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RESEARCH ARTICLE

Assessing Earthquake-Induced Vulnerability of Critical Infrastructure in Kahramanmaraş Using Geographic Information Systems and Remote Sensing Technologies

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Abstract

This study employs advanced technologies, specifically remote sensing (RS) and geographic information systems (GIS), to investigate the impact of earthquakes on critical infrastructure in Kahramanmaraş. Critical infrastructure encompasses physical and digital systems crucial for national security, economic stability, and public well-being. Disruption or failure of these interdependent systems, including energy, transportation, communication, water supply, healthcare, and emergency services, can have profound impacts on regional security and societal necessities. Protecting and prioritizing critical infrastructure during disaster response is vital for minimizing damage and expediting recovery. The study employs an innovative approach by integrating building damage assessment results with Point of Interest (POI) data to swiftly assess earthquake effects on critical infrastructure in Kahramanmaraş. Real-time earthquake vulnerability of 57 critical infrastructure elements in 15 POI categories is analyzed. Results indicate financial institutions and commercial areas as the most damaged POIs, while muster points exhibit the least damage. Historical facilities, health facilities, governmental institutions, road facilities, and sports facilities also show varying degrees of damage. Overall, 34% of critical infrastructure structures experienced damage. The proposed method offers a pragmatic approach for rapidly identifying damaged critical infrastructure POIs during disaster-based assessments, addressing a research gap.

Keywords Disaster management · Earthquake damage · Resilient cities · Spatial planning · Urban planning

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Introduction

Critical infrastructure is a keystone that encompasses the indispensable physical and digital systems necessary for national security, economic stability, and public health. These interconnected systems, covering energy, transport, communications, water supply, health, and emergency services, play a crucial role in maintaining societal equilibrium (Fekete, 2011; Chen et al., 2022; De Fino et al., 2023;). These infrastructures are all interconnected and their disruption or failure can significantly affect regional security, the economy, and the basic needs of citizens (Novotny & Janosikova, 2020; Liu et al., 2024; Amini et al., 2024; Fallahi et al., 2024). Critical infrastructure includes elements that are essential for the optimal functioning of the network and are strategic points that need to be protected against various threats, such as attacks and natural disasters (Latora & Marchiori, 2005; Ouyang & Fang, 2017; Xiao et al., 2021; Chen et al., 2022; Amini et al., 2024; Fallahi et al., 2024).

The importance of critical infrastructure underscores the need for a systematic and prioritized approach to post-disaster recovery. This involves evaluating the criticality of individual components—emergency services, healthcare facilities, utilities providing water and electricity, communication networks, and transportation systems—based on their profound impact on public safety and the overall functioning of society. The importance of this is in its role as a life support network that enables normal operations in industry and the local community, including production, delivery, supply chain operations, and daily life for various purposes (Oh et al., 2012; Xiao et al., 2021; Chen et al., 2022; Amini et al., 2024; Fallahi et al., 2024). In addition, critical infrastructure provides essential services to society and widespread disruptions can have significant social consequences (Svegrup et al., 2019; De Fino et al., 2023; Liu et al., 2024).

The strategies employed for assessing damage and facilitating recovery necessitate a comprehensive framework, encompassing preparatory measures, resilience-building initiatives, coordinated response and recovery plans, and the establishment of effective public-private partnerships. Governmental policies play a pivotal role in securing critical infrastructure through the continual formulation, enforcement, and improvement of regulations, standards, information-sharing mechanisms, and strategic investments in security measures. In the realm of seismic events, the assessment of damage requires a judicious blend of traditional and advanced methodologies. These encompass on-site field surveys, modeling and simulation techniques, machine learning for data analysis, RS using satellite imagery, GIS applications for spatial data analysis, and real-time data analytics. This methodological amalgamation provides a nuanced understanding of both the physical and operational impact on critical infrastructure. In the event of a disaster, protection, and prioritization of critical infrastructure is important to reduce damage and ensure rapid recovery. The protection of key infrastructure during disaster response should be thoroughly analyzed (Cvetković & Andrija, 2021; Chen et al., 2022; De Fino et al., 2023; Liu et al., 2024; Amini et al., 2024; Fallahi et al., 2024; Xiao et al., 2021). In the literature, there are many GIS-based studies that evaluate the effects of a possible earthquake on critical infrastructure elements and support these effects with scenarios (Adachi & Ellingwood, 2008; Theilen-Willige et al., 2012; Soden & Palen, 2016; Zhang et al., 2016; Yariyan et al., 2020; Chen et al., 2022; De Fino et al., 2023; Liu et al., 2024; Amini et al., 2024; Fallahi et al., 2024; Xiao et al., 2021). Lam et al. (2021) developed infrastructure vulnerability and seismic hazard maps with GIS. Then, a risk map was created by integrating the infrastructure vulnerability map with the seismic hazard map. Thus, infrastructure vulnerable to seismic hazards were identified. Mavroulis (2019) developed a model based on UAV and GIS integration for earthquake damage assessment in a region severely affected by earthquakes. Thus, a web application is presented for each building, including information on the type of structure, vulnerability class, type of damage, and degree of damage. Fallah-Aliabadi et al. (2020) evaluated the potential seismic risks and losses for hospital buildings and components in Yazd County using GIS and HAZUS. Codermatz et al. (2003) estimated risk for some industrial facilities and highways using GIS and HAZUS. Poljanšek et al. (2012) evaluated the seismic vulnerability of European gas and electricity transmission networks from a topological perspective. Using GIS methods, the study found that the gas network is more seismically vulnerable than the electricity network. The main objective of the study by Saputra (2017) is to provide a probabilistic model of the seismic vulnerability of buildings with GIS methods based on the damage data of the major earthquake that occurred in 2006. Munawar et al. (2021) emphasize the importance of technological development during disaster relief and propose the use of UAV and machine training to assess damage to critical urban infrastructure. Resilience and damage assessment are closely related, as highlighted by Sathurshan et al. (2022), who emphasize that performance indicators and damage assessment for different disaster phases should be considered to enhance the long-term resilience of critical infrastructure.

In this study, critical infrastructure is considered in the context of the Kahramanmaras earthquake disaster occurred in 2023. A review of the existing literature reveals that most of the studies are based on potential scenarios rather than the effects of an actual earthquake. These studies generally focus on train lines, highways, hospital buildings, and gas-electric transmission lines. In the study by Marvoulis (2019), an online damage assessment system was developed to analyze the current earthquake situation. In the light of these information, there is a critical need for comprehensive studies that focus specifically on the intricate details of earthquake-induced damage to different types of critical infrastructure. When seismic events, exemplified in Türkiye by the Kahramanmaras earthquake, upset this delicate balance, it becomes imperative to implement a carefully structured strategy aimed at strengthening and restoring these vital systems (Deelstra & Bristow, 2023; Chen et al., 2022; De Fino et al., 2023; Liu et al., 2024; Amini et al., 2024; Fallahi et al., 2024; Xiao et al., 2021).

The 2023 Kahramanmaraş earthquakes were a series of strong earthquakes that affected the Kahramanmaraş province of Türkiye. The earthquakes caused widespread damage to critical infrastructure in the region, including roads, bridges, power grids, water and wastewater systems, and hospitals. Regrettably, an important challenge that arose in the days following of the two massive earthquakes that occurred in Türkiye in February 2023 was the absence of geographical data, an essential prerequisite for swift, precise, and efficient reaction, recovery, and planning. The Ministry of Environment, Urbanization, and Climate Change, along with other authorized entities, have conducted evaluations to determine the extent of the structural damage suffered by structures that collapsed in the aftermath of the earthquake. Nevertheless, comprehensive data regarding the precise locations of critical infrastructure was not gathered, and there was a lack of examination regarding its relevance to the region's long-term recovery. The objective of this study is to provide a novel method for rapidly determining the impact of an earthquake on essential infrastructure in the Kahramanmaras province, namely in the Onikisubat or Dulkadiroglu districts. This will be achieved by combining building damage assessment results with Points of Interest (POI) data.

Digital spatial data, satellite imagery, orthophotos, and damage assessment data form the backbone of this investigation. The methodological framework, primarily centered on spatial layer overlay and category-based damaged POIs mapping, has proven highly effective in discerning the intricacies of building damage and its cascading effects on Kahramanmaras critical infrastructure. The integration of data sources from the Ministry of Environment, Urbanization, and Climate Change, coupled with contributions from Basarsoft Information Technologies Inc., has enriched the accuracy and depth of these findings. Systematically overlaying building damage maps with POIs has identified and classified critical infrastructure locations within damaged constructions. This approach not only offers a comprehensive understanding of the earthquake's impact on essential facilities but also serves as a valuable template for future disaster response planning and spatial analysis.

Urban areas, especially those located in seismically active regions, are under constant threat from earthquakes, which can have devastating consequences for critical infrastructure. The city of Kahramanmaraş, with its unique geographical and seismic characteristics, has experienced the effects of seismic events throughout its history. Understanding the impact of earthquakes on critical infrastructure is of paramount importance for disaster management, urban planning, and overall community resilience.

The main objective of the study is to provide a thorough and systematic assessment of the extent and nature of earthquake-induced damage to critical infrastructure in Kahramanmaraş. By comprehensively evaluating the damage using existing Point of Interest (POI) data, the study aims to analyze the spatial distribution of earthquake damage, identify hotspot areas, and understand the geographical patterns of infrastructure vulnerability. This detailed understanding will enhance the accuracy of emergency response planning and support targeted urban development strategies. Additionally, the study will classify the severity of damage into categories, ranging from collapsed structures to those requiring urgent demolition, which will aid in prioritizing response efforts and resource allocation. Ultimately, the study aims to offer actionable insights for effective emergency response strategies, including identifying critical infrastructure usable in the aftermath of an earthquake, thus assisting disaster management authorities in formulating strategies to optimize resources and minimize downtime of essential services. This study is motivated by a desire to fill the knowledge gap regarding the spatial distribution and severity of earthquake-induced damage to critical infrastructure in Kahramanmaraş, providing valuable insights for emergency response strategies and informed urban development planning. Recognizing that Kahramanmaraş, like many urban centers, faces increasing frequency and intensity of seismic activity, this research aims to offer practical solutions for creating more resilient urban environments. The use of state-of-the-art technologies ensures data accuracy and reliability, contributing to a nuanced understanding of earthquake impacts. The study's findings are expected to advance existing disaster management literature, informing evidence-based policy recommendations and urban planning strategies for a sustainable future. By incorporating POIs into current damage evaluation methods and leveraging field survey data, the study proposes a novel approach for rapidly identifying affected infrastructure, supporting both short-term and long-term decision-making processes, and mitigating economic losses in disaster strategies and action plans.

Study Area and Data

Study Area

Türkiye, which is located within the highly active Alpine-Himalayan orogenic system (Emre et al., 2018), was hit by a succession of significant earthquakes. The earthquakes with magnitudes of 7.7 and 7.6 on the Moment Magnitude scale, which occurred on February 6, 2023, in the Pazarcık and Elbistan districts of Kahramanmaraş, resulted in significant damage and losses in densely populated urban areas, small towns, and villages across the eleven provinces (Kahramanmaraş, Hatay, Gaziantep, Malatya, Diyarbakır, Kilis, Şanlıurfa, Adıyaman, Osmaniye, Adana, and Elazığ) (Fig. 1). The Ministry of Environment, Urbanisation, and Climate Change has reported that the total number of structures that were either instantly demolished, seriously damaged, collapsed, or moderately damaged in 11 provinces is estimated to be around 300,000. The United Nations Development Programme (UNDP) predicted that the earthquake incurred a cost above $100 billion, which is comparable to 11.6% of Türkiye's gross domestic product (GDP) in 2021 (United Nations, 2023).

The study area is located within the borders of Dulkadiroğlu and Onikişubat districts, which are the central districts of Kahramanmaraş province (Fig. 1). The total area of Kahramanmaraş province is 14,519 km^2, Dulkadiroğlu district is 1,176 km^2 and Onikişubat district is 2,429 km^2. The study area covers an area of 86.9 km^2. Within the study area, there are a total of 95 neighborhoods, 50 in Onikişubat and 45 in Dulkadiroğlu. The total population of the neighborhoods in the study area is 553,950 people.

Kahramanmaraş is located north of the Gölbaşı Segment of the Eastern Anatolian Fault Zone. The most destructive earthquakes in the history of Maraş, which has been affected by the earthquakes occurring on the Eastern Anatolian Fault Line throughout history, are the VII intensity İslâhiye Earthquake in 131 BC, the VIII intensity İslahiye and Maraş earthquake in A.D. 128, the IX intensity Cehyan-Maş earthquake in 1114. VIII intensity Islahiye and Maraş earthquake

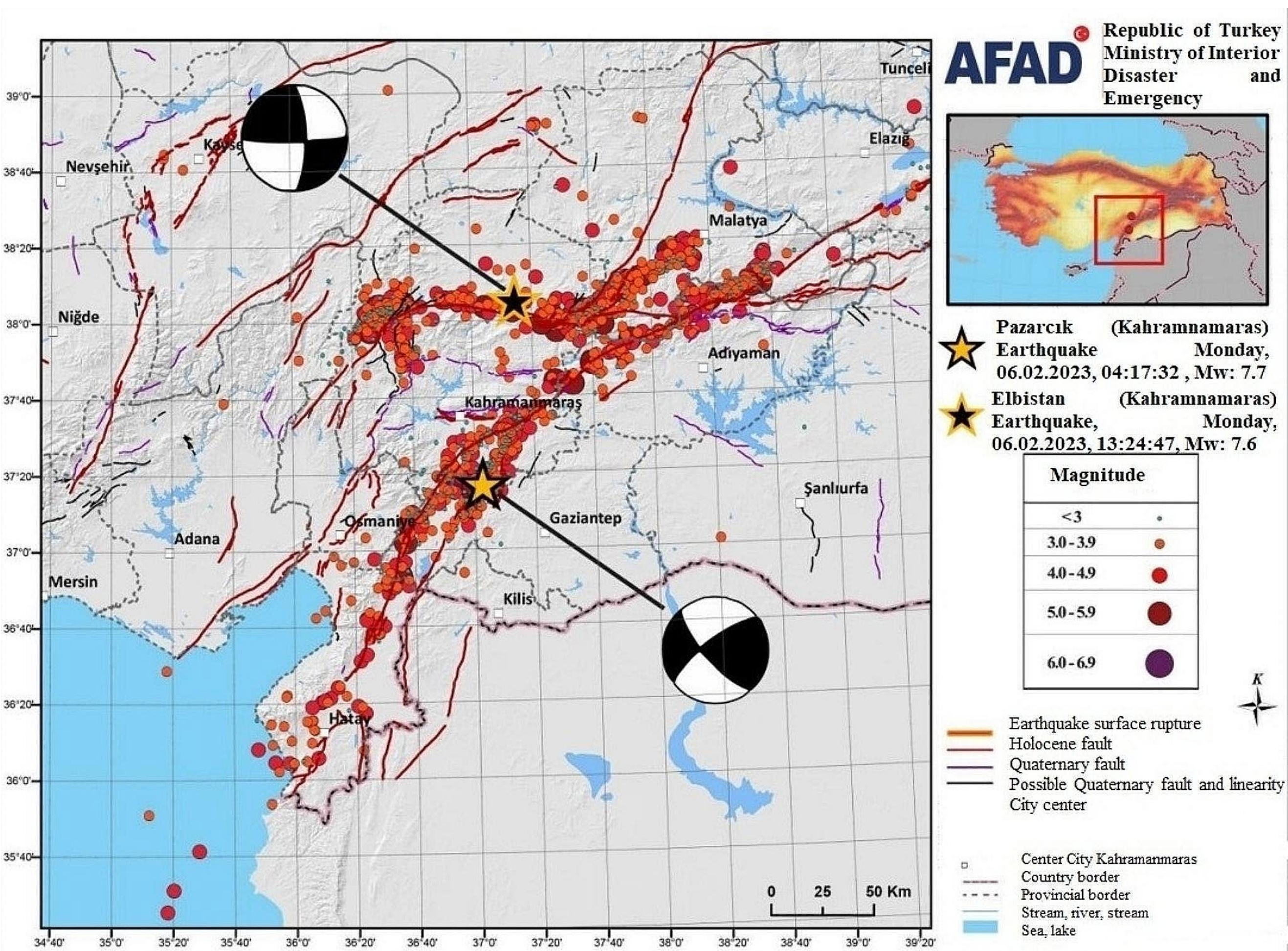

Fig. 1 06.02.2023 Pazarcık (Kahramanmaraş) Mw 7.7 and Elbistan (Kahramanmaraş) Mw 7.6 earthquakes and aftershock activity (DEMP-UDSEP, 2023) in 128 AD, IX intensity Cehyan-Maraş earthquake in 1114, 7.4 magnitude Gölbaşı earthquake in 1513, 6.8 magnitude Çardak Fault earthquake in 1544, and 7.3 magnitude earthquake in 1795 (Şaşmaz & Palutoğlu, 2017).

Materials

The main resources utilized in this research are the digital spatial data and the data gathered through field surveys conducted in the area prior to and following the 2023 seismic events. The damage assessment method primarily relied on the utilization of Planet satellite imagery, aerial photographs captured by UAVs in the field, orthophotos generated by the General Directorate of Mapping, and digital building data provided by Basarsoft Information Technologies Inc. The Ministry of Environment, Urbanization, and Climate Change utilized Damage Assessment data as an additional source to identify the demolished structures. Basarsoft Information Technologies Inc. also supplied the POI data, which serves as the crucial source for this research.

The research materials are comprehensively described in the following parts.

Digital Building Data

Basarsoft Information Technologies Inc. created digital building polygon data by digitizing satellite pictures and aerial photos with a precision of ±50 cm. Basarsoft, a company specializing in spatial data production and server services, consistently enhances digital building data using very precise aerial pictures. This study utilized the latest pre-disaster digital building data and aerial pictures to accurately identify the buildings that had collapsed (Fig. 2).

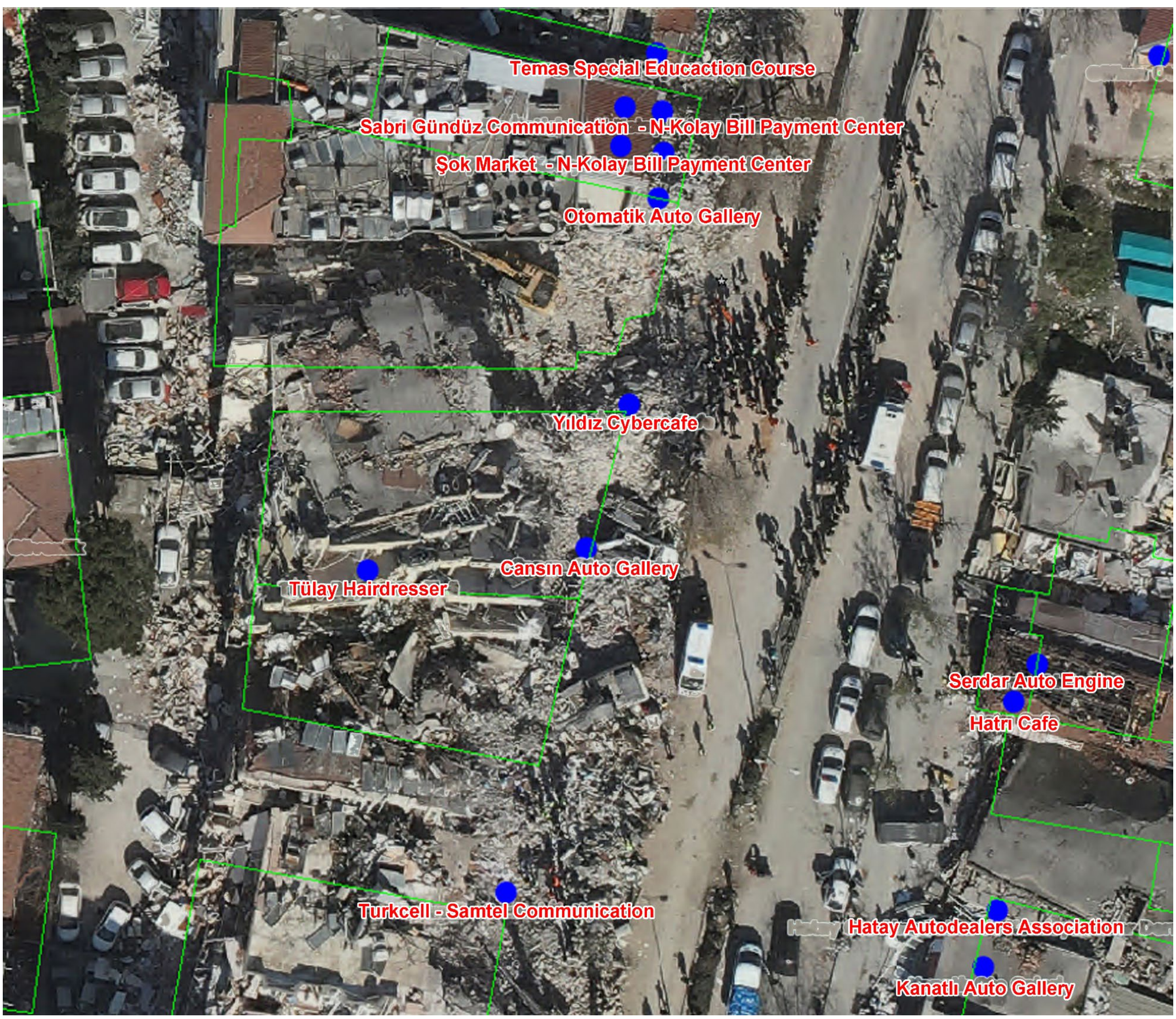

Fig. 2 The overlapped digital building data, satellite image, and POIs

POIs

The main data utilized to analyze the critical infrastructure in the research area were obtained from the POI data gathered through on-site surveys conducted by Basarsoft Information Technologies Inc. from 2020 to 2021, employing handheld GPS devices with an accuracy of ± 4 m.

The original POI data consists of 25 main categories such as shopping, residential areas, governmental institutions, health facilities, educational institutions, and commercial areas. Under these categories, there are 332 sub-categories in total. This makes it difficult to identify and interpret the initial effects and severity of the earthquake on critical infrastructure, which is especially important for post-disaster. Therefore, in the first stage, POIs related to critical infrastructure under the headings of military facilities, railways, airways, water, sewage waste structures, social facilities, muster points, telecommunications, sports facilities, energy distribution, highway facilities, official institutions, health institutions, historical and touristic facilities, commercial areas and financial institutions were evaluated separately from the others. As a result, 15 main POI categories were reorganized, covering a total of 58 subcategories (Table 1).

Aerial Photographs and Satellite Images

The study utilized aerial pictures and satellite images to identify the compromised structures. To achieve this objective, high-resolution Planet Satellite pictures with a resolution of 60 cm and orthophotos generated by the General Directorate of Mapping were supplied. The orthophotos generated by aerial vehicles from the General Directorate of Mapping were obtained from https://kure.harita.gov.tr (General Directorate of Mapping, 2023).

Building Damage Assessment data

In order to accurately identify damaged buildings, the field data from the Ministry of Environment, Urbanization, and Climate Change was used as a supplementary source

Table 1 Critical infrastructure POI categories and subcategories

Categories	Subcategories	Categories	Subcategories
Health institutions	Emergency service	Airways	Airport runway
	Dental hospital	Water, sanitary, waste	Water treatment plant
	Primary care clinic		Water Reservoir
	Dental clinic	Social facilities	Soup kitchen - food bank
	Dialysis center	Important places	Muster point
	Pharmacy	Telecommunication	Transmitting station
	Physiotherapy clinic	Sport facilities	Gymnasium
	Hospital		Stadium
	Laboratory		Ice skating
	Medical shop		Football field
	Policlinic		Sports complex
	Rehabilitation center	Energy distrubution	Intraurban transformer
	Other health institutions		Thermal power plant
Historical and touristic facilities	Public bath	Road facilities	Fuel station
	Guesthouses, training, and recreation facilities		Charging station
	Hotel		Gas station
	Hostel		Bus terminal
	Dormitory / Pension		Park lot
Commercial areas	Wholesale food market	Governmental institutions	Municipality presidency and units
	Generator		Electric administration
	Logistics warehouse		Police office
	Food market		Fire station
	Cold storage		District governorship
	Public toilet		Police center
Financial institutions	Atm		Post station
	Branch bank		Telecom office
	Insurance company		Governorship
Military facilities	Gendarmie station		Municipal police
Railways	Train station		

Table 2 Building damage evaluation listing of the Ministry

Damage categories
Collapsed
Severely damaged / urgent demolition needed
Moderately damaged
Slightly damaged
No damage
Unable to inspect (unable to enter, locked, out of scope)

Table 3 Precision parameters for geocoding

Focus object type	Alias
Building	Matched records up to building breakdown
Street	Matched records up to street breakdown
Neighbor	Matched records up to neighborhood
Nextdoor	Matched records up to next door
District	Matched records up to district
Apartment	Matched records up to apartment number
Province	Matched records up to province

of information. This was necessary because images alone could not detect buildings that seemed unchanged on a geometric level, despite having major column fractures and floor collapses. The Ministry of Environment, Urbanization, and Climate Change carried out an urgent operation to determine the extent of building damage in the earthquake-affected area by on-site surveys. The levels/severity of the building damages were identified across six categories, as illustrated in Table 2.

The data was acquired from the Ministry's website in text format using a web crawling approach with the assistance of request libraries in Python. To obtain coordinate data for the address information, the Geocoding approach was employed utilizing APIs in the Basarsoft Web Services, as the downloaded data did not include this information. The API offers precision metrics for automatically geocoded locations, allowing operators to assess the dependability of the data based on the varying coordinate precision. The precision parameters are provided in Table 3. Only data pertaining to "apartment", "building", and "nextdoor" were taken into account for the building detection method, while other data was disregarded due to insufficient coordinate precision.

Method

The main method employed in this work involves overlapping spatial layers and their subsequent comparisons, along with creating damaged POI maps based on different categories. The next step involved overlapping satellite pictures and aerial photographs with digital building data to detect any changes in building alignments and roof deterioration. This allowed for the identification of damaged structures. Subsequently, the impact of the earthquake on Maraş's critical infrastructure was assessed. Furthermore, the database is filled up with building damage assessment data acquired from the Ministry.

The building damage assessments were subsequently superimposed with POIs to identify the positions of vital infrastructure and determine which POIs are situated within the affected structures. The POIs situated within the affected structures were categorized and assessed based on specific classifications and sub-classifications. Figure 3 shows the order of operations followed in the investigation.

The following sections give detailed information about the methods applied throughout the study.

Digitizing Process

The satellite and aerial imagery were utilized to digitize the structures that had collapsed, structures that were tilting in a specific direction, and structures that had roof damage. All of these structures were categorized as "collapsed buildings" in the database and classified as damaged constructions. In

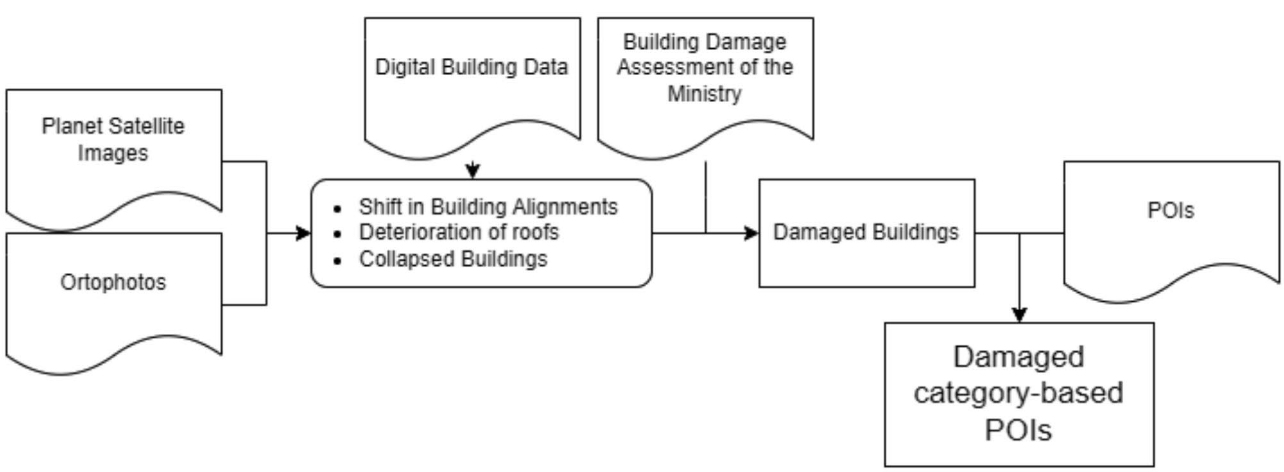

Fig. 3 The workflow of the study

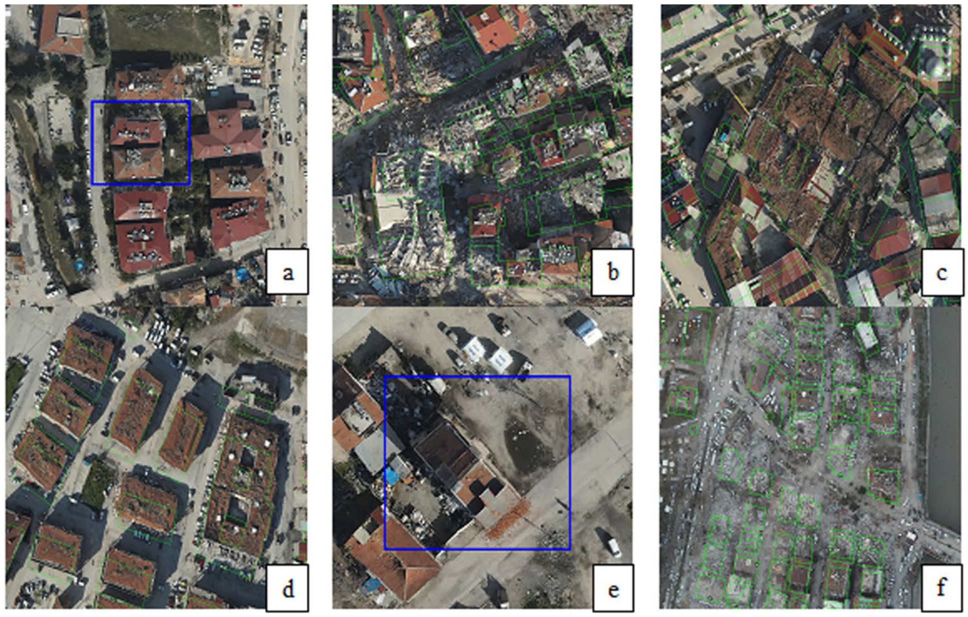

Fig. 4 Building damage samples in the study area **(a)** Leaning buildings **(b)** Collapsed buildings **(c, d)** Buildings with changed roof position, **(e)** Uncollapsed building with a collapsed floor **(f)** Regional damages

order to identify buildings that have not undergone geometric changes despite vital column fractures and floor collapses, the Ministry of Environment, Urbanisation, and Climate Change utilized the building assessment database. This database was compared with digitized layers to identify buildings that were damaged but not visually detectable. Due to the limited nature of the Ministry's available building database, these records were utilized as a supplementary data resource. The structures categorized as collapsed, seriously damaged, and requiring urgent destruction in this database were classified as damaged buildings. Figure 4 is an example of the process of digitizing a building.

Determination of Damaged Critical Infrastructure

Due to the time, cost, and difficulty associated with locating the damaged critical infrastructure by fieldwork, the POI data was layered on the data layer created for the damaged structures. The point data representing POI was linked to the polygon data representing buildings using a spatial join operation, specifically using a "completely within" relationship. Structures for which the extent of damage could not be assessed were classified as damaged. Following this procedure, the damage status of POIs was analyzed and recorded as an attribute.

Findings

This section presents the results obtained following the applied methods explained in the previous sections.

Table 4 Building damage status in the study area

Damage Categories	Number
Collapsed	464
Severely damaged / Urgent demolition needed	1,162
Moderately damaged	47
Slightly damaged	2,617
No damage	6,697
Unable to inspect (unable to enter, locked, out of scope)	1,425

Damaged Buildings

Through the utilization of digitization and examination of a damaged building database, it was determined that out of the total of 68,344 buildings in the research area, 18,212 were found to be damaged.

The Ministry's damaged building data, which were largely utilized with the digital building database and aerial/satellite images, were employed to validate the damaged building determination process. Accordingly, an overall of 12,412 buildings were inspected, representing 18.2% of all buildings in the study area.

Table 4 presents the distribution of the damaged structures examined by the field teams of the Ministry, categorized by the severity of damage. A total of 1,425 buildings, which is almost the same number as severely damaged, were unable to be evaluated due to certain limitations on access. Conversely, the combined count of buildings that were slightly damaged and undamaged amounted to 9,361. However, the data provided is incomplete for almost 80% of the structures.

Critical Infrastructure

The POI data were integrated with the buildings (polygons) in the GIS environment, facilitating the retrieval and identification of critical infrastructure data within the affected structures. The results of the mentioned query are summarized in Table 5.

The results reveal that the most damaged POIs were in the category of financial institutions and commercial areas, while the least damaged POIs were in muster points. In addition, there was no damage to military facilities, train stations, airports, soup kitchens, and water, sewage, and waste structures. During the earthquakes, 13 out of 97 muster points (13%) collapsed. In addition, the buildings of governorships and district governorships, the institutions responsible for coordination in the event of a disaster, were also destroyed during the earthquake. Nevertheless, according to rational assessment, 228 out of 417 structures, or 55%, under the category of financial institutions were damaged, reaching the highest level of destruction. In commercial areas, 19 out of 35 structures, or 54%, were destroyed, while all structures in the wholesale food market and generators subcategory under this category were destroyed. In addition, 43% of historical and touristic facilities were damaged, followed by health facilities (31%), government institutions (29%), road facilities (27%), power distribution (23%), and sports facilities (21%). Damaged structures listed under the telecommunications category were identified at 19%, making it the least affected POI category after muster points. Considering the sum of critical infrastructures that will support the affected population and emergency teams during the disaster response period, the results show that the proportion of damaged POIs is 34%.

Figure 5 shows the distribution of the category-based damaged critical infrastructure POIs in the study area. In both proportional and numerical terms, the most damaged financial institution POIs are concentrated and clustered in the city center, depending on the type of subcategory. A similar clustering pattern is also observed for the POI subcategories of health institutions and partially governmental institutions. On the other hand, energy distribution, road facilities, sports facilities, and commercial areas are generally dispersed around the periphery of the center of the study area.

Results

According to the findings, 34% of the vital infrastructure included in the 15 POI categories had damage, which amounts to 575 out of a total of 1,690 units. The city center and its surrounding areas have a concentration of critical infrastructures that have been damaged. These areas also have a high level of urban density. Due to the dysfunctional state of the damaged POIs, they were unable to be exploited during the following days of the earthquake. Identifying critical infrastructures that are essential for search, rescue, and survival processes is extremely important, particularly during the post-earthquake emergency response phase. This study not only detects and maps POIs that have been damaged but it may also be utilized to promptly discover POIs that have not been affected. During a crisis, it is advisable to prioritize the utilization of pre-existing facilities in essential infrastructure to support operations, taking into account the nature of the activity. Over the course of time, it is feasible to determine the caliber and quantity of POIs that have been harmed, categorized them by their type, and assess their influence on the recuperation of cities after a disaster. The study's methodology and findings can be utilized to formulate policies on the placement and rejuvenation of important infrastructures in the city center of Kahramanmaraş.

The aftermath of the disaster revealed a varied impact on critical infrastructure essential for coordination, logistics, security, and post-disaster support. While key structures like railway stations, airports, bus terminals, and logistics warehouses crucial for logistics operations remained unaffected, significant destruction was observed, encompassing all district governorship buildings and 30% of municipality structures intended for coordinating search and rescue efforts and post-disaster aid for affected individuals. Furthermore, security infrastructure suffered substantial damage, with 60% of police and police department buildings demolished, contrasting with the resilience of military installations. The disaster also severely impaired financial security mechanisms, with almost half of ATMs and bank branches destroyed, alongside an 81% loss of insurance company facilities. The integrity of water, electricity, and communication networks fared relatively better, except for challenges arising from the partial collapse of energy distribution transformers, impacting energy supply to specific city sectors, and the depletion of stores housing generators for backup power. Moreover, the widespread destruction of hospitals, emergency services, and vital centers like dialysis facilities presents formidable obstacles to post-disaster rescue and recovery operations. Preservation of deceased individuals becomes pivotal, highlighting the undamaged state of cold storages and ice rinks suitable for this purpose. While numerous structures for temporary shelter exist, with accommodation and sports facilities viable for this purpose, the destruction of 81% of hotels and 50% of stadiums poses challenges. Conversely, 80% usability of hostels, pensions, sports complexes, market areas, and parking lots provides essential shelter options. Hygiene concerns post-disaster are underscored by the observed 30% usability of public baths

Table 5 Damaged critical infrastructure POI categories in the study area

Categories	Subcategories	Total POI	Damaged POI	Ratio (%)
Military facilities	Gendarmie station	2	0	0
Railways	Train station	1	0	0
Airways	Airport runway	1	0	0
Water, sanitary, waste	Water treatment plant	1	0	0
	Water Reservoir	7	0	0
Social facilities	Soup kitchen - food bank	2	0	0
Important places	Muster point	97	13	13
Telecommunication	Transmitting station	16	3	19
Sport facilities	Gymnasium	23	6	26
	Stadium	2	1	50
	Ice skating	3	0	0
	Football field	47	9	19
	Sports complex	5	1	20
Energy distrubution	Intraurban transformer	325	75	23
	Thermal power plant	1	0	0
Road facilities	Fuel station	56	16	29
	Charging station	8	2	25
	Gas station	56	18	32
	Bus terminal	3	0	0
	Park lot	30	5	17
Governmental institutions	Municipality presidency and units	31	9	29
	Electric administration	4	0	0
	Police office	10	5	50
	Fire station	8	0	0
	District governorship	1	1	100
	Police center	2	0	0
	Post station	17	4	24
	Telecom office	2	1	50
	Governorship	1	1	100
	Municipal police	4	2	50
Health institutions	Emergency service	15	5	33
	Dental hospital	4	2	50
	Primary care clinic	62	13	21
	Dental clinic	6	3	50
	Dialysis center	7	5	71
	Pharmacy	209	61	29
	Physiotherapy clinic	1	0	0
	Hospital	11	5	45
	Laboratory	5	3	60
	Medical shop	28	14	50
	Policlinic	6	2	33
	Rehabilitation center	9	0	0
	Other health ınstitutions	14	2	14
Historical and touristic facilities	Public bath	13	9	69
	Guesthouses, training, and recreation facilities	8	1	13
	Hotel	26	21	81
	Hostel	5	1	20
	Dormitory/Pension	43	9	21
Commercial areas	Wholesale food market	9	9	100
	Generator	4	4	100
	Logistics warehouse	3	0	0
	Food market	14	5	36
	Cold storage	1	0	0
	Public toilet	4	1	25

Table 5 (continued)

Categories	Subcategories	Total POI	Damaged POI	Ratio (%)
Financial institutions	Atm	278	127	46
	Branch bank	56	34	61
	Insurance company	83	67	81

and 75% usability of public toilets, crucial for addressing immediate sanitation needs.

Despite their overall modest quantity, some of the damages in POI categories and/or subcategories appear to be rather substantial when the damage is evaluated proportionately. However, it is crucial to consider the kind, size, capacity, and frequency of usage when assessing the impact of this critical infrastructure. Hence, it is not logical to solely rely on damage ratios to evaluate and interpret the outcomes. For instance, among the POIs that have relatively low damage rates (23%), those categorized under energy distribution make up 20% of the entire number of POIs in the area, while the damaged ones account for 13% of all POIs. Hence, it is imperative to assess these findings in a thorough, cohesive, and focused manner for future research and practical use.

Furthermore, the methodology and findings outlined in this research have significant theoretical and practical ramifications for future endeavors. This study showcases the capability of UAV and GIS technologies to offer precise and prompt knowledge to disaster responders, enhancing earthquake damage assessment in critical infrastructure. Implementing the methods outlined in integrating these technologies can deliver more accurate and comprehensive data on the magnitude and severity of earthquake-induced damage. Utilizing this technology and methodology, together with effectively utilizing POI data, can assist local authorities in accurately evaluating the extent of earthquake damage, making informed judgments on rescue operations and resource distribution, and conducting comprehensive economic impact analysis. This research has the potential to enhance the methodology and improve its efficacy in other places susceptible to earthquakes.

Discussions

The results of this study provide critical insights into the impact of earthquakes on Kahramanmaraş's infrastructure, highlighting the need for strategic urban planning and disaster response. The thorough assessment of damaged critical infrastructure categories, ranging from financial institutions to health facilities, provides a nuanced understanding of vulnerability. Spatial analysis of the distribution of damage not only identifies hotspot areas but also reveals a differentiated impact across different urban sectors. Understanding the severity of the damage, from collapsed structures to those only moderately affected, allows for the prioritization and efficient deployment of emergency response efforts.

Furthermore, the study's focus on the classification of damage severity and its implications for emergency response strategies underscores the practical significance of its findings. The identification of critical infrastructure that remains operational after an earthquake facilitates rapid decision-making by disaster management authorities. The study provides valuable guidance for optimizing existing resources and minimizing the downtime of essential services, ultimately improving the city's resilience to seismic events.

If evaluated in conjunction with the research published in the literature, this study includes many different infrastructure elements (1690 in total) with the results obtained by considering the results of an existing earthquake. Lam et al. (2021) conducted risk map modeling on a specific segment of a traditional railway line in Japan, considering it as a vital element of critical infrastructure. Fallah-Aliabadi et al. (2020) assessed the result of a potential earthquake using two different scenarios. The study focuses on the water and fuel tanks, electricity, and gas stations associated with each hospital facility that are susceptible to potential impact. Poljanšek et al. (2012) investigated the condition of gas and electricity transmission networks in interconnected European countries in response to a potential seismic threat. Saputra et al. (2017) use a developed method to assess the risk of building damage. Researchers base their estimations on data from damaged buildings during the 2006 Yogyakarta earthquake. The above studies collectively provide a risk model that relies on several scenarios. They rely on one or several infrastructure components. Marvoulis et al. (2019) utilize actual earthquake data and develop a web-based GIS application designed for emergency responders to assess the condition of damaged buildings. However, in the context of this study, it does not rely on critical infrastructure components that were impacted by the earthquake.

In a broader context, this research makes a significant contribution to the global discourse on earthquake resilience and urban planning. The methods used, which integrate RS, GIS technologies, and damage assessment data, provide a model for other earthquake-prone regions around the world. The emphasis on tailoring recommendations to the unique characteristics of Kahramanmaraş ensures that the applicability of the study goes beyond theoretical

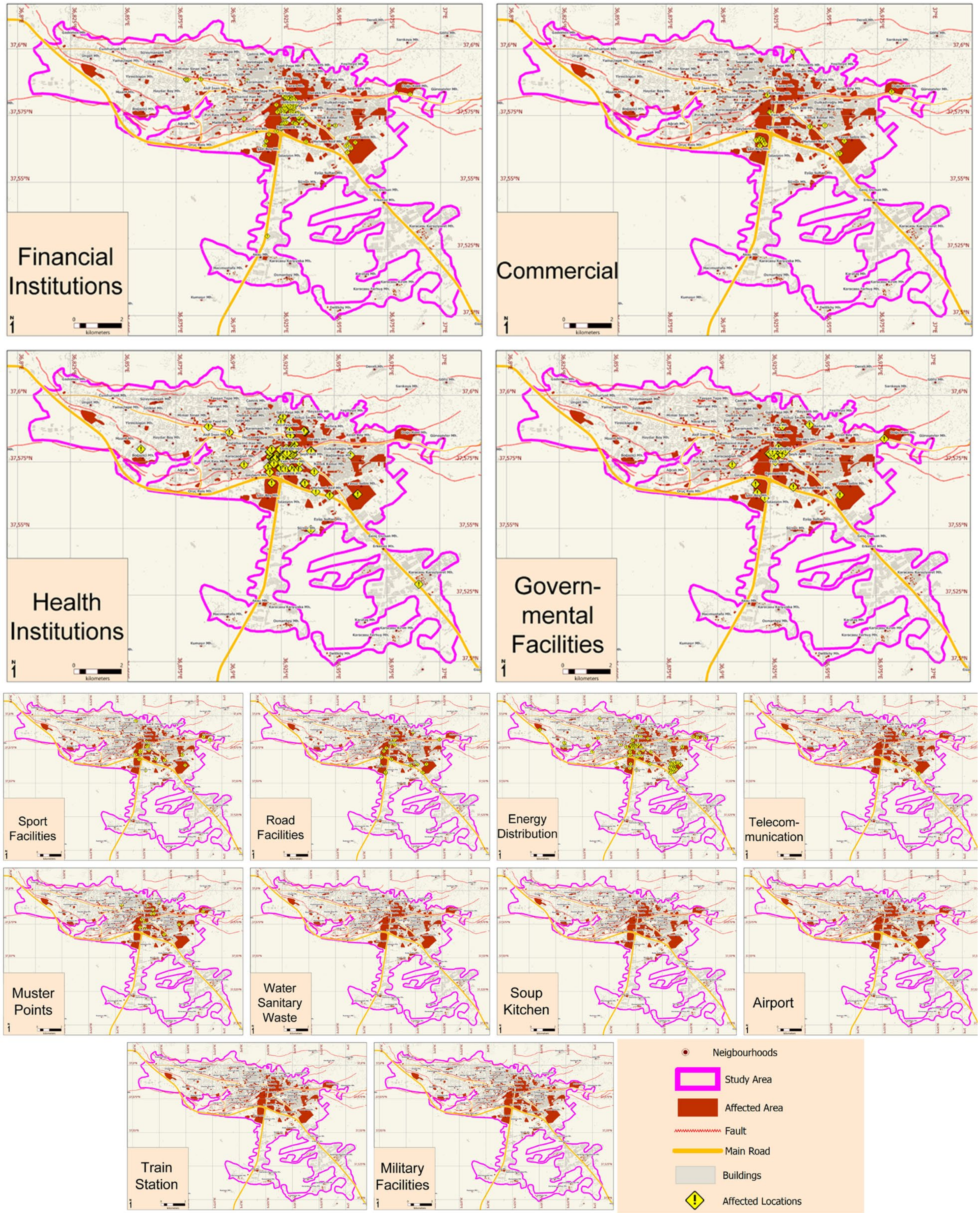

Fig. 5 Locations of the damaged critical infrastructure POIs in the study area

insights and provides practical solutions for urban planners and policymakers.

This study makes a significant contribution to the theoretical frameworks surrounding earthquake resilience and urban planning. By using advanced technologies such as RS and GIS, the research demonstrates the potential for integrating these tools into comprehensive damage assessment methodologies. The emphasis on understanding the spatial distribution of damage across critical infrastructure categories adds a layer of complexity to existing theoretical models. The results of the study can inform future theoretical developments by highlighting the importance of spatial analysis in assessing the aftermath of seismic events. Furthermore, the severity classification approach introduces a nuanced dimension to theoretical discussions on prioritizing emergency response efforts in the context of diverse infrastructure vulnerabilities.

From a practical perspective, the study has important implications for urban planners, emergency responders, and policymakers. The detailed assessment of damaged critical infrastructure provides actionable insights for immediate response efforts. Emergency responders can use spatial analysis to identify areas of concentrated damage, enabling them to allocate resources efficiently. Urban planners can use the severity classification to prioritize reconstruction and redevelopment initiatives, taking into account the urgency and extent of damage to different categories of infrastructure. In addition, the identification of operationally critical post-earthquake infrastructure serves as a practical guide for disaster management authorities, allowing them to optimize available resources for rapid recovery and restoration of services. The methodologies used in this study provide practical ways to integrate cutting-edge technologies into routine urban planning and disaster management practices, setting a precedent for improving the resilience of cities in seismic zones.

This study is of overarching importance in advancing our understanding of earthquake resilience and urban planning, particularly in the context of Kahramanmaraş. By meticulously assessing earthquake damage to critical infrastructure, the research reveals vulnerabilities, spatial patterns, and severity classifications that are critical for designing resilient urban plans. The findings are critical for emergency responders and decision-makers, helping to optimize resource allocation, formulate effective response strategies, and develop targeted urban development plans. Beyond immediate applications, this study contributes to a broader knowledge base that guides future urban planning initiatives worldwide by emphasizing earthquake-resistant measures. The localized focus on Kahramanmaraş ensures that the recommendations are tailored to the unique characteristics of the city, creating a practical bridge between research findings and tangible improvements in disaster preparedness and urban resilience. Ultimately, this research has the potential to reshape urban planning practices and provide a model for creating safer, more resilient cities in earthquake-prone regions worldwide.

In conclusion, this study goes beyond the mere examination of earthquake-induced damage and serves as a cornerstone for informed decision-making in disaster-prone urban areas. By combining local knowledge with global applicability, the research bridges the gap between theory and practice, offering tangible ways to create safer, more resilient cities around the world.

Conclusions

In conclusion, this study highlights the critical importance of identifying and prioritizing damaged critical infrastructure for effective post-earthquake emergency response. The comprehensive assessment of earthquake-induced damage in Kahramanmaraş reveals the vulnerability and spatial distribution of different categories of critical infrastructure. Understanding these patterns is critical for emergency responders to strategically allocate resources and quickly address concentrated areas of damage. The severity classification, ranging from collapsed structures to those requiring urgent demolition, provides nuanced insights that can guide the prioritization of response efforts.

Key findings from this research have significant implications for urban planning and disaster management. By highlighting areas of intense damage and categorizing severity, the study provides actionable information for urban planners and policymakers. The spatial analysis of critical infrastructure damage serves as a blueprint for targeted rehabilitation and reconstruction efforts. The identification of operational critical infrastructure post-earthquake becomes a guiding principle for disaster management authorities, helping to optimize resources for rapid recovery.

In proposing urban planning strategies, the study advocates a proactive approach to improving the resilience of critical infrastructure to future seismic events. The knowledge gained from this research can be used to develop land use regulations, building codes, and emergency response plans that specifically address the vulnerabilities identified. By integrating cutting-edge technologies into routine urban planning practices, cities in seismic zones can fortify themselves against potential disasters and promote a more resilient and safer urban environment. Ultimately, this study contributes to the evolving discourse on earthquake resilience by offering tangible pathways for both theoretical advancement and practical implementation. Furthermore, the theoretical implications of this study extend beyond

Kahramanmaraş and serve as a reference for earthquake-prone regions worldwide. The methodology used, which combines RS, GIS technologies, and damage assessment data, can be adapted and replicated in different urban environments facing seismic hazards. The results highlight the importance of integrating spatial analysis and technological tools into disaster management frameworks and provide a template for improving preparedness and response capabilities.

On a practical level, the study calls for a re-evaluation of current disaster response strategies and highlights the need for adaptive measures. Emergency response teams can use the identified critical infrastructure to optimize their actions, ensuring rapid and efficient assistance where it is most needed. By providing a comprehensive understanding of the affected areas, this study facilitates a targeted and resource-efficient approach to post-earthquake recovery.

In essence, the study calls for a paradigm shift in the way cities prepare for and respond to seismic events. By recognizing the specific vulnerabilities of critical infrastructure, urban planners and decision-makers can tailor policies and regulations to minimize the impact of earthquakes. This involves not only strengthening structures but also incorporating strategic urban development to ensure that vital facilities are strategically located and designed for resilience.

In conclusion, this research lays the groundwork for advancing earthquake resilience and urban planning practices. By integrating technology, spatial analysis, and a nuanced understanding of critical infrastructure damage, cities can move towards a more proactive and adaptive approach to earthquake risk. The findings of the study, both theoretical and practical, contribute to the broader discourse on disaster resilience and provide valuable insights for academics, practitioners, and policymakers alike.

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Code Availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

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