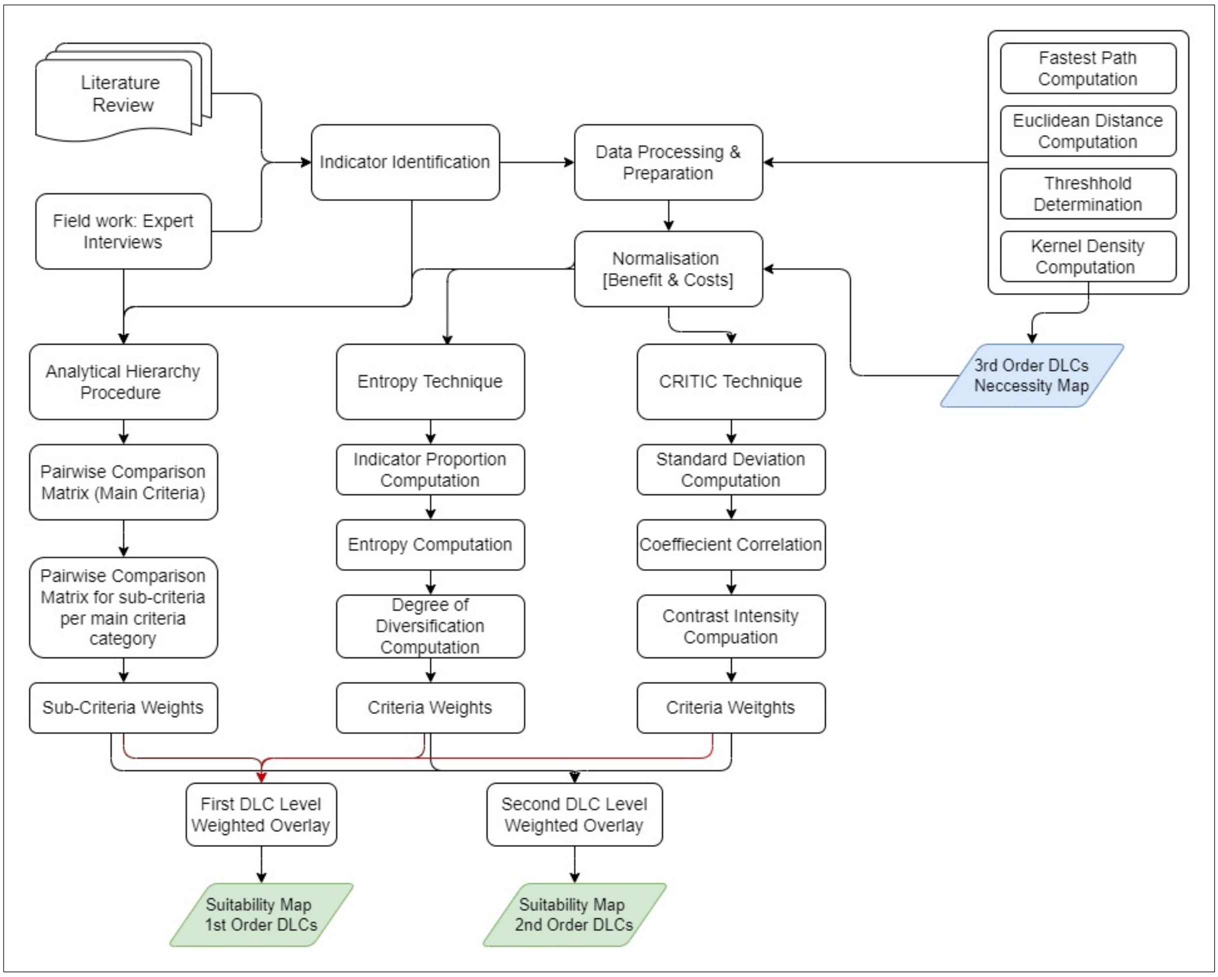

Figure 11: Summary of the methodology for DLCs Location-Allocation (Source: Author, 2024)

4. RESULTS

This chapter presents and analyses the findings pertaining to the study objectives. The interactions and spatial scale of geophysical, hydrological and NaTech hazards has been presented. Additionally, the chapter details the level of exposure by various EaR, such as buildings and critical facilities for emergency response. The chapter also presents the weights for criteria, computed using distinct MCDM weighting methods, and composite weights for each criterion. The necessity and suitability analysis for the three levels of DLCs, hence potential areas for locating DLCs in megacity Istanbul has also been analysed.

4.1. Multihazard Scenarios in Istanbul Megacity

4.1.1. Scenario 1: Geophysical Hazards

The overlay analysis of earthquakes, liquefaction and tsunamis, categorised as geophysical hazards, depicts that the southern part of Istanbul megacity is more prone to high intensity geophysical hazards as compared to the northern part of the city (*Figure 12).* Approximately 418.85 square kilometre, accounting for 8% of the surface area in Istanbul megacity is prone to impacts of earthquake intensities of 0.200 PGA above and a tsunami with wave height of at least 6 to 10 metres, in these high geophysical prone areas. Additionally, the study reveals that 2744.81 square kilometres (53%) and 1985.15 square kilometres (39%) of surface area in the city is susceptible to medium and low geophysical multi-hazard impacts, respectively. *Figure 12* shows the spatial overlaps and distribution of these hazards across Istanbul megacity boundaries.

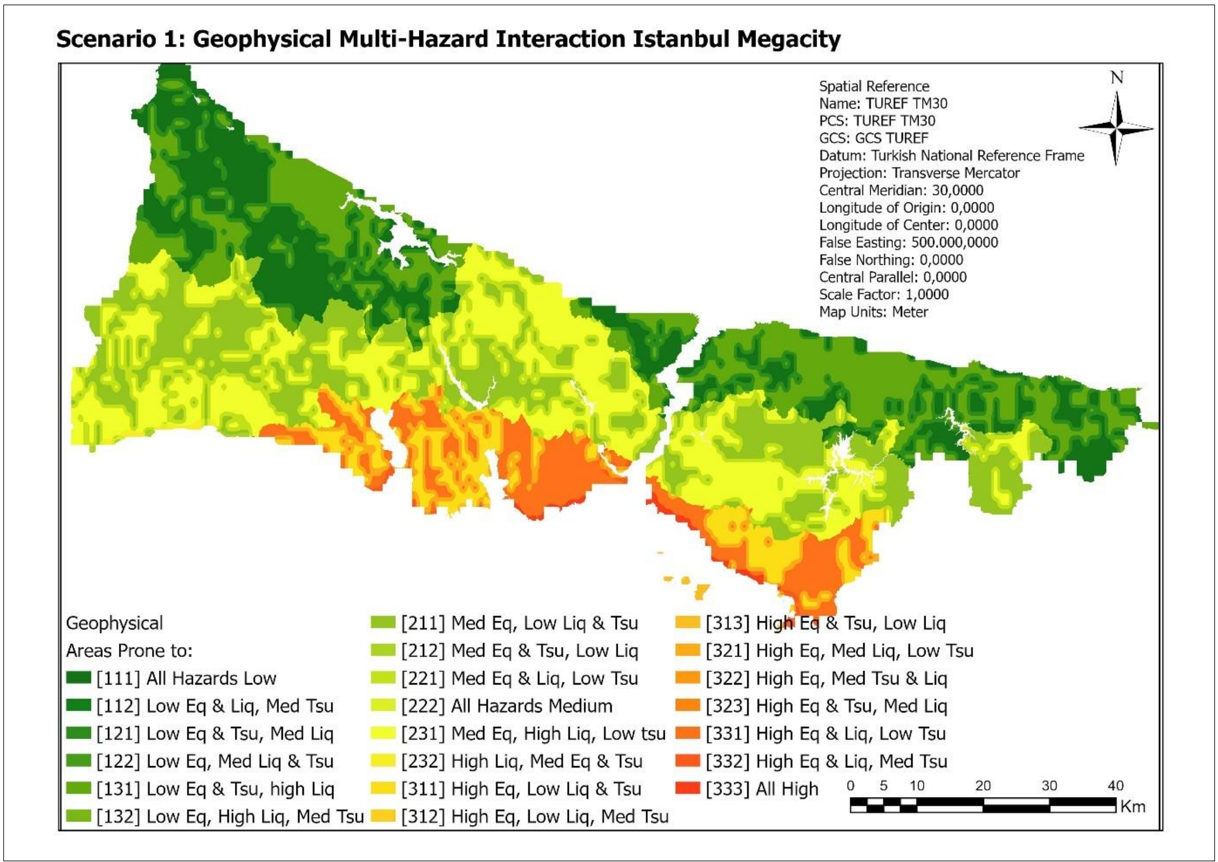

Figure 12: Geophysical multi-hazard intensity combination in Istanbul megacity (Eq= Earthquake acceleration, Tsu= Tsunami, Liq= Liquefaction) (Source: Author, 2024)

4.1.2. Scenario 2: Hydrological Hazards

Conversely, the study has revealed that only 427.058 square kilometres of land, which accounts for 8% of Istanbul surface area is prone to the impacts of flood hazards and 202.182 square kilometres (4%) is susceptible to landslides. Based on this scenario, 18.58 square kilometres of land might succumb the combined impacts of these two hydrological hazards in the city as illustrated in *Figure 13*. Having almost 88% of the total surface area of the city not susceptible to flood and landslide hazards, concurs with Gill & Malamud (2014) who illustrates these hazards as having a micro to sub-local spatial scale *(see Figure 2),* entailing their localised impacts on a defined spatial space. Additionally, compared to scenario 1, where the combined impacts of geological hazards are distributed in both the Anatolia and European side, the study findings depict the European side of Istanbul megacity to be more susceptible to hydrological multi-hazards, than the Anatolia side.

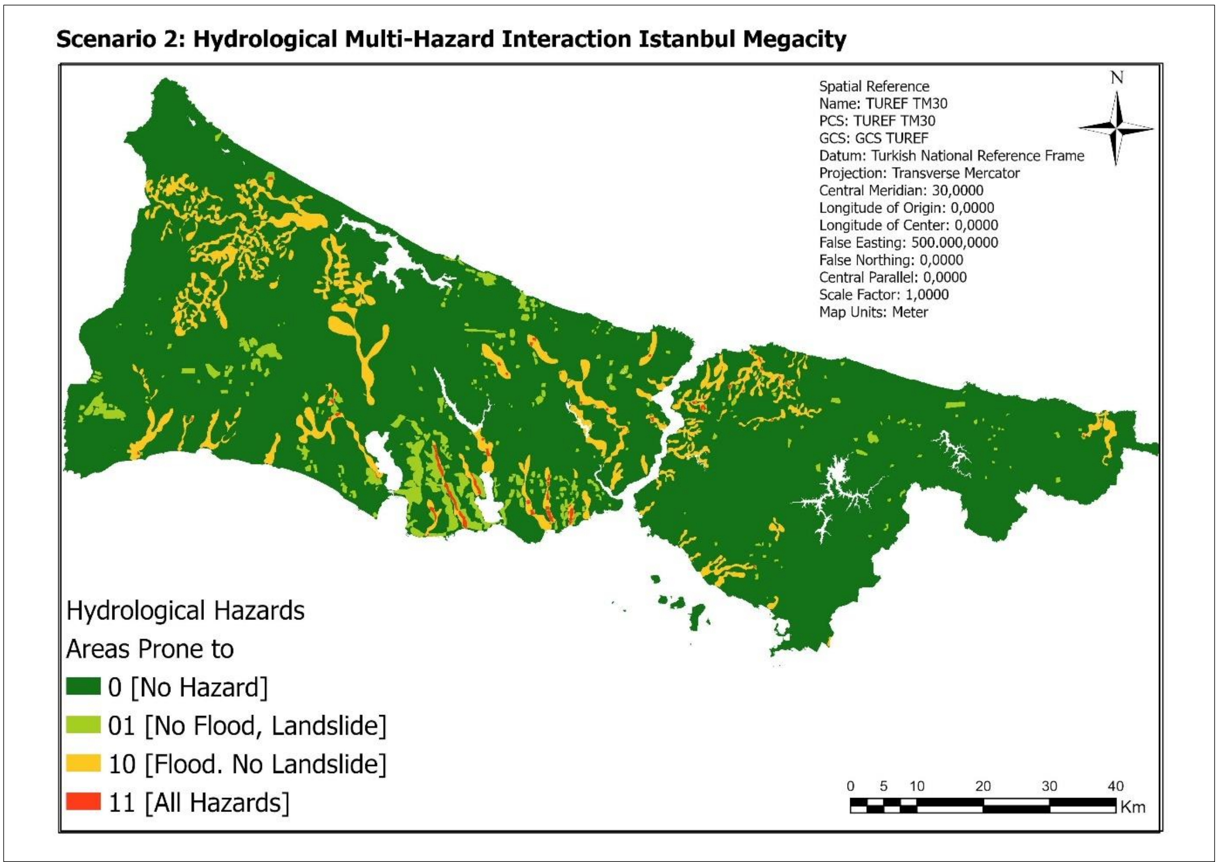

Figure 13: Hydrological multi-hazard map for Istanbul megacity (Source: Author, 2024)

4.2. Building Exposure to Multi-hazards in Istanbul Megacity

Upon identifying areas that are susceptible to the impacts of varying levels of geophysical and hydrological hazards in Istanbul megacity, number and percentage of buildings, as EaR exposed to such multi-hazards, were analysed.

4.2.1. Scenario 1: Building Exposure to Geophysical Multi-hazards.

The study has revealed that approximately 508,500 buildings in Istanbul megacity are exposed to high geophysical multi-hazard intensities, 776,200 to medium intensity and 222,100 to low geophysical multi-hazards, representing 39%, 51% and 10% of the total number of buildings, respectively. Additionally, as depicted in *Table 14*, among the three single geophysical hazards analysed, earthquakes have a higher percentage of buildings exposed to the high-intensity hazard class as compared to tsunamis and liquefaction, which have a majority of buildings falling in the low-intensity classes. For instance, it was revealed that 51% of the buildings are exposed to high-intensity earthquakes, while only 3% and 25% of buildings fall into the high-intensity tsunamis and liquefaction hazards, respectively.

Table 14: : Building exposure for each geophysical hazard (Source: Author, 2024)

	Hazard Intensity	**Earthquake**	**Tsunami**	**Liquefaction**
Number of Buildings Exposed	High	765010	54720	380805
	Medium	585666	117437	320496
	Low	156010	1334524	805382

Furthermore, utilising Emporis Standards[8] for building height categorisation, buildings were classified into three classes: low rise (3 floors and below), medium-rise (4-12 floors), and high-rise (above 13 floors). It was observed that, for geophysical multi-hazards, approximately 53% of the buildings in high-intensity areas are low-rise, 35% are medium-rise, and less than 1% are high-rise. Considering that earthquakes have a higher percentage of exposure among the three geophysical hazards, building heights in terms of number of floors were further analysed. It was observed that the majority of buildings exposed to earthquake are low-rise, having less than three floors. Specifically, 64% of the low-rise buildings are exposed to an earthquake acceleration of between 0.200 PGA and 0.450 PGA, which are considered as among the high and destructive levels. *Figure 14* depicts the number of buildings exposed to earthquakes of varying intensities, categorised by the number of floors.

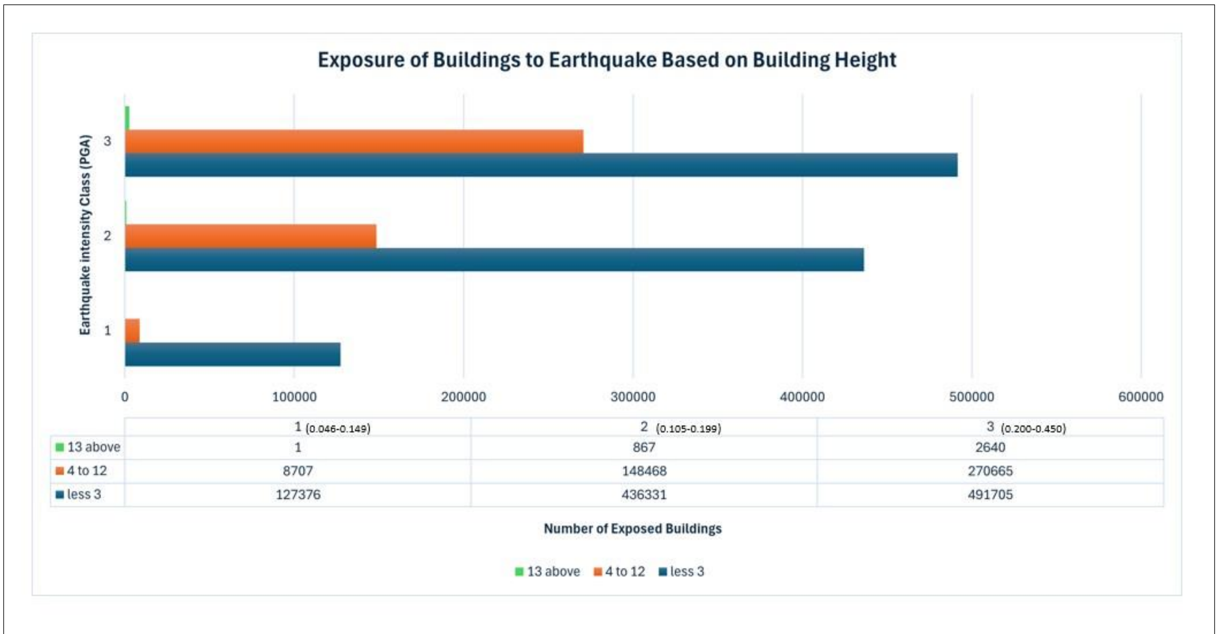

Figure 14: Number of buildings exposed to varying intensities of earthquakes in PGA (Source: Author, 2024)

As shown in *Table 15,* reinforced concrete and other construction types dominate as construction materials of buildings highly exposed to geophysical multi-hazards, with reinforced concrete amounting to 59% of the total number of highly exposed buildings in Istanbul megacity.

[8] Emporis standards is one the publicly available database on architectural and building data, that aims to index and provide comprehensive and reliable data on all buildings and structures in order to compare cities and regions (https://www.ipl.org/emporis-building-database/).

Table 15: *Construction type and building materials for buildings highly exposed to geophysical hazards in Istanbul megacity (Source: Author, 2024)*

Construction Type ID	Construction Type Description	Number of Exposed Buildings	Percentage of Exposed Buildings
0	Unknown	27101	5
1	Wood	9874	2
2	Reinforced Concrete	301086	59
3	Masonry	33166	7
4	Prefabricated	1815	0.4
5	Tunnel Mold	422	0.2
6	Steel	796	0.3
7	Collection	11415	2
9	Reinforced-concrete-wood	12	0.1
8	Other	122761	24

As *Figure 15* depicts, neighbourhoods in the southern part of the city have the highest percentage of buildings exposed and prone to geophysical hazards impacts. Among these neighbourhoods are all neighbourhoods in the Zeytinburn, Bakirkoy and Fatih provinces and approximately 80% of neighbourhoods in Beyoglu, Esenler and Esenyurt provinces in the European side of the city. Additionally, neighbourhoods in Kadikoy, Tuzla and Uskudar in the Anatolian side are also among areas the with highest percentages of buildings highly exposed to geophysical multi-hazards in the city.

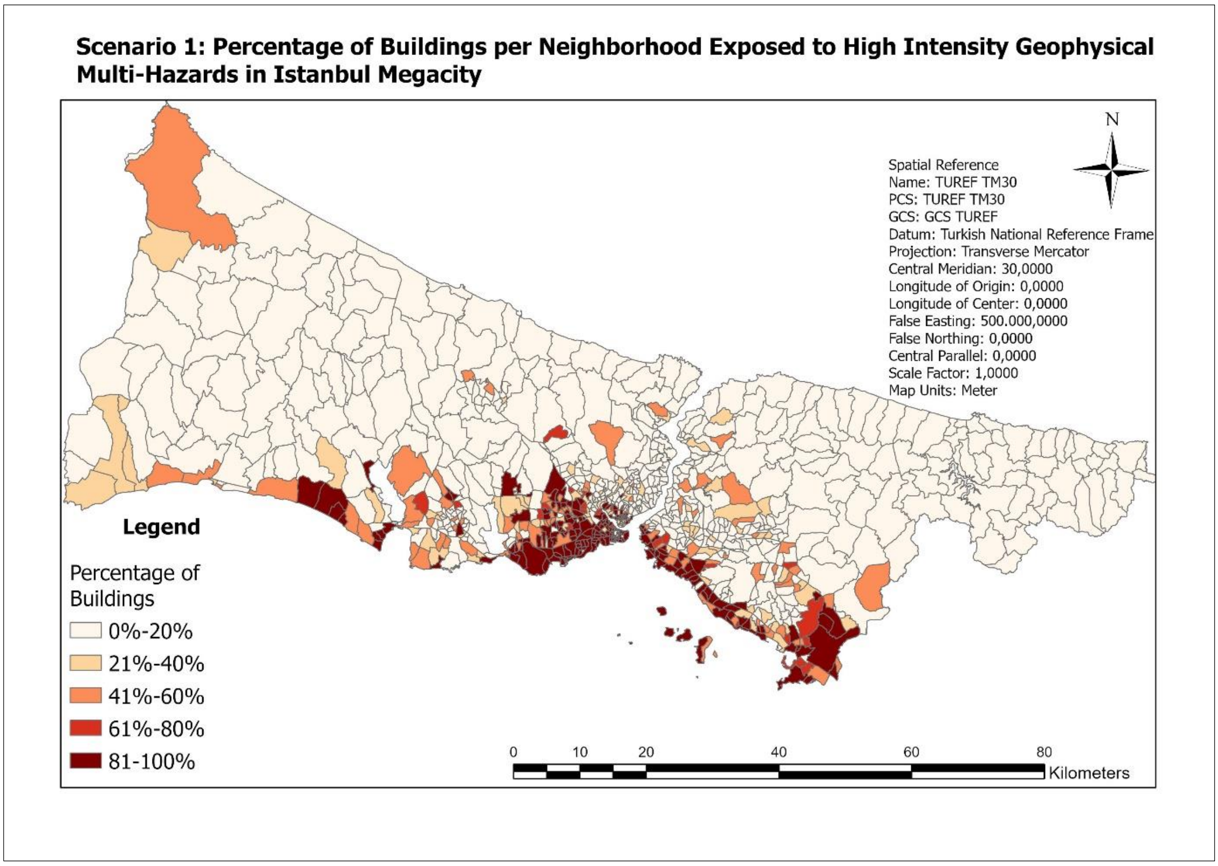

Figure 15: Neighbourhoods with high building exposure to geo-physical hazards in Istanbul.

4.2.2. Scenario 2: Building Exposure to Hydrological Multi-hazards.

Utilising single hydrological hazard maps, floods and landslides, for hydrological multi-hazard interactions, the study revealed that approximately 1% of the buildings are exposed to the combined impacts of the hydrological multi-hazards, while 19% of the total buildings to the impacts of at least one of these hydrological hazards. In this, 172, 400 buildings, representing 11% of the total buildings in Istanbul, are exposed to flood hazards alone, while 135600 (9%) buildings are exposed to landslides. Additionally, more than 50% of buildings in the 5 neighbourhoods of Siyavuspasa, Cirpic, Veliefendi, Sumer and Akeveler Mahallessi of Solak are exposed to the combined impacts of hydrological multi-hazards in Istanbul megacity. Unlike the geophysical hazards, where the impact was concentrated in the southern part of the city, it has been observed that building exposure to at least one of two hydrological hazards in distributed in both the southern and northern part of the megacity. *Figure 16* illustrates neighbourhoods with varying percentages of buildings exposed to hydrological multi-hazards. Furthermore, almost 63% of the buildings exposed to at least one or a combination of both hydrological hazards is made of reinforced concrete among other building construction types in Istanbul megacity (see *Table 16).* Of these buildings, 71% are low-rise with 29% being medium-rise.

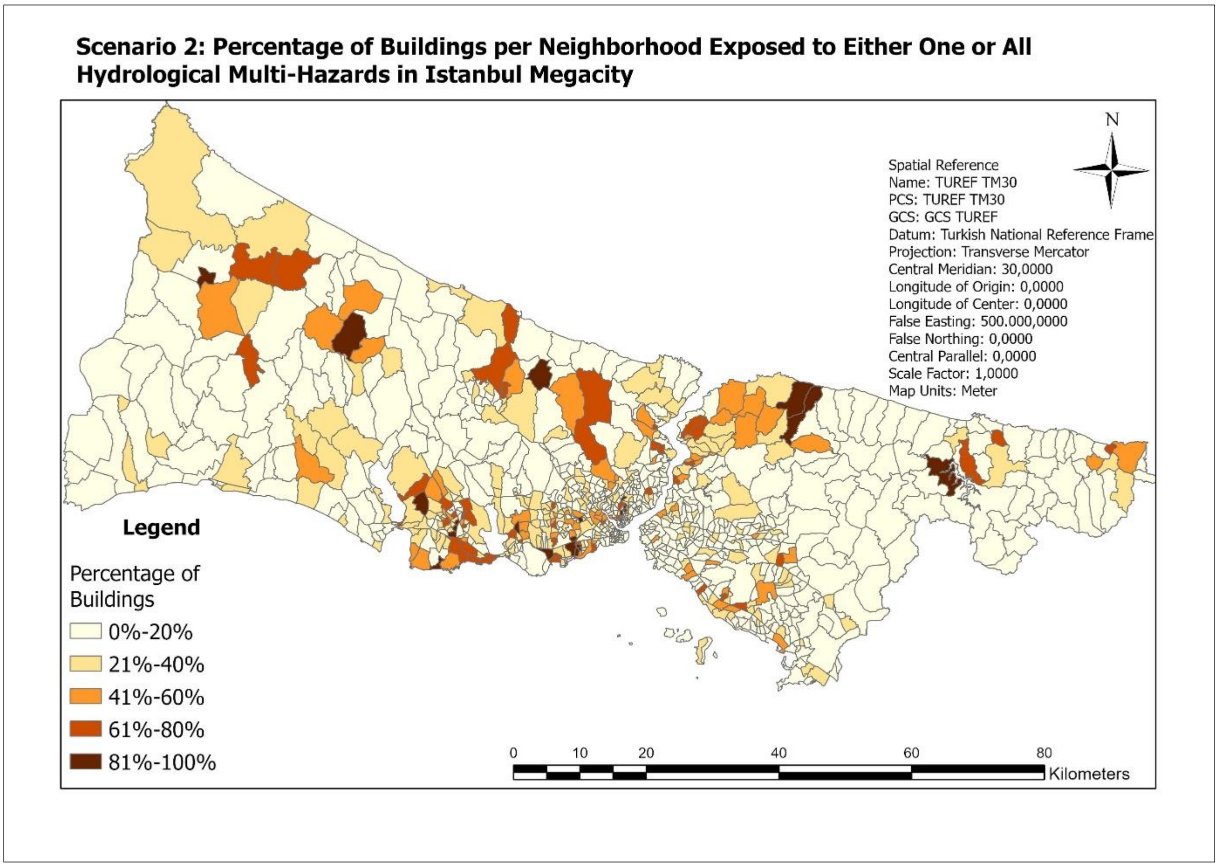

Figure 16: Neighbourhoods with high building exposure to at least one or both hydrological multi-hazards (Source: Author, 2024).

Table 16: Construction type and building materials for buildings highly exposed to hydrological hazards in Istanbul megacity (Source: Author, 2024).

Construction Type ID	Construction Type Description	Number of Exposed Buildings	Percentage of Exposed Buildings
0	Unknown	29319	10
1	Wood	2697	1
2	Reinforced Concrete	181113	63

3	Masonry	18811	7
4	Prefabricated	967	0.3
5	Tunnel Mold	67	0.02
6	Steel	210	0.07
7	Collection	5644	2
9	Reinforced-concrete-wood	3	0.001
8	Other	50981	17

4.2.3. Susceptibility of Istanbul Megacity to NaTech Hazards

Based on the density of industries exposed to medium- and high-intensity geophysical multi-hazard in Istanbul megacity, it was revealed that some neighbourhoods in Arnavutkoy, Basaksehir, Umraniye, Tuzla, Sancaktepe and Atasehir provinces are susceptible to NaTech disasters, in the events of such natural hazard occurrences. Among the most susceptible neighbourhoods are Orhanli, Aydinli, Mescit, Orta, Dudullu, Omeni, Ikitelli, and Maltepe, as shown in *Figure 17*.

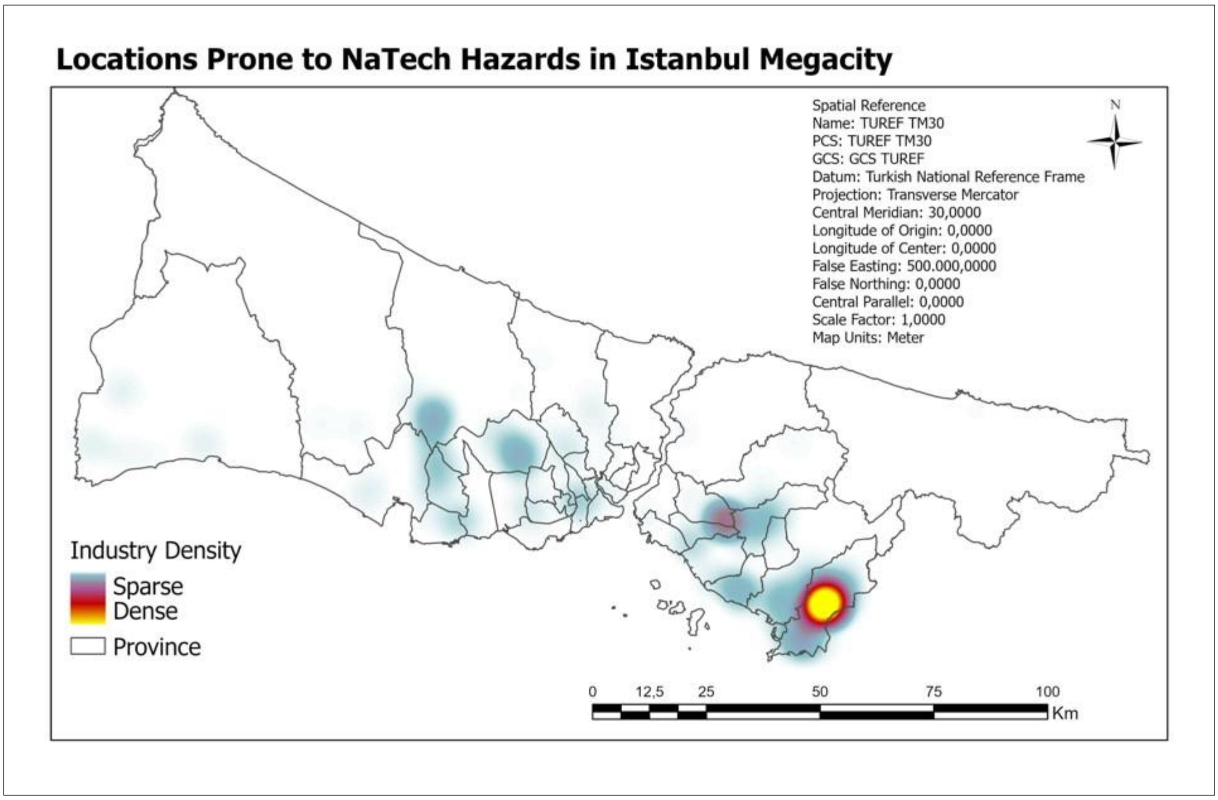

Figure 17: Areas prone to NaTech Hazards in Istanbul megacity (Source: Author, 2024).

4.2.4. Exposure of Critical Facilities to Multi-Hazards in Istanbul Megacity

The study findings, as shown in *Table 17,* reveal that more than 50% of airports, seaports and health facilities are exposed to high-intensity geological hazards in Istanbul megacity. Conversely, it has been observed that these critical facilities are more exposed to geological hazards compared to hydrological hazards, with all airports located in non-hazard prone areas. This therefore, calls for proactive measures to ensure that such facilities are safeguarded against the impacts of such hazards, to achieve effective emergency response.

Table 17: Exposure of critical facilities to the two scenarios of multi-hazards in Istanbul megacity (Source: Author, 2024).

Facility	**Scenario 1 Intensity and Percentage**						**Scenario 2 Status**		
	1		2		3		Safe	Prone	
Fire Stations	36	29%	53	42%	36	29%	106	19	15%
Airports	1	20%	1	20%	3	60%	5	0	0%
Seaports	10	20%	2	4%	38	76%	49	1	2%
Health Facilities	5	16%	10	32%	16	52%	23	8	26%

4.3. DLCs Location-Allocation in Istanbul Megacity

4.3.1. DLC Level 3 Location-Allocation: Necessity Analysis

As shown in *Figure 18 and 19*, areas with less building density per 200 square meters were deemed to be suitable for locating either permanently or temporarily locating 3rd level DLCs in Istanbul. When ground verification was conducted using World Imagery[9] in ArcGIS Pro, it was observed that such areas encompassed green areas and areas will less buildings, where buildings were not as clustered as compared to other areas (*Figure 19*). These areas are characterised by the presence of parks and large open spaces within neighbourhoods expected to be highly exposed to multi-hazard occurrences. Additionally, since some DLCs are temporary, zones designated for other uses, such as urban parks, were also suggested to accommodate temporary sites for emergency disaster response.

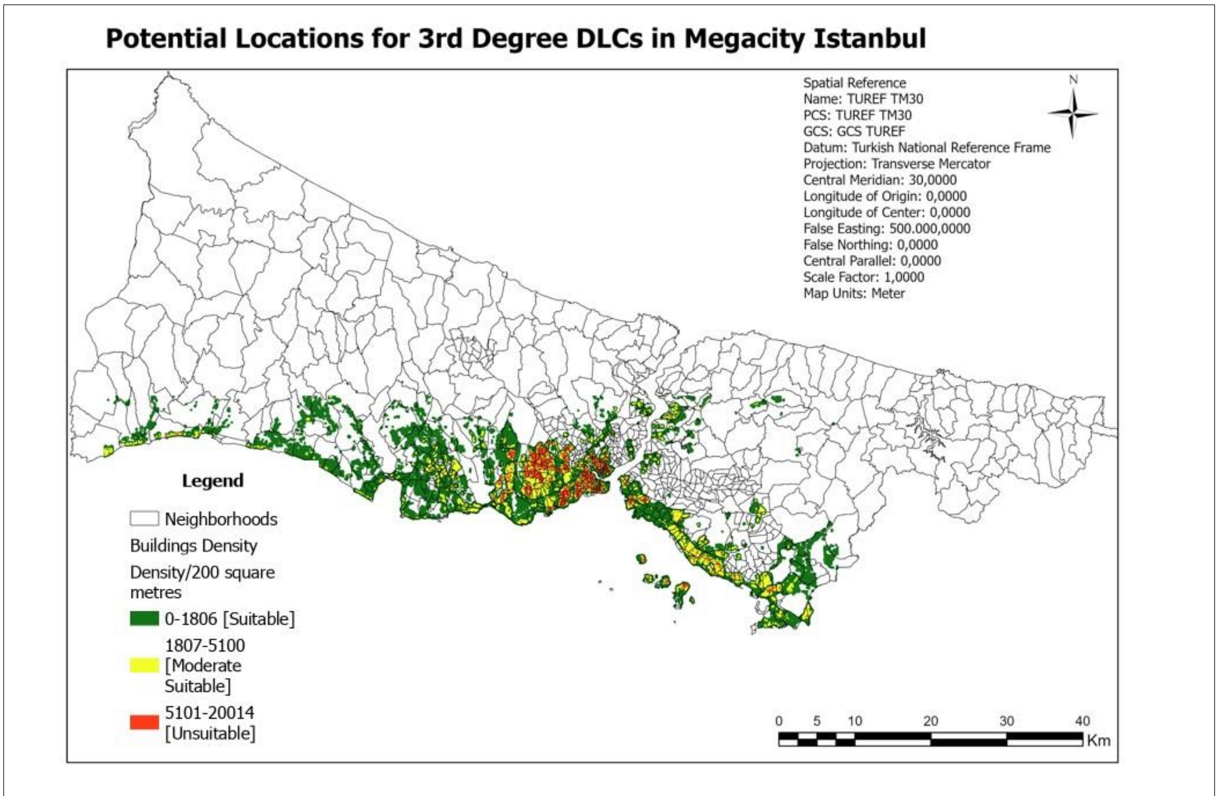

Figure 18: Building density and potential areas for 3rd degree DLCs location in Istanbul (Source: Author, 2024)

[9] World Imagery is a high-resolution satellite image provided by Esri, which is available as a basemap in platforms such as ArcGIS Pro, aiding visual inspection and spatial analysis.

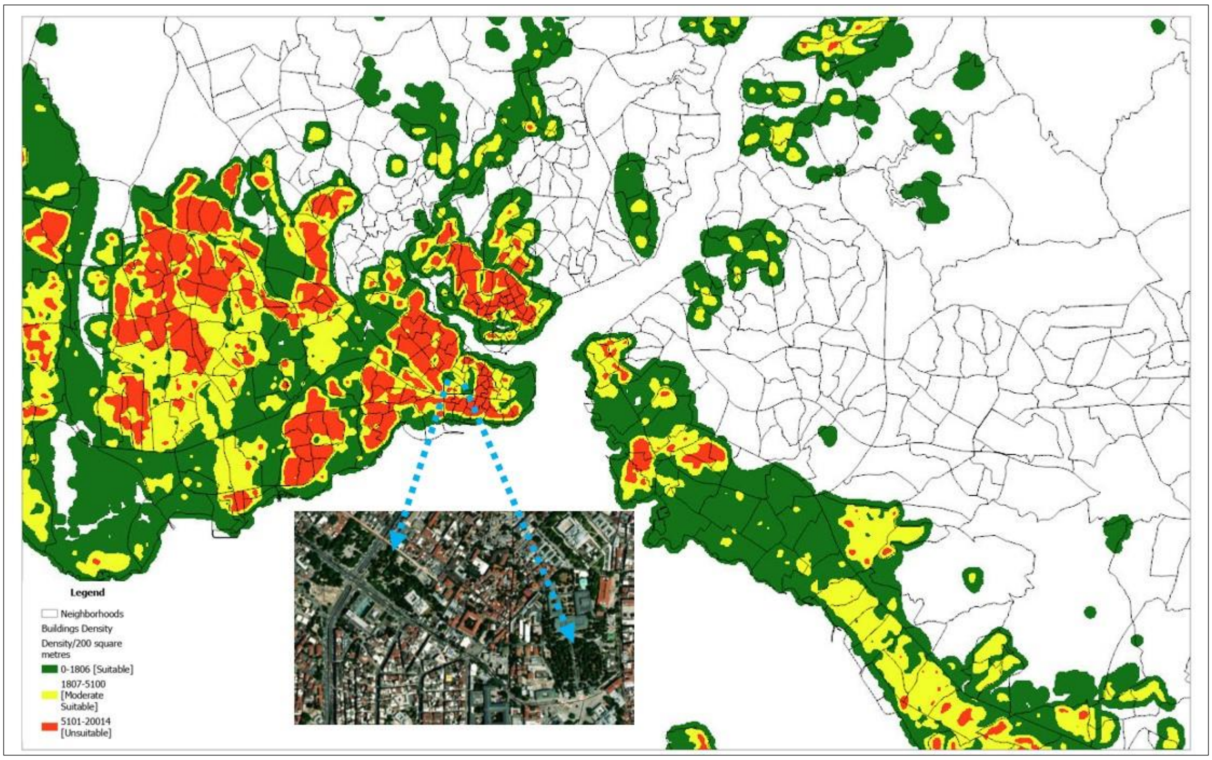

Figure 19: Example of areas deemed to be suitable for 3rd degree DLCs location in Istanbul (Source: Author, 2024)

4.3.2. Criteria Weights by Various Weighting Methods

4.3.2.1. First Level DLCs Criteria Weights

The study findings revealed that emergency roads were ranked high followed by geophysical multi-hazard criteria when AHP weighting method was employed for DLC level 1 criteria weight computation. On the other hand, criteria under the accessibility and geographic domain were deemed of relatively less importance by the expert at IMM. Conversely, utilising Entropy method, which is a data driven weighting method that looks at the diversification of variables, proximity to airports was ranked as the most important criteria, followed by evacuation points and geophysical hazards. Overall, Entropy method ranks the accessibility criteria of relative significance as compared to other indicators. Lastly, CRITIC which looks at correlation among criteria, ranks geophysical and hydrological hazards as the most significant criteria for locating first level DLCs in Istanbul. It can be seen that through this method geophysical and hydrological hazards correlate with each other. *Table 18* presents detailed weights assigned to each DLC level 1 criterion by distinct weighting methods.

4.3.2.2. Second Level DLCs Criteria Weights

The criteria weights computed using AHP depicts transportation criteria, encompassing emergency roads, have a high importance as compared to other criteria. This is followed by geophysical hazards, with water bodies and slope taking the least important ranks in determining sites for level 2 DLCs in Istanbul. Additionally, geophysical hazards have ranked high when Entropy method is utilised, followed by proximity to evacuation points. Conversely, CRITIC method ranks current development status as of high importance, with NaTech hazards and proximity to water bodies being of least significant criteria. *Table 19* presents detailed weights assigned to each DLC level 2 criterion by distinct weighting methods.

Table 18: First level DLC criteria weights by distinct MCDM weighting methods (Source: Author, 2024)

Criteria	Transportation	Safety & Natural Hazards			Accessibility				Geographic Location				
Sub-criteria	**C1.1**	**C2.1**	**C2.2**	**C2.3**	**C3.1**	**C3.2**	**C3.3**	**C3.4**	**C4.1**	**C4.2**	**C4.3**	**C4.4**	**C4.5**
AHP	0.3125	0.168	0.081	0.064	0.0591	0.0591	0.0347	0.0347	0.0357	0.0357	0.0357	0.0475	0.0554
Entropy	0.083719	0.112144	0.036498	0.00552	0.116156	0.14375	0.088462	0.112022	0.106102	0.006187	0.05629	0.081392	0.051761
CRITIC	0.076575	0.108058	0.108058	0.0644	0.077311	0.07711	0.061048	0.087555	0.043914	0.076013	0.076732	0.065409	0.077823

where: C1.1 is proximity to emergency roads
C2.1 is geophysical hazards
C2.2 is hydrological hazards
C2.3 is NaTech hazards
C3.1 is proximity to airports
C3.2 is proximity to evacuation points
C3.3 is proximity to seaports
C3.4 is proximity to railways
C4.1 is proximity to waterbodies
C4.2 is slope
C4.3 is current development status
C4.4 is land ownership
C4.5 is proximity to protected areas

Table 19: Second level DLC criteria weights by distinct MCDM weighting methods (Source: Author, 2024)

Criteria	Transportation	Safety & Natural Hazards			Accessibility			Geographic Location				
Sub-criteria	**C1.1**	**C2.1**	**C2.2**	**C2.3**	**C3.1**	**C3.2**	**C3.3**	**C4.1**	**C4.2**	**C4.3**	**C4.4**	**C4.5**
AHP	0.3125	0.169	0.085	0.065	0.05	0.0551	0.0551	0.0357	0.0357	0.0357	0.0475	0.0555
Entropy	0.089658	0.178018	0.076072	0.008126	0.06992	0.146464	0.023986	0.132192	0.006078	0.108502	0.033649	0.127336
CRITIC	0.042543	0.060604	0.060604	0.038922445	0.044258	0.042806	0.040855084	0.026742	0.049502808	0.500888	0.04137408	0.0509

where: C1.1 is proximity to emergency roads
C2.1 is geophysical hazards
C2.2 is hydrological hazards
C2.3 is NaTech hazards
C3.1 is proximity to health facilities
C3.2 is proximity to evacuation points
C3.3 is proximity to DLC level 3
C4.1 is proximity to waterbodies
C4.2 is slope
C4.3 is current development status
C4.4 is land ownership
C4.5 is proximity to protected areas

4.3.3. Comprehensive Criteria Weights and DLCs Suitability Maps

4.3.3.1. First Level DLCs Composite Criteria Weights

Composite criteria weights obtained from the normalised three weights of AHP, CRITIC and Entropy depict geophysical hazards as being the highly important criteria, followed by proximity to emergency roads, for locating first level DLCs in Istanbul. As illustrated in *Table 20,* the combined weights of these two criteria (0.584684) entail that they account for nearly 59% of the location-allocation decision for level 1 DLCs in the city, while remaining 41% is influenced by the other 12 criteria. Conversely, NaTech hazards and slope were deemed to be of least important among the criteria for site suitability and selection of level 1 DLCs. It can also be observed that accessibility criteria rank slightly higher than the geographic location criteria. Among the multi-hazard scenarios, geophysical hazards are seen to be highly ranked as compared to hydrological hazards, which are also deemed of importance as compared to NaTech hazards. Furthermore, proximity to evacuation points, under accessibility indicators ,ranks relatively higher followed by proximity to airports, with proximity to seaports ranking lower under this category.

As depicted in *Figure 20*, most of the areas that are far from the urbanised part of the city are deemed less suitable for locating first level DLCs in Istanbul. Since emergency roads and geophysical hazard ranked higher, most areas with higher intensity geophysical hazards were deemed not highly suitable, with those close to emergency roads being more suitable. This can also be seen in *Figure 20*, where suitable areas following the pattern of emergency roads. As compared to the European side, a larger percentage of areas in the Anatolian side are deemed to be highly suitable for locating first level DLCs in Istanbul, with smaller patches of land area seen as suitable in the European side.

4.3.3.2. Second Level DLCs Composite Criteria Weights

The composite weights computed from the normalised three weights illustrate that current development status and geophysical hazards have ranked highly in the location of second level DLCs in Istanbul. In this, proximity to emergency roads follows these two criteria, with slope ranking the least of all criteria in the city. Among the accessibility indicators, proximity to health facilities ranked relatively higher than other indicators of the category, while NaTech hazards ranked the least for the safety criterion. Table 21 shows the composite weights for each level 2 DLCs criterion.

Figure 21 depicts locations highly and least suitable for the location of the second level DLCs in Istanbul. With Geophysical hazards and current development status being the highly ranked indicators, it can be seen that a lot of urbanised areas and with high intensity geophysical hazards, especially the southern part of the city, are deemed unsuitable for locating DLCs of this level. The findings reveal that the central and northern parts of the city are relatively suitable for DLCs location, than the southern part of the city. Conversely, both the European and Anatolian sides of the city have patches of land more suitable for DLCs location.

Table 20: Composite weights for each criterion used for DLC level 1 site selection (Source: Author, 2024).

Criteria	**Transportation**	**Safety & Natural Hazards**			**Accessibility**				**Geographic Location**				
Sub-criteria	**C1.1**	**C2.1**	**C2.2**	**C2.3**	**C3.1**	**C3.2**	**C3.3**	**C3.4**	**C4.1**	**C4.2**	**C4.3**	**C4.4**	**C4.5**
Weight	0.28999	0.294694	0.046242	0.0033	0.0768244	0.09482	0.027126	0.049265	0.024078	0.00243	0.02232	0.0366051	0.0323035

where: C1.1 is proximity to emergency roads
C2.1 is geophysical hazards
C2.2 is hydrological hazards
C2.3 is NaTech hazards
C3.1 is proximity to airports
C3.2 is proximity to evacuation points
C3.3 is proximity to seaports
C3.4 is proximity to railways
C4.1 is proximity to waterbodies
C4.2 is slope
C4.3 is current development status
C4.4 is land ownership
C4.5 is proximity to protected areas

Table 21: Composite weights for each criterion used for DLC level 2 site selection (Source: Author, 2024).

Criteria	**Transportation**	**Safety & Natural Hazards**			**Accessibility**			**Geographic Location**				
Sub-criteria	**C1.1**	**C2.1**	**C2.2**	**C2.3**	**C3.1**	**C3.2**	**C3.3**	**C4.1**	**C4.2**	**C4.3**	**C4.4**	**C4.5**
Weights	0.183811	0.281158	0.060429	0.003170228	0.02386	0.05327	0.00832637	0.019461	0.001656376	0.29919	0.010197514	0.05547

where: C1.1 is proximity to emergency roads
C2.1 is geophysical hazards
C2.2 is hydrological hazards
C2.3 is NaTech hazards
C3.1 is proximity to health facilities
C3.2 is proximity to evacuation points
C3.3 is proximity to DLC level 3
C4.1 is proximity to waterbodies
C4.2 is slope
C4.3 is current development status
C4.4 is land ownership
C4.5 is proximity to protected areas

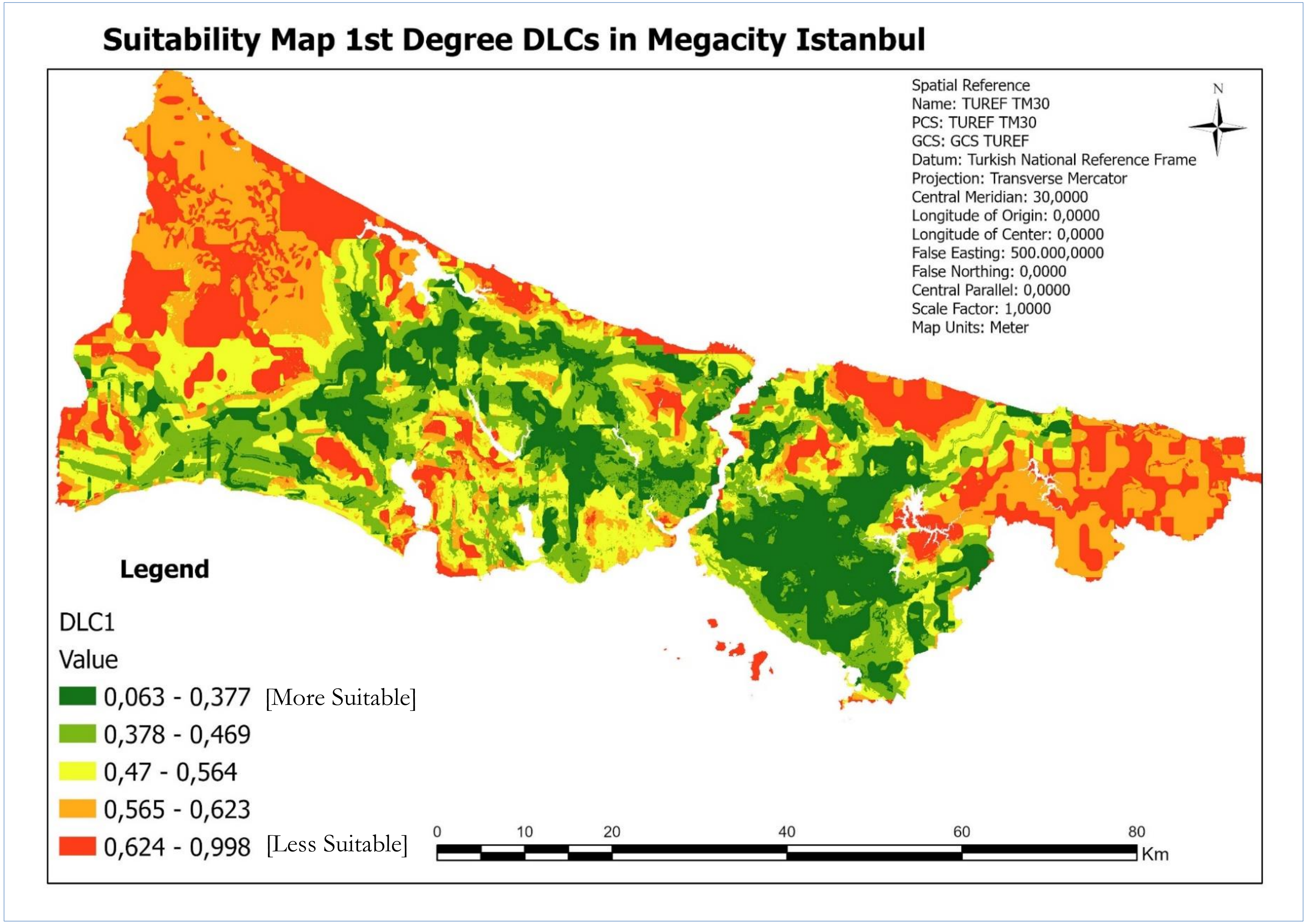

Figure 20: Level 1 DLCs site suitability map in megacity Istanbul (Source: Author, 2024).

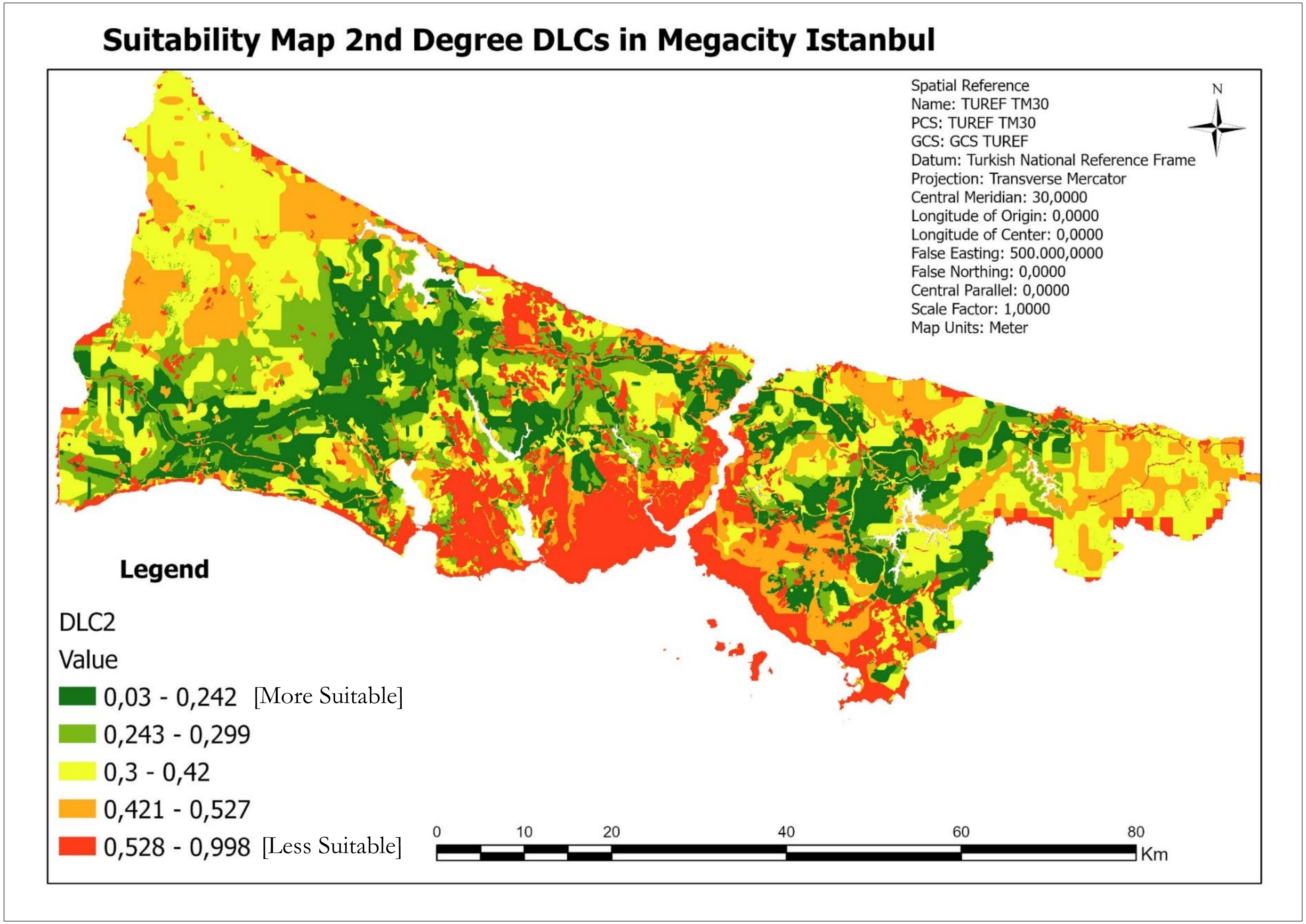

Figure 21: Level 2 DLCs site suitability map in megacity Istanbul (Source: Author, 2024).

5. DISCUSSION, CONCLUSIONS AND RECCOMENDATIONS

This section reflects on the main findings of the study, while relating them to existing literature studies. Spatial interactions of multiple hazards and their respective implications on building exposure have been presented. Additionally, critical criteria and their importance towards selection of optimal sites for distinct levels of DLCs in Istanbul, have been discussed. Overall, the discussion is divided into the two main methodological steps applied in this study: multi-hazard and exposure analysis (encompassing objective 1 and 2) and DLCs location-allocation (objective 3 and 4).

5.1. Multi-hazards Interactions and Exposure Analysis in Istanbul

5.1.1. Geophysical Hazards and Building Exposure

The study examined the interaction of geophysical hazards in Istanbul, focusing on earthquakes, liquefaction, and tsunamis, which together formed Scenario 1 of hazard interactions in the megacity. As presented in Chapter 5, these hazards were observed to have a significant spatial scale, with earthquakes and liquefaction hazards affecting almost every part of the city, despite varying intensities. While it is understandable for earthquakes to impact such a wide area, covering micro to regional scales as noted by Gill & Malamud (2014), the extensive spatial distribution of liquefaction can be attributed to the global dataset used in this study. Although the global liquefaction dataset was deemed well-suited for coastal regions and accurately predicted various intensities of liquefaction in Istanbul, the fact that it assigned liquefaction potential to each spatial cell in the city had a bearing in the study outcomes. For instance, the dataset accurately identified certain coastal areas, such as the historic peninsula, as highly susceptible to liquefaction, aligning with the findings of Aslan et al. (2018) and Masoumi et al. (2019). These studies argued that poor planning decisions and large-scale urbanisation have led to development on liquefiable soils in Istanbul and noted that reclaimed lands along Istanbul's coast experienced subsidence of up to 8±1.3 mm/year between 1992 and 2017. However, lack of data specifically modelled for Istanbul had a significant impact on the analysis and the study's results, as even areas without liquefiable soils in the northern part of the city but closer to water bodies were still assigned a liquefaction value.

Unlike earthquakes and liquefaction, tsunami hazards were concentrated in the city's coastal areas, with major effects expected on the Anatolian side and the Islands. Overall, it was observed that the southern part of Istanbul is substantially more exposed to high-intensity geophysical hazards than the northern parts. As observed by Erdik et al. (2003), this can be attributed to the fact that the area is relatively far from the fault line, coast lines and have more stable soils as compared to other areas in Istanbul.

Furthermore, the exposure analysis established that a significant percentage of buildings exposed to geophysical hazards were located in neighbourhoods of the southern part of the city. This can be attributed to development patterns that focused on inner-city growth, leading to linear development in the southern part while protecting forest land in the northern part (Kundak, 2004). Additionally, Masoumi et al. (2019) concur with this finding, noting that a significant portion of Istanbul’s developed areas are located in regions exposed to hazards, which increases the city’s overall risk.

Although buildings in these high-intensity areas are predominantly low-rise (approximately 53%), which typically translates into less vulnerability to geophysical hazards such as earthquakes compared to high-rise buildings (Demarchi, 2013), in the context of this study this assumption can be debatable, as mostly low-rise buildings may be old and fail to meet the city's planning standards. Kundak (2011) highlighted that settlement features in these areas, including unplanned and squatter developments built in the twentieth century due to insufficient urban planning processes and rapid development, increase the risk of geophysical hazards, particularly earthquakes. Reinforced concrete, constituting 59% of the buildings in high-intensity multi-hazard areas, is the most common construction material. While generally more resilient than other materials, the widespread use of reinforced concrete still calls for safety checks and building retrofitting to ensure that they withstand not to just single hazard, but all multi-hazards they are subjected to.

5.1.2. Hydrological Hazards and Building Exposure

In contrast to the concentrated impact of geophysical hazards, the exposure to hydrological hazards, such as floods and landslides, is more dispersed across Istanbul, with the European side being more susceptible to these hazards than the Anatolian side. Having almost 88% of the total surface area of the city not susceptible to flood and landslide hazards, concurs with Gill & Malamud (2014) who illustrates these hazards as having a micro to sub-local spatial scale, entailing their localised impacts on a defined spatial space. Although the study reveals only a small percentage of buildings are highly susceptible to hydrological hazards, measures need to be devised to prepare for future increases in such events, especially floods, given the current increase in such events amidst compact urban fabric and development patterns. Tuel & Eltahir (2020) emphasize that Istanbul's location in the Mediterranean basin, one of the world's most vulnerable areas to global climate change, will likely lead to more frequent hydrological events. Additionally, historical sources indicate that recent years have seen floods due to changes in climatic conditions and distorted urbanization (Tanyas et al., 2013), where Aman & Dal (2024) warn that Istanbul may face life losses due to overpopulation and dense urbanization, particularly in sensitive coastal areas.

Unlike geophysical hazards, a significant number of low-rise buildings (at least 71%) and medium-rise buildings (29%) in areas susceptible to hydrological hazards translate into higher vulnerability and risk, as buildings with fewer number of floors are more susceptible to damage of these hazards, especially floods, than high-rise structures. However, the fact that spatial datasets for both hydrological hazards (floods and landslides) were not derived from modelled scenarios, such as floods of specific return periods and intensities, rather they were based on georeferenced datasets that just indicated areas likely to flood due to their proximity to water bodies or areas identified to have active landslides also adds uncertainties in the study's outcomes. With this, it is assumed that with properly modelled dataset, which is lacking in Istanbul, the study's exposure estimations might either be over- or under-represented.

5.1.3. Critical Emergency Response Facilities and NaTech Hazards

Fire stations and hospitals are among the facilities that have proven critical for emergency response, during and after a disaster event. The study revealed that even though the European side of the city has a higher concentration of such services, a significant percentage of such facilities are highly susceptible to disaster impacts especially the geophysical hazards. These findings align with Dermachi (2013), who noted that in 2013, almost 30% of health facilities were in the most hazardous areas of the city (the southwestern neighbourhoods), making them unavailable during disaster response. An earthquake loss estimation study by IMM &Kandilli Observatory (2019) also revealed that almost 50% of essential facilities, such as health and education, in Istanbul are located in earthquake intensities of more 0.200PGA, considered as highly destructive. Dermachi (2013) further state that although the mere presence of emergency facilities might be an advantage, but their locations might hamper their maximal efficiency. Concurring with the findings that an area with several excellent emergency structures, such as the European side of the city, could be more vulnerable than another less-well equipped but in a better location. However, the fact that these are public buildings and facilities, the assumption is they might withstand the impacts of the disasters, as according to JICA & IMM (2002), public buildings are often constructed stronger or retrofitted as compared to other types of buildings.

Additionally, the study reveals the potential occurrence of NaTech hazards (such as fires), particularly following geophysical events in the city. Although both sides of the city are susceptible to these hazards, the Anatolian side shows the highest degree of susceptibility. However, JICA & IMM (2002) argue that the risk of fire spread is reduced due to the low ratio of wooden buildings in the city, which is less than 10% in all neighbourhoods. This finding is confirmed by this study, which has revealed that wooden construction materials are among the least used in the city, with concrete being the dominant material. Therefore, with efficient firefighting services in the city, the possibility of major NaTech events, especially large fires, is low.

5.1.4. Summary for multi-hazard scenarios and exposure analysis

In summary, it can be seen that a significant number of buildings and facilities are exposed to geophysical, hydrological and NaTech hazards in Istanbul. It is important to note that the study only presented the level of exposure of distinct EaR and not exact loss estimations. In this, loss estimations require not only the degree of exposure but also vulnerability levels of the EaR, which was not tackled in the study, considering time and spatial data limitations. Unless a detailed study that analyse the vulnerability of such EaR to multi-hazards is included, this study's outcomes only present degree of susceptibility and not actual loss in case of multi-hazard occurrences in the city. Even though the IMM & Kandilli Observatory (2019) conducted a loss analysis in Istanbul, the study only evaluated possible losses from earthquake hazards without considering other potential hazards in the city. The study estimated that an average of 57% of the buildings in Istanbul will not be damaged in the scenario earthquake of Mw=7.5 magnitude, 26% of buildings are expected to be lightly damaged, 13% to be moderately damaged, 3% to be heavily damaged and 1% to be very severely damaged. However, with the changing urban environments and the fact multi-hazards events are increasing in number, such analysis need to take a multi-hazard approach for comprehensive loss estimations to be achieved in megacities.

5.2. DLCs Location- Allocation Analysis in Istanbul

5.2.1. SMCA Criteria Weighting Methods

The study utilised three SMCA methods to assign weights to criteria: AHP, CRITIC and Entropy. It was observed that these methods assign distinct weights for various criteria. However, other criteria, such as geophysical hazards and slope, ranked relatively the same in both methods, although their weights changed. Feng et al. (2023) argue that these observed differences in computed weights and ranking of criteria by different methods is attributed to the characteristics of the methods. The authors further postulate that such differences in the assigned weights, justifies the reason for the need to complement diverse weighting methods in a SMCA approach. As aforementioned, entropy method determines weights of criteria based on the degree of diversification of the criteria, CRITIC is based on the comparative strength of the criteria and correlations among them, while AHP based on the subjective comparison of criteria by experts. However, it is worth to note that such analyses are as good as the subjective and spatial data utilised. With limitations encountered in extensive stakeholder involvement in the study, it can be seen that the data-driven methods of entropy and CRITIC played a crucial role in complementing the sketchy data obtained from an available expert in Istanbul.

5.2.2. 3rd Level DLCs Necessity Analysis

The realization that ineffective location selection for DLCs threatens the efficiency of humanitarian logistics operations and results in unnecessary costs (Pazour & Carlo, 2015) informed the analysis and selection of diverse indicators for different levels of DLCs based on their distinct missions. For 3rd degree DLCs, which must ensure prompt availability of materials to disaster-affected areas and victims, the main criteria were determined to be (i) proximity to disaster-affected or vulnerable areas and (ii) current development status. Dermachi (2013) argues that the availability of parks and open spaces is crucial for immediate response, both for shelter and evacuation during seismic disasters. Consequently, areas with low building density and vacant lots were proposed to accommodate these centres, which are usually temporary. The study findings revealed that some suitable areas are close to the coast, posing additional problems in case of tsunami hazards. This aligns with Dermachi (2013) observation that most open spaces in the city are along the seaside. Therefore, it is recommended that vacant spaces and lots within vulnerable neighbourhoods but far from the coast be considered. Ground verification using satellite imagery confirms that locations that were analysed as suitable using spatial analysis in GIS were feasible, highlighting the significance of integrating spatial analysis with on-ground assessments in urban planning.

5.2.3. 1st Level and 2nd Level DLCs Criteria Weights and Location Selection

In contrast to 3rd level DLCs, which must be located in areas vulnerable or susceptible to hazard impacts and can be temporary based on needs during disaster occurrences, 1st and 2nd level DLCs are usually permanent and situated in areas with little or no known hazard events. As such, the study utilized an SMCA approach to analyse and select indicators critical for the optimal location of DLCs in Istanbul. While different methods emphasized various criteria as critical for locating DLCs in the city, geophysical hazards relatively ranked higher for both levels of DLCs.

For 1st level DLCs, proximity to emergency roads and geophysical hazards were considered critical. On the other hand, for 2nd level DLCs, current development status and geophysical hazards were deemed crucial. This indicates that suitable locations for such DLCs in Istanbul should not be in areas with high multi-hazard risks, especially geophysical hazards, and should be easily reachable even during emergencies with minimal disruptions. Yilmaz and Kabak (2020) stipulate that prioritizing transportation as a critical factor for main distribution centres in emergency relief makes sense since these centres are expected to efficiently, and within shortest time possible, transport goods from various sources to lower-level logistic centres. Considering the terrain and development patterns in Istanbul, having slope as one of the least significant criteria is logical. Kilci et al. (2015) note that sometimes the costs of establishing a centre are secondary during emergencies. Additionally, with its terrain it can still be observed that developments in Istanbul already occur with little concern on the flatness of the area, which aligns with this finding.

Furthermore, the suitability maps for 1st and 2nd level DLCs illustrate that areas on the outskirts of the city are relatively unsuitable, calling for deliberate measures to enhance their viability. While these areas might initially appear suitable due to the presence vast undeveloped land, a multi-hazard approach reveals they rank as unsuitable. One reason could be the lack of essential facilities and infrastructure, such as emergency roads among others. The availability of pre-existing infrastructure is crucial to reduce setup time and avoid starting from scratch. Although IMM (2023) findings indicate less demand to necessitate the location of a number of 1st level DLCs in the Anatolian side, this study shows that the Anatolian side is actually more suitable for DLC locations than the European side. This suggests that the Anatolian side can host large centres in a single location, whereas the European side would need to distribute the same capacity across different areas.

5.3. Conclusions

The study provided a comprehensive analysis of distinct levels of DLCs in Istanbul, a megacity facing the threat of multi-hazard interactions amidst rapid urban development and population changes. This study developed an approach for selecting optimal locations for DLCs using SMCA to determine critical criteria to be utilised in megacities. By integrating three SMCA weighting methods (AHP, Entropy, and CRITIC) the study ensured that the most expert-valued, diversified, and non-redundant criteria are given higher weights, leading to more balanced and effective decision-making. The study has shown the significance of complementing expert judgements with data-driven methods, especially in times where stakeholder engagement is limited. Even though data-driven methods proved essential in scenarios of limited expert weighting of criteria, it is crucial to ensure extensive expert involvement, as data-driven methods are as good as the quality of the data utilised, hence prone to uncertainties and might not present stable results. However, regardless of the uncertainties, the study findings revealed meaningful trends and results pertaining to suitable locations and ranking of criteria for DLCs site selection of all levels in megacity Istanbul.

Additionally, the study findings reveal that megacity Istanbul is susceptible to a vast number of geophysical, hydrological and NaTech hazards. Among these hazard categories, geophysical hazards are seen to be more significant than other hazards. However, being a coastal city amidst changing urban patterns and increasing trends of climate change, it can be seen that the risk of other hazards is also increasing in Istanbul, further heightening the city's susceptibility to damaging impacts of hazards. This justifies the need for the shift from single-hazard to multi-hazard approaches in the urban development initiatives and risk analysis.

Furthermore, the fact that a significant number of EaR are located in multi-hazard prone areas increases the susceptibility of the area to multi-hazard impacts, even in the absence of loss estimation data. With the history of informal settlements coupled with inadequate planning and enforcement of building codes, the city is at high risk of succumbing to the damaging impacts of such hazards. The study findings also highlighted the importance of integrating geospatial analysis with spatial planning and humanitarian logistics to achieve resilient urban futures amidst increasing disaster risks, particularly in megacities. Utilising geospatial visualisation capabilities, the study was able to conclude that the European side of the city can accommodate for smaller units (in terms of area coverage) of DLCs structures especially for first level DLCs which require a large areal coverage. On the other hand, the Anatolian side exhibited large portions of suitable locations for DLCs, hence the same DLC unit can be accommodated on one location in the Anatolian side, can require more than one site in the European side.

Limitations: The most significant limitation encountered in this study was data availability. Data about hazards, which were crucial criteria in the study, were either georeferenced or derived from global datasets, with only the earthquake data accurately modelled from the IMM database. Digitizing can introduce errors, resulting in some offsets, such as in exact area coverage. Additionally, the liquefaction hazard was derived from a global dataset, presenting varying degrees of liquefaction potential even in areas that might not be significantly affected. The absence of local-specific datasets can produce uncertainties in the results. This highlights the continuous need for the provision and updating of hazard maps and other data sources to achieve concrete decision-making in cities. Continuous improvement of local datasets will help mitigate uncertainties and improve the accuracy of future studies.

Another significant limitation in this study was stakeholder involvement. During the field visits, the researcher encountered challenges to involve stakeholders in the selection and evaluation of the indicators for DLC allocation. This was due to political reasons, where the elections in the IMM coincided with the time for fieldwork in Istanbul. It proved difficult for the researcher to have interviews with the experts during such period. The other reason was language barrier. The researcher planned for oral interviews with the experts to ensure the questions were fully answered. However, due to the use of Turkish as the main communication language, experts were not comfortable, as such questionnaires were sent for them to answer, which could not address the issues as the oral interviews could have been. Due to these data gaps, especially on expert judgements on criteria, the researcher resorted into complementing the responses from one expert with data-driven approaches.

5.4. Recommendations for Further Study

Based on the study findings, the following recommendations can be made to be considered for further research:

1. It was noted that some areas, such as those in the northern part of the city, were initially deemed unsuitable, regardless of their low multi-hazard exposure. This can be attributed to the lack of essential facilities and infrastructure. To achieve long-term goals, providing these areas with necessary infrastructure and facilities can yield better results. Additionally, due to compact development patterns, which initially occurred in multi-hazard prone areas, it is inevitable that some DLCs especially in the second level might be in such areas in order to ensure prompt transportation to third level DLCs and beneficiaries. Therefore, future research could explore a cost-benefit analysis between two alternatives: (i) selecting DLC locations closer to urbanised and affected populations, which requires investing in constructing multi-hazard resilient buildings and facilities, or (ii) selecting locations further from urbanised areas, such as the north-western part, which are entirely safe from multi-hazard impacts, and focus on strategies that reduce increased travel and relief distribution travel time, brought by the absence of essential facilities and emergency roads.

2. The current study focused on analysing and recommending an approach for selecting suitable sites for DLCs in Istanbul. The main focus was on identifying relevant criteria to guide such decisions and applying them to determine suitable sites within the city's boundaries, using the qualitative approaches of SMCA. Therefore, future research could expand on this by focusing on vehicle routing problems and determining the best optimal locations from the identified suitable areas. An network analysis problem can be utilised where all network constraints such as road intersection, traffic congestion, road blockage, which affect travel times and speed during times of disasters can be input variables. In this, the computed suitable areas can act as points of origins while the evacuation sites and points of needs can serve as destination points. Mathematical models based on various assumptions and fewer criteria to decide which areas might be more optimal, would be an ideal approach. Through this, representative sites for each DLC level, that best serve their subsequent level can be determined. However, due to the complexity of the process, such studies might require smaller spatial units to achieve comprehensive results.

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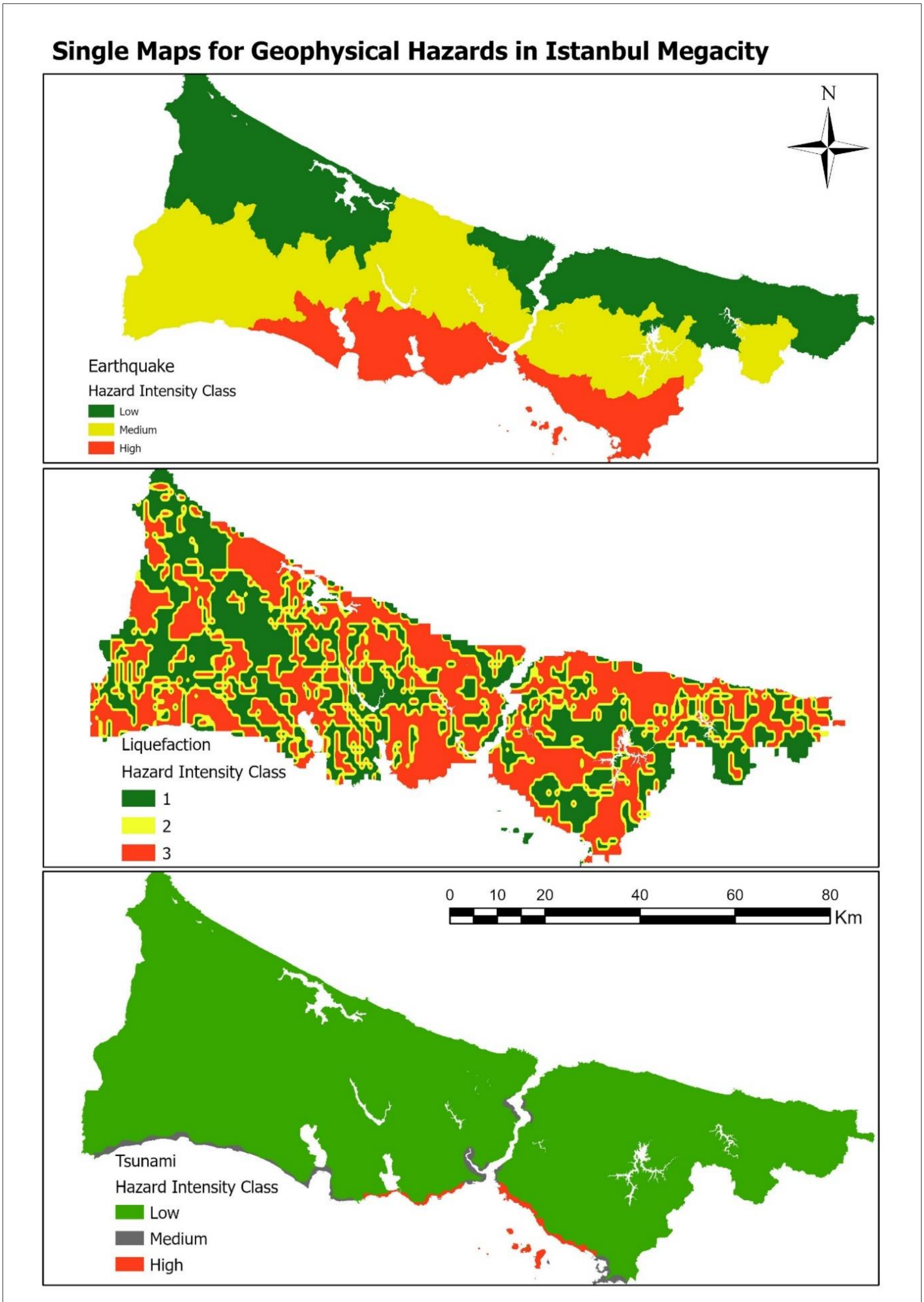
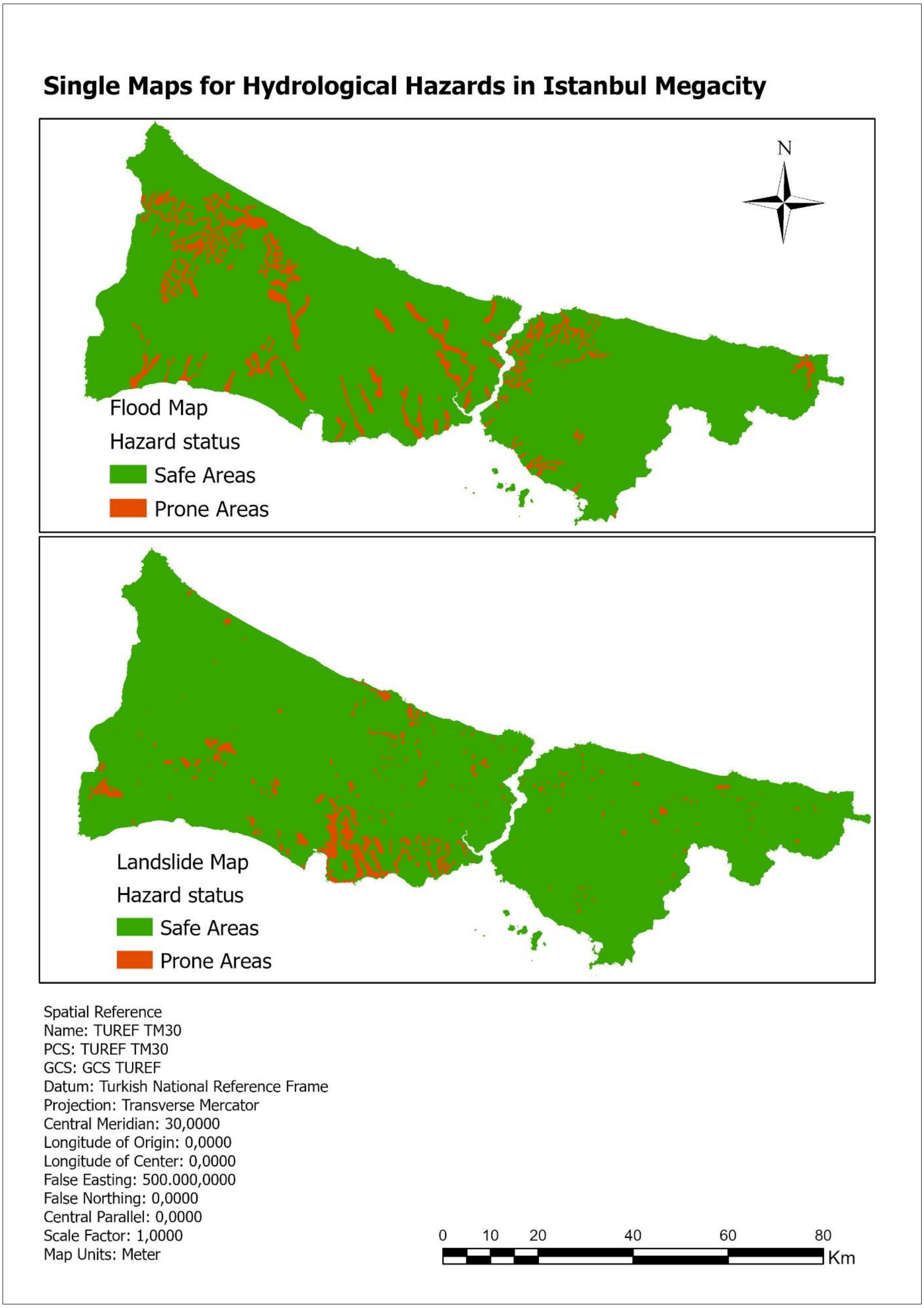
6. APPENDICES

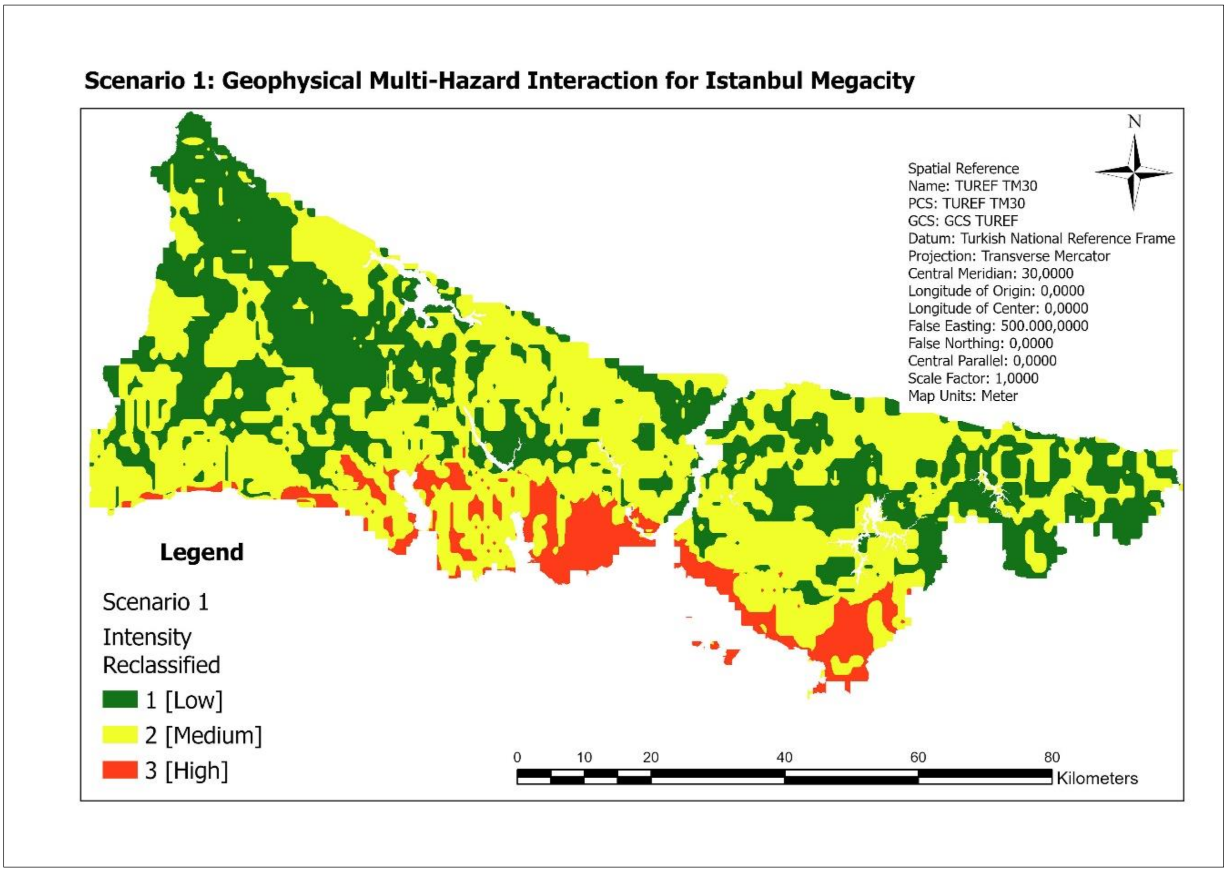
Appendix 1: Single Maps for Geophysical Hazards in Istanbul Megacity (Source: Author, 2024)



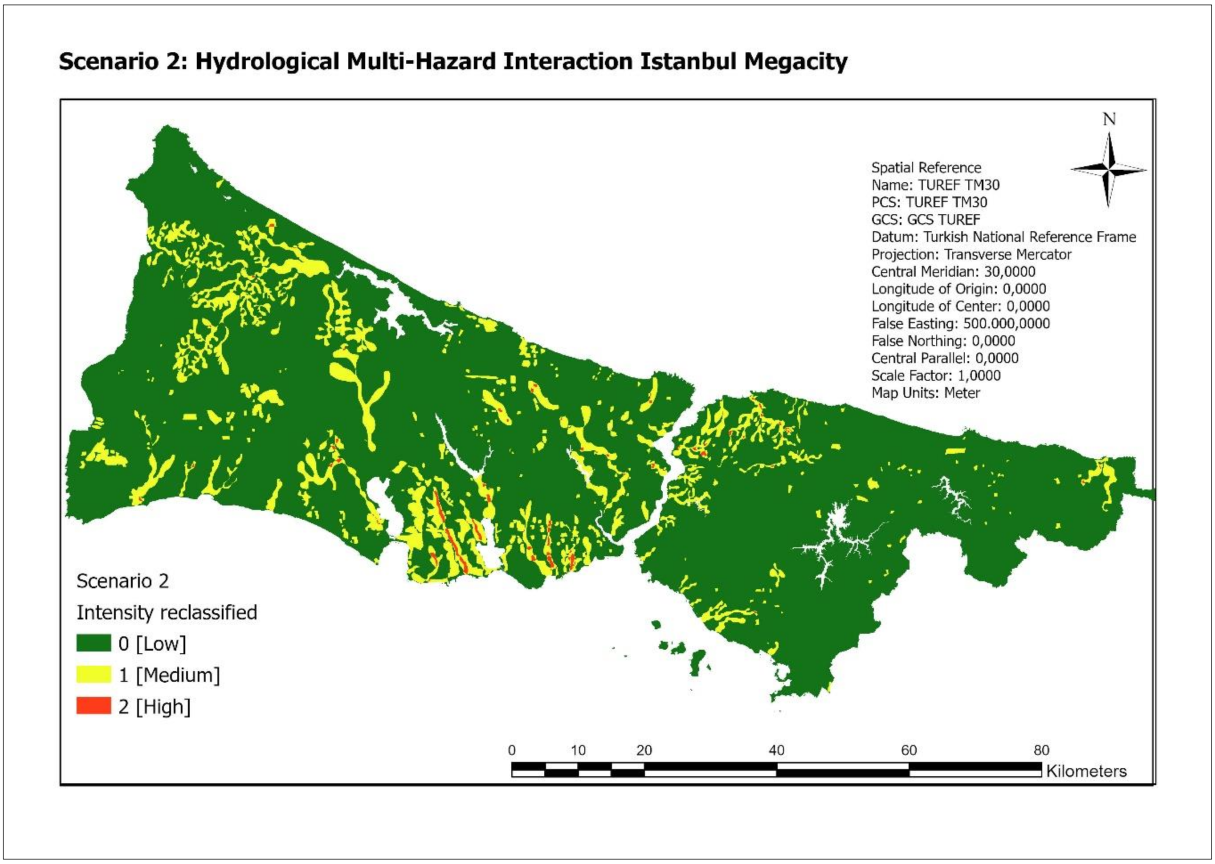
Appendix 2: : Single maps for Hydrological hazards in Istanbul megacity (Source: Author, 2024).



Appendix 3: Composite geophysical multi-hazard intensity map for Istanbul megacity (Source: Author, 2024)



Appendix 4:: Composite hydrological multi-hazard intensity map for Istanbul Megacity (Source: Author, 2024)



Appendix 5: Consent Form

CONSENT FORM

Research Title: ***Analysing and Selecting Key Indicators for Optimal Location of Disaster Logistics Centres (DLCs) in a Multi-hazard and Risk Context: Case of Istanbul Mega-city, Turkey.***

Researcher Information:

Name : Tionge Munthali- MSc student in Geo-information Science and Earth Observation, specialising in Urban Planning and Management

Affiliation : Faculty of Geo-information Science and Earth Observation (ITC), University of Twente, Netherlands
Paratus Project, University of Twente, Netherlands

Contact details : t.c.munthali@student.utwente.nl

I am an MSc student at the Faculty of Geo-information Science and Earth Observation at the University of Twente, the Netherlands. I am conducting a study on ***Optimal Location of Disaster Logistic centres (DLCs) in the Context of Multi-hazards and Risk in Istanbul Megacity***. The premise of the study is that amidst experiencing rapid and uncontrolled urban growth, Istanbul city is also exposed to a variety of natural hazards (such as earthquakes, floods, heat-waves etc); calling for a comprehensive analysis of measures and indicators used to optimally and strategically locate DLCs (e.g. evacuation shelters, warehouses, medical centres) so as to avoid and/or reduce human suffering and development losses in the city. Through a set of indicators that will be established by this study, it is believed that such indicators will be utilised to analyse the existing DLCs and identify potential new DLCs sites within the city, which will not only withstand the impacts of one natural hazard but a variety of spatially relevant hazards.

Based on my knowledge as a researcher (considering your day-to-day work activities), I deem you as a relevant official to help me with the information needed to make this study a success. It is through this form, therefore, that I request for your consent to participate in the study, which will involve semi-structured oral interviews and expected to take ***approximately 90 minutes.*** Thank you.

Please tick the appropriate box	***Yes***	***No***
I have read and understood the information about the study, and I voluntarily agree to participate in the aforementioned research study.	☐	☐
I understand and agree that I can refuse to answer any question or withdraw from participating in the study at any time.	☐	☐
I understand that there are no compensations (monetary and other benefits) attached to my participation in the study.	☐	☐
I agree that the researcher can audio record (later to be transcribed) the interviews and I assign copyright to such recording to the researcher.	☐	☐
I understand that my name, identity and information provided will be treated with high. confidentiality and anonymised.	☐	☐
I understand that even with the researcher's efforts of anonymisation, there is still a risk. that I could be identified based on my responses.	☐	☐
I understand that the information provided will be used purely for academic purposes. and the data will only be accessed by the researcher and where needed by the afore-mentioned affiliated institutions.	☐	☐

By signing below, you acknowledge that you have read and understood the information provided above.

Statement of Consent

I have read and understood the above-stated information and I voluntarily agree to participate in the study.

…………………………………………..	………………………..	……….……………
Name of Participant	Signature	Date

Appendix 6: Interview guides for the Key Informant Interviews in Istanbul Metropolitan Municipality

INTERVIEW GUIDE: KEY INFORMANT INTERVIEWS

My name is Tionge Munthali, a second-year MSc student at the Faculty of ITC, University of Twente, the Netherlands. I am conducting a study on ***Optimal Location of Disaster Logistic centres (DLCs) in the Context of Multi-hazards and Risk in Istanbul Megacity***. The research is done in partial fulfillment of the requirements of Master of Science in Geo-information Science and Earth Observation: Urban Planning and Management. Some study aspects such as emergency planning, preparedness and response activities together with historical experiences on the situation during, after and in the aftermath of a disaster event, require experts' knowledge and opinions, hence the reason behind the researcher approaching you. The main goal of the study is to come-up with a set of key indicators that can guide the planning of DLCs in the city, which is prone not to just one hazard, rather a multiplicity of natural hazards. Your participation in the study is highly appreciated. The interview will take ***25-30 minutes.***

Interview Date ……/…………/2024.

A. Institution, Roles and Responsibilities of Key Informants

Q1. What is your position at the institution?

Q2. Can you briefly explain your specific roles/ projects and experience pertaining to disaster emergency preparedness and response?

Q3. What are the general roles and responsibilities played by this unit, under IMM in disaster emergency planning, preparedness and response?

Q4. In executing your roles (*as a person & unit*), which other institutions, departments or players do you collaborate with in disaster emergency planning and preparedness?

B. Disaster Impacts and Subsequent Needs

Q1. Have you ever witnessed cases where different hazards occur simultaneously or have been triggered by a single initial disaster event?

Q2. Based on your past experience, which goods and services are usually needed to respond to the disaster impacts?

C. Disaster Logistic /Emergency/ Relief Centers Planning

Q1. Which natural hazards do you usually take into consideration when planning for and locating these DLCs?

Q2. Based on your experience, which of the following criteria highly influence the location of DLCs. *Rank from 1(less influence) to 5 (high influence)*

- Location and transportation
- Current situation and plan status
- Ownership information
- Integrated disaster risk status
- Proximity to protected areas
- *Others.*