Evaluating the role of critical infrastructure in disaster management

A case study of Hatay in 2023 Turkey - Syria earthquake

by

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Mine Imirzalioglu
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Executive summary

This thesis investigates the role of critical infrastructure (CI) in disaster management, focusing on Hatay in the 2023 Turkey - Syria Earthquake. Given the extensive destruction that impacted critical infrastructure systems, this study aims to investigate both the underlying factors that contributed to infrastructure failures and the effectiveness of the long-term recovery plans for the city. Through a case study approach, this thesis provides insights that not only aid in understanding the earthquakes impact on Hatay's infrastructure but also offers broader implications for improving resilience in other disaster-prone regions.

The earthquake devastated critical infrastructure in Hatay, delaying rescue and emergency response efforts and exacerbating loss of life and property damage. This research seeks to uncover the root causes that contributed to these failures and evaluate post-disaster recovery plans. The studys primary question centers on the planning and management shortcomings within critical infrastructure systems and explores how these might be rectified in future disaster responses. The objectives include identifying the key critical infrastructures, analyzing root causes of the key critical infrastructure's system failures, and evaluating the long-term recovery plans effectiveness in mitigating risks.

A mixed-methods approach was selected for this case study to provide a comprehensive understanding of the key factors at play. The study includes qualitative analysis based on semi-structured interviews enabling the identification of key critical infrastructures based on stakeholder experiences and perspectives. To investigate the root causes of system failures, Fault Tree Analysis (FTA) is employed, offering a systematic and logical approach to identify underlying issues and contributing factors. Additionally, the study evaluates the effectiveness of long-term recovery plans through a comparative analysis of retrospective and prospective risk assessments.

In the analysis of the interviews education sector, healthcare services and transportation systems emerged as the key critical infrastructure, with their failure significantly impeding immediate response efforts and their importance in recovery. The education sector, in particular, emerged as a crucial component for long-term recovery and the restoration of societal normalcy. Meanwhile, the healthcare system struggled to manage overwhelming patient surges, while transportation bottlenecks, worsened by damage to road networks and airports, severely delayed the delivery of essential services and resources.

The FTA revealed several critical failures in CI planning and management. Healthcare services experienced capacity overload and staff shortage resulting from resource allocation and distribution failures, lack of seismic retrofitting and neglected structural faults in hospital buildings and restricted access to hospitals originated from transportation system failure. Transportation systems suffered from non-functional airport and road network failure originating from poor site location, previous inaccurate site assessments, inadequate design for site conditions, lack of maintenance and lack of redundancy, leaving many areas inaccessible post-disaster. A recurring theme across CIs was a lack of region-specific resilience planning to account for Hatays unique geographic context.

While the recovery plans address several CI weaknesses identified in the root cause analysis, significant gaps remain, especially in aligning strategies with the identified pre-disaster vulnerabilities. Although the recovery efforts incorporate bed capacity improvements and increased redundancy, heightened risk concerning neglected structural faults inaccurate site assessment were observed.

The increased risk suggests that the recovery plans may be addressing symptoms rather than the root causes of vulnerabilities. This points to a need for recovery strategies that go beyond immediate repairs, focusing instead on addressing foundational risks to ensure lasting resilience and reduce the likelihood of repeated failures.

This case study highlights the devastating effects of infrastructure failures during disasters. By addressing the root causes of these failures and implementing more comprehensive, resilient recovery plans, Turkey can build a disaster management framework that is robust enough to withstand future natural disasters. Although disaster management is highly context-dependent and cannot be universally applied, this study is important at a broader level, highlighting the need to identify the root causes of system failures in order to effectively mitigate future disaster risks.

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Theory

1
Introduction

As population in urban areas increase and cities become denser, the potential for catastrophic impacts from both human-induced and natural disasters ranging from pandemics and industrial accidents to earthquakes and floods increases. Considering these escalating risks, significance of disaster management is higher than ever.

Critical infrastructure management is one of the key factors of disaster management, especially in the preparedness phase. Strong critical infrastructure enables communities to withstand and recover from disasters more effectively by ensuring the continuity of essential services such as transportation, energy, water, healthcare, and communication (UNDRR, 2022a).

Especially, countries which are vulnerable to specific natural disasters should prioritize disaster management, adapting their strategies to address their unique circumstances to increase resilience. Turkey is one of those countries that is vulnerable to earthquakes.

Turkey's vulnerability to earthquakes is primarily due to its geological position. The country is situated on several active fault lines, including the North Anatolian Fault (Erdik, 2013), which runs close to some of its most populous and economically significant cities like Istanbul, and East Anatolian Fault (McKenzie, 1976). Figure 1.1 illustrates the earthquake risk levels across Turkey, clearly indicating that a significant portion of the country is at high risk. According to the Disaster Risk Management Knowledge Centre (DRMKC) established by the European Commission, Turkey's overall risk profile is categorized as medium level, with a notable earthquake risk rating of 9.3 out of 10 (DRMKC, 2024).

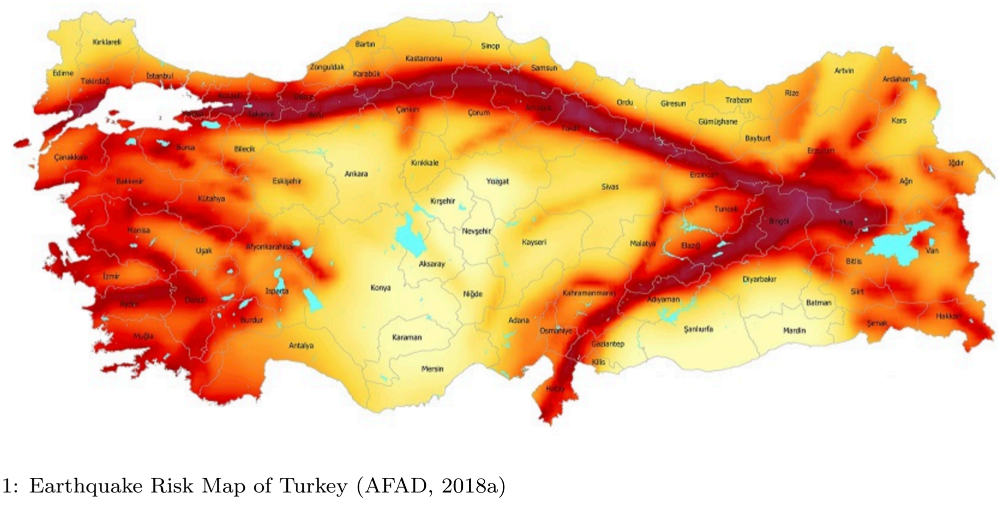

Figure 1.1: Earthquake Risk Map of Turkey (AFAD, 2018a)

Turkeys governance of critical infrastructure disaster management involves several key institutions. The primary agency responsible is the Disaster and Emergency Management Authority (AFAD), which operates under the Ministry of Interior (AFAD, 2017). AFAD coordinates all national disaster response efforts, including earthquake preparedness and mitigation. It works together with local municipalities, which have their own disaster management units. Additionally, the Ministry of Environment, Urbanization, and Climate Change plays a role in implementing building regulations to ensure that infrastructure can withstand seismic activities (AFAD, 2017). Other important stakeholders include the Turkish Red Crescent, which provides emergency relief and humanitarian assistance (Kzlay, 2024), and various NGOs that support community resilience initiatives.

AFADs disaster risk mitigation plan, the Turkey Risk Reduction Plan (TARAP) (AFAD, 2022b), and its disaster response framework, the Turkey Disaster Response Plan (TAMP) (AFAD, 2022a), are both currently in effect. Meanwhile, the post-disaster plan, the Turkey Post-Disaster Recovery Plan (TAYSB), has completed its preparation phase but has not yet been implemented (AFAD, 2018b). These nationally developed plans establish a strategic framework that outlines the tasks to be carried out before, during, and after a disaster, clearly designating the roles and responsibilities of the relevant institutions and organizations. TARAP and TAMP include action plans in local level with Provincal Disaster Risk Reduction Plan (IRAP) and Provincal Disaster Response Plans effective in all 81 provinces of Turkey. These plans set out the activities for risk reduction and response in according to special priorities in local level (UNDRR, 2022b). Detailed overview of disaster management in Turkey can be found in section 2.4.

Turkey has faced numerous devastating earthquakes over the years. One such event occurred in 1999 when the zmit earthquake, also referred to as the Kocaeli earthquake, devastated northwestern Turkey with a magnitude of 7.6 (Bakr & Boduroglu, 2002). This earthquake struck not only the city of Izmit but also carried out throughout the densely populated region, including Istanbul, often considered one of the most crowded cities in Europe. It resulted in widespread destruction, with thousands losing their lives and tens of thousands left homeless in the aftermath of the disasters (BBC, 2023). 1999 Izmit Earthquake drew attention to the country's lack of preparedness. As defined by Öcal (2021), the decade following this earthquake is referred to as the 'Awakening' period for this reason.

However, more than two decades later, Turkey was struck by one of the most devastating earthquakes in its history, raising questions about whether the country had learned from its past disasters (Ashdown, 2023). On February 6$^{\text{th}}$, 2023 southeastern Turkey was hit by two strong earthquakes, with magnitudes of 7.7 and 7.6, centered in Kahramanmaras and Elbistan (AFAD, 2023b). These earthquakes caused great destruction in both Turkey and Syria. The impact area of the earthquake in Turkey covered 11 provinces and affected a total of 14 million people (Independent, 2024) which is equal to 16% of the country's total population. In Turkey alone, more than 50.000 people lost their lives and 107.213 were injured (AFAD, 2023a). Among the injured, hundreds suffered the loss of a limb. Figure 1.2 illustrates the number of fatalities and injuries in each affected city. The data shows that these numbers are significantly higher in Hatay compared to other cities.

Search and rescue efforts began promptly after the earthquakes and continued tirelessly for days. The Turkish government has classified this earthquake as a Level-4 emergency under the Turkey Disaster Response Plan (TAMP), which is the highest level of crisis in the plan. This declaration calls for international aid in addition to the involvement of both first and second group supporting provinces and national resources (Balaban et al., 2024).

One month after the earthquake, the Presidency of Strategy and Budget announced that the total cost of this disaster to the country was 103.6 billion dollars (Strategy and Budget Office of the Presidency of the Republic of Türkiye, 2023). This amount represents a significant financial burden, equivalent to a substantial portion of the national budget, and underscores the extensive economic impact of the disaster.

The 2023 earthquake in Turkey highlighted critical deficiencies in the country's disaster preparedness and response, particularly regarding the management of critical infrastructure. It is important to recognize that the sheer number of casualties and extent of destruction cannot be attributed only to the earthquakes themselves. While powerful earthquakes are a common occurrence in various parts of the world, including countries like Japan and Chile, they do not always result in such catastrophic outcomes. The disparity in the impact of similar magnitude earthquakes can often be traced back to differences in disaster management.

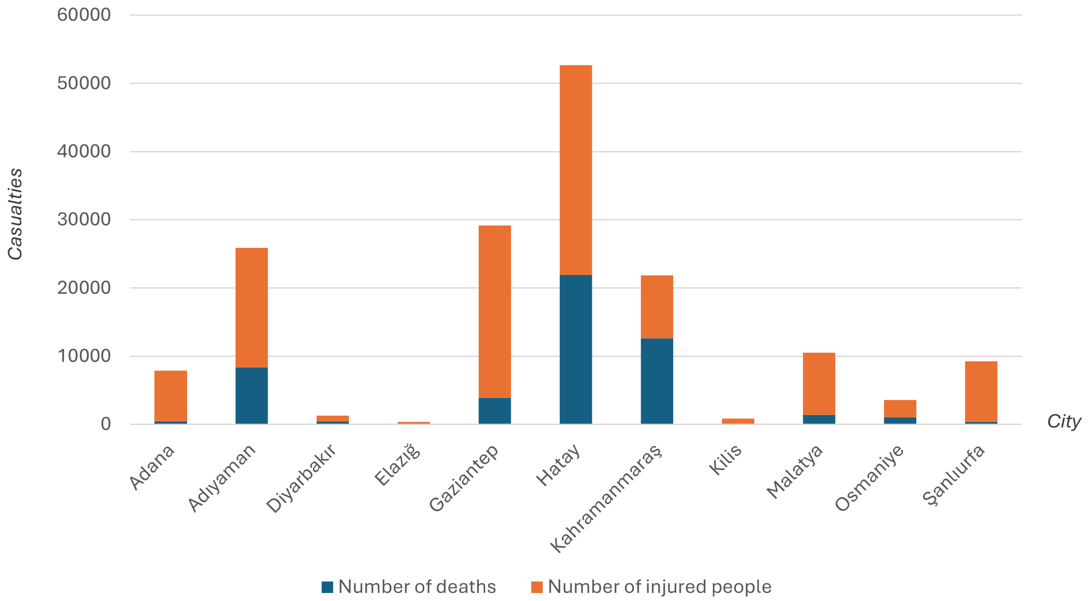

Figure 1.2: Number of deaths and injured people (AFAD, 2023a)

1.1. Problem statement

The 2023 Turkey Earthquake caused either complete collapse or severe damage to city of Hatay's critical infrastructure. Affected facilities include the airport, water pipeline, telecommunication systems, railroad tracks, main roads, hospitals, and the harbor (Hatay Planning Office, 2024). The damage to the airport and main roads caused significant delays and difficulties in search and rescue efforts, as aid and emergency services struggled to reach the city in time.

The problem, therefore, lies in the shortcomings within disaster management processes and the planning and management of critical infrastructure. These issues led the earthquake to become such a catastrophic event in Hatay. This extensive damage not only increased the immediate destruction but also severely hindered rescue and relief operations, as critical facilities were rendered inoperative or difficult to access. The root causes of these failures remain unknown more than a year after the earthquake. Understanding what went wrong is essential to fixing these problems and building resilience against future disasters. Hatay was chosen as the case study for this research due to its high level of impact and the extensive damage to its critical infrastructure and the significant loss of life and injuries. The city's experience during the 2023 earthquakes provides an example of how failures in critical infrastructure planning and management can increase the destruction effects of natural disasters.

1.2. Knowledge gap and research objectives

The current literature on post-disaster recovery mostly focuses on evaluating the implementation and outcome of recovery plans but often neglects pre-disaster vulnerabilities and the root causes of critical infrastructure failures. In implementation evaluations, the focus is on whether the plans are being carried out as intended, while outcome evaluations assess both the alignment of the plans with their intended goals and the effectiveness of the final results. While studies on critical infrastructure and disaster response offer insights into system vulnerabilities, they largely overlook the factors contributing to these failures. Additionally, recovery policies are often reactive, hastily developed in response to urgency. This reactive approach, combined with a lack of flexibility, frequently results in policies that are misaligned with essential needs, leaving them unused or ineffective when action is needed. These policies also tend to overlook the deeper causes of vulnerability, potentially exacerbating social, economic, and environmental issues. Moreover, in disaster management and critical infrastructure planning, it is crucial to consider the specific location of the target area. These plans cannot be generic as they are highly context dependent since the needs and influencing factors vary significantly based on geographic and local conditions. This research aims to bridge the gaps by investigating the root causes of vulnerabilities in critical infrastructure and evaluating recovery plans in terms of whether and how they address these weaknesses, with a focus on the specific needs and conditions of the region.

1.2.1. Research questions and objectives

The objective of this research is to systematically analyze the factors contributing to the failure of critical infrastructure during the 2023 Turkey earthquake in the city of Hatay and to evaluation of subsequent long-term recovery plans. For this purpose, the main research question in this thesis is defined as the following:

What role did planning and management of critical infrastructure played in Hatay during 2023 Turkey - Syria Earthquake?

Objectives to answer main question subsequent sub-questions build upon each other, with the analysis of each providing essential input for the next in line which as follows:

1. Identification of key critical infrastructure: Determine which critical infrastructure failure contributed most to the widespread destruction.

   RQ1: During and in the aftermath of the earthquake, which critical infrastructure failures had the most significant impact on resilience and immediate recovery?

2. Analysis of disaster planning and management of CIs: Investigate the management practices of critical infrastructure before the earthquake to identify root causes of these failures and their impact on disaster resilience and immediate recovery efforts.

   RQ2: What key factors and resulting consequences in critical infrastructure planning and management contributed to widespread destruction?

3. Evaluation of long-term plans: Assess the impact of long-term recovery plans on previously identified risks associated with the earthquake, specifically examining whether these plans have mitigated these risks over time.

   RQ3: How have long-term recovery plans for critical infrastructure changed the risks identified after the disaster?

By analyzing Hatay's response to the 2023 earthquakes, this research seeks to provide valuable insights into improving critical infrastructure management in disaster management strategies not only for Turkey but also for other countries and regions vulnerable to similar natural disasters.

1.3. Research approach

This study adapts a case study approach with mixed-method that combines both qualitative and quantitative methods to evaluate Hatay's infrastructure resilience and recovery processes. This provides a comprehensive analysis of critical infrastructure failures and post-disaster recovery efforts. The methodology developed for this study includes Fault Tree Analysis (FTA) and risk assessment, which can be replicated in similar research contexts.

1.3.1. Mixed-methods approach

The mixed-methods approach to capture both qualitative insights and quantitative data to explore critical infrastructure resilience and post-disaster recovery. Mixed methods allow for a comprehensive understanding of complex concepts by integrating qualitative insights with the statistical support of quantitative data. The mixed-methods approach enables the research to bridge the gap between individual, context-specific narratives and generalizable, data-supported patterns. This approach allows for the triangulation of findings, where qualitative and quantitative data can confirm, complement, or highlight discrepancies in the analysis. This triangulation enhances the validity and reliability of the findings.

The qualitative component involves thematic analysis of interviews and reports to understand root causes of infrastructure failures and how these factors influenced disaster response and recovery efforts. The goal is to undercover the factors that contribute to infrastructure vulnerabilities and the effectiveness of recovery efforts. By capturing personal narratives and contextual information, research aims to provide a deeper understanding of how pre-existing conditions and local policies impact disaster response and recovery processes.

In addition to qualitative data, the research incorporates quantitative methods to support and enrich the findings. This includes collecting and analyzing data on infrastructure capacity and risk assessments that are relevant to post-disaster recovery. While quantitative data adds a valuable dimension to the analysis, the primary emphasis remains on the qualitative insights.

1.3.2. Case study approach

Figure 1.3: Satellite view of Antakya, Turkey, captured on December 22, 2022 (Google Earth, 2022)

Figure 1.4: Satellite view of Antakya, Turkey, captured on March 03, 2024 (Google Earth, 2024)

The research approach selected for this study is a case study approach. Disaster management is inherently context-dependent, as the effectiveness of strategies and interventions varies based on regional vulnerabilities, geographical characteristics, political dynamics, and geological contexts. A case study approach is particularly useful for understanding infrastructure resilience in a real-world setting, as it allows for an in-depth analysis of unique regional and systemic challenges.

This approach facilitates a comprehensive examination of how specific pre-existing conditions and policies influence a city's disaster response and recovery efforts after an earthquake. By employing a case study methodology, the goal is to explore the dynamics between various factors, such as infrastructure's capacity and resource allocation, which are critical for effective disaster management.

Figure 1.3 and Figure 1.4 illustrate the extensive damage inflicted on Antakya, Turkey, by the 2023 Turkey-Syria earthquake. The satellite view captured on December 22, 2022, shows the city in its pre-earthquake state, while the subsequent image from March 3, 2024, reveals a stark transformation, depicting how the area appears nearly wiped out. Such visual evidence underscores the catastrophic impact of the disaster and highlights the critical need for robust disaster management strategies designed for to the region's specific vulnerabilities.

While Hatay was chosen due to the high impact of the earthquake in the area, the regions specific geological and geophysical conditions provide new insights into how local circumstances can affect disaster management practices. It is important to acknowledge that the outcomes of this case study may be specific to Hatay's context, which limits generalizability. The nature of disaster management as its highly context-dependent makes it challenging to apply findings universally. Nonetheless, this research aims to offer valuable insights for infrastructure resilience planning in regions facing similar risks, while recognizing the limitations inherent in transferring lessons learned from one context to another. Another limitation of this study is data availability as access to detailed and up-to-date data on infrastructure conditions and government disaster management and recovery plans might be limited.

2
Literature Review

2.1. Search description and criteria

For this literature review, aim is to explore existing research on disaster management, critical infrastructure, and resilience, with a focus on understanding the factors contributing to the failure of critical infrastructure during an earthquake. Relevant research and case studies were investigated. The review includes studies from peer-reviewed journals, conference proceedings, and relevant reports and publications. The search was conducted in databases such as PubMed, Web of Science, and Google Scholar. Key search terms are "disaster management", "critical infrastructure", "resilience" and "earthquake". The search was limited to publications with languages Turkish and English.

2.2. Disaster management

Disaster management encompasses a comprehensive range of activities aimed at addressing issues throughout all phases of the disaster cycle: preparedness, response, and recovery. These phases are crucial in ensuring that communities can effectively mitigate, respond to, and recover from disasters (López-Carresi et al., 2014).

- Preparedness is planning and training activities designed to ensure resilience and effective response.
- Response is plan of the immediate actions taken to ensure safety during the disaster.
- Recovery focuses on the bouncing back and rebuild efforts after-math of the disasters. (Oloruntoba et al., 2017)

Theoretical models such as Disaster Management Cycle (DMC) (Tay et al., 2022) and the Pressure and Release (PAR) Model (Wisner et al., 2004) and frameworks such as Sendai Framework of United Nations Office for Disaster Risk Reduction (UNDRR, 2023) are often used to understand the dynamics of disaster management and the vulnerabilities that contribute to disaster risk.

Main goal of disaster management is to increase the resilience of the communities and systems affected by disasters, enabling them to withstand and bounce back more effectively (Sandifer & Walker, 2018).

Resilience is the capacity of a system, community, or society facing risks to withstand, absorb, adjust to, and recover from the impacts of disasters promptly and effectively (UNDRR, 2007a). The 3-D Resilience framework of Béné et al. acknowledges resilience as the capacity to address adverse changes and shocks, encompassing aspects like buffering impacts, bouncing back, absorbing shocks, adapting, and transforming. It identifies absorptive, adaptive, and transformative capacities as core components of resilience (Béné et al., 2012). Resilience encompasses a wide range of factors, including physical infrastructure, social networks, economic resources, governance structures, and cultural practices.

2.3. Critical infrastructure and services in disaster management

The Sendai Framework which represents the United Nations' primary strategy for mitigating disaster risk from 2015 to 2030 (Nekoei-Moghadam et al., 2024), highlights the importance of making critical infrastructure resilient as one of the key elements for reducing disaster risk. (UNDRR, 2022a). The framework emphasizes that poor management of critical infrastructure can result in significant economic losses and loss of life (OECD, 2019).

Indicators distinguishing critical infrastructure from regular infrastructure include the scale of impact in case of failure, the essential nature of the services provided, and the extent of interdependency with other systems (Setola et al., 2016). The definition of critical infrastructure differs among countries. National Cyber Security Center of UK defines critical infrastructure as 'national assets that are essential for the functioning of society' (National Cyber Security Center, 2024), while according to Federal Emergency Management Agency in the US, it is the combination of three interwoven elements: physical (tangible property), cyber (electronic information and communication systems) and human (critical knowledge of functions or people) (FEMA, 2013).

Despite these divergent definitions, the most widely accepted one was done by UNDRR, defining critical infrastructure as the physical structures, facilities, networks and other assets which provide services that are essential to the social and economic functioning of a community or society.' (UNDRR, 2017). Services and assets that are most frequently linked with this term include: transportation systems, security services, telecommunication, education, shelter, health services, and energy and water supply. Transportation systems enable distribution of essential supplies such as food, medical aid, and equipment. Moreover, transportation is fundamental to economic activities and the supply chain, influencing national productivity and global trade (Dias et al., 2018). Security services maintain law and order, prevent crime, and ensure public safety (Phillips, 2011). Telecommunication services essential for governance and national security (Gurlev et al., 2018). During emergencies and disasters they provide timely communication between emergency respond agents and people who need of help. Unreliable communication hinders efficient coordination and decreases the effectiveness of relief operations (Patricelli et al., 2008). Education is considered as critical infrastructure because it is considered fundamental for the functioning society (Grigore, 2021). Shelters can be considered in few categories and emergency shelters, temporary shelters and permanent housing are examples for the categories (Bashawri et al., 2014). In literature, housing is essential for society as they ensure well-being, security and stability of people. Moreover, housing has significant importance for the economy. Access to safe, affordable housing is fundamental to social stability, community and economical development, and overall quality of life (Kraatz et al., 2022). Healthcare provides essential services that protect public health ensuring medical treatment and emergency services which are vital for maintaining societal well-being (Lavin et al., 2006). Lastly, water and energy supply considered as critical infrastructure as they provide supplies to support basic human needs and societal functioning. While water is essential for drinking, sanitation, agriculture and overall public health, energy is necessary for heating, power homes and businesses, healthcare services, and communication services (Al-Saidi et al., 2020).

Additionally to being essential on their own, critical infrastructures also highly interdependent to each other. A failure in one critical infrastructure could potentially trigger cascading effects across other systems. For instance, blocked roads disrupt healthcare access by delaying ambulances and the delivery of medical supplies, critically impacting emergency care. Transportation blockages also prevent heavy machinery from reaching disaster sites to clear rubble, delaying access to people trapped beneath and increasing the risk of casualties. Road damage similarly delays crews from repairing electricity and water systems, leading to prolonged outages affecting hospitals. Communication networks suffer, as delays in restoring connectivity complicate coordination between emergency teams and isolate affected communities. Rescue teams face access challenges, and waste management services are limited, creating unsanitary conditions and raising health risks. In the case of Hatay, many earthquake victims were forced to rescue their loved ones trapped beneath rubble on their own, as blocked roads severely delayed aid from reaching certain areas. This situation was particularly prevalent during the critical first two days following the earthquake, when widespread road damage made it difficult for rescue teams and equipment to access affected zones in a timely manner (Karakas, 2023). Moreover, damage to electricity supply affected healthcare services. At Kirikhan Public Hospital, a power outage occurred, and the backup generator failed to start. Response teams were unable to reach the hospital in time due to blocked roads, preventing them from addressing the issue. The loss of electricity was particularly critical for ICU patients, who rely on life-supporting machines. In Kirikhan Public Hospital, 20 ICU patients lost their lives as a result of the power outage (Tahincioglu, 2024). In this case, we see the interdependencies between transportation, electricity, and healthcare. Thus, it is important to investigate these structures considering their dependency to each other as exploring one structure alone does not give a complete picture of the overall resilience and functionality of critical infrastructures. Interconnectedness of critical infrastructures in literature was further investigated more in subsection 2.3.4.

In conclusion, all of these services are essential for stability within community. Moreover, interruption in them can lead to increasing effects on the initial impact and potentially causing widespread chaos and vulnerability (Gordan et al., 2024).

2.3.1. Education sector in disaster management

Education has an important role in disaster management by promoting resilience within communities and ensuring the continuity of social functions. Schools can be considered as community hubs, and they are not only responsible for educating children but also serve as shelters, information, coordination, and psychological support centers during and after disasters. The resilience of school infrastructure, disaster preparedness education in schools and the ability of educational institutions to maintain functionality during crises, is crucial in disaster risk reduction and community recovery.

Education is widely recognized as a critical component of disaster risk reduction (DRR). It ensures children and communities have the knowledge and skills necessary to respond effectively to disasters. Baytiyeh (2017) highlights the importance of school resilience, where schools can act as centers of social unity and community support during recovery efforts (Baytiyeh, 2017). This underscores the educational sector's dual role in both mitigating immediate disaster impacts and contributing to long-term recovery and resilience.

According to research by Tong et al. (2012), education about disaster preparedness, particularly in vulnerable regions, significantly reduces the effects of disasters. Educating students and teachers on disaster preparedness strategies enables them to act as informative actors within their communities, thereby extending the reach of disaster risk reduction efforts beyond the school setting (Tong et al., 2012).

The role of education in promoting disaster awareness is also evident in international frameworks such as the Hyogo Framework for Action (UNDRR, 2007b) and the Sendai Framework (UNDRR, 2023), both of which emphasize the need for integrating disaster risk reduction into educational curriculum.

The structural resilience of school buildings is another concern of disaster management policies. Schools often function as emergency shelters and relief distribution centers during and after disasters. Therefore, ensuring their resilience is essential. The literature identifies several challenges to achieving this resilience, particularly in earthquake-prone regions. To assess the earthquake resilience of school buildings, Fontana et al. (2021) propose disaster resilience indicators specifically designed for school infrastructure in their research which was used in their case study in Calabria Region, Southern Italy. The indicators in this study have been broken down into three components: baseline conditions, resources, and functionality (Fontana et al., 2021). These indicators give valuable insights on how resilience of buildings in education sector can be measured. Using these indicators they asses the resistence of school buildings in Calabria and focus on the issue of outdated and structurally inadequate school infrastructure in the region. For instance, for their case study approximately 40% of school buildings are located in seismic risk-prone areas, yet only 13% have been built according to seismic construction standards (Fontana et al., 2021). This gap in infrastructure resilience creates extra difficulties in recovery periods and adds to increased social vulnerability, especially in regions with socioeconomic weaknesses.

Despite the acknowledged significance of education in disaster management highlighted in the literature, it remains an often neglected aspect of disaster planning and recovery, underscoring the need for greater investment in school infrastructure and disaster preparedness education.

2.3.2. Healthcare services in disaster management

Healthcare services are a critical component of disaster management, particularly during the response phase, where they often stand as the most vital element. In the immediate aftermath of a disaster, the timely and effective delivery of medical care can make the difference between life and death for those affected. Rescue teams and healthcare services collaborate closely during disaster response efforts. While rescue teams focus on locating and saving survivors from the rubble, healthcare services provide essential treatment to the injured and prioritizing those with life-threatening conditions to minimize fatalities and long-term harm. Their role becomes even more crucial when medical assistance is required during rescue operations, such as in cases where amputations or other complex procedures are needed on-site, ensuring that survivors receive the immediate care necessary to improve their chances of recovery. As Gert (2005) states that emergencies differ from typical medical scenarios. In his paper, he mentions three criteria for situation to be an emergency: there should be a risk of significant harm, there should be an action that can be done in order to prevent or lessen that harm, and the situation must require urgent attention due to time constraints (Gert, 2005). In the immediate aftermath of a disaster, nearly every situation is an emergency within this definition. This is why healthcare services during disasters differ significantly from normal situations, and why it's crucial to take proactive measures for preparedness before a disaster strikes. Anticipating the surge in emergency cases, planning for resource allocation, training personnel for high-pressure scenarios, and ensuring the availability of necessary medical supplies are all important steps to ensure healthcare systems can respond effectively (Noji, 2000).

Pourhosseini et al. (2015) tries to identify the key factors that influences healthcare management during a disasters by qualitative approach where they did content analysis on interviews they made with 30 disaster experts. At the end, they identified eleven themes including human resources management, physical resources management, technology, information and communication management as well as mental health control. They suggest that effective healthcare in disaster requires a holistic approach with emphasis on coordination. This study highlights the complexity of healthcare services in disaster management and the need for integrated management approach to address the complexity and various challenges (Pourhosseini et al., 2015). World Health Organization (2019) introduced a framework focusing on management of healthcare services in disaster management to enhance coordination, efficiency and effectiveness of healthcare services that responses to disasters. Framework outlines risk management concepts and the essential components and functions of effective Health Emergency and Disaster Risk Management (EDRM) including implementation guidance. This framework also aligns with the International Health Regulations and the Sendai Framework (World Health Organization, 2019).

Hospital surge capacity is one of the key components in management of healthcare services during disaster. It refers to a hospital's ability to expand its services and accommodate sudden increases in patient number, specifically during emergencies or disasters (Weinstein et al., 2024). Surge capacity has four main components (Hasan et al., 2023):

- Staff: includes all medical personnel to doctors and nurses to technicians and people responsible for hospital operations. Surge capacity includes the capability to increase the number of medical and support personnel available. This might involve mobilizing additional staff or employing temporary staff.
- Stuff: includes all equipment from consumable supplies such as medications and oxygen to medical equipment such as syringes and dialysis machines.
- Space: refers to the number of available beds and the ability to set up additional beds. Bed capacity is a critical component of healthcare infrastructure, directly affecting a hospital's ability to deliver timely and quality care. It determines how well hospitals can manage patient inflows, especially during times of crisis. Adequate capacity ensures that hospitals are prepared to handle both routine patient care and sudden surges caused by emergencies.
- System: involves the policies and procedures that ensure effective coordination and communication between various hospital departments and with external organizations to manage patient flow and resource allocation effectively.

The bed capacity, as defined by World Health Organization (2024), of a hospital refers to the total number of beds that are consistently available and staffed for providing full-time care to inpatients. These beds are located in areas where continuous medical attention is offered. Total bed capacity includes ICU beds, palliative care beds, ER beds, dialysis beds and in-patient care beds. Beds used for healthy newborns, such as cribs and bassinets, are excluded from this count unless special care is required (World Health Organization, 2024). Ma et al. (2018) determines a standard for number of beds per thousand people in relation with population size. Tables for city scale standard and number of beds standard can be found in subsection A.1.1.

Healthcare service management plays a key role in disaster management, ensuring that medical care is delivered quickly and efficiently when it's most needed. It helps coordinate resources, staff, and infrastructure to handle the sudden increase in patients during a disaster, which is vital to saving lives and reducing long-term harm. By focusing on careful planning, increasing hospital capacity, and improving communication, healthcare service management not only supports immediate disaster response but also strengthens the ability of healthcare systems to handle future emergencies.

2.3.3. Transportation systems in disaster management

Transportation systems play a critical role in disaster management, particularly during immediate response efforts. They enable emergency responders to reach affected areas fast and effectively. Networks of roads, railways, and air routes ensure the rapid delivery of medical aid, efficient evacuations, and the transport of essential supplies and resources to those in need. Disruptions to transportation can impede evacuation, delay rescue operations, and slow down the delivery of humanitarian aid, which exacerbates the impact of disasters (Aksu & Ozdamar, 2014). Consequently, resilience of transportation systems is vital for minimizing the adverse effects of disasters and ensuring fast recovery.

In literature there are many definitions for resilience in the context of transportation systems. Literature review on the term of resilience for the transportation systems done by Zhou et al. (2019) comes to conclusion that the definitions in the literature assess the term from one or both of the following: the capacity to sustain functionality during disruptions and the time and resources needed to return to the original performance level following the disruptions. In same paper, literature review on measuring resilience of transportation systems was also done. The literature was reviewed to analyze metrics, mathematical models for measuring resilience, and strategies for improving it. The review identify three types of metrcs: topological metrics, attribute-based metrics and performance-based metrics. For improving resilience strategies include retrofitting, resource preparation for fast post-disaster response and defining and allocating resources for based on the importance of components such as bridges (Zhou et al., 2019).

Edrissi (2015) underscores the importance of reliability of transportation networks during emergency responses to reduce fatalities. In this study network reliability was defined as the ability of the network to remain functional during and after a disaster to ensure transportation of aid and supplies. One crucial term used in this study is link importance which is identifying the critical transportation links to maintain connectivity. For the purpose of measure reliability, measure which considers both network connectivity and efficiency was introduced in the study with a mathematical model to maximize the reliability.

Another mathematical model that was introduced in literature focuses on the restoration processes of roads following a disaster to. The main goal of the model is to prioritize the clearance of blocked roads increase accessibility and effective evacuation, particularly during the first three days, which are deemed the most critical for response efforts. The proposed model addresses the dynamic scheduling and optimization for clearing the roads. The model was evaluated in two districts of Istanbul to verify its effectiveness in managing complex networks (Aksu & Ozdamar, 2014).

The literature offers numerous examples of indicators used to assess the resilience of transportation systems (Bruneau et al., 2003; Cox et al., 2011; Faturechi & Miller-Hooks, 2014; King et al., 2019). Leobons et al. (2019) presents a comprehensive set of resilience indicators derived from a systematic literature review, which highlights four key resilience properties: robustness, redundancy, resourcefulness, and rapidity. Robustness reflects the system's ability to withstand disruptions, while redundancy refers to the availability of alternative options. Resourcefulness represents the availability of both personnel and materials to respond to disruptions, and rapidity measures how quickly the system can return to normal or near-normal functionality. Each of these resilience properties contains specific indicators that enable the measurement of resilience in transportation systems. In the study, robustness and redundancy were seen as directly linked to the transportation system's ability to sustain an acceptable level of service. On the other hand, resourcefulness and rapidity are mostly related to the intensity of the disaster event (Leobons et al., 2019).

Ultimately, enhancing the resilience of transportation systems is crucial for effective disaster response and recovery. Resilient networks ensure that emergency responders can reach affected areas quickly, facilitating the rapid delivery of aid and supplies. Studies highlight the importance of maintaining functionality during disruptions and emphasize critical indicators such as robustness and redundancy (Leobons et al., 2019). Literature suggest that by investing in retrofitting and optimizing resource allocation, communities can improve their capacity to respond swiftly and recover effectively from disasters (Zhou et al., 2019). Therefore, fostering resilient transportation infrastructure is essential for safeguarding lives and ensuring effective disaster management.

2.3.4. Interconnectedness of CI's

One of the relevant studies is Lam and Shimizu's case study of Japan (Lam & Shimizu, 2021). The study analyzes the impacts of earthquake cascades on infrastructure using a causation and network modeling and to identify critical infrastructure damage types and intermediate effects while providing insights for disaster preparedness and risk mitigation strategies. They investigate the infrastructures of medical facilities, educational institutes, public buildings; electricity, gas and water supply facilities and transportation services such as railway, airport and port. They've evaluated data from 131 earthquake cases and identified 875 incident chains. This study offers valuable insights on the interconnectedness of the critical infrastructure and how earthquake cascades can propagate through these interconnected systems, resulting in significant infrastructure damage.

Similar work was done by Shubandrio et al. with the case study for Padang City in Indonesia (Shubandrio et al., 2022). Study's main focus is risk assessment and inter-dependencies between Critical Infrastructures (CIs). The study developed a modified criticality map showing how infrastructure interdependencies amplify the risk to upstream infrastructures like roadways. Their analysis identified hospitals, power substations, and telecommunication towers were rated as "vital" infrastructures when it comes to critical infrastructure dependencies. Furthermore, road networks found to be critical for accessing key services, especially hospitals. The findings underscore the importance of addressing infrastructure interdependencies to enhance disaster resilience and support sustainable urban development.

Lin et al. (2017) conducts two case studies to understand impact of critical infrastructure distruptions using the Input-Output Interdependency Model which was developed to understand interdependencies among critical infrastructures. Study investigates physical interdependencies including their economic impact and does critical sector idenification for each case study. Two case study include Singapore Pulau Bukom Island Fire and Japan Tohoku Earthquake. For the second case study, findings show cascading effects on transportation services and telecommunication systems (Lin et al., 2017).

These case studies were conducted in regions with different geological and socio-economic contexts than Hatay. However, both studies aim to investigate the relationships within critical infrastructures and between these infrastructures and disaster management efforts. They offer valuable insights into the interconnectedness of critical infrastructures.

Another study that emphasized on critical infrastructure interdependencies was done by Rinaldi (2004). The paper classifies interdependencies in four categories: physical interdependency, cyber interdependency, geographic interdependency and logical interdepencency. Variety of interdepencency classes creates need for different modeling and simulation approaches for analysis of the infrastructures. Additionally, the paper highlights that factors such as time scales further complicate the analysis of interdependencies. It reviews several methods and tools developed for this purpose, including dynamic simulations and agent-based models. The study concludes by underscoring the need for a deeper, multidisciplinary understanding of critical infrastructure interdependencies to effectively prevent cascading infrastructure failures that could lead to catastrophic events (Rinaldi, 2004).

Given the interconnected nature of critical infrastructures, a System Dynamics (SD) model can be effectively utilized to illustrate these complex interdependencies. This approach has been employed in various studies in literature. For instance, the CRISADMIN project developed a Decision Support System (DSS) based on an SD model to analyze the interdependencies among critical infrastructures (Crisadmin, 2022). By simulating these interactions, the CRISADMIN model provides understanding into the potential cascading effects of disruptions and the effectiveness of different investment strategies for enhancing infrastructure resilience and security (Cavallini et al., 2014).

2.4. Disaster management in Turkey

Disaster management in Turkey is a structured and collaborative effort involving multiple stakeholders across different levels of government, the private sector, and civil society. The Disaster and Emergency Management Authority (AFAD), which operates under Ministry of Inferior, is the principal authority for disaster management in Turkey (AFAD, 2024). It was established after 2009 in response to 1999 Izmit earthquake for the need of centralized authority for preventing disasters, reducing their impact, planning and coordinating responses after disasters, and fostering collaboration among different government agencies (AFAD, 2021). 1999 Izmit earthquake showed critical deficiencies in Turkey's disaster management system as mentioned in chapter 1 and AFAD's main goal is to emphasize shifting Turkey from crisis management to risk management. Currently, AFAD operates 81 provincial branches and 11 search and rescue units throughout the country. (United Nations, 2024).

Turkey Disaster Risk Reduction Plan (TARAP) is AFAD's comprehensive framework for managing and reducing risks from different kind of disasters in Turkey. This plan contains three timeframes over eight year period: short term (2022 - 2024), medium term (2022 - 2028), and long term (2022-2030). It aligns with international standards, such as Sendai Framework of UNDRR. Public institutions, local governments, private sector, NGOs, and universities are included in this plan for risk reduction efforts towards all types and scales of disasters that can occur in Turkey. The plan contains 17 objectives, 66 targets, and 227 actions towards 11 different disaster types from earthquake and floods to major industrial accidents and mass migration. There are 7 targets in the plan that is specific to earthquakes (AFAD, 2022b).

Turkey's Disaster Response Plan (TAMP) is the key framework for managing and coordinating disaster response efforts in Turkey developed by AFAD and was first published and came into effect in the Official Gazette numbered 28871 on January 3, 2014 (Turkish Presidency, 2014). The necessary amendments were made to TAMP, and it was republished in the Official Gazette on September 15, 2022 (Turkish Presidency, 2022). In this plan there are 25 national-level and 23 local-level disaster groups. The coordination at the national level is handled by the Disaster and Emergency Management Board (AADK), while coordination at the local level is maintained through the Provincial and Emergency Coordination Board and the Provincial-District AFAD Centers. The Provincial and Emergency Coordination Board meets under the chairmanship of the relevant governor. In cases of disasters and emergencies, it meets at the Provincial AFAD Center without waiting for a call or instructions (AFAD, 2022c). The main solution partners are the Presidency Directorate of Communications, the Ministry of Interior, the Ministry of Family and Social Services, the Ministry of Environment, Urbanization and Climate Change, the Ministry of Energy and Natural Resources, the Ministry of Treasury and Finance, the Ministry of Health, the Ministry of Agriculture and Forestry, the Ministry of Transport and Infrastructure, and the Turkish Red Crescent. Other ministries, institutions, and organizations serve as supporting solution partners (AFAD, 2022c). Local authorities, including municipalities and provincial disaster and emergency directorates, play a crucial role in implementing disaster response plans at the local level. They manage emergency services, conduct risk assessments, and coordinate with AFAD to ensure that local needs and resources are addressed effectively. These local units are essential in providing immediate support and managing evacuation and relief efforts in their respective areas. Alongside with Turkish Red Crescent, various non-governmental organizations (NGOs) are crucial in delivering humanitarian aid, medical assistance, and psychological support during and after disasters. Their efforts complement those of government agencies by providing on-the-ground support and facilitating community-based disaster response (Freedom House, 2023).

TAMP includes specific procedures for responding to different types of disasters, such as earthquakes, floods, and industrial accidents. For instance, in the case of earthquakes, TAMP outlines procedures for immediate search and rescue operations, including the activation of specialized teams and the use of urban search and rescue equipment. It establishes a clear command and coordination structure for disaster response, outlines how resources (personnel, equipment, supplies, etc.) should be mobilized and allocated, includes strategies for communicating with the public during a disaster, and is responsible for training plans of AFAD employees and volunteers (AFAD, 2022c).

In the TAMP, intervention impact levels are defined according to the degree of impact as shown in Table A.2. When a disaster occurs, these impact levels are determined by the magnitude of the event and the extent of the damage and affected area. S1 indicates a level where local resources are sufficient, S2 indicates a situation where, given the magnitude of a disaster or emergency in a province, the resources of that province are insufficient, requiring support from neighboring provinces, S3 denotes a level where national support is needed, and S4 represents a level where international support is required. As mentioned in chapter 1, AFAD categorized the earthquake on February 6, 2023, as an S4 level impact disaster. Coordination levels by impact levels within TAMP can be seen in Figure 2.1.

Turkey currently lacks an operational framework for a post-disaster recovery plan. Although the Turkey Post-Disaster Recovery Plan (TAYSB) was developed in 2017 and a decision was made at the Disaster and Emergency High Council meeting in December 2017 to finalize and implement it, the plan has yet to be put into action. This plan also involves various stakeholders, ranging from governmental bodies to the public sector (UNDRR, 2022b). For the 2023 earthquake, recovery plan was done by the Presidency of Strategy and Budget. This plan includes assessments for needs of each city, stakeholders, reconstruction goals (including critical infrastructure), economic recovery plan, social

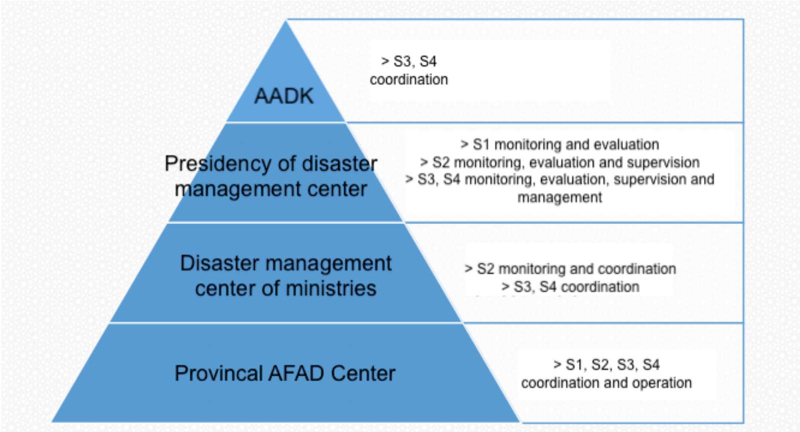

Figure 2.1: Coordination levels by impact levels (AFAD, 2022a)

support initiatives, risk reduction strategies for future, sustainability goals, and strategies for cultural heritage preservation for the region (Strategy and Budget Office of the Presidency of the Republic of Türkiye, 2023).

Overall, disaster management in Turkey is has a high degree of collaboration and coordination among various entities, trying to ensure a comprehensive and effective approach to managing and mitigating the impacts of disasters.

2.5. Root cause analysis

Root cause analysis (RCA) is a method to find underlying causes of system failures. There are several techniques that can be used to find root cause depending on the nature of the system or of the problem. One example is 5 Why's technique which is asking consequently "Why?" to problems until finding the root cause of a problem. It is more suitable for simple problems where multiple root causes are unlikely (Williams, 2001). Another method that is widely used is Pareto Analysis which is also called 80/20 rule because it suggests that 80% of the problems come from 20% causes (Powell & SammutBonnici, 2015). Causal Tree or Fault Tree Analysis (FTA), is a top-down technique that tries to find a root cause of a problem or failure using a map that looks like a tree. Biggest problem or failure is placed at the top of the tree and with deductive approach causes are identified by one by until its the root (Williams, 2001).

In literature, there are limited number of examples for finding a root cause of system failures during natural disaster. When it comes to man-made disasters, such as construction accident (Suraji, 2021) or coal mining accident (Bhattacharjee et al., 2019) research about identifying root causes is more. Suraji (2021) presents a framework to identify the causes construction accidents in their research called Constraint-Response Analysis of Causation of Construction Accidents (CRACCA). Their model, as the name suggests, is based on constraint-response theory. The framework's principle is closer to causal network rather than a tree diagram where paths are non-linear unlike causal trees (Suraji, 2021). On the other hand, Bhattacharjee et al. (2019) uses models like Accident Causation Tree (ACT), which is a causal tree model, and 5 whys to identify root causes of mining accidents. Another example of use of causal tree in root cause identification has been done in research about furniture industry (Aaltonen et al., 1996). In this study ACT was used to identify causes of furniture factory accidents. They differ from other studies with their data collection method, which was done in real time. FORIN framework is a framework that was developed to identify root cause of disasters by Integrated Research on Disaster Risk (IRDR) program (Fraser et al., 2016). It tries to identify the chain of events that lead to increase in the risk of disaster by investigating multiple dimensions such as disaster management strategies, historical, structural social and economical inequalities, spatial differences and infrastructure weaknesses. FORIN uses both quantitative and qualitative methods in the root cause identification (Oliver-Smith et al., 2016). The FORIN framework is highly relevant to this research because it not only focuses on identifying the root causes of disasters but also incorporates an analysis of infrastructure vulnerabilities.

2.6. Post-disaster recovery plan evaluations

The literature provides numerous examples of post-disaster recovery plan evaluations. These evaluations can be categorized into three types: pre-implementation evaluations, evaluations during the implementation phase, and outcome evaluations. Ge et al. (2010) evaluates the plans during their implementation phase after 2008 Wenchuan Earthquake in China. Their main goal is to assess the efectiveness of achieving goals in this evaluation. Although paper emphasizes the importance of disaster mitigation, which is a pre-event consideration, its primary focus remains on the implementation of recovery plans. Song et al. (2017) evaluates the same plans with an emphasis on sustainability. Although the plans are identical, this evaluation is conducted without examining the process or outcomes. The study develops a template to systematically evaluate how sustainability was reflected in the recovery plans and concludes that the plans lack sufficient sustainability. Ryan et al. (2016) states that evaluations frequently concentrate on processes (how effectively recovery efforts were carried out) rather than on outcomes (the success of those efforts). They argue on the importance of outcome-focused evaluations that measure the impact of recovery plans. The paper introduces a topology that categorizes disasters based on their characteristics. Examples for these characteristics are disaster type, location, and impact. They propose that this typology can be used to define the evaluation methods applied across various disasters. Brown et al. (2008) introduces 'Recovery Project' which aims to enhance understanding of disaster recovery. They define indicators to assess recovery including vulnerability, services, housing, infrastructure, and environment. Examples of these indicators include employment rates, income levels, water quality, and access to education. Their focus for this evaluation is primarily on during and after the implementation phase of the plans.

2.7. Research gap

Although there are many example for evaluation of post-disaster recovery plans in the literature (see section 2.6), when compared, process and outcome evaluations has the most coverage. These evaluations primarily focus on assessing how effectively plans are executed in response to disasters and whether they achieve the intended goals of recovery plans done after disasters. However, they often overlook pre-disaster vulnerabilities and fail to address the initial adequacy of recovery plans in mitigating those vulnerabilities.

Additionally, despite valuable research on critical infrastructure systems (Lam & Shimizu, 2021; Lin et al., 2017; Rinaldi, 2004; Shubandrio et al., 2022) and the impact of earthquake cascades, there is a notable gap in the literature concerning the underlying causes of critical infrastructure failures during such disasters. Literature presents an in depth analysis of critical infrastructures for man-made disasters (Bhattacharjee et al., 2019; Suraji, 2021); however, there remains a gap in research focused on the root causes of system failures in the context of natural disasters.

Literature suggest that recovery plans are often formulated hastily in response to urgent needs after disasters and neglects the root causes of vulnerability. Such reactive measures can, over time, exacerbate social, economic, and environmental issues, transforming natural disasters into more severe crises (Ingram et al., 2006). To recover effectively and build resilience for the future, it is essential to understand and address the root causes of system failures. Without this understanding, recovery efforts may fail to prevent future vulnerabilities, limiting long-term resilience. That is why a proactive approach, incorporating a thorough pre-disaster assessment of vulnerabilities and critical infrastructure weaknesses, is essential for developing effective recovery strategies that address the underlying causes of disaster impacts and enhance resilience in the long term.

This research fills the gap in the literature by addressing the root causes of critical infrastructure (CI) failures during a disaster. Unlike previous studies that mainly assess the implementation and effectiveness of recovery plans, this study analyzes how identified vulnerabilities are incorporated and mitigated within these plans.

3 Methodology

This research has a mix-method approach aimed at identifying factors contributing to the destruction caused by the earthquake and assessing resilience and recovery plans for critical infrastructure accordingly. The study begins with qualitative analysis on semi-structured interviews to identify key CI components, using an initial code list derived from relevant reports. It is followed by root cause analysis which explores the management processes of CI's prior to the earthquake, examining planning factors as well as consequences of earthquake on the relevant CI. The tool used for root cause analysis is Fault Tree Analysis (FTA) which systematically analyzes factors contributing to the potential failures until root causes are found. Finally, post-earthquake recovery plans phase assesses proposed plans for CI, focusing on the root causes from FTA. Visual representation of the research flow can be seen in Figure 3.1.

3.1. Key CI Identification

Critical infrastructure as explained in literature review emerges as a complex concept containing diverse systems, structures, and factors crucial to resilience. However, in the interest of targeted research, it is important to recognize the necessity of prioritization. Hence, the initial step of this research entails selecting the most crucial elements of critical infrastructure that significantly influenced the outcomes of the disaster. For this purpose, semi-structured interviews conducted by the international research group involved in the project "Long-term Recovery Strategies in the Aftermath of the 2023 Impacts of the Gaziantep Earthquakes in Turkey" (Aydin, 2023) in June 2023 was used for content analysis. The interviews includes questions that explore participants personal experiences, needs, and challenges related to post-disaster recovery with an emphasis on understanding the social, institutional, and logistical aspects of rebuilding (Aydin et al., 2024). They began with a general question about participants' experiences during the earthquake, followed by inquiries into their post-disaster lives. A total of 13 interviews with diverse stakeholders, including government officials, members of professional chambers, private sector participants, representatives from legal and institutional bodies, academic professionals and people who live in tent and container settlements, analyzed for this study. Analysis was done through a thematic analysis, which is a widely used method for identifying, analyzing, and reporting patterns (themes) within data.

The analysis involves a process of coding and categorizing data, combining both deductive and inductive approaches and employing a middle ground between loose and tight approach. The initial code list comprised all structures identified as critical infrastructure. This list was then refined by analyzing causality reports specific to these infrastructures. The focus was narrowed to include only those critical infrastructures that sustained severe damage in the Hatay region, ensuring that the final code list was directly relevant to the most significantly impacted structures. Once the appropriate codes were selected for the code list, semi-structured interviews were analyzed using Atlas.ti software. In this analysis, the process began by identifying and extracting the portions of the interviews where participants discussed topics related to the predefined codes. Following this, the content was thoroughly analyzed to deepen the understanding of the themes and patterns emerging from the interviews. Based on this detailed content analysis, a comprehensive codebook was developed. The codebook provided a

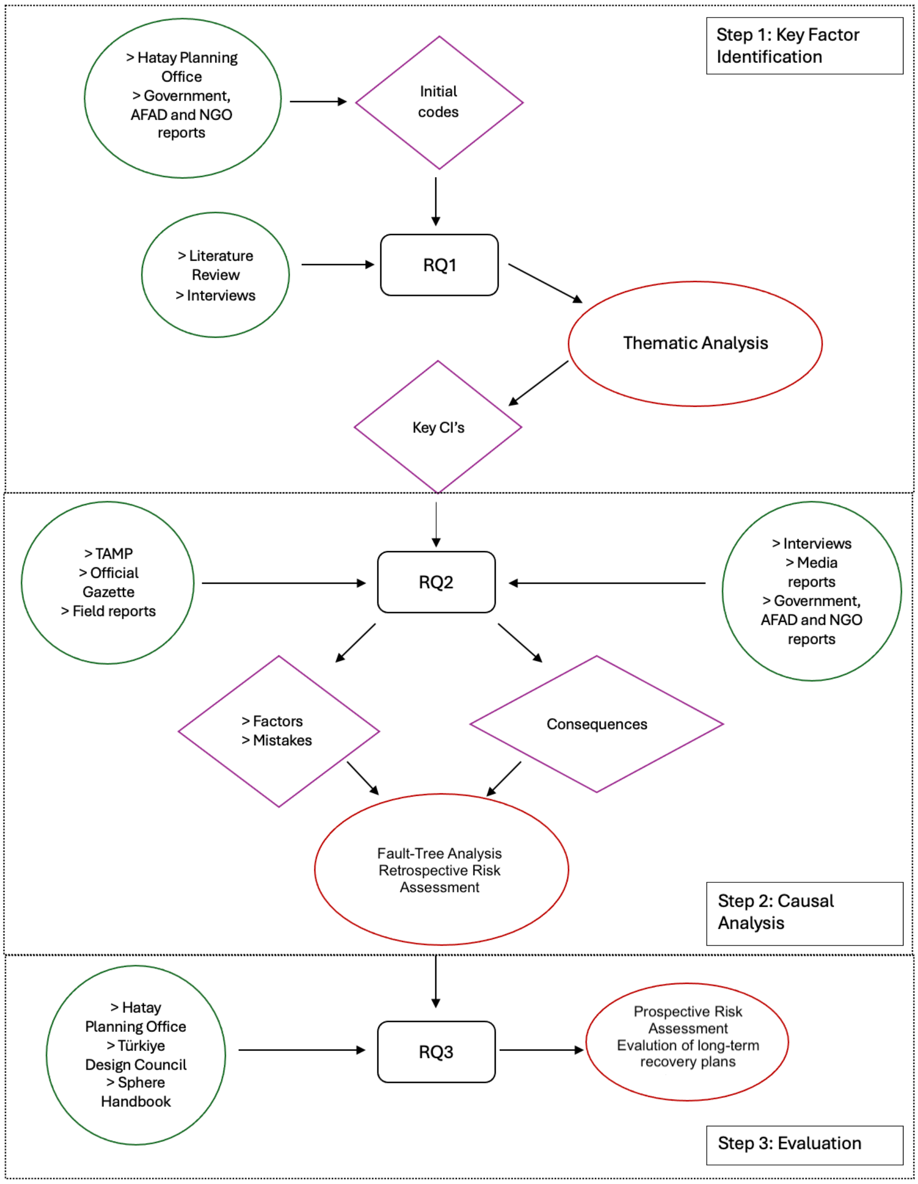

Figure 3.1: Research Flow

structured guide, categorizing the data into meaningful codes that reflected both the initial deductive framework and any newly discovered information from the inductive process. Once the codebook was finalized, analytical techniques were employed to further explore the relationships between codes. Co-occurrence analysis was conducted to identify instances where different codes appeared together within the same excerpts. To achieve this, the code co-occurrence analysis tool in Atlas.ti was utilized to create a co-occurrence matrix which generates a matrix that counts and displays instances where two or more codes co-occur within the data. This helped reveal potential connections or interactions between themes, offering insights into how various factors were interrelated. In addition, a word cloud analysis was performed to visualize the most frequently occurring words across the interviews in the context of specific structures. This provided an overview of key terms and concepts, highlighting dominant themes within the data. After these analyses, key critical infrastructures were selected by identifying those that appeared most relevant based on thematic connections and their importance to the overall findings. This relevance was determined through a combination of co-occurrence patterns, content analysis, and expert judgment, ensuring that the focus remained on the infrastructures that were critically damaged and played a significant role in the regions immeadiate recovery efforts. The decision to focus on key critical infrastructures rather than investigating all in this study was made by the need to ensure a focused and in-depth analysis. By narrowing the scope to the selected infrastructures, the study could delve deeply into their critical roles and investigate interconnectedness, thereby providing a more in depth understanding of their impact on the recovery process in Hatay. Focusing on a limited number of infrastructures allows for a thorough examination of each sectors specific challenges, vulnerabilities, and contributions to the overall recovery effort.

3.2. Root cause analysis

After the selection of key critical infrastructures, a comprehensive analysis was conducted to explore the root causes underlying the management processes of CI's prior to the earthquake. Qualitative Fault Tree Analysis (FTA) was selected as a root cause analysis tool for this research. As mentioned in section 2.5, FTA is a deductive, top-down approach used for analyzing various combinations of faults or events that could lead to system failure. These diagrams systematically breaks down the failures into their constituent events and conditions, illustrating the logical relationships between them. By constructing a fault tree diagram, which visually represents the logical relationships between these events and their potential consequences, the analysis aims to identify the critical pathways through which the infrastructure could fail during an earthquake event. The first step in the FTA for each critical infrastructure is to define the top event, which represented the system's overall failure during the earthquake. From there, branches were developed to identify the various contributing factors and failure modes that led to this top event until root causes were found.

In this step, it is essential to examine how these infrastructures were managed and maintained before the disaster and the factors that contributed to their decision making processes. Pre-disaster management includes planning, risk assessment, maintenance protocols, and the implementation of preventative measures as well as the states and conditions of the critical infrastructure before the earthquake. Understanding these factors provides insight into the vulnerabilities that existed before the earthquake and how they may have contributed to system failures. By reviewing these pre-disaster management strategies; gaps, oversights, or planning mistakes that left the infrastructure exposed to damage or malfunction can be identified.

Causality reports, which detail what occurred during and after the earthquake, offer a critical perspective on how these planning shortcomings translated into real-world consequences. To address these aspects government reports, TAMP, and field reports were investigated. These reports shows the impact of the disaster on infrastructure, such as the failure of power grids, water supply systems, healthcare facilities, or communication networks. With this information, the sequence of events that led to these failures can be traced.

For each type of critical infrastructure, there are distinct factors to evaluate when assessing pre-disaster management and planning, as these factors depend on the specific functions and vulnerabilities of each system. For example, in the healthcare sector, focus can be on bed capacity, which directly affects a facility's ability to handle patient surges during emergencies. Meanwhile, in transportation systems, the emphasis shifts to redundancy, ensuring there are alternative routes available if primary pathways are damaged or blocked. Given these differing priorities, FTA analysis also identifies the key factors to focus on for each type of critical infrastructure.

The methodology of Fault Tree Analysis (FTA) involves several systematic steps to identify and evaluate potential system failures. The process begins by defining the top event, which represents the undesired failure or hazard under investigation. From there, major contributing factors to the system failure are identified as intermediate events. The analysis continues by decomposing these events until the root causes are uncovered. This decomposition is guided by logical relationships represented by gates, such as AND and OR gates, which illustrate how different events combine to lead to the top event. An AND gate indicates that all input events must occur for the output event to occur, while an OR gate signifies that any one of the input events can lead to the output event. By tracing these pathways, FTA helps to uncover root causes of failures and vulnerabilities within the system. Event and gate symbol explanations for FTA can be found in Figure A.4. Following the Fault Tree Analysis (FTA), a qualitative retrospective risk assessment was conducted to evaluate the risks associated with each identified root cause.

3.3. Risk assessments

This study adopts a twofold risk assessment approach, encompassing both a retrospective analysis of risks before the earthquake and a prospective risk assessment after implementing long-term recovery plans. The risk assessments follows a Fault Tree Analysis (FTA) structure, whereby the probability and severity of each root causes impact on system failure are assessed, moving progressively upward through events until reaching the risk of the main event.

Retrospective risk assessment involves systematically reviewing and analyzing past risks to identify vulnerabilities in the pre-earthquake context. By examining risks that have already occurred as well as those that existed as potential threats, this assessment highlights the systems historical weaknesses and provides insights into the root causes of failures. The primary purpose of retrospective assessment is to understand how past risk factors contributed to system breakdowns, offering a foundation for targeted mitigation efforts.

Prospective risk assessment, in contrast, focuses on evaluating future risks in light of new long-term recovery plans. It is to identify the risks for an event that is not occurred yet. In this phase, the risks for each root cause and intermediate event are re-assessed within the context of long-term recovery initiatives.

In this study, both risk assessments were conducted through a Fault Tree Analysis (FTA) for critical infrastructures, focusing on identifying the probability and severity of each root causes contribution to system failure. A risk matrix, shown in Figure A.5, classifies each root causes associated risk level, ranging from very low to extreme. From these initial values, the risk of intermediate events is subsequently calculated by moving upward through the FTA tree. Using qualitative risk assessment principles, the probability of each intermediate event is determined as follows (NASA, 2022):

- AND gate: Both events must happen for the intermediate event to occur. Thus, the probability of both happening is constrained by the least likely event.
- OR gate: The intermediate event occurs if any one of the contributing events happens. Thus, the probability of the intermediate event is determined by the most likely contributing event, as it only takes one for the failure to occur.

The impact of the intermediate event is taken to be the highest impact among the contributing events in both cases, as the failure will reflect the consequences of the most severe event (Pimentel, 2021).

3.4. Evaluation of long-term recovery plans

In this step fault-tree analysis will be used to evaluate future plans for Hatay. These plans, accessible on the Hatay Planning Office's (Hatay Planning Office, 2024) websites and the Presidency of Strategy and Budget's earthquake assessment report (Strategy and Budget Office of the Presidency of the Republic of Türkiye, 2023). The goal of this analysis is to assess the potential impacts of these proposed plans on the resilience and sustainability of Hatays critical infrastructure systems. The evaluation also focuses on whether these new plans address the root causes identified in previous failures and demonstrate a recognition of past mistakes and shortcomings.

A key component of this evaluation involves conducting a qualitative prospective risk assessment, where risk assessment techniques are reapplied considering a future event. This process aims to determine how effectively the new plans mitigate the risks associated with the root causes identified earlier. By doing so, it allows for a direct comparison between the vulnerabilities revealed in the first analysis and the proposed measures designed to address them. Each risk is reassessed in the context of the new plans, identifying improvements and uncovering any remaining gaps in risk mitigation.

The primary purpose of conducting both retrospective and prospective risk analyses is to compare the changes in risk before the earthquake and after the implementation of the long-term recovery plans. Although the analysis is qualitative, meaning the exact risk levels may vary depending on the interpreter's perspective, the focus is on maintaining consistency in the methodology used for risk assessment across both phases. The key takeaway is not the precise risk levels but rather the changes in risk levels between the retrospective and prospective assessments, which highlights the effectiveness of the recovery plans in addressing the identified vulnerabilities.

The insights derived from this analysis does not only highlight areas where improvements have been made but also indicate which risks have been sufficiently mitigated and which may still pose a threat.

II

Results

4

Key CI identification results

4.1. Defining the code list

The code selection was based on the literature review and earthquake impact data sourced from the HPO, government agencies, AFAD, media, and various NGO reports.

The education sector has been deeply affected. As demonstrated in Figure 4.1, out of 1,405 schools, 45% were either destroyed, in urgent need of demolition or moderately damaged. Another 29% of schools were slightly damaged, while only 26% remained undamaged. In areas such as Antakya, Defne, Samandag, skenderun, Kirikhan, Hassa, and Yayladag, school capacity has become insufficient due to destruction (Hatay Planning Office, 2024), further complicating the situation for students and educational continuity. Figure 4.2 highlights these districts on the map of Hatay. The education sector was included in the initial code list as 'Education' due to the extensive damage it sustained and it's role in disaster management as stated in subsection 2.3.1. This code's definition encompasses everything related to the education sector, from school buildings to teachers.

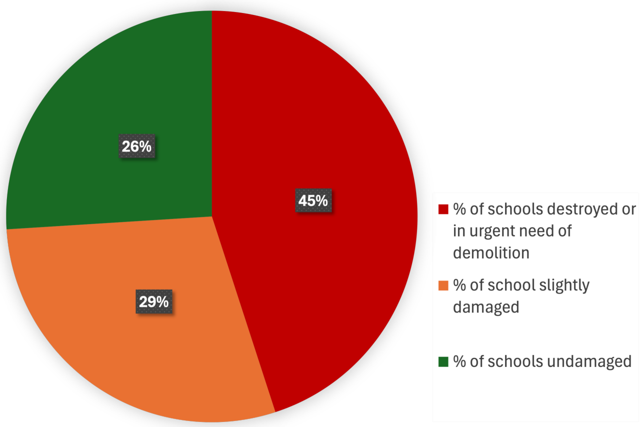

Figure 4.1: Impact of earthquakes on public schools adapted from (Hatay Planning Office, 2024)

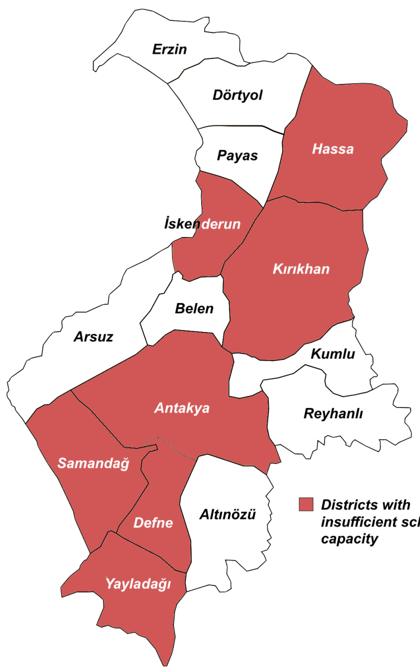

Figure 4.2: Districts with insufficient school capacity adapted from (Hatay Planning Office, 2024)

Public buildings were similarly impacted, with 19% of the 8,500 structures either collapsed, demolished, or marked for controlled demolition due to severe damage (Hatay Planning Office, 2024). This substantial loss underscores the vulnerability of critical government and public service facilities in the region. For this reason another code 'Public Buildings' was added to the code list.

When it comes to healthcare services, 6 out of the 12 public hospitals in the region, along with 57 out of 196 family health centers, were heavily damaged or destroyed (Strategy and Budget Office of the Presidency of the Republic of Türkiye, 2023). In response, seven field hospitals have been established to provide temporary medical services in the region (Hatay Planning Office, 2024), attempting to meet the urgent healthcare needs. As a result, 'Healthcare' code added to initial code list. This code encompasses all aspects related to healthcare services from ambulances to doctors and nurses.

Another challenge in the immediate recovery efforts was the delay in deploying security services. According to media reports, although the military is integrated into rescue operations under the Turkish Disaster Response Plan (TAMP) (AFAD, 2022c), AFAD's request for military assistance came 36 hours after the earthquake (SolTV, 2023), significantly slowing the response efforts (Sardan, 2023a). In addition to this delay, incidents of looting began to emerge in the affected areas, leading to complaints about the lack of security (Uludag, 2023). To address these issues, police and military services were included in the code list under the new code 'Safety and Security.'

A report published by The Presidency of Strategy and Budget states that Hatay had 847,380 houses before the earthquakes. Of these, 215,255 either collapsed, suffered severe damage, or needed urgent controlled demolition. Additionally, 25,957 were moderately damaged, while 189,317 sustained light damage (Strategy and Budget Office of the Presidency of the Republic of Türkiye, 2023). Figure 4.3 illustrates the impact of the earthquake on houses. As a consequences of this destruction to housing, thousands of people left homeless, leading to an urgent need for shelters. For this reason, 'Shelter' was added to the code list, covering all shelter solutions: short-term (tents), medium-term (containers and prefabricated houses), and long-term (permanent residential housing).

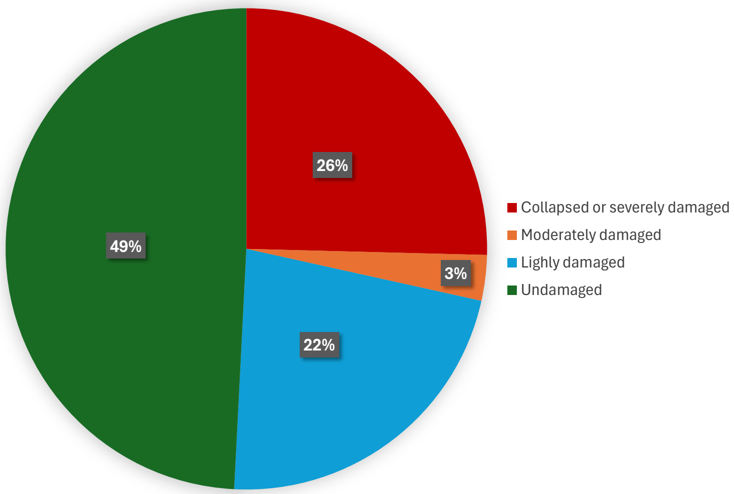

Figure 4.3: Impact of earthquake on houses adapted from (Hatay Planning Office, 2024)

According to media, telecommunication services played a crucial role in the immediate aftermath of the earthquake, significantly aiding recovery efforts. In numerous instances, individuals trapped under rubble were able to send text messages to their friends and family, providing their locations and increasing their chances of rescue (Haber, 2024; Haberal, 2023; scen, 2023). Additionally, search and rescue teams closely monitored social media platforms, particularly Twitter, where people were posting urgent pleas for help. This real-time communication allowed rescuers to respond more effectively to specific needs and target their efforts in areas where assistance was most urgently required. However, the earthquake also severely impacted telecommunication infrastructure, leading to connectivity issues. The limited and unstable connection created significant challenges during rescue operations. Furthermore, on the second day of the rescue efforts, access to Twitter was restricted by the government (NetBlocks, 2023; Ylmaz, 2023), severely hindering communication and disrupting the coordination of rescue operations.

Due to its critical role in rescue operations, a 'Telecommunication' code was added to the list to encompass all aspects of telecommunication services.

Damage to transportation systems caused by the earthquake was another major obstacle to rescue efforts. Hatay Airport, Iskenderun Harbor, the Iskenderun-Bahçe railway line, the Antakya-Iskenderun bus terminal, main arterial roads, the Belen road, and numerous bridges and rural routes all sustained severe damage (Hatay Planning Office, 2024). Containers in the Iskenderun port area were overturned, igniting a fire that destroyed 1,730 containers. The fire was extinguished a week after the earthquake, on February 13 (Sardan, 2023b). A 'Transportation' code was added to the list, covering all transportation systems, from rural roads and bridges to airports.

The water supply infrastructure also sustained severe damage. Approximately 142 kilometers of drinking water and main distribution lines were affected in the city. Additionally, five wastewater treatment plants and one drinking water treatment facility were heavily damaged (Hatay Planning Office, 2024). This disruption in water services poses a serious threat to public health and safety, further exacerbating the region's recovery challenges. The Presidency of Strategy and Budget reported that the energy sector, including electricity and gas infrastructure, suffered damages totaling 256 million dollars in Hatay (Strategy and Budget Office of the Presidency of the Republic of Türkiye, 2023). The loss of electricity and gas was especially devastating as the disaster struck in the middle of winter, leaving many regions without heat or power during freezing temperatures. This lack of essential services not only hindered rescue and recovery operations but also heightened the suffering of survivors, who were forced to endure harsh conditions without the basic utilities necessary for warmth, cooking, and sanitation. A 'Water-Energy Supply' code was added to list that encompasses all water, electricity and gas supply services.

As a result, initial code list for the qualitative analysis of semi-structured interviews as follows:

- Education
- Public Buildings
- Healthcare
- Safety and Security
- Shelter
- Telecommunication
- Transportation
- Water-Energy Supply

For each code, the table that shows the specific terms categorized under that code can be seen in the Table A.3.

4.2. Analysis on semi-structured interviews

In the analysis process, the content was thoroughly examined to define categories and sub-categories with precision. During this in-depth investigation, it became evident that discussions about one type of infrastructure often led to the mention of other infrastructures that were considered essential to its function. In these instances, the analysis took into account the interconnectedness of various infrastructure types as suggested in literature review in subsection 2.3.4. As a result, there were situations where a code initially assigned to represent one type of infrastructure ended up being categorized as a sub-category under another infrastructure code. This was done to reflect the hierarchical or interdependent relationships between different infrastructures within the broader context of the analysis. Regarding codebook for the analysis can be found in subsection A.2.2. Co-occurences and word cloud analysis were used to analyse the interviews in depth.

In the interviews, the code 'Education' emerged as one of the frequently mentioned topics, underscoring its importance for recovery, not only for children but for the entire community. Many interviewees emphasized that those who left the city after the earthquake are unlikely to return unless there is a school available for their children to attend. The importance of 'Education' in these discussions is notable, as it frequently appears in conjunction with other infrastructure related codes as can be seen in

Figure 4.4. It can be seen that code 'Education' appeared together with every other infrastructure code except 'Water-Energy Supply'. This high level of co-occurrence suggests that 'Education' is considered a crucial component that intersects with various aspects of community rebuilding and development. The code 'Shelter' showed the highest level of co-occurrence with 'Education.' A closer examination of the interviews reveals two primary areas where these topics intersect. First, there is a significant concern about inadequate shelter for teachers, which disrupts the continuity of education. Second is the discussion about the potential of utilizing school buildings as temporary shelters. As it can be seen in subsection 2.3.1 of literature review, literature also suggests school buildings can be used as shelters and coordination hubs during immediate response and recovery. In the interview with Hatay Mustafa Kemal University's board members, it was revealed that the university was center of the coordination in Hatay for many institutions, including National Medical Rescue Team (UMKE) and The Red Crescent. Furthermore, the university played a critical role as a shelter, as evidenced by the fact that bureaucrats from the Ministry of Environment and Urbanization were accommodated there. University hospitals were also integral to the rescue operations, with ambulances stationed on campus to respond to 112 emergency calls. Discussions about telecommunication services mostly emerged in the context of conversations about education. Interviewees suggested that internet services is a necessity for continuity of education. For this reason, telecommunication become sub-category of code 'Education'.

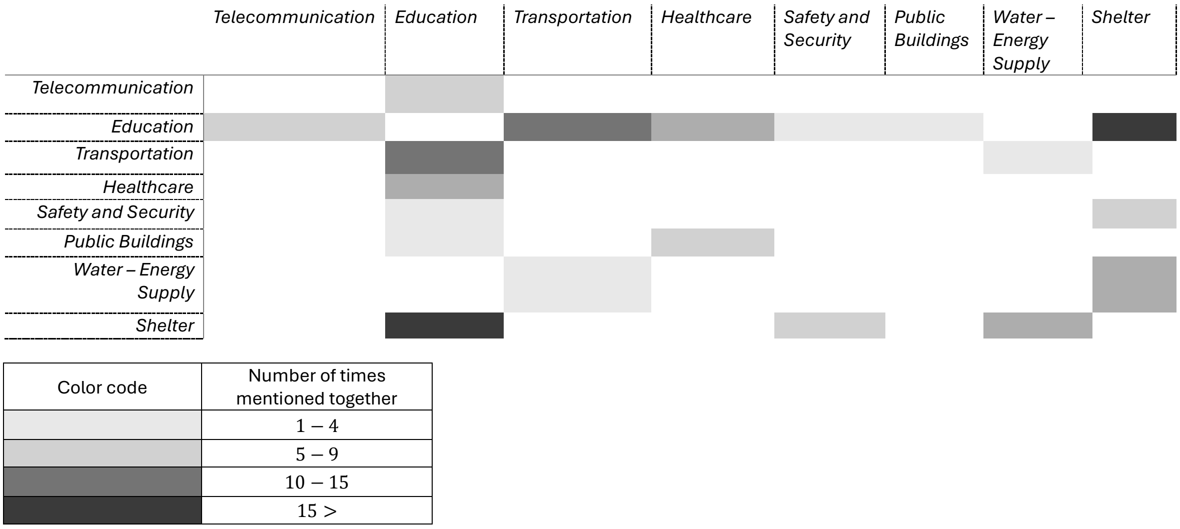

Figure 4.4: Co-occurence Matrix with Color Coding

Healthcare services emerged as a major area of concern, not only due to the frequency that it was discussed but also because of the content of the discussions. The inadequacy of healthcare services in immediate recovery was attributed in part to the destruction of half of the public hospitals during the earthquake, where interviews revealed that this destruction was an excepted outcome due to known structural vulnerabilities of public hospital buildings. This suggested that the healthcare system had existing vulnerabilities long before the disaster struck. These pre-existing weaknesses had already been affecting the quality and accessibility of healthcare services, compounding the challenges brought on by the earthquake. Particularly, inadequate spatial planning was a significant issue that was raised. Certain areas, such as Defne, lacked a public hospital even before the disaster, highlighting a long-standing gap in healthcare infrastructure. Additionally, the eastern part of the city was already deficient in hospital facilities, further underscoring the uneven distribution of healthcare resources across the region. The code 'Healthcare' and its high co-occurrence with the code 'Education' comes from their equal significance in the recovery phase. When discussions focused on the essential factors for encouraging those who left to return, healthcare and education services consistently topped the list of priorities.

Another system that emerged as a significant critical infrastructure in the analysis was transportation services. The damage inflicted on transportation systems by the earthquake created significant obstacles, both for immediate rescue efforts and the broader recovery process. These disruptions hindered the delivery of essential aid and slowed the city's overall path to recovery. Within the code of 'Transportation', two main systems emerged: airport and arterial road. The airport, in particular, faced significant criticism, especially regarding its spatial planning. Concerns about its location had been a subject of debate for years prior to the earthquake, with many highlighting that the ground on which it was built was not resistant. This longstanding issue resurfaced in the aftermath, as the airport's vulnerabilities became even more apparent. Some interviewees even suggested that, rather than rebuilding the airport at the same site, it should be relocated to a more suitable and safer area. Another pre-existing vulnerability highlighted during the analysis was the city's dependence on a single arterial road, which serves as the only main route for entering and leaving the city on single lane. This road sustained heavy damage during the earthquake and was consequently blocked, further complicating emergency response efforts and isolating the city. Third system that was emerged in analysis about transportation services was bridges. Many of these structures failed to withstand the earthquake, leading to further disruptions and creating additional barriers to rescue and recovery efforts. The code "Transportation" showed a strong co-occurrence with the code "Education." Further analysis revealed that this high co-occurrence was caused by the crucial role transportation systems play in enabling access to education, emphasizing how educational services are dependent on reliable and effective transportation infrastructure.

The discussion about safety and security was evolved in two ways. First, there were significant concerns about the lack of security during the initial three days of the immediate response. The military's intervention was delayed, and police forces were inadequate, leading to a period of chaos. This instability was marked by looting, which only ceased once the military arrived. Second, the significant reduction in the populationdue to both loss of life and migration to other cities city was empty. Consequently, residents felt increasingly unsafe and reluctant to walk through the empty streets after certain hours.

In the case of public buildings, it was only mentioned within legal and procedural issues that had arisen regarding inheritance. The collapse of public buildings has made essential documents like death certificates inaccessible, complicating the process of establishing legal heirs and resolving related matters.

The analysis of water and energy supply services revealed that the most pressing issue was the lack of access to clean water in shelters and sewage issues. Additionally, it was found that there was no water supply in some areas during the first two weeks following the earthquake.

In the aftermath of the earthquake, shelters were another discussed issue, appearing in two contexts: the need for immediate shelters (such as tents), the challenges within temporary shelters, and ongoing housing concerns. Temporary shelters faced significant difficulties in meeting basic needs like clean water, food, and medical care, which created severe stress on the affected population. This explains the relatively high co-occurrence of the codes "Shelter" and "Water-Energy Supply," as access to these essential services was a common problem in the temporary shelters. Many of those who had the opportunity to relocate to other cities did so, primarily due to the lack of adequate shelter in the affected areas. Interviews further revealed the uncertainty surrounding long-term housing solutions, adding to the sense of instability and insecurity for those displaced by the disaster.

4.3. Conclusion and key CI selection

In conclusion of these analysis, key critical infrastructures for this study as follows:

- Education sector
- Healthcare services
  - Hospitals
- Transportation systems
  - Airport
  - Arterial road

Semi-structured interviews highlighted the critical roles that these infrastructures play in the recovery and rebuilding of the Hatay region after the earthquake. Among them, education emerged as one of essential infrastructures, showing strong interconnections with other structures. Consequently, education was selected as a key focus for further analysis. Two primary research areas emerged from the education-related discussions: the role of education in long-term recovery and the importance of school buildings and university campuses in immediate response and recovery efforts. For the selected critical infrastructures, word clouds were formed to analyze them further and understand the important concepts within each structure. Word cloud for the code 'Education' can be seen in Figure 4.5. It can be observed that words such as 'recover', 'come', 'live', 'priority' and 'bring' occurred multiple times. These words reflect discussions emphasizing the need to prioritize education as a critical step in encouraging families to return to the city and bring their children back, which is essential for long-term recovery. The greatest obstacle to educational continuity appears to be the lack of adequate shelter for teachers, as suggested by the frequent occurrence of words like 'teacher,' 'tent,' 'container,' and 'house.' For the immediate response efforts, coordination in university was given an example.

Figure 4.5: 'Education' Word Cloud

Figure 4.6: 'Healthcare' Word Cloud

Figure 4.7: 'Transportation' Word Cloud

Healthcare was selected for its crucial role in addressing both the immediate medical needs following the disaster and as a necessity for long-term recovery. The destruction of healthcare facilities, combined with pre-existing vulnerabilities in the healthcare system, underscored the need for a robust and accessible healthcare infrastructure to support the regions recovery. The importance of healthcare is amplified by its direct impact on overall quality of life and its influence on the decision of displaced residents to return. It was observed that spatial planning of the hospitals was a discussion topic during interviews. As can be seen in word cloud for the code 'Healthcare' in Figure 4.6, the words 'east' and 'Defne' stood out. This reflects concerns about the lack of hospitals in the eastern part of the city and in the Defne region. Adding more to spatial planning, the placement of hospitals on agricultural land was a point of significant criticism during the interviews, hence the appearance of words 'agricultural' and 'olive'.

Lastly, transportation with a focus on the airport and main road was chosen due to its critical role in facilitating rescue operations and delivering aid during the immediate response and recover and enabling access to essential services such as education and healthcare for long-term recovery. The location of the airport faced criticism for being built on the basin of the drained Lake Amik. It revealed itself to be a topic of debate for years, as the airport was already prone to flooding, which significantly increased its maintenance costs. The arterial road was another major topic of discussion in the interviews, not only due to its lack of resistance but because it was the city's only main thoroughfare. The road sustained severe damage during the earthquake, making access to various parts of the city nearly impossible. The damage to the Belen road was frequently highlighted, as it created significant obstacles for both immediate response and recovery efforts. Figure 4.7 illustrates the frequency of these words appearing within the code 'Transportation'.

In conclusion, education sector, healthcare services, and airport and main arterial road within transportation systems were selected as key critical infrastructures. These structures appeared not only fundamental to meeting the immediate needs of the population but also essential for ensuring long-term resilience in Hatay. This focused approach enhances the quality and depth of the analysis, and provides more precise and actionable insights for addressing the recovery needs of the Hatay. The next chapter will continue with the analysis which delves deeper into these three critical infrastructures through an in-depth causal investigation, identifying the root causes of their failures.

5

Root cause analysis results

This chapter offers a thorough analysis of the critical infrastructures identified as key CIs in the previous chapter. The main focus of the chapter is on root cause analysis, where the factors contributing to the failures of these critical infrastructures are explored in depth. Each section begins with an examination of the earthquake's impact on the respective infrastructure. This process enables the tracing of how the earthquake affected the systems, undercovering the disruptions. The investigation highlights the specific issues and damages caused by the earthquake to each infrastructure. Once these issues were identified, they served as the basis for branching the Fault Tree Analysis (FTA) to determine the root causes of failure for each CI. Following this, a retrospective risk assessment was performed to evaluate the broader implications of these root causes and their contribution to system failures. This assessment involved evaluating both the impact and the likelihood of contributing to system failure for each event in the tree, providing an understanding of both the realized and potential risks involved. Finally, a color-coded FTA based on the risk levels for each CI were presented, which was used for comparison with the prospective risks in the subsequent chapters.

Before delving into the details of this chapter, it is important to clarify that the education sector, although identified as one of the key critical infrastructures in the previous chapter, was not included in the subsequent analysis. This decision was made due to a significant lack of available data pertaining to the education sector, which hindered the ability to conduct a comprehensive and meaningful analysis. Critical information, such as data on casualties related to schools, construction times, capacities, and other infrastructure-specific details, was either severely limited or entirely unavailable. Without this crucial data, it would not be feasible to generate an accurate evaluation of the education sector's vulnerabilities. Therefore, this sector has been excluded from the analysis, ensuring that the findings are based on reliable, available data for the other critical infrastructures under examination.

5.1. Healthcare Services

5.1.1. Impact of the earthquake

Before the earthquake, Hatay had twelve public hospitals. The locations of these hospitals are shown on Hatay map in the left image of Figure 5.1. As illustrated, four districts: Payas, Arsuz, Belen, and Defne, lacked public hospitals entirely. The earthquake resulted in either complete collapse or severe damage to more than half of the public hospitals, making them unusable and necessitating their evacuation. At the end, districts had public hospital were Dörtyol, Hassa, Kumlu and Yayladagi. Status of each hospitals within a one month period after earthquake from causality and assessment reports can be found in subsection A.3.3. Public hospitals in Altnözü and Erzin collapsed (TMA, 2023h). The intensive care unit (ICU) of Iskenderun Public Hospital also collapsed (TMA, 2023f), resulting in approximately 250-300 fatalities within the facility (TMMOB, 2023a). Due to significant structural damage, the rest of the hospital had to be evacuated for safety reasons (TMA, 2023h). At Kirikhan Public Hospital, a power outage occurred, and the generator failed to activate, leaving the hospital without electricity for three days. This resulted in the death of 20 ICU patients (Yldz, 2024) and led to the evacuation of the facility (TMA, 2023h). Additionally, Hatay training and research hospital in Antakya (TMA, 2023f) and Reyhanli Public Hospital (TMA, 2023h) were evacuated due to damage to their buildings. Samandag Public hospital sustained severe damaged (TMA, 2023g). The MKU Hospital continued its operations until February 20th; however, the earthquake that struck the region on that day necessitated the evacuation of the hospital (TMA, 2023b). Before the earthquake, the new building of Hassa Public Hospital was over 90% complete. The old building, still in use at the time, sustained severe damage during the earthquake. However, operations were able to be transferred to the new building, allowing Hassa to retain its public hospital and continue providing services without interruption (TMA, 2023g).

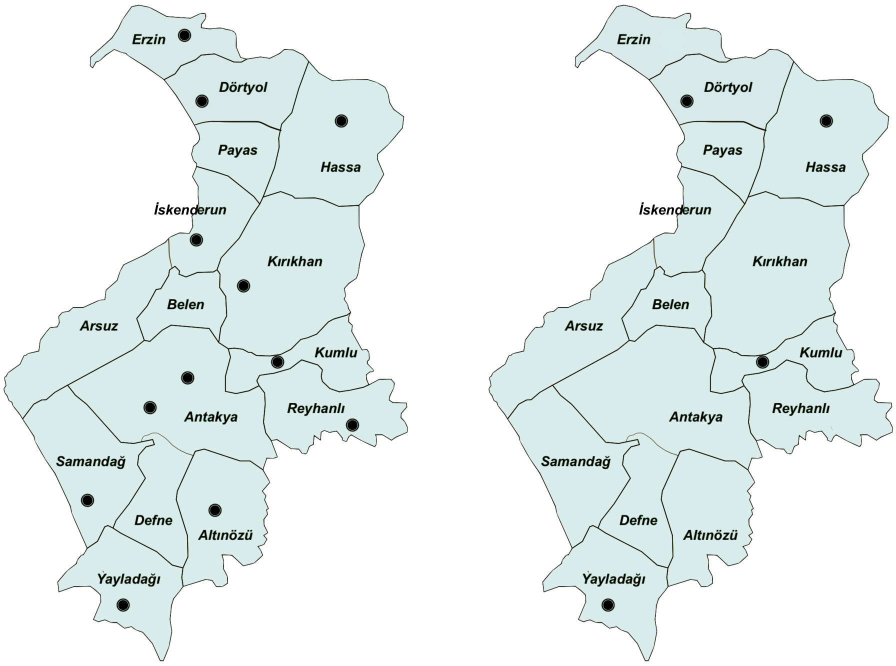

Figure 5.1: Public hospitals' locations before and after the earthquake

Dörtyol Public Hospital played a crucial role after the earthquake, as it sustained no damage and was able to continue operations without disruption (Zeren, 2023). With the highest bed capacity and resources among the undamaged hospitals, it took on a significant portion of the earthquake's burden, serving more patients than its capacity by increasing beds to 405 from 160 by adding extra beds (TMA, 2023c). However, Dörtyol Public Hospital alone could not meet the city's entire healthcare needs due to the extensive demand for medical services and a shortage of staff (Zeren, 2023).

5.1.2. Fault-Tree Analysis

As a result of the information given in subsection 5.1.1, at the top of the Fault Tree Analysis, healthcare system failure was identified as the ultimate undesired event. After the earthquakes, four hospitals in Hatay continued to operate within their buildings. Of these, only the hospitals in Dörtyol and Hassa had ICU capacity, with 62 beds in Dörtyol and 8 in Hassa as can be seen in detail in subsection A.3.4, highlighting Dörtyol's significantly larger capacity. After the earthquake, Dörtyol Public Hospital emerged as the most well-equipped hospital in the city. However, both media and government reports noted that it struggled with capacity overload and staff shortages (TMA, 2023c; Zeren, 2023). Same was observed in field and tent hospitals that were built for the immediate recovery period (Salam, 2024). Thus, hospital capacity overload and staff shortages were determined as two driven factors for the main event, healthcare system failure. These two factors were connected using an OR gate because staff and the capacity are both essential elements for the effective functioning of a healthcare system. Either one alone, whether it be the overwhelming of hospital resources or the shortage of sufficient medical personnel, could independently disrupt healthcare services, leading to the failure of the system.

Hospitals' capacity overload

As stated in literature review in subsection 2.3.2, bed capacity has an important role in the overall effectiveness of healthcare system. Insufficient bed capacity can lead to overcrowding, delayed treatments, and compromised care, whereas adequate capacity ensures that hospitals can efficiently manage patient inflows while maintaining the quality of care, even in crisis situations.

The hospital capacity was insufficient after the earthquake, as mentioned in subsection 5.1.1. However, for this research, it is essential to evaluate whether there was a pre-existing vulnerability in the healthcare infrastructure by analyzing bed capacities prior to the disaster. This assessment helps determine if the region was already under strain before the earthquake occurred.

Table A.5 presents the total bed capacities for each district, along with the number of beds per thousand people. This data was utilized for a spatial analysis of bed capacity across districts, as illustrated in Figure 5.2. This figure shows the spatial representation of bed capacities prior to earthquake. Results in Figure 5.2 reveals notable spatial differences in capacity distribution. The issue extends beyond just the uneven allocation of resources as the overall capacity was insufficient to meet the population's needs. As outlined by Ma et al. (2018) and shown in Table A.1, Hatay, with a population of 1,686,043, is classified as a large city. According to their study, the bed capacity standard for a city of this size is 6-7 beds per thousand people, while this number is 1,5 in Hatay which highlights a significant shortfall.

Figure 5.2: Spatial analysis on bed capacity pre-earthquake

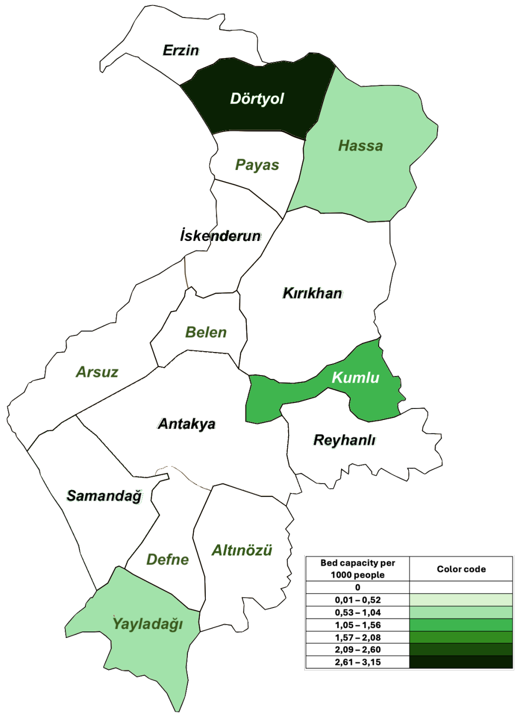

Figure 5.3: Spatial analysis on bed capacity post-earthquake

Furthermore, when examining bed capacity at the district level, none of the districts individually meet the established standards. This shows a critical deficiency in resource allocation for both uneven distribution and insufficient resource availability prior to earthquake. This deficiency indicates that healthcare infrastructure in Hatay was not adequately equipped to handle the population's needs, especially in the event of a disaster. The combination of uneven distribution and overall insufficient bed capacity left the region vulnerable prior the earthquake.

Following the earthquake, more than half of Hatay's hospital buildings became unusable, leading to a further reduction in the city's bed capacity. Figure 5.3 presents a spatial analysis of bed capacity after the disaster, factoring in the non-functional buildings and the increased bed capacity at Dörtyol Public Hospital in the aftermath of the earthquake.

This analysis identified two key factors contributing to the hospital capacity overload: the pre-existing bed capacity shortage and the loss of the hospital buildings due to earthquake damage. These factors were connected using an OR gate, which indicates that the occurrence of just one of the contributing factors is enough to result in 'Hospitals' capacity overload.' This gate was chosen because either the significant loss of functional hospital buildings or the sudden increase in demand would have been sufficient to overwhelm the remaining healthcare infrastructure. In this case, the OR gate effectively models the situation where either event alone could push the healthcare system beyond its capacity, and the combined occurrence of both events makes the overload even more inevitable. The root cause of the pre-earthquake bed shortage was traced to failures in resource allocation and distribution. These two root causes were connected with an AND gate to result in the intermediate event 'Bed capacity shortage'. The AND gate indicates that for the shortage to occur, both factors; resource allocation failure and resource distribution failure, must happen simultaneously. The rationale behind using an AND gate here is that if only the distribution failure occurred, other regions with sufficient bed capacities could have potentially alleviated the healthcare systems burden. Conversely, if there were only an resource allocation failure, but an effective distribution system was in place, beds could still have been redirected and utilized more efficiently across regions. Therefore, it is the combination of both failures that led to the critical bed capacity shortage.

When investigated, three events contributed to unusable hospital buildings; power outages, heavily damaged buildings that had to be evacuated and completely collapsed buildings. These events were connected to 'Non-operable hospital buildings' by an OR gate because occurrence of any one of these events alone would be sufficient to render a hospital non-operational. The inability of hospital buildings to operate during the power outage was traced to an energy supply services failure. Heavily damaged and collapsed buildings caused by vulnerable structures. In order to understand the cause of this vulnerability, the hospital structures were examined in this study.

It was discovered that the disparity in damage compared to other hospitals can be attributed to the hospital's structural design. Dörtyol Public Hospital was the only public hospital in Hatay that had seismic isolators in its design. Seismic isolators are a reinforced concrete load systems that isolates the effects of earthquake (TIS, 2023). Dörtyol Public Hospital being only structurally strong hospital shows the deficiency in other hospitals' design.

Moreover, a further inspection on structural vulnerabilities of hospitals revealed a critical neglection. Iskenderun Public Hospital was built in 1968 (Iskenderun Gov., 2017). Although there were addition of new buildings, the building (Block A) was built in the beginning which is years before 1999, where significant updates were done in building regulations for earthquake risk. After the earthquake on 6^{th} of February, for the collapsed buildings multiple lawsuits were filed. The report which was filed by the chamber of civil engineers within The Union of Chambers of Turkish Engineers and Architects (TMMOB) was found during the lawsuit concerning Iskenderun Public Hospital. This report, which was filed in 2012, stated that Iskenderun Public Hospital's Block A, was not earthquake resistant due to high groundwater level, which exceeded building regulation standards, and the presence of weak columns. The report also stated that this building had to be demolished due to level of risk (Tokat, 2023). After being filed, these risk report goes to Ministry of Environment, Urbanization and Climate Change in Turkey, and the ministry had to take necessary actions depending on the report (Turkish Presidency, 2012). The cause in this scenario is failure to act on identified risks, specifically the lack of timely intervention after a formal risk assessment. Despite the report in 2012, and the recommendation for demolition, no action was taken by the responsible authority (the Ministry of Environment, Urbanization, and Climate Change). This reflects a breakdown in risk mitigation processes and institutional failure to address known structural vulnerabilities.

Thus, the root causes of the vulnerabilities of the buildings were identified as the lack of seismic retrofitting and neglected structural faults, both of which were connected to the intermediate event 'Vulnerable structures' using an OR gate. The OR gate was chosen because the presence of either root cause alone is sufficient to make a structure vulnerable, meaning that even one of these issues would significantly compromise the building's resilience.

Staff shortage

Staff shortage was the second major contributing factor to the collapse of hospital services system. Unfortunately, one key cause of this shortage was the loss of healthcare personnel, as many staff members were directly affected by the collapse of hospital buildings or their houses. Therefore, the staff shortage is tied to both hospital and residential building collapses. The OR gate was used here because the death or injury of healthcare workers could occur as a result of either the collapse of the hospitals where they worked or the homes where they lived. Both events independently contribute to the loss of life, and only one event's occurrence is sufficient for the outcome to materialize. For both cases, vulnerability of structures is the reason, where its root causes where identified above.

Additionally, significant challenges arose in the efforts to bring aid from outside the city and other regions. Critical transportation system failures contributed to the collapse of the broader infrastructure, a topic that is thoroughly investigated and explained in detail in section 5.2. For the staff shortage, the loss of medical personnel and restricted access to hospitals were connected using an AND gate. This was because, although there was a shortage of local medical staff, outside aid could have alleviated the problem. The AND gate reflects the fact that both the loss of personnel and the inability to bring in outside medical staff had to occur simultaneously for the shortage to become a critical factor in the healthcare system's collapse. If either of these factors had been avoided, the shortage could potentially have been mitigated. The visual representation of the Fault Tree Analysis (FTA) for healthcare services is illustrated in Figure 5.4.

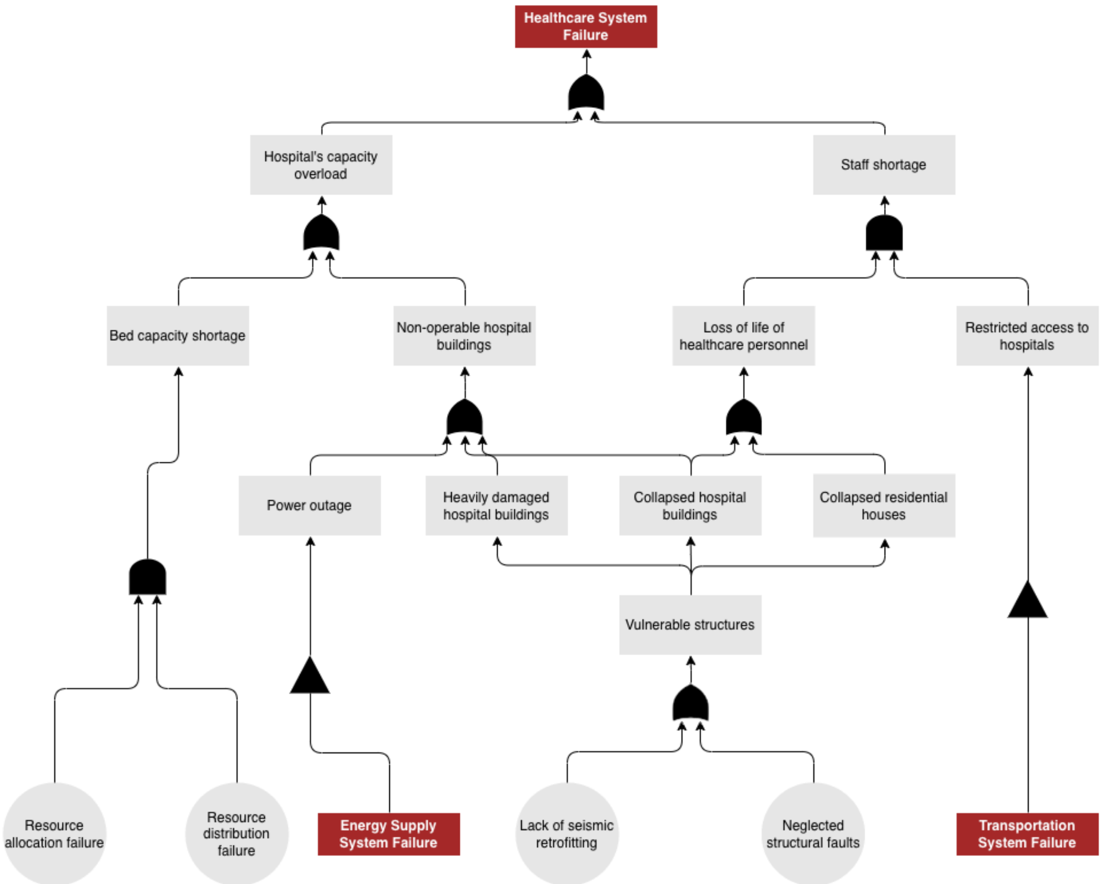

Figure 5.4: Fault Tree Analysis of healthcare services

5.1.3. Retrospective risk assessment

In this section, the retrospective risks of healthcare system failure due to identified root causes were examined. First, the risk level for each root cause was assessed, followed by a risk evaluation across the Fault Tree Analysis (FTA), progressing through each level until reaching the main event.

- Resource allocation failure: A critical deficiency in resource allocation significantly undermined the resilience of Hatays healthcare system even prior to the earthquake. Bed capacity, in particular, fell far below established standards. With only 1.5 beds per thousand people, substantially less than the recommended 6-7 beds (Ma et al., 2018) for a population of Hatays size, the system was already operating under severe constraints. This gap indicates that even if all hospitals had remained fully operational, available resources would still have been insufficient to manage the

Root cause	Impact	Probability	Overall risk level
Resource allocation failure	5	5	Extreme
Resource distribution failure	3	3	Medium
Lack of seismic retrofitting	5	4	Extreme
Neglected structural faults	5	2	High

Table 5.1: Retrospective risk assessment of healthcare system root causes

needs of the population. During the earthquake, the limited allocation of resources exacerbated the crisis, as hospitals struggled to manage patient inflows. Consequently, the impact of resource allocation failure was assigned the score of 5, reflecting the disruption caused by this significant pre-existing shortfall. Given the inadequacy of bed capacity, the probability of failure due to resource allocation was also rated as 5, indicating a near certainty that the healthcare system would be overwhelmed during a high-impact event. Therefore, the overall risk level for healthcare system failure due to resource allocation failure has been classified as 'Extreme', as indicated in Table 5.3.

- Resource distribution failure: The failure to effectively distribute available healthcare resources across Hatays hospitals played a significant role in the system's overall vulnerability, though with a more moderate impact compared to resource allocation deficiencies. Some districts, such as Payas, Arsuz, Belen, and Defne, did not have public hospitals at all, which left large areas without local access to healthcare services. As a result, the impact of resource distribution failure was rated as 3, reflecting a serious, though localized, disruption in healthcare services, with certain areas more acutely affected than others. The probability of failure due to distribution issues was also rated as 3, as these geographic imbalances and lack of local facilities were likely to result in care delays and overcrowding during emergencies, although not across all regions. Consequently, the overall risk level for healthcare system failure due to resource distribution failure has been classified as 'Medium'.
- Lack of seismic retrofitting: The absence of seismic retrofitting in Hatays healthcare facilities significantly increased their vulnerability to collapse or severe damage during the earthquake. Findings indicate that only one hospital in the region, Dörtyol Public Hospital, was equipped with seismic isolators to mitigate earthquake impacts, and there is no record of retrofitting for other hospitals. Given that the collapse of hospitals results in an immediate loss of critical healthcare capacity, the absence of retrofitting measures essentially jeopardizes the entire healthcare system's functionality. Consequently, the impact of lacking seismic retrofitting was assigned the highest score of 5, as hospital collapses have a direct and catastrophic effect on healthcare availability and emergency response. The probability of failure due to lack of retrofitting was also rated as 5, reflecting the elevated risk of collapse given the regions seismic activity and the lack of protective measures in most facilities. Therefore, the overall risk level for healthcare system failure due to lack of seismic retrofitting has been classified as 'Extreme'.
- Neglected structural faults: Neglected structural faults present a significant risk to the integrity and functionality of healthcare facilities, especially in seismic regions. In the case of Hatay, one hospital, Iskenderun Public Hospital, was identified as having pre-existing structural vulnerabilities that had been documented in a prior risk assessment but left unaddressed. This neglect contributed to the hospitals collapse during the earthquake, resulting not only in the loss of healthcare capacity but also in fatalities among patients and staff. Given the direct consequences of such structural faults, the impact of neglecting these issues was rated as 5, indicating a serious disruption to healthcare services when these vulnerabilities lead to structural failures. However, the probability of failure due to neglected structural faults was rated relatively lower, at 2, as there is currently only one documented case of such oversight, affecting a single hospital. While the likelihood of occurrence is relatively low, the potential impact remains substantial. As a result, the overall risk level for healthcare system failure due to neglected structural faults has been classified as 'High'.

After the retrospective risk assessments of the root causes, next step was to assess the retrospective risk for each intermediate event. The risk assessment of intermediate events was conducted by following the logic outlined in chapter 3. For events connected by an OR gate, the probability of the intermediate event is determined by the root event with the highest probability, as it represents the most likely cause for the intermediate event to occur. In contrast, for events connected by an AND gate, the probability of the intermediate event is calculated by considering the least probability of all root events occurring together.The impact, however, is defined by the highest impact value among the connected root events in both cases. This approach ensures that both the probability and severity of intermediate events are accurately assessed based on the nature of the logical relationship between the root causes.

Intermediate event	Impact	Probability	Overall risk level
Bed capacity shortage	5	3	Very high
Vulnerable structures	5	4	Extreme
Non-operable buildings	5	4	Extreme
Loss of life of healthcare personnel	5	4	Extreme
Restricted access to hospitals	5	5	Extreme
Hospital capacity overload	5	4	Extreme
Staff shortage	5	4	Extreme

Table 5.2: Retrospective risk assessment of healthcare system intermediate events

- Bed capacity shortage: This intermediate event is connected to two root causes with an AND gate. Thus, the probability of its occurring is restricted by the lowest probability, which is resource distribution failure with probability level 3. Impact level of bed capacity shortage determined to be 5 which is coming from the resource allocation failure since it is the most severe contributing event. Thus, overall risk level of bed capacity shortage to the healthcare system was identified as 'Very high'.

- Vulnerable structures: The two root causes connected to this event are 'Lack of seismic retrofitting' and 'Neglected structural faults', which are linked through an OR gate. The 'Lack of seismic retrofitting' probability establishes the intermediate event's likelihood at level 4, as the occurrence of just one of the root causes is sufficient for the intermediate event to occur and 'Lack of seismic retrofitting has the highest probability of occurrence. In terms of impact, both root causes share an impact level of 5. For an OR gate highest impact level defines the intermediate event's impact level like an AND gate, thus impact level of 'Vulnerable structures' is identified at level 5. Consequently, the overall risk level for this event is classified as 'Extreme'.

- Non-operable hospital buildings: Three events with OR gate is connected to this intermediate event; power outage, heavily damaged hospital buildings and collapsed hospital buildings.

  - Although power outage was excluded from the initial analysis as it is linked to the failure of another critical infrastructure, the probability of a power outage can be estimated using data, where one out of twelve hospitals was rendered non-operational due to power failure (Kirikhan Public Hospital), leading to an estimated probability level of 1. The impact was assessed at level 4, given that a power outage in a hospital can cause significant disruption, especially to critical areas such as ICU.

  Since this event is connected by an OR gate, the probability is determined by the highest probability of the contributing events, which in this case is level 4, as the event occurs if either contributing event happens. The impact, however, is still defined by the most severe impact level, which is at level 5. Therefore, the overall risk level for 'Non-operable buildings' was determined to be 'Extreme'.

- Loss of life of healthcare personnel: The intermediate event 'Loss of life of healthcare personnel' is linked to two contributing events, 'Collapsed hospital buildings' and 'Collapsed residential houses', connected by an OR gate. Both contributing events share the same probability and impact levels, driven by 'Vulnerable structures'. As a result, the risk assessment for this intermediate event mirrors the contributing events, with an impact level of 5 and a probability level of 4. This places the overall risk level at 'Extreme'.

- Restricted access to hospitals: This event is directly related to transportation system failure, which was analyzed in section 5.2. The overall risk associated with transportation system failure was classified as 'Extreme,' with both the probability and impact levels rated at 5.

- Hospitals' capacity overload: This major contributing event leading to the overall system failure was connected to "Bed capacity shortage" and "Non-operable hospital buildings" through an OR gate. As impact level defined by the highest and both factors had the impact level of 5, the overall impact was also rated at 5. The probability was assessed as 4, with the highest probability coming from 'Non-operable hospital buildings'. As a result, the overall risk level was classified as 'Extreme'.

- Staff shortage: This major contributing event to system failure was connected to two intermediate events with an AND gate. For this reason, its impact level was rated at 5, with both intermediate events having rating 5. Moreover, probability was restricted with 'Loss of life of healthcare personnel' event's probability at 4. Overall risk level found out to be 'Extreme'.

Two events were identified as major contributing factors to the system failure of the healthcare services, connected by an OR gate: 'Hospitals' capacity overload' and 'Staff shortage.' Consequently, the probability level of system failure is derived from the probabilities of these events, both rated at 4, resulting in a probability level of 4. The impact level was assessed at 5, based on the individual impact ratings of 'Hospitals' capacity overload' and 'Staff shortage.' Overall, the risk level associated with the failure of healthcare services was classified as 'Extreme.' A risk-based color-coded Fault Tree Analysis (FTA) based on this risk assessment can be found in Figure 5.5.

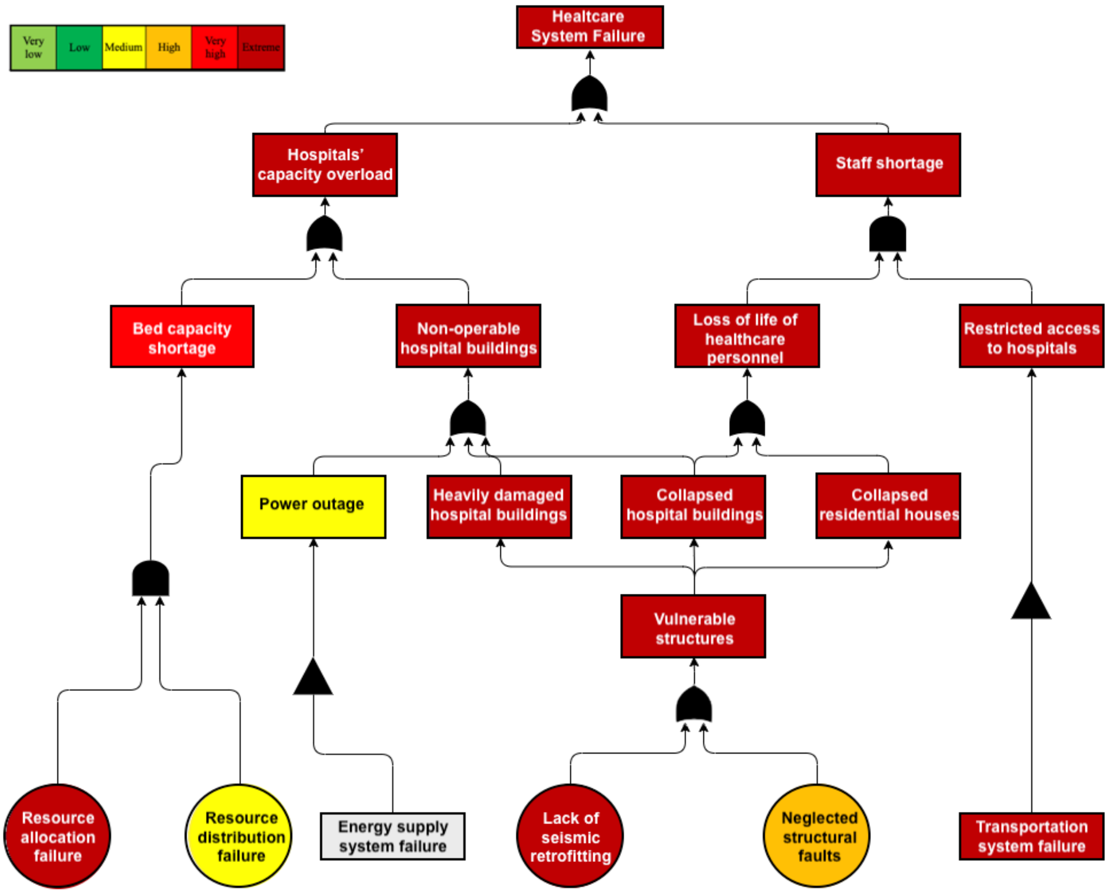

Figure 5.5: Fault Tree Analysis of healthcare services with risk levels

5.2. Transportation Systems

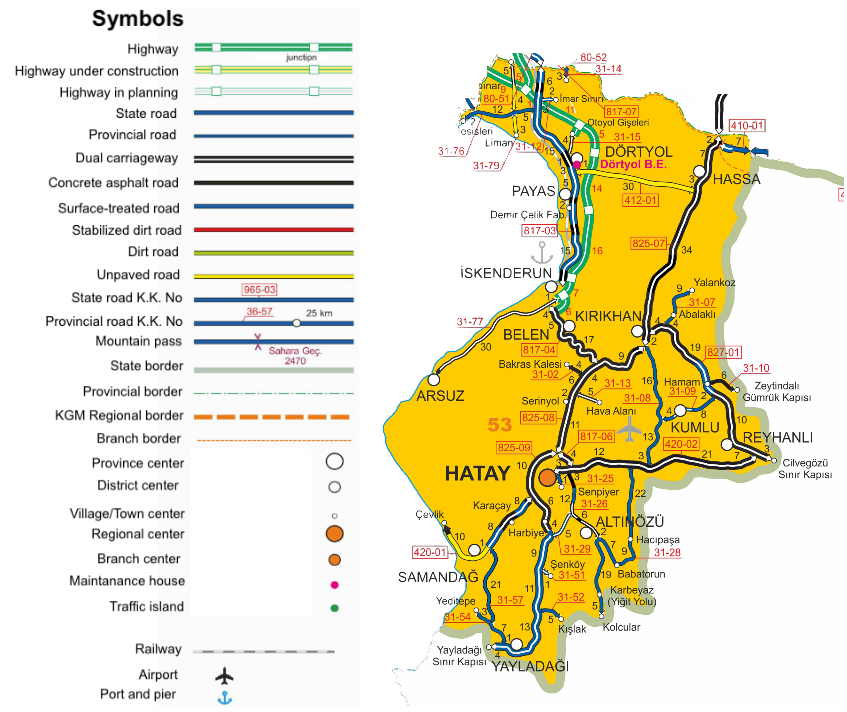

Figure 5.6: Hatay road network map (KGM, 2024)

5.2.1. Impact of the earthquake

Hatay Airport

Based on interviews and media reports, it was evident that the earthquake caused extensive damage to Hatay Airport, making it unusable during the initial emergency response efforts (CNBC, 2023, A.2.2). Hatay Airport was closed to traffic due to fractures and cracks at 45 different points along the 3-kilometer runway after the earthquake (Palabiyik, 2023). Presidency of Strategy and Budget damage control reports also confirmed that the runway sustained significant damage, resulting in fractures on it, and the apron experienced severe structural damage. Furthermore, ground settling was observed at the airport, indicating potential subsidence of the soil, which led to uneven surfaces and further complications for aviation operations. Additionally according to the reports infrastructures within the airport such as drainage, electrical and mechanical systems were non-functional, increasing the challenges for recovery efforts and operational readiness of the airport. Planned expenditure of Presidency for Hatay Airport for these damages were announced to be around 135 million dollars (Strategy and Budget Office of the Presidency of the Republic of Türkiye, 2023). After extensive repairs, Hatay Airport was finally reopened in April 2024, more than a year after the earthquake (Ministry of Transport and Infrastructure, 2024b).

Roads

According to the preliminary assessment report by TMMOB (2023b), the transportation infrastructure in Hatay was non-functional for the first two days following the earthquake. As a result, aid trucks were unable to reach the city during this critical period. Moreover, heavy construction equipment, such as caterpillars, required for rubble removal for access to people under and rescue teams could not access the city due to the severe damage on the roads (TMMOB, 2023a). Figure 5.6 illustrates the road network map for Hatay. The General Directorate Of Highways (KGM) reports confirmed that four key routes in Antakya were closed to traffic. These include the roads between Antakya and Reyhanli (No: 420-02), Antakya and Kirikhan (No: 825-08), Antakya - Kirikhan and Belen (No: 817-04), as well as the route in Antakya that is connecting Serinyol to Hatay Airport (No: 31-13) (TMMOB, 2023b).

5.2.2. Fault-Tree Analysis

Hatay's unique geographical position places it in a distinct situation than other cities within the country. While its eastern and southern borders are surrounded by the national boundary with Syria, its western side is bordered by the Mediterranean Sea. This leaves the city with only its northern border providing land access, making it more geographically isolated and reliant on a limited entry point for overland transportation and connections.

Transportation system in Hatay involves many components. Iskenderun and Antakya are critically important for the road network in Hatay because they serve as key transit points. Iskenderun's location along the Mediterranean coast provides access to domestic and international shipping routes, with the harbor that is in the district. Meanwhile, Antakya link various regional roads and serving as the center of the province, further enhanced by the presence of the airport.

As illustrated in the road network map in Figure 5.6, Hatay has four primary land entry points for domestic access. However, only one of these is a highway, and it terminates in Iskenderun, limiting its reach to the rest of the province. Additionally, two of the entry roads converge near the city's border, reducing their effectiveness as alternative access routes. Moreover, within the city's borders, there is a noticeable lack of alternative routes connecting districts. For instance, Arsuz can only be accessed from Iskenderun via only one road (31-77), and Antakya is only reachable through the Serinyol road (825-08). Furthermore, the Belen road (817-04) is the sole route linking the western and eastern parts of the city, while Serinyol (825-08) remains as a critical road that provides a shortest north-to-south connection.

As mentioned in section 4.1, all transportation systems, including the harbor and airport, suffered severe damage due to the earthquake. Consequently, the main event for the FTA was defined as the failure of the transportation system. While the damage and non-functionality across various transport services in Hatay were significant contributors to the overall system failure, this study focuses specifically on the airport and road networks as they were identified as key infrastructures in chapter 4. These failures were connected with an OR gate because each system is vital to the transportation infrastructure, and the failure of any one of them is enough to cause severe disruption. Hatay's geographical location makes the region particularly vulnerable to transportation challenges during disasters. The region is heavily dependent on each transportation system, meaning that if any one mode of transport becomes inoperable, it can cripple the citys ability to function, both for emergency response and daily logistics.

Non-functional airport

The first major factor contributing to the failure of the transportation system analyzed in this study is the non-operational status of Hatay Airport. This condition arose from the dysfunction of both water and energy infrastructure, as well as substantial damage to the runway and damage to connection road of airport to the city. These three contributing intermediate events are connected to the airport's non-operational state via an OR gate, as the functionality of the airport would be compromised by the occurrence of any one of these events. The first intermediate event highlights failures in the water and energy supply systems which are the factors beyond the scope of this study; however, it is important to mention these two system failures were connected via OR gate, because each independently contributes to the overall infrastructure failure of the airport. This investigation focuses on the runway damage and damage to airport connection road which was investigated in "Road network failure" branch (see Figure 5.8).

The decision to build the airport at its current location was a subject of debate in both interviews and media reports. Therefore, the analysis begins with an investigation of the airport's site selection. Before the airport was built, four potential locations were proposed: Topboaz, Serinyol, Iskenderun, and the Amik Valley (Karagoz et al., 2023). These proposed locations are shown in Figure A.6. Ultimately, in 2007, Hatay Airport was constructed and opened in the Amik Valley (Ministry of Science, Industry and Technology, 2024), which is located in the region bordered by the regions Antakya, Reyhanli, and Kirikhan.

Prior to 1955, Lake Amik existed on the northwest of the Amik Valley, where the airport now stands. In 1955, drainage work began on Lake Amik to combat malaria and expand agricultural land and the project was completed in the 1980s (Özelkan et al., 2011). Since it is a lake basin, ground of the airport is an alluvial soil. Even though alluvial soil is considered as one of the best soils for agricultural reasons (Torreano, 2004), it has considerable disadvantages in terms of resilience and supporting building structures due to poor load-bearing capacity (Valverde-Palacios et al., 2013), making it unable to support heavy infrastructure.

Another disadvantage of these type of soils is being prone to liquefaction, which means ground to lose strength and behave like a liquid during seismic activity because of their loose structure (Ibrahim, 2014). Furthermore, poor drainage of these soils can cause water retention and surface flooding, in heavy rain and it can even cause runways to crack upward due to underground water pressure (Kowalik, 2006). As noted in interviews and media reports discussed in subsection 5.2.1, the maintenance costs for the airport have been high due to the recurring flooding, and the efforts to address these issues have proven insufficient.

The airport is situated at the intersection of three faults, Dead Sea Fault, Karasu Fault, and Cyprus-Antakya Fault (Ozsahin, 2015) and it is highly earthquake-prone zone. The combination of high earthquake risk and alluvial soil based ground presents significant challenges for the structural integrity and long-term viability of the airport. Building on this, the study conducted by Ozsahin (2015) thoroughly examines the various risks associated with the location of Hatay Airport, highlighting its significant vulnerability to both environmental and geological factors. In its conclusion, the study asserts that Hatay Airport faces a high risk of both flooding and earthquakes, underscoring the urgent need for comprehensive preventive measures to mitigate these hazards.

Consequently, both spatial vulnerability and structural vulnerability were identified as critical factors contributing to the runway damage, connected through an AND gate. The rationale for this gate selection is that both factors had to be present simultaneously for damage to occur on the runway. Specifically, even in the presence of spatial vulnerability, a resilient structure could have mitigated the risk of damage. Conversely, structural vulnerability would have been less significant if spatial vulnerabilities had not posed a threat to the structure.

It was discovered that the site assessments conducted before construction were inaccurate, as liquefaction occurred in the areas where it had not been anticipated (Hatay Planning Office, 2024). This failure in the predicting soil behavior during seismic activity exposed serious gaps in the pre-disaster evaluations. Consequently, poor site selection and inaccurate site assessments were identified as the root causes of spatial vulnerability. These two root causes were connected using an OR gate in the Fault Tree Analysis, as either factor alone could lead to the vulnerability of the infrastructure.

Poor site selection refers to the failure to avoid areas already known to have high risk to hazards, such as regions with loose, water-saturated soils prone to liquefaction. Even though certain areas had

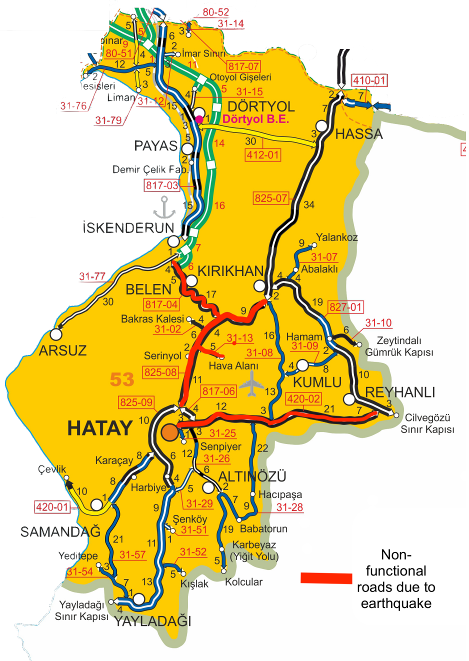

Figure 5.7: Hatay road network map post-earthquake (KGM, 2024)

documented vulnerabilities, these risks were overlooked, contributing to the damage. On the other hand, inaccurate site assessments involve failures in geotechnical investigations that should have identified risks, like soil instability, but did not adequately account for these factors. This misjudgment resulted in unexpected vulnerabilities in areas where construction had otherwise been deemed safe.

The use of an OR gate here was chosen as either poor site selection or inaccurate site assessments on their own could result in spatial vulnerabilities. Even if one of these issues had been addressed, inaccurate assessments of soil and terrain could still lead to infrastructure failure, and vice versa. Thus, both factors independently contribute to the overall spatial vulnerability, leading to increased damage during the earthquake.

The decision to construct the airport on alluvial soil within a seismic hotspot introduced inherent risks that were inadequately addressed during the design and construction phases. This oversight, combined with high seismic activity, insufficient drainage, and the soil's low load-bearing capacity, created significant structural challenges that were left unaddressed, ultimately resulting in extensive damage during the disaster. Moreover, high maintanance needs came from spatial vulnerabilities were not adequately addressed to support the structure. For this reasons, ineadequate design for site conditions and lack of maintanance were identified as root causes of structural vulnerability connected with an OR gate.

Road network failure

Most of the critical roads sustained serious damage because of the earthquake and they were non-functional in the immediate response efforts. Belen road (817-04), Hatay - Kirikhan connection which is also called Serinyol road (825-04), Hatay - Reyhanli connection (420-02), and Serinyol - Hatay Airport connection (31-13) were closed due to damage during immediate response. Non-functional roads can be observed in Figure 5.7. Thus, earthquake damage to roads is a identified as a contributing factor.

Although the collapse of three major roads in a city is a significant event, it cannot be viewed as a primary contributing factor on its own. In Hatay, both critical access points and alternative routes are notably inadequate. For example, there are only three roads connecting the city entrance to Iskenderun, with one approaching from the opposite side of the city. From Iskenderun to Belen, Kirikhan, and Antakya there is only one connection which was entirely blocked following the earthquake.

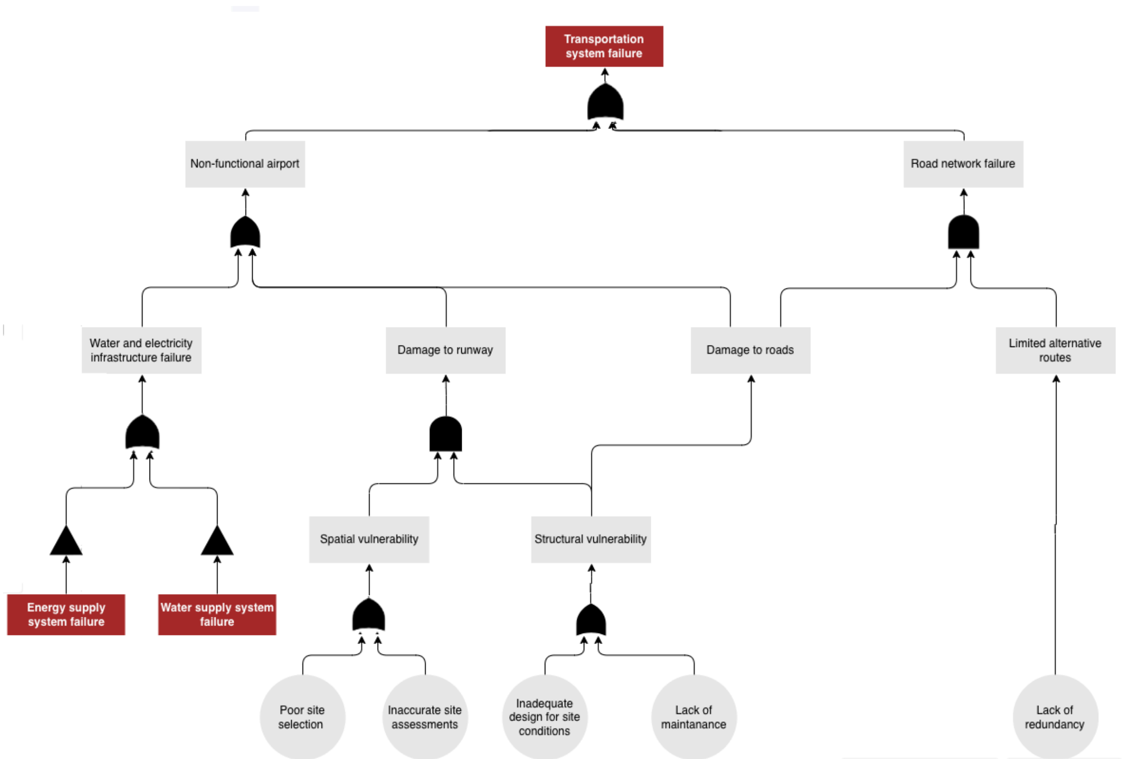

Figure 5.8: Fault Tree Analysis of transportation systems

For these reasons, while the failure of the road network is recognized as a major contributing factor to the overall transportation system failure, the damage to roads and the limited availability of alternative routes were also significant contributors to the road network's dysfunction. These events were connected to road network failure with an AND gate, as both conditions must occur simultaneously to result in the overall failure of the road network. If either event were absent, the road network might still function adequately. Additionally, while road damage relates to structural vulnerability, the lack of redundancy emerged as one of the root causes. Visual representation of FTA for transportation systems can be seen in Figure 5.8.

5.2.3. Retrospective risk assessment

Root cause as risk factor	Impact	Probability	Overall risk level
Poor site selection	4	5	Extreme
Inaccurate site assessments	5	3	High
Inadequate design for site conditions	5	5	Extreme
Lack of maintenance	3	4	High
Lack of redundancy	5	4	Extreme

Table 5.3: Retrospective risk assessment of transportation system root causes

- Poor site selection: The selection of locations for transportation routes is crucial for maintaining the resilience and functionality of infrastructure, especially in seismically active regions like Hatay. While spatial vulnerability does not inherently lead to system failure, effective design is essential. When structures are built according to necessary engineering standards that account for geographical constraints, resilience can still be achieved. However, the greater the vulnerability of a location, the more challenging it becomes to design suitable structures that can withstand potential hazards. Consequently, the impact of poor site selection was assigned a high score of 4. In this case, poor site selection played a significant role in the failure of the transportation system, contributing to its overall impact during the disaster. Probability level of system failing due to poor site selection was identified as 5, indicating a very high likelihood. This assessment is based on geological conditions that show specific areas in Hatay are prone to both seismic and hydrological risks. The level of vulnerability faced by the airport due to its location is significantly high. Consequently, the probability of failure resulting from this poor site selection has been classified as very high, indicating a strong likelihood of transportation system failure attributable to this issue. The overall risk level for transportation system failure due to poor site selection has been classified as 'Extreme'.

- Inaccurate site assessment: Inaccurate site assessments significantly undermine the integrity and resilience of infrastructure. There are severe consequences that can arise from such assessments. Inaccurate evaluations can lead to the construction of buildings in unsuitable locations or the use of inappropriate materials, making them vulnerable to environmental stressors, including earthquakes. Thus, impact level was identified at 5. However, the probability rating was assessed at 2, reflecting to the fact that only one specific region has been identified with inaccurate site assessments. As a result, the overall risk level associated with this root cause was classified as 'High'.

- Inadequate design for site conditions: Some structures were inadequately designed for the specific site conditions they occupy, failing to account for the unique geological challenges of the area. When structures are not built to the necessary standards that address the inherent risks of their locations, they become highly prone to failure. The more challenging the site conditions, such as unstable soil, existence to fault lines, or flood-prone areas, the more critical it is that designs incorporate appropriate reinforcements and mitigation strategies. In this case, the impact of inadequate design for site conditions was assigned a score of 5, indicating a significant level of disruption to the transportation system was due to the design during the earthquake. Moreover, the probability of failure resulting from inadequate design has also been classified as 5, indicating a very high likelihood of system failure due to design conditions. As a result, the overall risk level for transportation system failure due to inadequate design for site conditions has been classified as ’Extreme’.

- Lack of maintenance: A lack of maintenance can lead to gradual deterioration, ultimately jeopardizing the safety and functionality of infrastructure. Given the prolonged nature of this issue, the impact level has been rated at 3. Additionally, the probability level has been assessed at 4, reflecting a moderate likelihood that maintenance efforts may be insufficient due to the high demands posed by geographical constraints. Consequently, the overall risk level associated with this root cause has been classified as ’High’.
- Lack of redundancy: The design and operation of transportation infrastructure must incorporate redundancy to ensure resilience, which refers to the presence of alternative routes or systems that can be utilized when primary pathways become obstructed or fail. The impact of the lack of redundancy was assigned a score of 5, indicating a critical level of disruption to the transportation system during the earthquake. Furthermore, given the notable shortage of alternative routes in Hatay, the probability of system failure due to lack of redundancy was rated as 4, meaning a high likelihood of failure under adverse conditions. This assessment is informed by analyses of the transportation network, which revealed that the absence of alternative routes left multiple areas vulnerable during the emergency. As a result, the overall risk level for transportation system failure due to lack of redundancy has been classified as ’Extreme’.

After the retrospective risk assessments of root causes, intermediate events’ retrospective risks were found below following the same logic outlined in chapter 3 and used in Table 5.2.

Intermediate event	Impact	Probability	Overall risk level
Spatial vulnerability	5	5	Extreme
Structural vulnerability	5	5	Extreme
Water and electricity infrastructure failure	3	3	Medium
Damage to runway	5	5	Extreme
Non-functional airport	5	5	Extreme
Road network failure	5	4	Extreme

Table 5.4: Retrospective risk assessment of transportation system intermediate events

Consequently, the risk of transportation system failure due to the non-functionality of the airport and road network has been assessed at an overall risk level of "Extreme," characterized by both an impact level and probability level of 5. A risk-based color-coded Fault Tree Analysis (FTA) based on this risk assessment can be found in Figure 5.9.

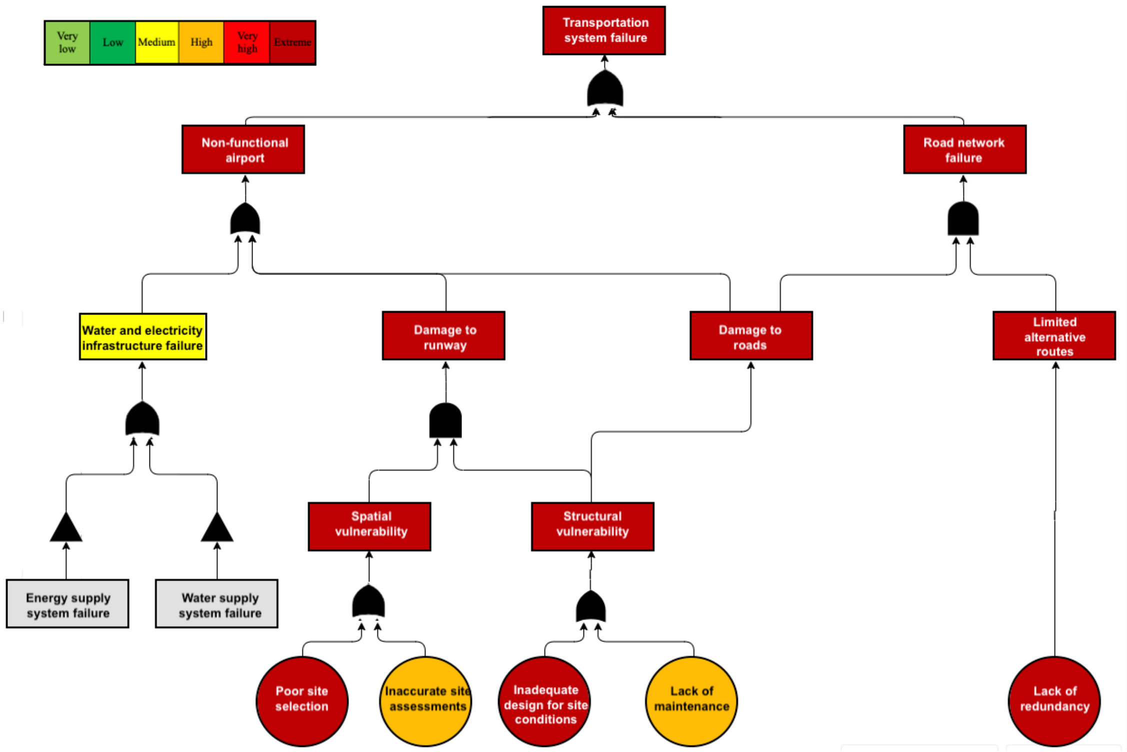

Figure 5.9: Fault Tree Analysis of transportation system with risk levels

Having identified the root causes of both critical infrastructures and assessed their associated risks, the next chapter evaluates the long-term recovery plans. This evaluation focuses on how these plans addresses the identified root causes and their potential to alter the overall risk levels of the systems.

6

Evaluation of long-term recovery plans

Following the identification of root causes and retrospective risk assessments in prior chapter, this chapter focuses on the resilience initiatives proposed as long-term recovery plans. Specifically, for each critical infrastructure, investigation on the details of long-term recovery plans done, analyzing their potential impact on the root causes that have contributed to system failures.

The process begins by examining the proposed long-term recovery plans in detail and identifying specific interventions for each infrastructure. For example, in the healthcare system, measures to improve hospital capacity, seismic retrofitting, and resource allocation were evaluated for their anticipated effects on resource scarcity and structural integrity. Similarly, for transportation systems, resilience measures such as route redundancy, structural reinforcements, and site-specific design adaptations were reviewed for their potential to address issues like poor site selection and inadequate site-specific designs.

Once the potential impacts of these recovery initiatives on each root cause were analyzed, the study continues with a prospective risk assessment to determine the revised risk levels for each CI. This step involves reassessing the probability, impact, and overall risk levels of previously identified failure events, taking into account the mitigation effects of the planned improvements. Each root cause is then re-evaluated within the context of these updates, and the results are presented in tables. Finally, revised color-coded Fault Tree Analyses (FTAs) for each CI are provided, reflecting the updated risks after the long-term recovery measures.

6.1. Healthcare services

As discussed in section 5.1, one of the primary causes of the healthcare system's failure was the inadequate resource allocation and distribution, largely driven by insufficient bed capacity at both the city and district levels, with some districts lacking public hospitals altogether.

The healthcare recovery plans for Hatay include the construction of three new hospitals in the districts Antakya, Iskenderun, and Payas as well as four emergency hospitals in the districts Antakya, Iskenderun, Altnözü and Erzin (Hatay Planning Office, 2024). First, the districts that previously lacked hospitals (Payas, Belen, Arsuz, and Defne) and the districts that lost their hospital due to the earthquake (Erzin, Iskenderun, Kirikhan, Reyhanli, Antakya, Samadag, and Altnözü) were evaluated to determine if these plans address those deficiencies. According to Ministry of Health (2023), construction of public hospitals had already begun in the districts of Arsuz and Belen prior to the earthquakes and a new hosptial in Defne, which the Official Gazette confirmed (Turkish Presidency, 2023) is in plans. In addition, MKU hospital in Antakya and hospitals in Kirikhan and Samandag-which were evacuated after the earthqaukes- started operating within their old buildings (Hatay ISM, 2022a, 2024f; TMA, 2024). As a result, districts that previously lacked hospitals are set to receive them under long-term recovery plans. However, in the case of Reyhanli, a district that lost its hospital in the earthquake, there is, to the best of current knowledge, no specific recovery plan in place to address this loss. Comparison of spatial analysis for pre- and post-disaster as well as the recovery plans can be seen in Figure 6.1. Resource distribution shows progress compared to the pre-earthquake distribution. Moreover, it can be observed from the figure that, with the exception of Reyhanli (due to the loss of the public hospital) there has been no reduction in bed capacities across the other districts. However, as previously noted, the standard for bed capacity in a city with Hatay's population should be a minimum of 6 to 7 beds per 1,000 people. Since the recovery plans only increase the bed capacity in Hatay from 1.5 to 2.7 beds per 1,000 people, it still falls significantly short of the established standard (see Table A.6). When examined on a district basis, Antakya is the only district that meets the standards for bed capacity.

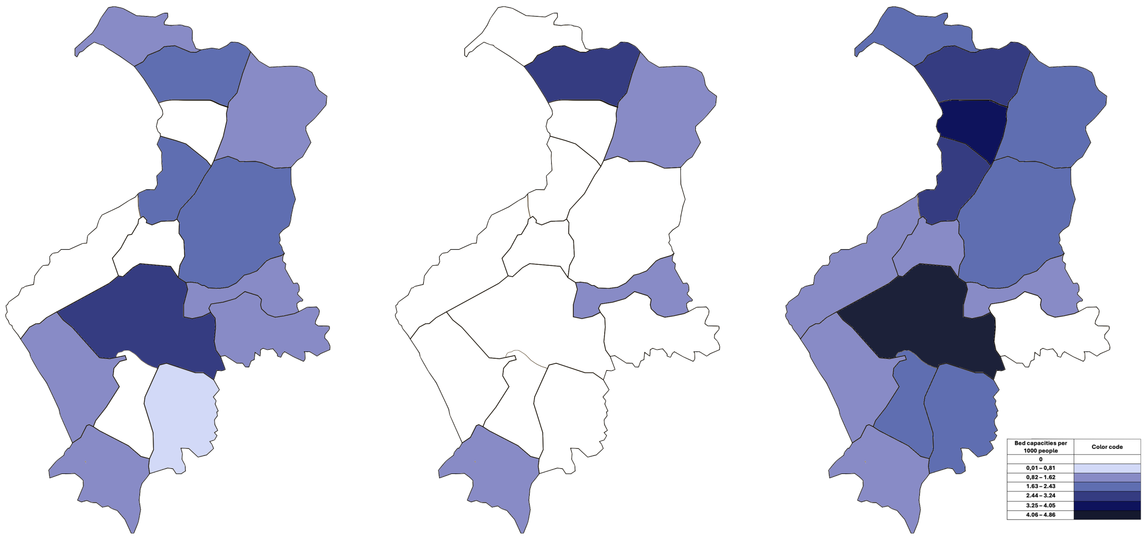

Figure 6.1: Spatial analysis on bed capacity pre-earthquake, post-earthquake and in recovery plans

Another identified root cause for healthcare system was neglected structural. It was discovered that, although three hospital buildings resumed operations in their original buildings after needing evacuation following the earthquake, only one of them had undergone retrofitting (TMA, 2024). The immediate need for evacuation reveals significant structural weaknesses, underscoring these buildings vulnerability to seismic activity which adds to the documented examples of neglected structural faults within healthcare infrastructure.

Regarding newly planned hospitals, only those in Antakya and Iskenderun are specifically designed with earthquake-resistant structures. One of the upcoming hospitals in Antakya will feature steel construction (Ministry of Health, 2023), which has several advantageous properties for seismic resilience (Pujari & Momin, 2023). Additionally, construction plans for the new hospital in Iskenderun include seismic isolators to enhance earthquake resilience (Ministry of Health, 2023). These isolators are the ones that was used in Dortyol Public hospital.

Hatay Planning Office (2024) states that the energy released during earthquakes and the resulting ground deformations have altered the geophysical, geological, and geotechnical conditions of the region. Furthermore, Hatay Planning Office (2024) highlights that in the most recent analysis conducted in 2018, liquefaction was not anticipated for Iskenderun and Antakya; however, subsequent studies confirmed that liquefaction did occur. This discrepancy indicates an error in those studies and renders them inadequate for informing new decisions. As a result, current site evaluations are likely inaccurate. Despite this, the official gazette's decision on new hospital locations includes urgent expropriation. However, from the time of the earthquake until the release of the decision on new hospitals, neither the official gazette nor any other governmental publications specified any site assessments or plans for the designated hospital locations. Therefore, to the best of current knowledge, these locations were selected without clear planning for updated site evaluations. Without updated site evaluations that account for post-earthquake changes in ground conditions, building new hospitals in these areas increases the risk of liquefaction and other structural vulnerabilities.

6.1.1. Prospective risk assessment

In this section, the prospective risks of healthcare system failure examined considering the long-term recovery plans that were investigated above.

Root cause as risk factor	Impact	Probability	Overall risk level
Resource allocation failure	4	4	Very high
Resource distribution failure	2	1	Very Low
Lack of seismic retrofitting	5	3	Very high
Neglected structural faults	5	4	Extreme

Table 6.1: Prospective risk assessment of healthcare system root causes according to long-term recovery plans

- Resource allocation failure: The recovery plans have made some progress in expanding healthcare capacity by proposing the construction of new hospitals in critical districts, including Antakya, Iskenderun, and Payas, and the addition of emergency hospitals in Altnözü and Erzin. However, the projected increase in bed capacity remains insufficient, raising it only to 2.7 beds per 1,000 people, which is still significantly below the literature's recommended standard of 6 to 7 beds per 1,000 people. This inadequate expansion indicates that the healthcare system would remain vulnerable to being overwhelmed in future crises. Therefore, the impact of resource allocation failure is rated at 4, as the shortfall in capacity directly affects the systems ability to respond to emergencies. The probability of this shortfall affecting the system decreased to 4, due to the increase in the capacity; however, still remaining limited. Thus, the overall risk level for healthcare system failure due to resource allocation failure classified as 'Very high'.
- Resource distribution failure: The distribution of healthcare resources across Hatays districts has shown some improvement, with new hospitals planned for previously underserved areas. The impact of resource distribution failure has been rated as 2, reflecting that the existing distribution issues are less severe compared to other factors, particularly given the ongoing efforts to improve access. The probability of experiencing distribution issues is now rated as 1, as the planned improvements are expected to alleviate past challenges. Although resources remain insufficient, fairness in distributions of them is higher. Therefore, the overall risk level for healthcare system failure due to resource distribution is classified as 'Very low'.
- Lack of seismic retrofitting: While some planned new hospitals incorporate earthquake resistant features, such as steel construction in Antakya and seismic isolators in Iskenderun, many existing hospitals remain vulnerable as no comprehensive retrofitting plan or designs for seismic resilience has been detailed for future hospitals. Given that seismic resilience is crucial for hospital resilience in an earthquake-prone area like Hatay, the lack of widespread retrofitting leaves facilities vulnerable. Therefore, the impact of lacking seismic retrofitting is rated 5 (Extreme), as structural failure directly jeopardizes the healthcare systems capacity. The probability of failure due to the absence of retrofitting decreased to 3 due to new design plans; however, still reflecting a moderate likelihood of future failures without more thorough comprehensive design plans. The overall risk level for lack of seismic retrofitting is therefore classified as 'Very high'.
- Neglected structural faults: Only one hospital from the those evacuated after the earthquake undergone retrofitting while others resumed operations in damaged structures, indicating a persistence of structural vulnerabilities. The impact of neglected structural faults remains at 5 since structural vulnerability directly effects hospital's operations in the case of an earthquake. The probability of encountering issues due to neglected structural faults increased to 4, as structural weaknesses were not adequately addressed in the recovery plans and number of structures with known weaknesses are higher than before. Thus, the overall risk level for neglected structural faults increased to higher classification of 'Extreme'.

Based on the updated risk levels of the root causes, the prospective risk levels for the intermediate events were calculated in Table 6.2.

Intermediate event	Impact	Probability	Overall risk level
Bed capacity shortage	4	1	Medium
Vulnerable structures	5	4	Extreme
Non-operable buildings	5	4	Extreme
Loss of life of healthcare personnel	5	4	Extreme
Restricted access to hospitals	5	3	Very high
Hospital capacity overload	5	4	Extreme
Staff shortage	5	3	Very high

Table 6.2: Risk assessment of healthcare system intermediate events after long-term recovery plans

The updated color-coded Fault Tree Analysis (FTA), reflecting the prospective risk levels can be seen below.

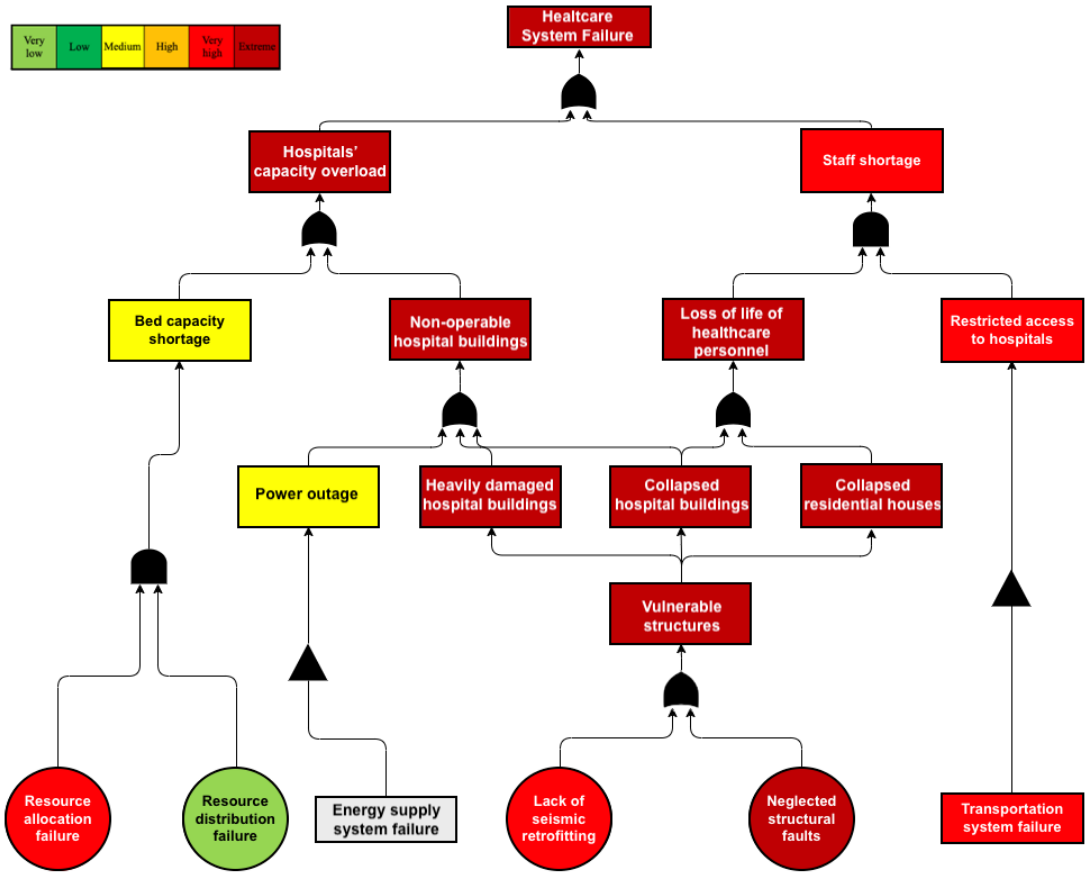

Figure 6.2: FTA of healthcare services with risk levels after long-term recovery plans

6.2. Transportation systems

For the transportation systems two events was investigated in root cause analysis, non-functional airport and road network failure (see Figure 5.8). The analysis revealed that the root causes of these failures were linked to poor site selection, inadequate design adjustments for site-specific conditions, and an overall lack of redundancy in road networks. These weaknesses contributed significantly to failure of transportation system during earthquake and thus delays in emergency response.

According to (Ministry of Transport and Infrastructure, 2024a), instead of changing Hatay Airport's location, it was decided to implement various prevention measures to enhance its resilience. These measures include strengthening the airport's infrastructure (water and energy supply), renovating existing runway, and reinforcing the soil to prevent liquefaction and surface deformations. Additionally, security walls surrounding the airport were raised, and repairs were made to cracks to mitigate the risk of flooding (Ministry of Transport and Infrastructure, 2024a). However, plans do not show any preventive measures regarding groundwater pressure that caused by heave rainfall which is a main reason hydrostatic uplifts that can weaken or damage the runways structural integrity, potentially leading to cracks, surface deformation, or even displacement of runway materials as mentioned in Figure 5.8.

Long-term plans also do not include any indication of a thorough location-based risk assessment to determine whether these mitigation measures are adequate for the specific challenges posed by the site. Without the analysis to evaluate the sites safety, it remains uncertain whether the planned reinforcements can sustain the airport's long-term operational viability. Ideally, a detailed study of the airports geographic risks should be conducted to assess whether relocating to a safer, less seismically active area would offer a more sustainable and reliable solution. In the absence of such an analysis, relying solely on structural upgrades may expose the airport to significant operational disruptions, especially during emergencies when its functionality is most critical (Hatay Planning Office, 2024).

The newly proposed transportation plans for Hatay include several new routes as can be seen in Figure 6.3. Previously, only an unpaved road connected Hassa to the city's western areas without requiring a southern detour (see Figure 5.6). The updated plans propose a new highway along this route, branching off from the existing highway at Payas. While the current road runs from Dörtyol to Hassa, the planned highway connecting from Payas enhances connectivity points (critical points). Given that the previous route was an unpaved earth road, this analysis previously identified the Belen road as the only viable west-east connection within the city. The new Payas-Hassa connection offers an alternative route for west-east connection of the city and increases the redundancy.

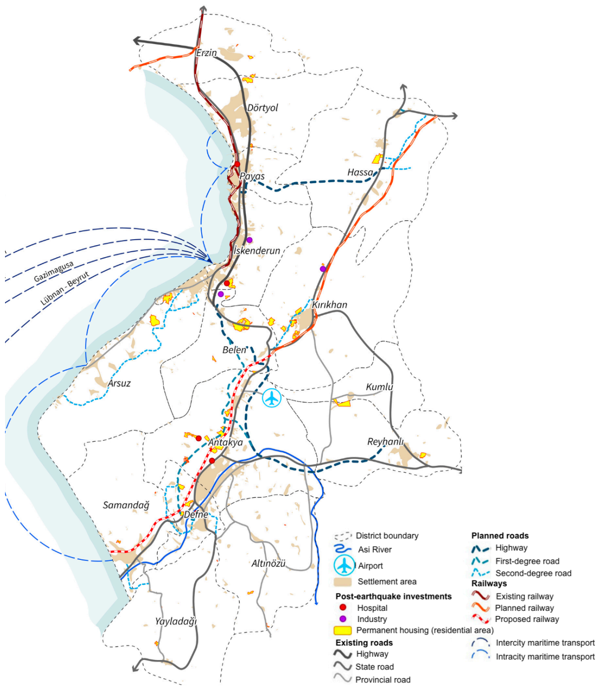

Figure 6.3: Current and planned transportation networks (Hatay Planning Office, 2024)

Additionally, the existing highway, which previously ended in Iskenderun, is now extended to reach Reyhanli, passing through the districts of Belen and Antakya. This planned highway represents a significant improvement over the previous road infrastructure, which was inadequate to handle the growing traffic demands of the region. As found out in interviews, traffic jams in Belen were already discussion topics prior to earthquake (A.2.2). Previous road was on a single lane connecting the most densely populated districts. Moreover, this road became non-functional during emergency response efforts, significantly impacting rescue operations. In fact, all connections from Iskenderun to Reyhanli through Belen and Antakya were rendered unusable. The extension of the highway to Reyhanli improves connectivity between Iskenderun, Belen, Antakya and Reyhanli. This upgrade will provide a more reliable route that can accommodate increased traffic volumes, helping to reduce delays during emergencies.

The planned highways increase the number of critical points and alternative routes, thereby enhancing the region's transportation network and increasing the redundancy. This improvement is expected to facilitate smoother traffic flow, which is essential for both everyday commuting and emergency response situations. By increasing redundancy, the new infrastructure will reduce dependency on single pathways, making the network more resilient to disruptions.

In addition to the highway, there is a planned first-degree road that will connect Belen to Defne through Antakya. This road is crucial for enhancing accessibility within the region, as Belen is a critical district with significant traffic flow. Having these alternative routes is particularly beneficial, especially considering that, prior to these plans, there was only one road passing through Belen. The introduction of multiple connections for the district of Belen marks a significant improvement in the city's redundancy and overall transportation resilience.

In the analysis, the districts identified as least accessible were Arsuz, Altnözü and Kumlu. The recovery plans propose an alternative road to improve the connection between Iskenderun and Arsuz. However, the current plans do not indicate any improvements to Altnözü's road connections. While the new connection in Arsuz enhances the district's redundancy, it doesn't solve all regions accessibility problems.

Another identified root cause was inadequate design for site conditions; however, there is a notable lack of data regarding the design of the new road network. While it is commendable that the plans do not indicate a reliance on outdated site analyses, the absence of a current assessment raises significant concerns. Given that ground conditions may have changed drastically following the earthquake, previous analyses may no longer be applicable or sufficient. Consequently, in the absence of any indication that new site assessments are planned for the locations of the new road network, there is an increased risk that the new infrastructure could be vulnerable to similar issues observed in the previous designs.

6.2.1. Prospective risk assessment

In this section, the prospective risks of transportation system failure examined considering the long-term recovery plans that were investigated above.

Root cause as risk factor	Impact	Probability	Overall risk level
Poor site selection	4	4	Very high
Inaccurate site assessment	5	4	Very high
Inadequate design for site conditions	5	3	Very high
Lack of maintenance	2	2	Low
Lack of redundancy	3	3	Medium

Table 6.3: Risk assessment of transportation system root causes according to long-term recovery plans

- Poor site selection: The impact of poor site selection remains significant due to ongoing geographical vulnerabilities. While some mitigation measures, such as infrastructure improvements, have been implemented, the inherent risks associated with the airport's location persists. Consequently, the impact score stays at level 4. Additionally, there is no evidence that comprehensive assessments have been conducted to evaluate the suitability of the proposed locations for the new road networks outlined in the updated plans. Given that these locations likely carry similar risks, especially considering Hatay's numerous geographical constraints and vulnerabilities, the probability level remains considerably high at level 4. Thus, overall risk level of system failure due to poor site selection is classified as 'Very high'.

- Inaccurate site assessment: As previously mentioned, the significant impact and magnitude of the earthquake likely altered geological conditions. As a result, the HPO recommended a reassessment of earlier evaluations. However, the current road extension plans remain unchanged from the original locations, and there is no indication that re-evaluations are being considered. Therefore, while the impact level remains the same, the probability of failure has increased to level 4, raising the overall risk level to 'Very High'.

- Inadequate design for site conditions: Despite the proposed long-term recovery plans aimed at enhancing resilience, the inherent risks associated with site-specific factors remain. Impact of inadequate design has been assigned a high impact score of 5, reflecting the potential for substantial disruptions in transportation operations due to inadequate design. Furthermore, the probability of failure due to design deficiencies is rated at 3, indicating a decreased likelihood of encountering challenges due to preventive measures taken for the airport. As a result, inadequate design for site conditions continues to be a significant concern within the transportation infrastructure of Hatay with overall risk rate of 'Extreme'.

- Lack of maintenance: Maintenance requirements have been reduced, particularly for the airport, due to measures taken to mitigate flooding risks. These actions are expected to lessen the airport's vulnerability. Consequently, the overall impact is now projected to be lower at level 2, as not all transportation systems would be affected to the same degree as before. The probability of failure has also decreased to level 2, given the reduced likelihood of failure due to lack of maintenance. Thus, overall risk level of this root cause identified as 'Low'.

- Lack of redundancy: The impact of the lack of redundancy has decreased to 3. With the introduction of new transportation routes, including the Payas-Hassa connection and the extension of highways to Reyhanli, the overall redundancy of the transportation network has been improved. While some areas may still face challenges, the availability of multiple routes means that the impact of disruptions is less likely to affect the entire city, isolating only specific regions instead. However, road extensions still exclude some districts that previously had limited accessibility, such as Kumlu and Altnözü. Thus, the probability of transportation system failure due to lack of redundancy has decreased to 3, though remaining at a moderate level. The new transportation plans provide alternative routes that enhance connectivity and reduce dependency on single pathways. This diversification decreases the likelihood of systemic failure during emergencies, as there are now viable alternative options for transportation. At the end, overall risk level of system failing due to lack of redundancy decreased to the level of 'Medium' after improvement plans.

Based on the updated risk levels of the root causes, the prospective risk levels for the intermediate events were calculated as below Table 6.4.

Intermediate event	Impact	Probability	Overall risk level
Spatial vulnerability	5	4	Extreme
Structural vulnerability	5	3	Very high
Water and electricity infrastructure failure	3	3	Medium
Damage to runway	5	3	Very high
Non-functional airport	5	3	Very high
Road network failure	5	3	Very high

Table 6.4: Risk assessment of transportation system intermediate events after long-term recovery plans

Following the revised risk levels across the entire tree, an updated color-coded Fault Tree Analysis (FTA) for transportation systems is shown in Figure 6.4.

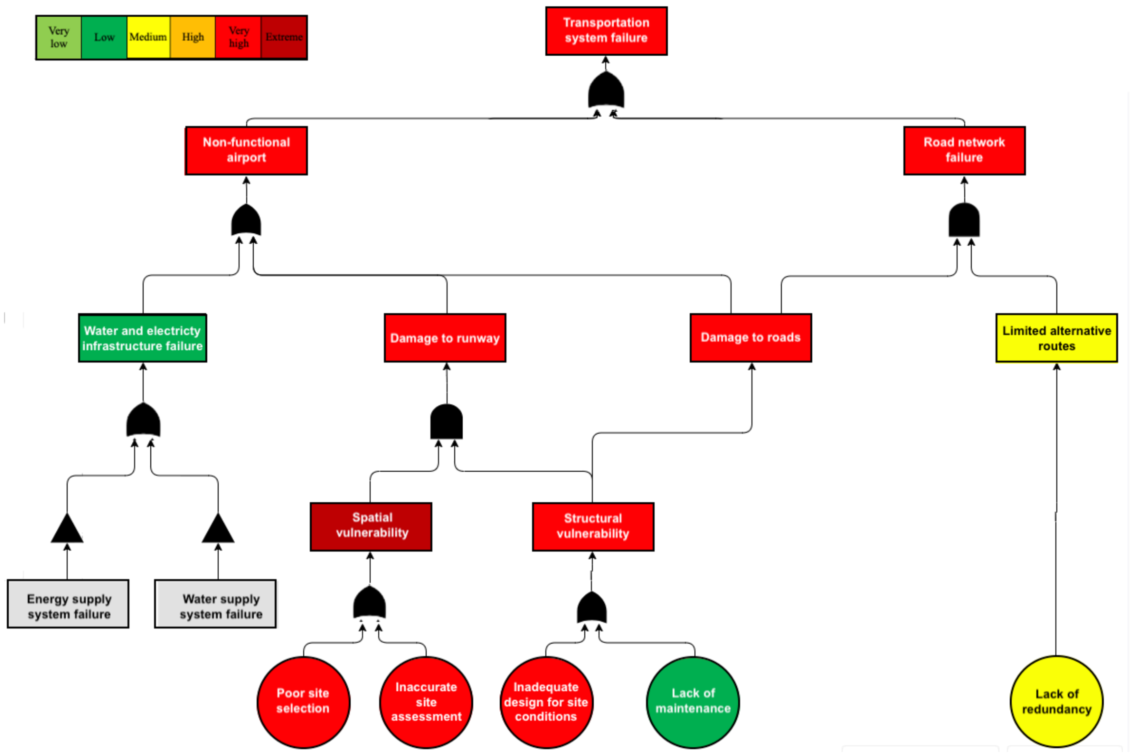

Figure 6.4: FTA of transportation system with risk levels after long-term recovery plans

The findings from this chapter, along with those from the previous chapter, are further analyzed and contextualized in the following discussion section.

III

Discussion and conclusion

7
Discussion

7.1. Analysis prior to the implementation of recovery plans

7.1.1. Healthcare Services

The analysis of healthcare system failures following the earthquake revealed deep-rooted vulnerabilities that extends beyond immediate disaster impacts. One of the most significant findings is the insufficient bed capacity in Hatay before the earthquake, with the region's bed capacity being markedly below recommended standards for its population. This critical failure, originating from both resource allocation and resource distribution points to systemic issues that were not addressed prior to the disaster, making the region especially susceptible to such an event, turning hazard into disaster. This shortage was not just a consequence of the earthquake but reflects a long-standing issue of under-resourced healthcare infrastructure, which could have severely limited response efforts even without such high magnitude event.

This insufficiency was compounded by the loss of hospital buildings due to earthquake damage, which further overwhelmed the already strained healthcare system. The combination of pre-existing shortages and the sudden loss of infrastructure created a highly vulnerable system, where the demand for healthcare services far exceeded the available capacity.

The vulnerability of hospital structures was found out to be a key factor in the collapse which led to significant losses, including fatalities among patients and healthcare staff. The lack of seismic retrofitting and the neglect of identified structural vulnerabilities were found to have a direct impact on the functionality of hospitals, increasing the likelihood of failure. The failure to act on already conducted risk assessments, illustrates a serious neglection and significant breakdown in risk mitigation processes.

The staff shortage was another major contributing factor to the healthcare system's collapse. This shortage was not only due to the direct loss of healthcare personnel, caused by the collapse of hospital buildings and residential homes, but also the inability to bring in external aid due to transportation system failure. This shows critical infrastructure interdependencies. A disruption in one sector led to a cascading failure in the other, amplifying the overall impact of the disaster.

The retrospective risk assessment underscores the severity of these vulnerabilities. The high number of events marked by extreme risk levels illustrates how deeply these factors contributed to the systems collapse. It also highlights how risks originating from a single root cause can cascade through connected events, ultimately leading to system-wide failure. Finding and addressing the root causes of extreme risks in a system is essential for truly understanding the pathways that lead to system failure during a disaster. Without this root cause analysis, efforts to strengthen the healthcare system might focus only on the symptoms of the problem, such as overwhelmed hospitals or staff shortages, rather than the foundational issues that lead to these outcomes. Root cause identification provides a clearer insight into how risks originate and propagate through a system.

7.1.2. Transportation system

The failure of transportation systems in Hatay during the earthquake highlights the critical vulnerabilities inherent in the regions infrastructure. It was found out in the analysis that these vulnerabilities are originating from poor site selection, inaccurate site assessment, inadequate design for site conditions, lack of maintenance and lack of redundancy. Notably, many of these root causes are intrinsically linked to the region's geographical characteristics, highlighting how local context and site-specific requirements profoundly influence the planning and management of critical infrastructure.

The location and design of Hatay Airport were the key factors in its failure. Situated on alluvial soil and on seismic ground where different fault lines cross over, the airport was exposed to spatial vulnerabilities that were not addressed in its design. Alluvial soil's poor load-bearing capacity, makes it particularly ill-suited for heavy infrastructure such as an airport. Furthermore, the grounds susceptibility to liquefaction caused by seismic activity increased the airport's structural vulnerabilities, leading to significant damage to the runway.

The Fault Tree Analysis (FTA) underscores that the failure of either the airport or the road network was enough to bring the entire transportation system to a halt. Each component contributed independently to the overall transportation system collapse. While geographical constraints present challenges for Hatay, these issues should have been anticipated and addressed through accurate geographical assessments and strategic infrastructure planning.

While the earthquakes direct impact on roads was severe, the systemic weaknesses in the design of Hatays road network were equally critical. The lack of redundancy in the system meant that the failure of a few key roads crippled access to essential regions, including Iskenderun, Belen, and Antakya. Road network initiatives should have included prioritizing expanding the road network, creating alternative routes, and increasing the number of critical access points to enhance resilience in the face of disasters.

The retrospective risk assessment of the root causes and intermediate events underscores the extreme risk posed by the lack of redundancy, poor site selection, and inadequate design while other root causes also carry 'High' level of risk. The extreme risk levels attributed to most of the factors highlight the importance of addressing the vulnerabilities in future infrastructure planning and disaster preparedness strategies to effectively mitigate the risk.

7.2. Analysis after the implementation of recover plans

7.2.1. Healthcare services

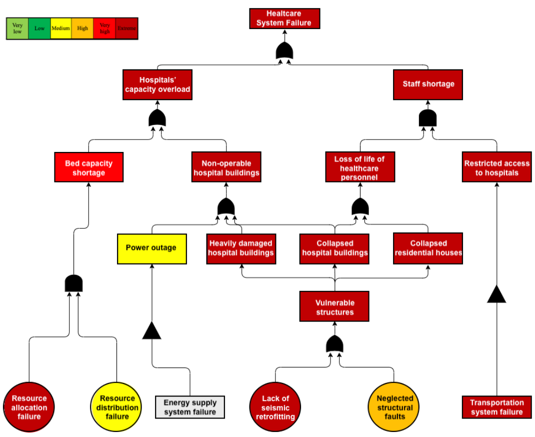

Figure 7.1: Fault Tree Analysis of healthcare services with retrospective risk levels

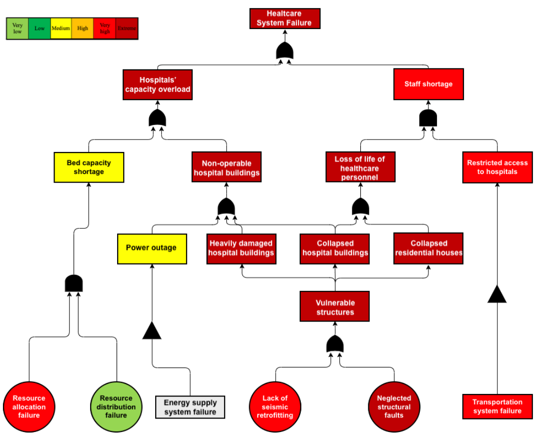

Figure 7.2: Fault Tree Analysis of healthcare services with prospective risk levels

After implementing the long-term recovery plans, certain risks to healthcare services were mitigated. Although progress has been made in redistributing resources more evenly across districts, the planned increases in bed capacities remains insufficient to meet the needs of the population. Without a significant expansion in bed capacity, the healthcare system risks being overwhelmed in future disasters.

Additionally, an unexpected finding emerged: the risk level for "Vulnerable Structures" remained at an "Extreme" level because of an increased risk of a root cause. The risk level changes before and after the recovery plans can be observed in Figure 7.2. Although retrofitting efforts for planned hospitals resulted in a moderate reduction in risk from this root cause, concerns remain. Notably, no earthquake resilience measures have been specified for other planned hospitals, preventing the risk associated with a lack of seismic retrofitting from decreasing further. While the risk from a lack of seismic retrofitting decreased, the risk due to neglected structural faults increased. This rise in risk effectively neutralized any improvements gained from retrofitting, leaving the overall vulnerability of healthcare structures essentially unchanged. The increased risk from this unresolved root cause highlights a critical flaw in the recovery planning process. For long-term resilience, recovery plans must comprehensively address all significant root causes. In this case, the failure to address structural integrity issues not only allowed the risk to persist but caused it to intensify, illustrating a significant neglect of the fundamental causes of the system's failure.

Another important finding from the FTA is the observed decrease in 'Staff shortage' risk, closely tied to the transportation system's resilience. While staff shortage was associated with two factors, 'Loss of healthcare personnel' and 'Transportation system failure', the risk of 'Loss of healthcare personnel' remained unchanged. However, the reduction in the risk of transportation system failure led to a decrease in the risk of staff shortage. As a result, improvements in transportation accessibility directly impacted a risk of major contributing event for healthcare system failure, showing how critical infrastructure interdependencies can support overall system resilience.

Additionally, the hasty decision-making process regarding hospital site selection, without thorough geological assessments, raised concerns about the long-term viability of these new infrastructures. For the recovery efforts to be truly effective, they must comprehensively address these root failures.

Despite these specific gains, the overall healthcare system failure risk remains at an "Extreme" level. This analysis proves that without addressing all root causes effectively long-term plans cannot fully mitigate risk. The persistence of high vulnerability highlights the need for recovery strategies that comprehensively target the primary causes of failure. Insufficient and imbalanced risk mitigation efforts leave the healthcare system vulnerable to future disasters, demonstrating that a more thorough, root-cause-driven approach is essential for sustainable disaster resilience.

7.2.2. Transportation Systems

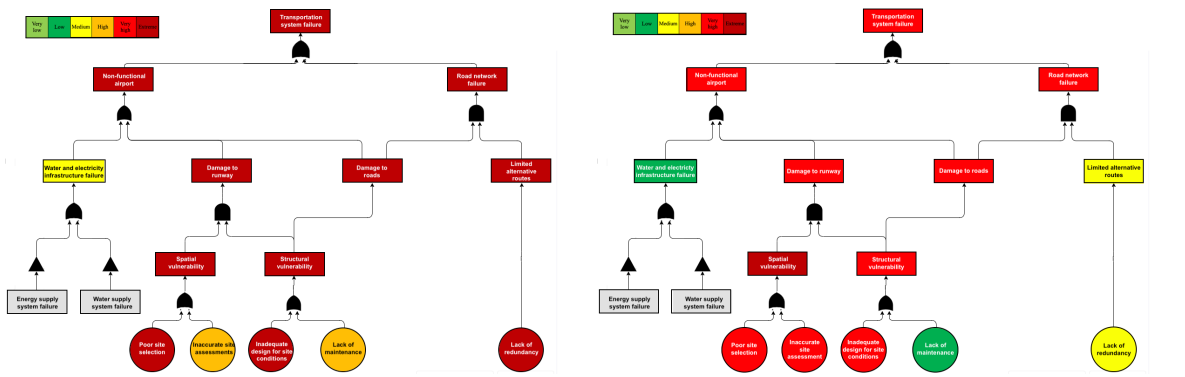

Figure 7.3: Comparison of retrospective and prospective risk-based color-coded FTAs for transportation systems

The analysis reveals that while risks associated with lack of maintenance and lack of redundancy have decreased to a manageable extent, other crucial factors have not seen sufficient improvement. Notably, the risks tied to poor site selection and inadequate design for site conditions have not been adequately mitigated. Although the decrease in risk for poor site selection appears promising, this progress has been offset by a rise in the risk of inaccurate site assessment, which has left the overall risk of spatial vulnerability unchanged at the "Extreme" level.

Although structural reinforcements, such as runway renovations and upgraded flood barriers, are intended to enhance the airports resilience, these interventions alone may not be sufficient in the event of a high-impact disaster. These measures address immediate concerns but do not eliminate the fundamental risks associated with the airports geographic and geological setting. Flood barriers, for example, may temporarily protect against surface water, but they are unlikely to prevent groundwater pressure, especially during heavy rainfall. This hydrostatic uplift can weaken or damage the runways structural integrity, potentially leading to cracks, surface deformation, or even displacement of runway materials.

In terms of structural resilience, the significant reduction in maintenance related risks, alongside a minor reduction in risks linked to inadequate design, has slightly improved the overall risk of structural vulnerability. However, the combined effect of an unchanged spatial vulnerability and marginal structural improvements has proven insufficient to bring a meaningful reduction in the likelihood of severe damage to runway, considering an increased risk in inaccurate site assessments. This gap highlights the necessity for updated site evaluations to ensure that new road designs account for the current geological and environmental conditions.

This outcome appears to come from a modest decrease in risk related two root causes ('Poor site selection' and 'Inadequate design for site selection') and an increase in risk related to one ('Inaccurate site assessment'). Similar to findings in healthcare services, the plans targeting the transportation system have limitations in accurately identifying root causes and tailoring effective, targeted interventions. The increase in risk for one root cause suggests a substantial oversight or misidentification in problem assessment, thus there remains a pressing need for further improvements in the plans..

In conclusion, the long-term recovery plans have led to some improvements in the transportation systems resilience, yet significant vulnerabilities remain. Following the implementation of long-term recovery plans, the overall risk level of transportation system failure expected to reduce from 'Extreme' to 'Very High'. While this reduction marks some progress unlike healthcare services, it still leaves the transportation system at a considerably high risk level. The persistence of extreme risk associated with spatial vulnerability and only modest gains in structural resilience demonstrate that the current recovery strategies may lack the necessary depth and precision. Particular concern is the increase in risk associated with inaccurate site assessment, which not only offsets improvements made in other areas but also indicates a critical oversight in identifying and addressing foundational issues. This increase suggests serious flaws in risk management, as any rise in the risk level, especially for such a core aspect of infrastructure, can have cascading effects that compromise the entire systems integrity. Addressing these gaps will require a reassessment of recovery priorities to ensure that both spatial and structural vulnerabilities are comprehensively mitigated, ultimately aiming to reduce the transportation systems risk to an acceptable level.

Furthermore, comparing the analysis and long-term recovery plans with established global frameworks provides valuable guidance and insights for enhancing their effectiveness. The Sendai Framework emphasizes eliminating disaster risks at their source by addressing existing vulnerabilities and integrating risk reduction into every phase of disaster management (UNDRR, 2015). Analysis and evaluation methods in this study aligns with key principles of Sendai Framework, such as addressing root causes, integrating risk assessments, proactive planning, and enhancing critical infrastructure resilience. However, when it comes to alignment of future plans of Turkey for Hatay, gaps were observed compared to global frameworks. While Hatay's recovery plans have factors on critical infrastructure improvements, such as healthcare capacity and transportation network redundancy, they often address immediate needs without fully mitigating root causes, which contrasts with the Sendai Framework's emphasis on eliminating risks at their source. Turkey's disaster management strategies could benefit from integrating these global frameworks , and aligning recovery policies with long-term resilience metrics within these frameworks. Enhanced alignment with global best practices, particularly in governance, risk assessments, and cross-sector resilience building, would strengthen Turkey's ability to adapt recovery strategies to its unique geographic and seismic challenges.

8 Conclusion

This thesis investigated the extensive damage and critical infrastructure failures that occurred in Hatay due to the 2023 Turkey-Syria earthquake. On February 6, 2023, southeastern Turkey experienced two devastating earthquakes, measuring 7.7 and 7.6 in magnitude, which left significant destruction across 11 provinces, with Hatay being among the hardest hit. This region, already vulnerable due to its geographic proximity to active fault lines, witnessed unprecedented impacts on all of its infrastructure. The collapse or severe impairment of these systems led to high casualties, hindered immediate rescue operations, and prolonged recovery efforts, exposing pre-existed vulnerabilities in the regions disaster preparedness and resilience planning.

The purpose of this study was to examine the root causes behind these infrastructure failures and assess the effectiveness of the recovery plans implemented in response to the disaster. By investigating pre-existing weaknesses and evaluating post-disaster recovery plans, this research aimed to uncover the critical gaps that increased the earthquakes impact in Hatay. Understanding these gaps and failures have a potential to provide valuable insights for future planning of critical infrastructure for disaster management that can mitigate the effects of similar events in Turkey and other regions vulnerable to earthquakes.

To address the core research objectives, three key questions guided this investigation. Below are the questions along with the findings derived from the study:

RQ1: During and in the aftermath of the earthquake, which critical infrastructure failures had the most significant impact on resilience and immediate recovery?

To address this question, a qualitative analysis was conducted using semi-structured interviews conducted in June 2023 (Aydin, 2023), three months after the disaster. While all critical infrastructure in Hatay experienced severe damage, the interviews revealed that the most significant impacts were felt in healthcare services, transportation systems, and educational facilities. Hospitals sustained extensive structural damage, severely limiting their ability to manage the influx of casualties and urgent medical needs. This greatly hindered the region's capacity for a fast and effective response, as overwhelmed facilities and insufficient resources resulted in delays in treatment. Similarly, interviews confirmed that damage to transportation networks, including roads and airports, hindered the timely arrival of rescue teams and essential aid, further exacerbating the crisis. Educational facilities, which in literature often served as emergency shelters, were also compromised, reducing safe spaces for displaced residents and negatively impacting community resilience. Furthermore, interview analyses highlighted the continuity of education as a crucial factor for long-term recovery.

RQ2: What key factors and resulting consequences in critical infrastructure planning and management contributed to widespread destruction?

While education sector was excluded from the study due to lack of sufficient data, it was found out that, key factors contributing to the widespread destruction for the healthcare services included inherent resource distribution and allocation failures for hospital capacities and lack of seismic retrofitting and neglected structural faults in hospital buildings. More than half of the hospitals sustained severe structural damage due to inherent structural vulnerabilities, overwhelming an already strained healthcare system with insufficient capacity and delaying treatment for the injured. For transportation networks spatial and structural vulnerabilities, insufficient maintenance, and a lack of redundancy in critical services contributed to the system failure. Moreover, poor site selection, such as locating the airport on unstable, liquefaction-prone ground, and inaccurate site assessments overlooked significant geological risks, leading to structural failures during the earthquakes. Additionally, transportation infrastructure designs did not adequately account for the areas geological conditions, compounding the damage. Increased need of maintenance for the airport that was not answered further heightened these vulnerabilities, resulting in service disruptions and delays in emergency response. Infrastructure flaws led to severe consequences that hindered both immediate rescue efforts and long-term recovery. Blocked road networks, impassable arterial routes and lack of alternative routes isolated affected areas, delaying aid delivery and limited the access to hospital which contributed to staff shortage for hospital services.

RQ3: How have long-term recovery plans for critical infrastructure changed the risks identified after the disaster?

The long-term recovery plans revealed both progress and critical gaps. Improvements, such as added hospital bed capacity and increased redundancy in transportation, demonstrate advancements in addressing key vulnerabilities. However, significant risks considering both critical infrastructure persist due to increased threats from specific root causes, like neglected structural faults in healthcare facilities and inadequate site assessments for transportation networks. These issues highlight that selective mitigation, without comprehensive root-cause targeting. The rise in risk in certain areas underscores the need for deeper root-cause analysis. For sustainable resilience, recovery strategies must comprehensively address all foundational vulnerabilities rather than focusing on isolated areas.

The implications of these findings extend beyond the immediate aftermath of the earthquake. The need for long-term recovery plans that address these systemic weaknesses is crucial for enhancing the region's resilience to future disasters. While Hatay's recovery is ongoing, this studys analysis of system failures provides valuable insights into the necessary improvements that can help safeguard against similar disruptions in the future.

Contributions and significance of the research

This research makes three primary scientific contributions to disaster management literature. First, it adapts root cause analysis (RCA) to critical infrastructure failures which is typically applied in man-made disaster scenarios like industrial accidents in literature, to a natural disaster context. By applying RCA to the earthquake, this thesis identifies foundational weaknesses in critical infrastructure systems, offering a structured approach for tracing infrastructure vulnerabilities against natural disasters to their origins in planning and design. Second, this thesis includes a pre-implementation evaluation of long-term recovery plans, a significant shift from the common focus on process and outcome evaluations. By examining recovery strategies before they are implemented, based on root cause findings, this research enables proactive adjustments to address pre-existing vulnerabilities, bridging the gap between identified risks and effective recovery planning. Lastly, the study employs a dual retrospective and prospective risk analysis to evaluate long-term recovery plans in a natural disaster context. This approach, traditionally used in evaluating man-made disasters, offers a comprehensive assessment framework that enhances disaster management theory by directly linking past infrastructure failures to future resilience strategies.

The practical contributions of this thesis include actionable insights for improving disaster preparedness and critical infrastructure resilience in disaster-prone regions like Hatay. By delving into the root causes behind infrastructure failures, this research underscores the importance of identifying and addressing these underlying vulnerabilities to develop more resilient and sustainable systems. For policymakers, this approach offers a framework to build back better by learning from past mistakes and integrating these lessons into future planning. Understanding the root causes of previous failures enables targeted recovery plans that not only address immediate needs but also fortify critical infrastructure against future risks. Additionally, the thesis introduces a framework for evaluating recovery plans in development through retrospective and prospective risk analysis. By using this framework, policymakers can refine recovery strategies to be both adaptive and forward-looking, ensuring that they effectively mitigate risk and enhance infrastructure resilience, thus protecting communities more effectively against future disasters.

While it is crucial to recognize that disaster management is highly context-dependent as its largely influenced by specific geological conditions and regional characteristics, the necessity of identifying root causes of infrastructure failures holds universal significance for all disasters and disaster-prone regions. The insights and recommendations provided in this research are critical not only for improving disaster preparedness and response in Turkey but also for their broader applicability in diverse contexts around the world.

Policy Implications and Recommendations

This research has significant implications for policy, especially in disaster-prone regions. First, policy frameworks should prioritize proactive, context-specific vulnerability assessments that can identify and address root causes before disasters strike. Such assessments should account for regional conditions, including geological risks, to ensure that policies are relevant and actionable.

Second, enforcing strict building standards tailored to the unique conditions of the region is crucial for safeguarding infrastructure against failures. Many failures observed in Hatay were linked to inconsistent enforcement of regulations. Transparent resource allocation, community education, and interagency coordination are also essential to reduce redundancy and ensure effective, unified responses to future events. Additionally, building codes and regulations should be tailored to the unique geological conditions of each region, as this study reveals the significant impact of regional conditions on infrastructure resilience.

Furthermore, the design and construction of new buildings, roads, and infrastructure should embrace state of the art technologies that are specifically engineered to withstand the unique challenges posed by local environmental and disaster risks. This goes beyond replicating previous technologies and practices, which may no longer be adequate given evolving risks and challenges. The integration of cutting-edge materials, construction techniques, and innovative engineering solutions should be considered essential for all new infrastructure projects.

Moreover, effective disaster response requires policies that integrate interagency coordination and cross-sectoral planning, as critical infrastructures are often highly interdependent. Integrated emergency response systems that streamline operations across sectors can facilitate fast, unified responses, minimizing the disasters impact on affected populations.

Finally, given the dynamic nature of recovery, ongoing evaluations are essential to ensure resilience remains aligned with evolving challenges. Recovery is a continuous process, and thus, regular assessments must become an integrated part of infrastructure management, adapting as new information and risks emerge.

Challenges and limitations

The educational infrastructure was ultimately excluded from this analysis due to significant data limitations, which restricted the ability to assess its resilience and recovery status accurately. Although initially identified as one of the key critical infrastructures in chapter 4, the absence of detailed data on school damage levels, capacities, structural conditions, and even precise locations necessitated its exclusion from this study.

The method of this study, which focused on specific key critical infrastructures, presented certain challenges due to the inherent interconnectedness of these systems. By concentrating on healthcare and transportation infrastructures, the study captured a snapshot of critical vulnerabilities but inevitably limited the scope to only parts of the infrastructure network. This selective focus chosen to increase in-depth analysis for CI's that were investigated; however, posed challenges, as critical infrastructures rely on each other to some extent to function fully. For example, in the healthcare sector, uninterrupted electricity supply is essential for powering the equipment and maintaining patient care. However, any disruption in energy supply, a dependency not fully captured in this study, directly compromised healthcare delivery. Similarly, transportation systems dependency on a reliable water and energy supply to function efficiently and support maintenance and recovery was observed but not fully investigated. Furthermore, by narrowing the scope to specific systems within the broader category of transportation, risks associated with the harbor and railway systems in Hatay were not included. These omissions may have affected the comprehensiveness of the findings, as risks associated to these systems could have amplified vulnerabilities in both the healthcare and transportation sectors. Thus, while selecting key critical infrastructures was necessary for feasibility, it limits the studys ability to assess the full extent of systemic risk within Hatays infrastructure network.

Moreover, another limitation in this study was from the reliance on interviews that were not conducted firsthand. Observing interviews personally allows for capturing subtle non-verbal cues, such as facial expressions, gestures, and voice tone, which can provide important context and deeper insight. This reliance on secondhand data may have led to the loss of certain nuances that only a firsthand interviewer might perceive, potentially affecting the depth of analysis. To address this limitation, particular attention was paid to word choice and phrasing within the interview transcripts to infer possible emphasis or emotion conveyed by the participants. While this approach cannot fully replace the insights gained from observing non-verbal cues, focusing on specific language patterns provided an alternative means of enriching the analysis, aiming to capture some of the subtleties that may otherwise have been overlooked.

Finally, the qualitative nature of this study introduced a level of subjectivity in the assessment of retrospective and prospective risks. As previously noted, qualitative assessments of both retrospective and prospective risks can vary depending on the researchers perspective and interpretation. This subjectivity introduces a potential for inconsistency, as different researchers might assign different risk levels based on their unique interpretations and analytical approaches. However, in this study, the primary focus was on identifying and understanding potential shifts in risk between retrospective and prospective analyses. To enhance consistency and reliability in these observations, a standardized approach was prioritized. This approach involved adhering to a consistent logic and set of explanations throughout the risk assessment process. By maintaining a uniform evaluative framework, the study aimed to minimize interpretive bias and provide clearer insight into how recovery plans changes the risks.

Future work

Building upon the findings of this study, future research should broaden its scope to include all critical infrastructures within Hatay, extending beyond the focus on healthcare and transportation. This expanded analysis is necessary to understand the full range of interdependencies that exist between various infrastructure sectors. By examining the broader network of critical infrastructures, research can identify how vulnerabilities in one infrastructure may amplify or mitigate risks across others. For instance, the functioning of healthcare and transportation infrastructures is often closely linked with energy supply, water management, and communication systems, and disruptions in any of these can create cascading failures. A comprehensive analysis would provide a more nuanced understanding of how these systems contribute to or detract from overall regional resilience, uncovering systemic vulnerabilities that may otherwise remain hidden when considering infrastructures in isolation.

Following this, evaluating the implementation process and outcomes of recovery plans should also be a key focus in future research. It is important not only to examine whether recovery strategies were successfully implemented as they were but also to assess the long-term sustainability of these efforts. Recovery is an ongoing and dynamic process, thus plans should be agile enough to be able to response to do changing circumstances. Specifically, future studies should investigate how well infrastructures can adapt to evolving and changing risks. This evaluation would ensure that recovery efforts are not just immediate, but also prepare these systems for changing environment, enhancing their capacity to endure and recover from new challenges.

While this study incorporates a quantitative component, future research could benefit from increasing the emphasis on quantitative analysis to further support the qualitative findings. By integrating more quantitative methods, such as statistical modeling or data-driven risk assessments, the study would gain a more objective, empirical basis to support the qualitative insights. This strengthened approach would improve the depth and reliability of the findings.

Additionally, integrating environmental risk assessments into infrastructure planning is crucial, especially as climate change increases the frequency and severity of natural disasters. Infrastructure must now withstand not only seismic events but also climate-related hazards like flooding, extreme temperatures, and severe storm that might be unexpected for certain regions, which compound existing vulnerabilities. By incorporating climate and environmental factors into recovery and planning strategies, future efforts will better address the heightened risks posed by climate change, ultimately supporting more sustainable and resilient infrastructure systems.

A

Appendices

A.1. Literature review

A.1.1. Standard for number of beds

City Scale	Small City	Middle City	Large City		
			I	II	III
Population Size (ten thousand)	<20	20 - 50	50 - 100	100 - 200	200
Number of beds per thousand people	4 - 5	4 - 5	4 - 6	6 - 7	7

Table A.1: The standard for bed numbers classified with population size(Ma et al., 2018)

A.1.2. Disaster management in Turkey

Level	Impact	Support status by type and scale of the event
S1	Local resources are sufficient	Provincal AFAD Center
S2	Reinforcements from supporting provinces are needed.	Provincal AFAD Center + 1st group support provinces
S3	National level support is needed	1st and 2n group support provinces + National capacity
S4	International level support is needed	1st and 2n group support provinces + National capacity + International support

Table A.2: Level - Impact - Support Status (AFAD, 2022a)

A.2. Key CI identification

A.2.1. Associated terms for code list

Code	Terms
Education	school, teacher, university, student,
faculty, campus, classroom	
Public Buildings	municipal office, government building
Healthcare	hospital, clinic, ambulance, doctor,
nurse, medical staff, pharmacy, medicine, treatment	
Safety and Security	police, military, fire department,
security, crime, protection, surveillance	
Shelter	tent, container, emergency shelter,
house, residence	
Telecommunication	phone line, internet, signal, connectivity
Transportation	highway, road, railway, port,
airport, bus, train, route	
Water and Energy Supply	water distribution, sewage, drainage, electricity,
power, energy grid, generator, power outage,	
water outage, gas, gas line	

Table A.3: Associated terms for code list

A.2.2. Codebook

Category	Subcategory	Definition	Example
Education	Shelter	Need for shelters to be able to start education	"The biggest problem is our teachers. We opened the school, I think it's great for the children. But it's a very chaotic situation for the teachers. Because they all have problems. And not all our teachers could come because they have nowhere to stay. We have a lot of teachers whose houses were destroyed. Everyone wants a container. But I don't know any teachers who have a container. I'm staying in a container that I found myself."
			"Our teachers have a housing problem"
		Dual role: School buildings for shelter purposes	"Because the university hosted the coordination of the crisis from the first day of the earthquake. Many institutions intervened in the crisis from here. For example, all the experts and bureaucrats of the Ministry of Environment and Urbanization stayed at the university. They opened their workplaces in containers at the university. Emergency 112 removed all the ambulances from here. UMKE teams were here. The police were here. The Red Crescent was here."
			"The only hospital providing health services here was our university's hospital."
	Telecommunication	Need for telecommunication services to start education	"They had the same problems. I say, they opened the school but they don't have internet. When there is no internet, you can't communicate, you can't do anything. We still don't have internet."
	Recovery	Need for education to start recovery process	"Our priority is housing...' But people would not come just for housing. If you do not build a school, as you said Mr. President, I will not bring my wife, I will not bring my child. Build me as many houses as you want, but if there is no school, I cannot bring them here."
			"It is not possible without school. Just as a school is not a living space like a house, education cannot be in a tent because the child's living space is a tent."
			"I think that the most definitive way to reduce or eliminate the effects of the earthquake is education, health and production-trade."
			"Therefore, education needs to recover quickly here. We need to recover from kindergarten to university."
Healthcare Services	Pre-disaster vulnerabilities	Existing vulnerabilities before disaster in spatial planning and structure	"If there is an earthquake, there is no hospital on the east side of the city"
			"There were already no adequately planned and foreseen areas in terms of health, education and tourism."
			"I don't know if you've seen the airport, it has sunk 60-70 centimeters. We were going up on level ground, now it's gone down. Unfortunately, the same thing is happening in the public hospital."

Figure A.1: Codebook Page 1

			"There is a huge destruction in the health sector here. I remember the first days of the earthquake... The public hospitals was destroyed. There were two public hospitals, both of them... There was no state hospital in Defne anyway, as far as I know."
	Recovery	Need for heathcare services for recovery to start	"There is a need for doctors and health services here. Where will these people go? The closest place is Adana."
			"I think that the most definitive way to reduce or eliminate the effects of the earthquake is education, health and production-trade."
Transportation Systems	Roads	Having one arterial road alternative in the city	"We were predicting the inadequacy of the infrastructure. I was predicting that the main arterial road would be blocked. And unfortunately, it happened. There were fuel supply problems. Hatay's biggest problem is that the main arterial road is on a single lane. A single road."
			"One of the biggest problems is our main arterial road, it was blocked. We didn't have any alternative roads. One of the biggest salvation issues of Hatay is infrastructure, the other is the main arterial road and the alternative road should be produced."
			"That's why houses are constantly being built around that main road, and industrial sites are being built on the plain... I had started to build a road from Serinyol to Tarsus when the earthquake happened. I had started to build it in the fall. It upsets me that there is only one entrance to Hatay, normally the government should build the roads between the districts."
	Airport	Demolition of the airport runway	"I don't know if you've seen the airport, it has sunk 60-70 centimeters. We were going up on level ground, now it's gone down."
		Necessity of rebuilding the airport for recovery period	"We said that solving the problems experienced at the Belen crossing and reopening Antakya airport to full capacity will contribute to solving the transportation problem experienced in our city."
		Spatial planning	"The choice of location is very wrong, that's another matter. Because that's the deepest point of Amik [1:29:06]. That's where it last dried up, you know, the waters recede in the summer... That's the deepest point and the surrounding area is alluvium. Now that airport ended, it has a 300-meter-long runway, it's basically where conventional, heaviest cargo planes can land and take off."
			"Belen should be passed with more than one alternative, actually what is it in my heart is: close the airport. Let it be a lake basin again. Build a new airport."
	Bridges	Increased difficulties in rescue	"After the earthquake, we shouted loudly that the bridges would be damaged, they were damaged and almost collapsed."

Figure A.2: Codebook Page 2

		efforts due to collapsed bridges	"And the roads are closed, the bridges are destroyed, and even if they are not destroyed, cars cannot go."
Public Buildings	Immediate response	Demolition in public buildings caused difficulties in immediate recovery	"Right now, it's very serious, inheritance. Normally, an inheritance document could be obtained from a notary after death. Right now, no one has become anyone's heir. It's not clear who came before whom. It should be accepted simultaneously and, at the simplest, a lawsuit should be filed in the [9:10] court... In terms of sanctions on contractors, if there is a death, something has definitely been initiated about them. Because public buildings have collapsed."
Safety and Security	Immediate recovery	Security issues resulting from the city's depopulation	"Everyone was walking, in the morning, in the evening... After a certain hour, I said, no, this is not safe... I realized that this was not a place where I could walk by myself. So, these kinds of problems occurred."
			"They say the security problem here is very serious. After a certain hour, there is no one on the streets. It is an abandoned city."
	Immediate response	Decreased security and safety in the first few days	"Isn't there a security problem? Of course there is. You can't say there isn't any. A chaos... Of course, they had to ask for soldiers at that time because the police were insufficient. When the police were insufficient, they had to ask for soldiers. Both the soldiers and the police are sufficient now."
			"There are many Syrians in Kumlu. Right after the earthquake, there was chaos here, between Syrians and locals. We experienced it. Very bad things could have happened. Thank God, our soldiers and police arrived on the third day. Otherwise, people would have eaten each other here. Because the Syrians had stopped looting, they had stopped looting food, they had started looting things of economic value. They were entering people's houses, they started looking for valuables under the rubble, etc. I don't want to talk about bad things. When our police and soldiers arrived, they took over the security."
Telecommunication	Immediate response	Not having connection during rescue operations	"Our phones did not work for the first eight days."
Water – Energy Supply	Water supply	Lack of services	"Water bursts, pipes burst, I don't know what's going on. You call HATSU, there's no answer."
			"This can be sewage, this can be water. All of the services are insufficient.
	Electricity supply	Lack of services	We still need services of all kinds. From electrical failures to plumbing failures...
Shelter	Lack of shelters	Inadequate planning of shelters	"All of the citizens are experiencing housing problems. Earthquake victims were shifted to hotel accommodations all over Turkey. Citizens say, 'Open the hotels'. You look at the realistic solution, there is a capacity of one million seven hundred and fifty thousand. When you include all the KYK dormitories, it becomes three million two hundred and fifty thousand with one and a half million. There are twelve million earthquake victims. Let's say the five or six million who were transferred. How are you going to solve the housing needs of all these people?
			"There are problems with accommodation. Everyone is waiting for that process."
			"We lived in cars for a while. After that, we couldn't hold on, unfortunately. On the sixth day, we had to go out of town, unfortunately. Unfortunately, the tent didn't come for a very long time."

Figure A.3: Codebook Page 3

A.3. Root cause analysis

A.3.1. Fault Tree Analysis symbols

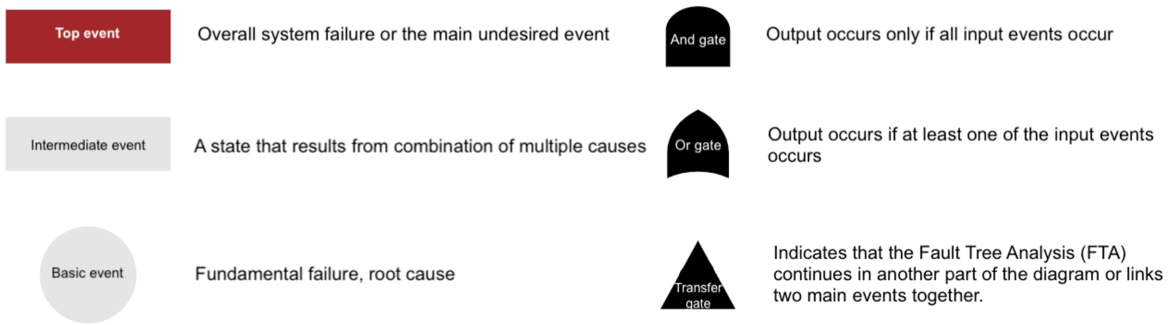

Figure A.4: FTA symbol definitions

A.3.2. Risk matrix

Probability↑ / Impact→				
Medium	High	Very high	Extreme	Extreme
Medium	Medium	High	Very high	Extreme
Low	Medium	Medium	High	Very high
Very low	Low	Medium	Medium	High
Very low	Very low	Low	Medium	Medium

Figure A.5: Risk matrix

- Impact level: Measures how severely a particular factor would disrupt the transportation network if it were to fail during a disaster
  - Very low (1): Minimal consequences, typically affecting only a small portion of the system or causing a temporary inconvenience without long-lasting effects.
  - Low (2): Minor issue, limited impact on operations.
  - Medium (3): Moderate issue, can lead to disruptions.
  - High (4): Major issue, significantly impacts operations and safety.
  - Very high (5): Extensive consequences resulting from the occurence, leading to system-wide disruptions.
- Probability of Occurrence: Measures how likely is this root cause to contribute to failure.
  - Very low (1): The likelihood of failure is highly unlikely. Under normal conditions, the event would not be expected to occur.
  - Low (2): The event may occur under very specific or adverse conditions.
  - Medium (3): A moderate likelihood of failure exists, particularly when the system is under stress or subjected to unusual conditions.

– High (4): There is a high chance that the event will occur if exposed to relevant conditions.
– Very high (5): Failure is almost certain under expected conditions.

A.3.3. Hospitals' status over time

Table A.4: Hospital Status Over Time

Hospitals	06.02.2023	20.02.2023	21.02.2023	22.02.2023	24-25.02.2023	02-04.03.2023	06-09.03.2024
Erzin State Hospital	Heavily damaged, evacuated (TMA, 2023g).				The hospital is providing services in tents and containers that they acquired through their own efforts (TMA, 2023a).		Operating in containers that were set up in the garden (TMA, 2023g).
Dörtyol State Hospital	Undamaged (TMA, 2023c).	Bed capacity was increased to 405 from 160 (TMA, 2023c).					New building started operating, total bed capacity is 405 (TMA, 2023g).
Hassa State Hospital	Moved to 90% finished new building (TMA, 2023g).						Polyclinics have started operating (TMA, 2023g).
Iskenderun State Hospital	One part of the building collapsed. Approximately 250-300 people lost their lives in the building (TM-MOB, 2023a).	New building accepting patients (TMA, 2023d).	New building was evacuated (TMA, 2023d).				

Table A.4: Hospital Status Over Time (continued)

Hospitals	06.02.2023	20.02.2023	21.02.2023	22.02.2023	24-25.02.2023	02-04.03.2023	06-09.03.2024
Kirikhan State Hospital				Evacuated after the earthquake on 20th (TMA, 2023b).			Operating withing the field hospital and buildings emergency part with 250 beds (TMA, 2023g).
Kumlu State Hospital					Providing emergency services with only two general practitioners (TMA, 2023a).		Stated as undamaged; however one building was closed because of damage it contained, Outpatient treatment continues, but there are no inpatient treatments autocitetmamart-2023.
Reyhanli State Hospital				Damaged, staff refuses to enter, operating in private hospital building (TMA, 2023b).			Operating in the building with 100 beds (TMA, 2023g).
Hatay Training and Research Hospital				Trying to provide emergency services in tents in the garden (TMA, 2023b).		Operating in field hospital in the garden (TMA, 2023f).	

Table A.4: Hospital Status Over Time (continued)

Hospitals	06.02.2023	20.02.2023	21.02.2023	22.02.2023	24-25.02.2023	02-04.03.2023	06-09.03.2024
MKU Hospital				Evacuated after the earthquake on 20th (TMA, 2023b).		Operating in field hospital in the garden (TMA, 2023f).	
Samandag State Hospital	Damaged (TMA, 2023h).						Operating in tents in the garden(TMA, 2023h).
Altnözü State Hospital	Damaged (TMA, 2023e).						Operating in tents (TMA, 2023e).
Yayladagi State Hospital	Undamaged (TMA, 2023e).						

A.3.4. Bed capacities by district

District	Population (2022) (TUIK, 2022)	Total bed capacity	ICU capacity	Beds per 1000 people
Antakya (Hatay ISM, 2024a, 2024d)	399.045	1.070	214	2,7
Iskenderun (Iskenderun Gov., 2017)	251.682	600	84	2,4
Defne	165.494	-	-	0
Dörtyol (Hatay ISM, 2023a)	128.941	250	62	1,9
Samandag (Hatay ISM, 2024f)	123.447	160	4	1,3
Kirikhan (Hatay ISM, 2022a)	121.028	210	14	1,7
Reyhanli (Hatay ISM, 2024c)	108.092	103	34	1,1
Arsuz	101.233	-	-	0
Altinozu (Hatay ISM, 2022c)	60.344	50	20	0,8
Hassa (Hatay ISM, 2024e)	56.675	50	8	0,9
Payas	43.919	-	-	0
Erzin (Hatay ISM, 2022b)	41.558	50	-	1,2
Yayladagi (Hatay ISM, 2024b)	36.803	36	-	1
Belen	34.449	-	-	0
Kumlu (Hatay ISM, 2023b)	13.333	20	-	1,5
TOTAL	1.686.043	2.599	440	1,5

Table A.5: Population and bed capacities by district

A.3.5. Proposed locations for the airport

Figure A.6: Proposed locations for the Hatay Airport

A.4. Evaluation of long-term recovery plans

A.4.1. Post-disaster bed capacities

District	Total bed capacity	Beds per 1000 people
Antakya	1.920 (Ministry of Health, 2023)	4,8
Iskenderun	800 (Ministry of Health, 2023)	3,2
Defne	300 (Ministry of Health, 2023)	1,8
Dörtyol	400 (Hatay ISM, 2023a)	3,1
Samandag	160 (Hatay ISM, 2024f)	1,3
Kirikhan	210 (Hatay ISM, 2022a)	1,7
Reyhanli	0	0
Arsuz	100 (Ministry of Health, 2023)	1
Altnözü	120 (Hatay ISM, 2022c)	2
Hassa	120 (Ministry of Health, 2023)	1,8
Payas	147 (Ministry of Health, 2023)	3,3
Erzin	100 (Kalkan, Hakan, 2024)	2,4
Yayladagi	36 (Hatay ISM, 2024b)	1
Belen	30 (Ministry of Health, 2023)	0,9
Kumlu	20 (Hatay ISM, 2023b)	1,5
TOTAL	4.543	2,7

Table A.6: Current and planned bed capacities by district

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