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Efficient disaster waste management: identifying suitable temporary sites using an emission-aware approach after the Kahramanmaraş earthquakes

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Abstract

The clean and sustainable disposal of waste generated by natural disasters is crucial for effective disaster waste management. The initial stages of waste management involve determining the quantity of waste and identifying suitable temporary sites for its disposal. This study estimates that the Kahramanmaraş province produced approximately 15 million tons of construction and demolition waste and 41,000 tons of household waste following the recent Kahramanmaraş Earthquakes on February 6, 2023. Additionally, the study proposes eight temporary disaster waste sites considering various environmental and technical criteria. It should be noted that this is the first study to factor in emissions from waste transportation when selecting temporary disaster waste sites. An algorithm that considers the transportation network to calculate emissions for each map pixel is developed and integrated with geographic information system to identify the best temporary disaster sites. The results show that the most suitable location for temporary sites is southeast of the city center. The transportation time of the waste to the most suitable temporary site is found to be 98 days when 1000 trucks are in operation. The estimated emissions due to the transportation of the waste to the recycling facilities in this region are approximately 88,000 tons of carbon dioxide, 4.4 tons of sulphur oxide, 7.6 tons of nitrogen oxide, and 47.7 tons of particulate matter. The approach employed in this study can be utilized to identify suitable temporary sites for waste management after any natural disaster.

Keywords Analytical hierarchy process · Disaster waste management · Environmental impact of natural disasters · Kahramanmaraş Earthquake · Technique for order of preference by similarity to ideal solution · Temporary disaster site selection

Introduction

The number of natural disasters has increased considerably in recent years (Yılmaz et al. 2022), leading to substantial economic, environmental, and social losses. When these disasters impact regions, particularly urban areas, they can lead to notable socioeconomic ramifications such as loss of life, destruction of physical and intangible infrastructure, and disruption of financial resources (Marin and

Modica 2017). Additionally, natural disasters also generate a significant amount of waste, adding to the burden on affected communities (Zhang et al. 2019). The amount of waste produced due to a natural disaster depends on both the severity of the event and the number of people living in the affected area. For example, reported natural disasters, such as Hurricane Katrina, the Wenchuan earthquake, and the Great East Japan earthquake, produced 100 million, 380 million, and 28 million tons of waste, respectively (Hu and Sheu 2013; Domingo and Luo 2017; Lorca et al. 2017). The waste after a natural disaster can have far-reaching effects on the population living in the affected area, impacting their health, safety, economic well-being, and quality of life. Therefore, the waste generated after a natural disaster should be removed as soon as possible (Domingo and Luo 2017). However, the treatment of the waste should be environmentally sustainable and economically viable (Tabata et al. 2017). The process of removing and treating the waste

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poses a significant challenge as it involves the clearance of a substantial amount of debris, which is a costly and complex operation that may take months or even years to complete (Askarizadeh et al. 2016). Consequently, it is essential to develop waste management strategies that prioritize the safe removal, transportation, and disposal of waste while minimizing any adverse impact on the environment (Kabirifar et al. 2020). To achieve this, waste management programs should incorporate sustainable practices such as recycling, reuse, and energy recovery, to mitigate the environmental impact and reduce economic costs (Gordon and Dion 2008; Passos et al. 2020). Two review papers on waste management after natural disasters (Brown and Milke 2016; Zhang et al. 2019) revealed research gaps in the planning for disaster debris, waste management and treatment, and environmental, economic, and social impacts of the waste.

Recycling and reuse of disaster waste are one of the most important issues due to its benefits such as recovering economic value from materials and reducing landfill space usage (Brown and Milke 2016; Zhang et al. 2019). Once disaster waste is subjected to measures such as segregation, classification, pulverization, burning, crushing of concrete, and shredding of wood at temporary storage locations, some or all of the waste can be transported to a landfill or incinerator for disposal, while other portions can undergo additional processing for recycling and subsequent reuse or sale (Boonmee et al. 2018; Tabata et al. 2019). Disaster waste can be recycled by processing various materials such as vegetation, construction and demolition debris, vehicles, white goods, and electronic waste. In contrast, landfill cover, aggregate used in concrete production, land reclamation, and slope stabilization are some examples of how disaster waste can be reused (Kabirifar et al. 2020). Despite the apparent advantages of recycling disaster waste, there are several obstacles that impede this process, such as the challenge of physically separating materials, limited time to process the waste, inadequate recycling facilities, and higher costs (Brown and Milke 2016).

Effective waste management and treatment are critical for mitigating adverse effects of natural disasters and promoting efficient recovery processes (Brown et al. 2011; Crowley and Flachsbart 2018; Zhang et al. 2019; Lee et al. 2022). The type of disaster, topology, and geography are key factors in the waste management and treatment process (Trivedi et al. 2015). Furthermore, the timing of waste management activities is also crucial for successful disaster recovery (Galderisi et al. 2022). In addition, it is essential to address the proper handling of construction and demolition (C&D) waste resulting from natural disasters (Karunasena and Amaratunga 2016). It is suggested that C&D waste due to a natural disaster be temporarily stored at separation sites (Karunasena et al. 2009; Wang et al. 2019) before being transported to incineration, landfill, or recycling facilities

(Boonmee et al. 2018). Temporary disaster waste sites serve as staging areas where the collected waste can be efficiently sorted, categorized, and processed before its final destination (Alshami et al. 2023). These sites are strategically designed to accommodate temporary storage needs and often include designated areas for different types of waste, such as organic materials, hazardous substances, and recyclable materials. By implementing appropriate separation techniques and waste management protocols at these sites, the efficient categorization and segregation of waste are ensured (Gálvez-Martos et al. 2018), enabling effective utilization of available resources and minimizing potential environmental risks. Moreover, temporary storage at these sites allows for the assessment of the waste's composition and volume, aiding in the development of informed decisions regarding the most suitable disposal or recycling methods (Fetter and Rakes 2012). This staged approach not only optimizes the overall waste management process but also facilitates the identification of potential opportunities for resource recovery, such as salvaging reusable materials or extracting valuable resources from certain waste streams (Karunasena et al. 2009). Therefore, the establishment of temporary disaster waste sites acts as a crucial component of efficient and sustainable waste management practices in the aftermath of natural disasters, contributing to effective recovery processes and minimizing the environmental impact (Trivedi et al. 2015; Brown and Milke 2016; Domingo and Luo 2017).

The selection of a temporary storage site for the waste after a natural disaster should be done with careful consideration given to several factors including the sorting, processing, and storage of the waste, as well as the logistic and environmental challenges associated with such activities (Hayashi and Katsumi 1996; Karunasena et al. 2009; Cheng and Thompson 2016; Tabata et al. 2017, 2019; Lee et al. 2022). It is essential to choose a site that can effectively manage the volume of waste produced and ensure that the sorting and processing procedures are carried out efficiently (Karunasena et al. 2012; Grzeda et al. 2014). Furthermore, the site should be accessible to transportation routes and be located in an area that minimizes any potential adverse environmental impacts (Cheng and Thompson 2016; Lee et al.2022). Numerous prior studies have overlooked the crucial aspect of determining the appropriate location for temporary storage sites (Özdamar and Demir 2012; Sahin et al. 2016) and have assumed that the locations of the temporary storage sites are already established (Wang et al. 2019). While several studies have employed multi-criteria decision-making (MCDM) tools to locate appropriate landfill sites (Lin and Kao 2005; Sadek et al. 2006; Alves et al. 2009; Eskandari et al. 2012; Gbanie et al. 2013; Motlagh and Sayadi 2015), the studies focusing on temporary storage sites are rare (Cheng and Thompson 2016).

Among studies attempting to select temporary storage sites, Grzeda et al. (2014) utilized binomial cluster analysis to identify potential temporary storage sites that varied according to federal, state, county, and local laws and regulations. Wang et al. (2019) proposed a multi-objective, mixed-integer linear optimization model that aims to minimize both removal time and cost. In a recent study, Lee et al. (2022) presented an approach for selecting suitable sites for temporary disaster waste management systems in highly developed and densely populated cities. The approach employs geographic information system (GIS) analysis techniques and a weighted sum rating method based on selected constraints to identify suitable sites. Nickdoost et al. (2022) proposed an integrated framework to determine optimal locations for temporary debris management sites that minimizes the social and economic impacts on the community resulting from uncollected debris sourced from a hurricane. Using GIS and an agent-based model, the framework optimizes temporary waste storage locations to minimize both debris collection time and the negative impacts of uncollected debris. Onan et al. (2015) proposed a framework that integrates loss estimation with post-disaster waste management and employs an evolutionary multi-objective optimization approach. The approach produces a Pareto optimal set of solutions instead of a single one and has low complexity. However, the mathematical model presented in the study does not include the constraints associated with the technical limitations of a temporary storage site.

In view of the research gaps identified in prior studies (Brown et al. 2011; Zhang et al. 2019), the present study focuses on the selection of temporary disaster waste sites, with particular attention paid to the recycling facilities available in the area. As mentioned earlier while previous research has emphasized the importance of effective waste management and treatment in mitigating the adverse effects of natural disasters and promoting efficient recovery processes (Brown et al. 2011; Crowley and Flachsbart 2018; Zhang et al. 2019; Lee et al. 2022), the specific aspect of determining appropriate locations for temporary storage sites has received limited attention (Özdamar and Demir 2012; Sahin et al. 2016). Furthermore, existing studies often assume that the locations of temporary storage sites are already established (Wang et al. 2019). In contrast, this study recognizes the significance of selecting suitable temporary storage sites and considers various criteria to identify optimal locations. The analytical hierarchy process (AHP) was employed to prioritize the criteria (Yılmaz et al. 2023; Demir et al. 2023). A case study was conducted investigating the Kahramanmaraş Earthquakes that occurred on February 6, 2023, one of the most devastating earthquakes in history. To the best of the authors' knowledge, this is the first study in which the selection of temporary disaster waste sites is undertaken with consideration given to the

carbon dioxide emissions that result from the transportation of waste both to the temporary site and after the temporary site. To calculate the emissions of each pixel throughout the map due to waste transportation, a code was developed in MATLAB that considers the real transportation network of the province. This code was then integrated with ArcGIS, which also incorporates other criteria, to identify the most suitable temporary disaster sites. Finally, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) analysis was employed to prioritize the suitable regions. In the context of this study, the emissions resulting from the transportation of disaster waste in Kahramanmaraş are also presented. The fieldwork for this study took place following the Kahramanmaraş earthquake in March 2023, and the numerical studies were concluded in April 2023.

Materials and methods

Case study area

Kahramanmaraş center-based earthquake caused widespread destruction and extensive damage in a large geography. Two earthquakes with magnitudes of M7.7 and M7.6, which occurred in the Pazarcık and Elbistan districts of Kahramanmaraş on February 6, 2023, caused loss of life and destruction in 11 neighboring provinces including Adana, Adıyaman, Diyarbakır, Elazığ, Gaziantep, Hatay, Kahramanmaraş, Kilis, Malatya, Osmaniye, and Şanlıurfa. Figure 1 illustrates the epicenters of the two earthquakes and the study area of this research. Although damage in neighboring provinces was significant, this study focuses solely on the area within the boundary of Kahramanmaraş.

Estimation of the amount of waste after the earthquake

Estimation of the waste after an earthquake involves assessing the damage caused by the earthquake, identifying the types and quantities of debris, and estimating the resources needed for its removal and disposal. The categorization of disaster waste comprises inert waste and hazardous and non-hazardous waste (Villoria-Sáez et al. 2020). The recyclability of these waste streams can be affected by the degree of mixing (Brown and Milke 2016). Furthermore, inaccurate estimations of waste volumes may lead to significant financial costs (Lorca et al. 2017). Thus, precise prediction of the quantity of disaster waste is beneficial for mitigating costs. Mathematical models and technology-based analytical tools are commonly employed for quantifying disaster waste (Zhang et al. 2019). The current study utilizes a combination of mathematical models, in situ surveys, and officially published reports to calculate the quantity of disaster waste.
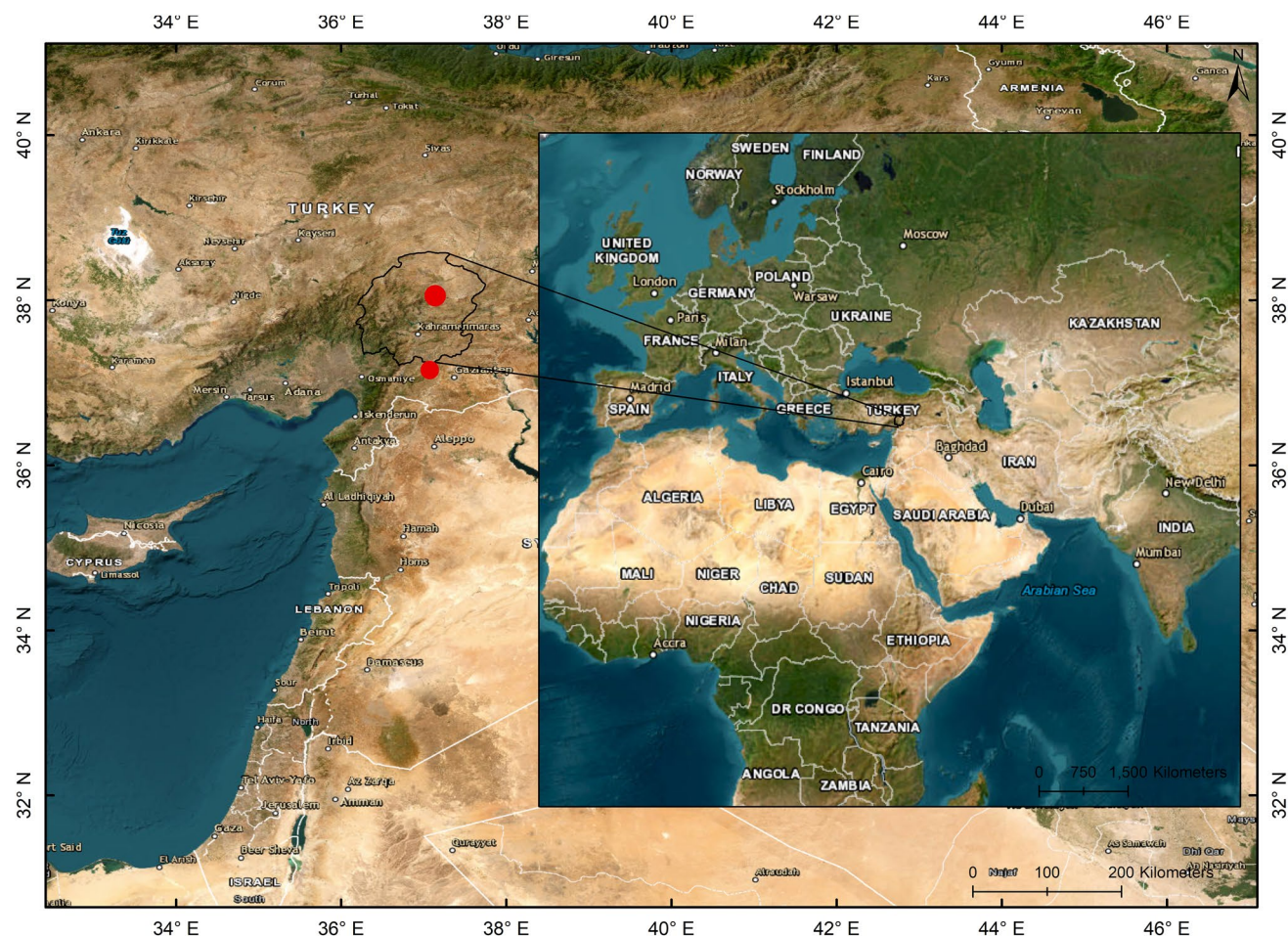
Fig. 1 The case study area

Firstly, to calculate the amount of disaster waste, the number of affected units should be determined. Different software such as Hazus (National Institute of Building Sciences 2012), or ELER (Hancilar et al. 2010) was proposed to calculate the loss estimation after a natural disaster. Since different official reports were available, and the Kahramanmaraş earthquake was new during the preparation of this paper, enabling in situ surveys, no software was preferred to be used in determining the amount of disaster waste. According to a report by the Ministry of Environment, Urbanization, and Climate Change of Türkiye (T.C. Çevre Şehircilik ve İklim Değişikliği Bakanlığı 2023), the total count of failed and severely damaged buildings in Kahramanmaraş is 3752 and 22,113, respectively. Furthermore, the number of households residing in these structures is reported to be 15,940 and 84,059, respectively. Taking the unit density to be 1.00 t/m^2 (Villoria-Sáez et al. 2020) and considering the average size of a residential unit in Türkiye to be 150 m^2, the estimated total quantity of C&D waste generated in Kahramanmaraş would be approximately 15 million tons. Taking the density of C&D waste as 1.65 t/

m^3 (Maçin and Demir 2018; Bandara et al. 2023), the volume of the waste is calculated as approximately 9.1 million m^3. Accordingly, the estimated amount of steel used in the construction of buildings affected by the disaster is approximately 1 million tons based on the 1998 Turkish Building Code proposed by (AFAD 1998). It is worth noting that the building code was revised multiple times since 1998, and most recently in 2019. However, the heavily damaged or demolished buildings were found to have been constructed before the version of the building code was published in 2007; hence, the amount of steel was calculated using the older version of the code.

In addition to C&D waste, waste from household items also contributes to the total waste and should be included in the recycling process. Therefore, the quantity of household items should also be calculated. In a previous study, a total mass of 424.16 kg per household was calculated, taking into consideration white goods, electronic waste, furniture, and animal carcasses (Hernández-Padilla and Angles 2021). In the present study, the total amount of household items was modified to be 414 kg per household for Türkiye after an

in situ investigation. Consequently, a total amount of 41,000 tons of waste from household items in Kahramanmaraş was expected.

To sum up, the total quantity of C&D waste and household items in Kahramanmaraş was estimated to be 15 million tons and 41,000 tons, respectively.

Environmental evaluation of the disaster waste

In this study, the environmental burden due to transportation for disaster waste from heavily demolished areas to temporary disaster sites and from temporary disaster sites to recycling centers was taken into consideration. Transportation was assumed to be conducted by 10-ton trucks producing carbon dioxide (CO_2), sulphur oxide (SO_x), nitrogen oxide (NO_x), and particulate matter (PM) emissions per ton-kilometer as 0.127, 6.32×10^{-6}, 1.09×10^{-5}, and 6.88×10^{-5} kg, respectively (Tabata et al. 2017). The daily working hours of these trucks were assumed to be 8 h.

In order to calculate the emissions resulting from transportation, it is necessary to have information about the transportation distance and the quantity of waste. The calculation of the quantity of disaster waste was presented in the previous section. The transportation process can be divided into two parts. The first part involves calculating the emissions resulting from transportation from heavily demolished areas to temporary disaster sites. To include emissions in the decision-making process, the emissions of each pixel throughout the case study area need to be determined. To accomplish this, an optimization procedure was developed and is explained in detail in the following section. By utilizing this procedure, the emissions resulting from the transportation of disaster waste from heavily demolished areas were calculated for each pixel. Similarly, the emissions resulting from transportation from temporary disaster sites to recycling centers can be determined using the same procedure. This time, the locations of recycling facilities are known, and the emissions of each pixel are calculated based on the distance to these facilities.

Estimation of temporary storage sites

In this part, the application of the AHP combined with GIS to identify the optimal regions for temporary waste storage sites in Kahramanmaraş is investigated.

Emission and waste transportation time calculations

The computation of emission and waste transportation relies on the actual distance traveled from the point of departure to the point of arrival. A technique was devised to determine the actual transportation distances between a designated number of departure points and every pixel within

the province, or vice versa, utilizing a map of the province's transportation network. This technique ensures the shortest possible distance between two pixels.

The proposed method involves generating one or more swarm members from a designated departure point. These members can traverse through the province's transportation network by examining the adjacent cells to identify the available roads. The roads are visually differentiated on the map using different colors, enabling the member to detect the road in its vicinity and proceed toward one of the neighboring pixels. Upon reaching a new pixel, the member deposits the milestone it carries by modifying the color of the pixel to a different hue. During the member's movement, there are some possible cases in which the motion of the member should be specified for completeness and optimality condition.

The method allows for multiple approaches to reach the destination pixel. Instead of determining the optimal route for the member, the technique involves generating new members to explore potential moves. As a result, the member proceeds toward a feasible pixel in its vicinity and dispatches new members to explore other potential pixels. This approach ensures the completeness of the map by exploring every dead end. Additionally, each member can only proceed to a pixel without a milestone or with a milestone greater than the one it carries. Consequently, if a member reaches a dead end or runs out of feasible pixels to explore, it "commits suicide" and relinquishes the roads to members with smaller milestones.

In Fig. 2, a small map is depicted, where the roads are denoted by black color. Two members enter the map with different milestones, represented by varying shades of green (Fig. 2a). A darker green shade denotes a heavier milestone, indicating that the member has traveled from a farther distance. At a junction, both members clone themselves, as shown in Fig. 2b. If two members encounter each other on a road, the one with a smaller milestone continues its journey, while the other member commits suicide (Fig. 2c). In Fig. 2d, member 5 reaches a dead end, and therefore, in the subsequent step of movement shown in Fig. 2e, it commits suicide. Eventually, only member 1 remains, as shown in Fig. 2 (f). However, in the next step, member 1 also commits suicide since the neighboring pixels have smaller milestones than the one carried by member 1. In other words, the position of member 1 in Fig. 2f represents the most remote pixel in the map.

The AHP

The AHP is a MCDM method that involves the identification and prioritization of criteria used to evaluate different alternatives (Saaty 1980). The process begins with the definition of the decision problem and the development of a hierarchical

Fig. 2 Position of swarm members at time **a** t, **b** 6t, **c** 7t, **d** 8t, **e** 9t, **f** 14t (where t indicates time)
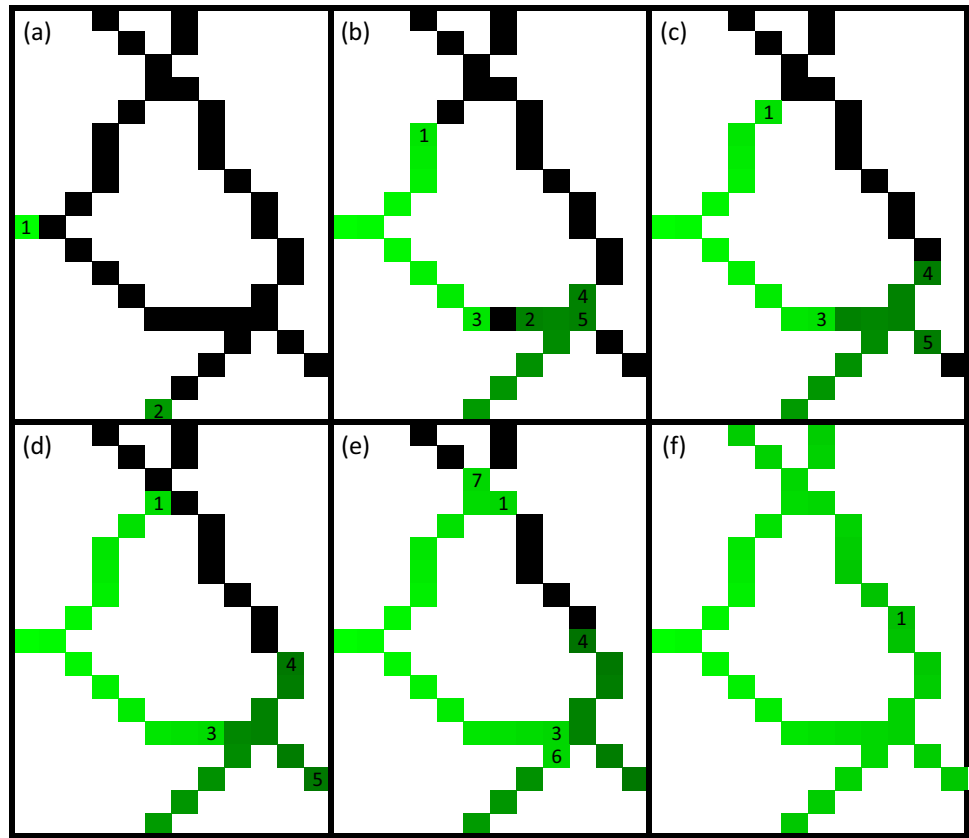
structure that shows the relationships between the criteria and sub-criteria. Next, pairwise comparisons are made between each criterion in a square matrix to determine the relative importance of each criterion compared to the others. These pairwise comparisons are then converted into numerical weights using a mathematical formula that ensures consistency. The weighted sum of each alternative is then calculated for each criterion to determine its score, and the weighted sum of each alternative's scores is calculated to determine its overall score. Finally, the alternative with the highest overall score is selected as the best option (Saaty 1980, 2008).

It should be added that AHP uses a mathematical formula called the Consistency Index (CI) to measure the consistency of the pairwise comparisons made by the decisionmaker. The CI compares the ratio of the inconsistency in the pairwise comparison matrix to the consistency of an ideal pairwise comparison matrix. If the ratio exceeds 0.10, the pairwise comparisons are considered inconsistent, and the decision-maker must revise them to ensure a more accurate representation of their true preferences (Saaty 1980).

Criteria included in the temporary disaster waste site selection

The criteria list used in the site selection process of disaster waste is shown in Table 1. The weights were calculated

using the AHP method, and both literature and expert opinions were utilized to select the sub-criteria. The remaining part of this section briefly explains all the criteria.

Land use The type of land use and cover affects the suitability of the site for temporary waste storage and disposal. For example, sites located in residential or densely populated areas may have negative impacts on the health and wellbeing of the local community. Furthermore, areas covered with crops or trees should not be used for the disposal of disaster waste due to potential environmental damage and contamination. Therefore, it is important to consider the land use and land cover characteristics of the site during the site selection process to ensure that the temporary waste storage site is safe, environmentally sustainable, and socially acceptable. In this study, land cover, presented in Fig. 3a is used as a restricted criterion instead of incorporating it into the AHP. Specifically, bare ground and rangeland were deemed suitable sites, while water bodies, trees, flooded vegetation, agricultural land, and built-up areas were considered restricted sites.

Distance to heavily demolished area The site selection process should consider the location of the disaster area and the distance from the site to minimize the transportation time and cost of disaster waste disposal. Furthermore, the

Table 1 The criteria list used in the site selection process of disaster waste

| Criterion	Weight	Sub-criteria	Indicators	Criteria	Weight	Sub-criteria	Indicators
Waste transportation time (day)	33	< 25	9	Distance to the populated area (km)	11	0–0.5	Restrained
		25–50	8			0.5–1	7
		50–100	7			01-Feb	9
		100–200	6			> 2	6
		200–400	5				
		400–600	4				
		> 600	3				
Distance to heavily demolished area	22	0–0.5	Restrained	Distance to the roads (km)	7	0–0.1	Restrained
		0.5–2	9			0.1–1	9
		02-Apr	8			01-Feb	8
		04-Jun	7			02-Apr	7
		06-Aug	5			04-Aug	6
		Aug-16	3			> 8	3
		> 16	1				
Slope (%)	5	0–5	9	CO_2 emissions due to transportation of concrete (t)	11	< 3525	9
		05-Oct	8			3525–7050	8
		> 10	Restrained			7050–14,100	7
						14,100–28,200	6
						28,200–56,400	4
						> 56,400	2
Elevation (m)	4	< 600	9	CO_2 emissions due to transportation of steel (t)	3	< 19,000	9
		600–700	8			19,000–24,500	7
		700–800	7			24,500–30,000	5
		800–1000	5			> 30,000	3
		1000–1500	3				
		> 1500	Restrained				
Distance to the rivers (km)	3	0–0.1	Restrained	CO_2 emissions due to transportation of plastic and household waste (t)	1	< 10.5	9
		0.1–1	2			10.5–21.0	8
		> 1	9			21.0–42.0	7
						42.0–84.0	6
						84.0–168.0	4
						> 168.0	2

disaster area may have limited accessibility and pose logistical challenges for waste transportation (Lee et al. 2022). The distance from the heavily demolished area is shown in Fig. 3b. In this study, a buffer zone of 500 m from the heavily demolished area was used.

Slope A steep slope can pose a risk of landslides or erosion (Sabzevari et al. 2022), which can result in the displacement of waste and increase the risk of contamination. Additionally, a site with a steep slope may pose difficulties in transporting the waste and limit the accessibility of the site.

Choosing a site with a gentle slope can improve the safety and stability of the temporary waste storage site and ease the separation works performed in the temporary disaster waste site. Fig. 3c displays the slope distribution as a percentage. Areas with slopes exceeding 10% were deemed unsuitable for temporary sites in this study.

Elevation The difference in elevation can affect the transportation and disposal of the waste, and a site with a significant difference in elevation may pose logistical challenges. As depicted in Fig. 4a, the heavily demolished area has an
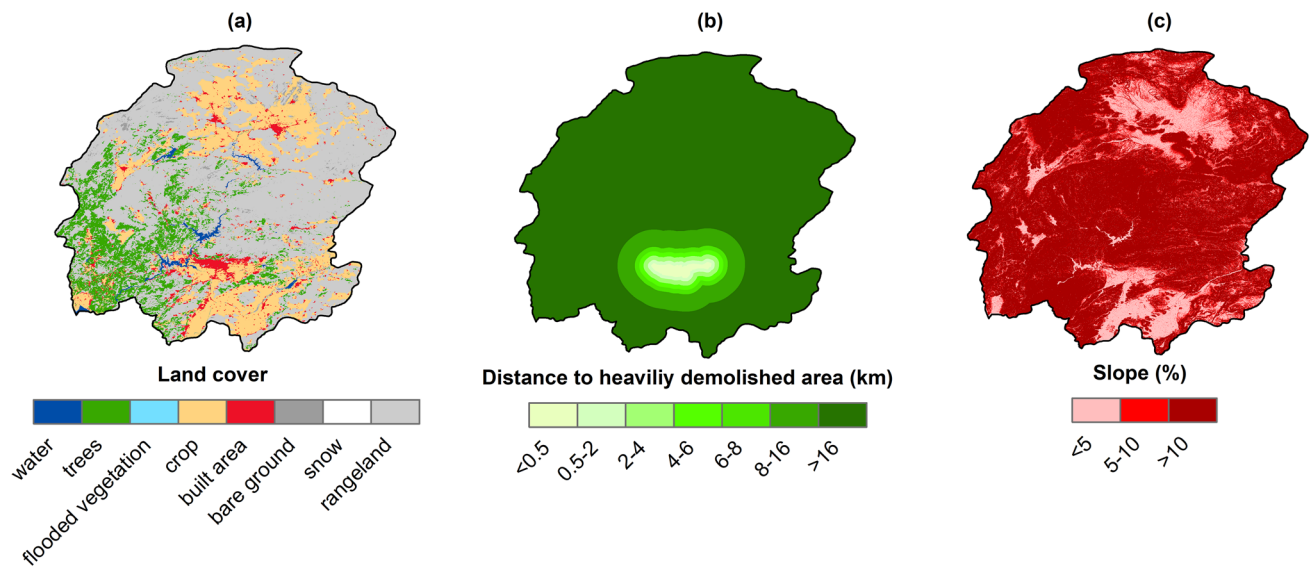
Fig. 3 Land cover, distance to heavily demolished area and slope

elevation of approximately 570 m above sea level. In light of this, buffer regions were defined as areas with elevations greater than 1500 m in this study.

Distance to the populated area A temporary waste storage site located too close to populated areas can pose risks to public health and safety (Cheng and Thompson 2016; Nickdoost et al. 2022). The waste may emit hazardous gases or attract pests that can negatively impact the health and well-being of nearby residents. Additionally, the presence of waste storage sites near residential areas can create aesthetic and social concerns, affecting the quality of life of local communities. Accordingly, a buffer zone of 500 m was established around the populated area. The established buffer zone, even though the increase in population in Kahramanmaraş was less than 1% between 2020–2022

(TUİK 2023), can still be advantageous when considering urbanization factors. Given the relatively short duration of the activities at the temporary disaster sites and the slow population growth in Kahramanmaraş, the chosen buffer zone can be deemed appropriate.

Furthermore, it was determined that the optimal distance between the temporary site and the populated area should range from 1 to 2 km. The classification of distance to the populated area is given in Fig. 4b.

Distance to the roads A site that is easily accessible by road can facilitate the transportation of waste to the storage site, as well as the removal of waste from the site for disposal. If the temporary waste storage site is too far from the road, the cost of transportation may increase, and it may take longer to remove the waste, which can lead to health and environ-
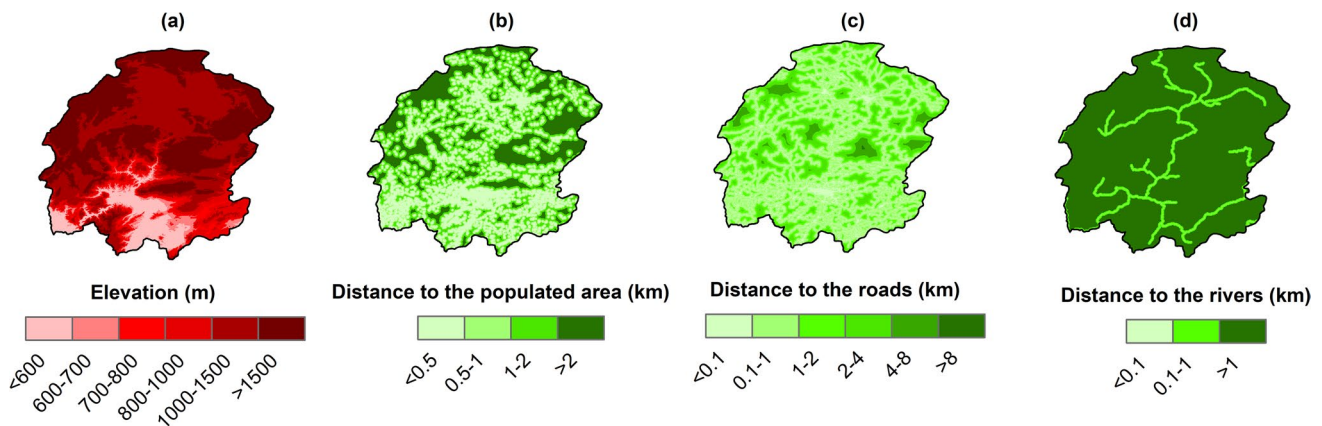
**Fig. 4** Elevation, distance to the populated area, distance to the roads and distance to the rivers

mental risks. However, to facilitate relief and evacuation efforts in the aftermath of disasters, a buffer distance should be established between temporary disaster sites and main roads aiming to promote the efficient functioning of various activities during post-disaster operations (Cheng and Thompson 2016). The buffer distance from the roads was preferred as 100 m. Distance to the roads through the case study area can be seen in Fig. 4c.

Distance to the rivers Fig. 4d presents distance to the rivers of the possible temporary waste sites. Rivers are natural water bodies that can potentially become contaminated due to the accumulation of waste and debris resulting from the disaster. If the selected temporary site is situated in close proximity to a river, there is a risk of pollution of the water body, which can lead to further environmental and health-related issues. Therefore, a safe distance from the river should be considered when choosing a suitable temporary site for disaster waste management. In this study, a buffer zone of 100 m was established around the selected site. Furthermore, areas located within a range of 1 km from rivers were deemed less suitable sites for the establishment of temporary disaster waste sites.

Emissions due to the transportation from temporary disaster site to the recycling facilities If the temporary waste storage site is located too far from recycling facilities, the cost and time associated with transportation of waste to the recycling facilities may increase, making recycling less feasible. Furthermore, if the distance between the temporary disaster waste site and recycling facilities is long, the emissions associated with transporting the waste to the recycling facilities would increase significantly. The recycling facili-

ties considered in this study were classified into three types: concrete, plastic, and steel. Plastic recycling centers were assumed to have, or be able to construct, facilities to recycle household waste. Emissions resulting from the transportation of waste between temporary disaster sites and recycling facilities calculated using the real transport network of the province as explained in section 2.2 are shown in Fig. 5. Notably, emissions associated with the transport of waste to incineration facilities or landfill areas were not taken into account in the site selection process for temporary disaster sites. The rationale for this decision is that new incineration facilities must be constructed, and these facilities can be located in proximity to the temporary disaster sites. Moreover, the identification of suitable landfill areas requires a thorough examination of the area, which is outside the scope of this study.

Waste transportation time The accumulation of waste in the disaster area poses a significant risk to public health and the environment. Therefore, minimizing the transportation time is necessary to ensure timely removal of waste. Moreover, shorter transportation times reduce the emissions resulting from transportation activities, contributing to the overall sustainability of the disaster waste management process. In this study, waste transportation time was calculated using 10-ton trucks with an average speed of 40 km/h. A total of 1000 trucks were assumed to be used for waste transportation, and the daily working hours were considered to be 8 h (Tabata et al. 2017). The method explained previously was used to calculate the total transportation time considering real road data. The resulting waste transportation time through the entire region within the boundary of Kahramanmaraş is presented in Fig. 6.
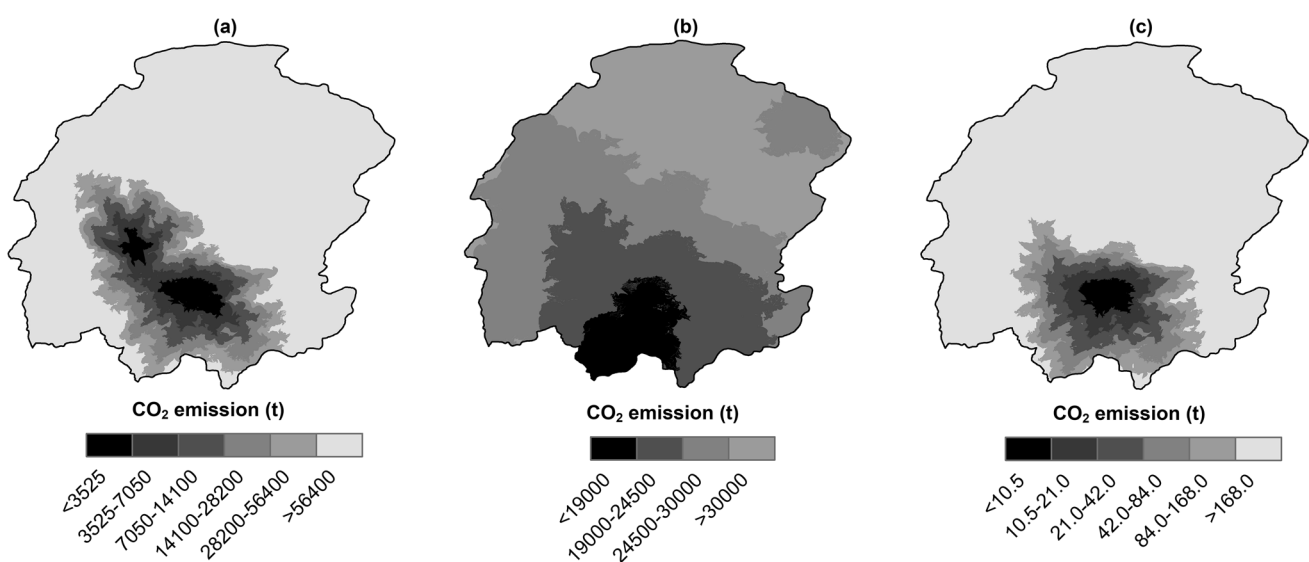
Fig. 5 CO$_2$ emissions due to transportation of the waste for **a** concrete, **b** steel and **c** plastic and household items

The area of temporary disaster waste site

To estimate the area of temporary disaster site, the following equation was performed (Tabata et al. 2017).

$$A = \frac{V}{Hr} \tag{1}$$

where A is the land area of the temporary storage site (in m^2), V is the volume of the waste (in m^3), H is the height at which the waste can be stacked (in m), and r is the ratio of waste storage to the total storage area, which is typically taken as 60% (Tabata et al. 2017).

The present study found that approximately 9.1 million m^3 of waste was generated. To calculate the volume, the total mass (about 15.04 million t), including both C&D waste and household items, was divided by the waste density of 1.65 t/m^3 (Maçin and Demir 2018; Bandara et al. 2023). With a stacking limit of 3 m for combustibles (Tabata et al. 2017), it was determined that approximately 5.06 km^2 of area would be needed to store the waste.

According to FEMA's report (FEMA 2007), historic disasters have shown that approximately 0.52 km^2 of temporary disaster waste area is required for every 1 million m^3 of waste. However, it should be noted that 60% of this area is used for buffers, roads, burn pits, and other purposes. Considering the total waste amount to be 9.1 million m^3, the area required to process this waste was found to be 4.74 km^2. The difference between this value and our previous calculation

Waste transportation time (day)

Fig. 6 Disaster waste transportation time from heavily demolished area

is attributed to the stacking height. However, given the large area involved, the difference is not significant. Therefore, to be on the safe side a temporary site of 5.06 km^2 was preferred for this study.

The TOPSIS method

After finding the suitable regions for the temporary disaster waste sites, the TOPSIS method, used to rank alternatives based on their proximity to the ideal solution, was employed to prioritize these regions among each other (Hwang and Yoon 1981). The process of conducting a TOPSIS analysis involves several steps. Firstly, the criteria or attributes used to evaluate the alternatives are defined. A decision matrix is created where each row represents an alternative and each column represents a criterion. The matrix is then normalized to eliminate any scale differences among the criteria. Next, weights are assigned to the criteria to reflect their relative importance. The normalized decision matrix is multiplied by the weights to obtain the weighted normalized decision matrix.

The ideal solution and the negative-ideal solution are determined by identifying the highest and lowest values for each criterion, respectively. Euclidean distances are calculated between each alternative and both the ideal and negative-ideal solutions.

To determine the proximity to the ideal solution, the distance to the negative-ideal solution is divided by the sum of the distances to both the ideal and negative-ideal solutions. This proximity measure quantifies how close each alternative is to the ideal solution. Finally, the alternatives are ranked based on their proximity measures. The alternative with the highest proximity measure is considered the most favorable, while the one with the lowest proximity measure is considered the least favorable (Olson 2004).

Results and discussion

Temporary storage sites

In this study, the city center of Kahramanmaraş was identified as having a high number of demolished buildings, making it crucial to remove the disaster waste from the area. Fig. 7 presents the possible temporary sites for disaster waste disposal, categorized as unsuitable, moderately suitable, suitable, and very suitable regions, and Table 2 presents the share of these regions. Although the majority of sites are unsuitable (as shown in Table 2), there are still suitable areas along the border of Kahramanmaraş. The suitability of sites is mainly affected by waste transportation time from the city center to the temporary site. As a result, the suitability of sites increases when approaching the city center. One very
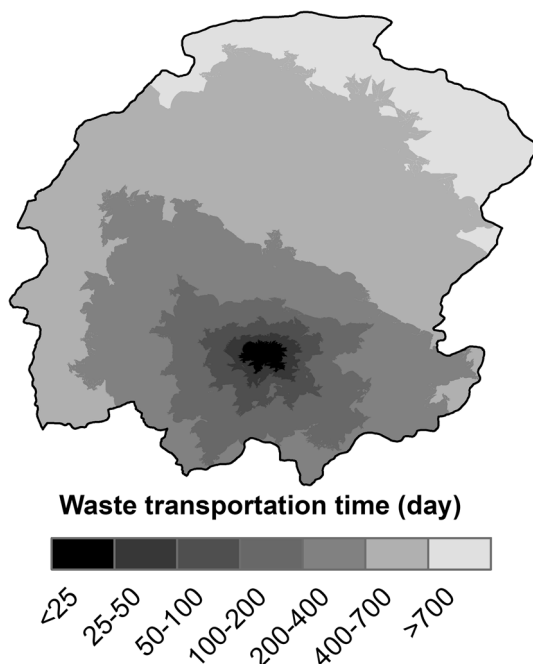
suitable site is identified southeast of the city center, with more suitable regions located to the east and southeast near the boundary of Kahramanmaraş and Gaziantep. Moderately suitable sites are also available to the north of Elbistan, but these are relatively distant from the city center.

To determine the preferred sites, the suitable regions are detailed in Fig. 8 and Table 3. Figure 8 displays the proposed regions in polygon form, while Table 3 outlines the area, owner, and waste transportation time from the demolished area to the temporary disaster site when 1000 trucks are in operation. The most suitable region is labeled as (1), and it is located between Yeniyurt and Denizli villages. This region has a higher elevation than the surrounding villages and belongs to the municipality. Furthermore, due to its closer proximity to the heavily demolished area, the transportation time of the disaster waste is the least. Additionally, the close proximity implies lower transportation costs, and no significant additional expenses are incurred for the lease of

Table 2 The share of suitable regions

Suitability	Area (km^2)	Percentage (%)
Unsuitable	13,949	96.0
Moderately suitable	375	2.6
Suitable	156	1.1
Very suitable	44	0.3

the area since it is owned by the municipality, making it the best option. This is also evident from the TOPSIS analysis conducted for the regions as shown in Fig. 9.

The second region is divided into two parts, with half of it located in the very suitable region and the other half in the suitable region. The transportation time of waste in this region is 1.5 times that of the first region.
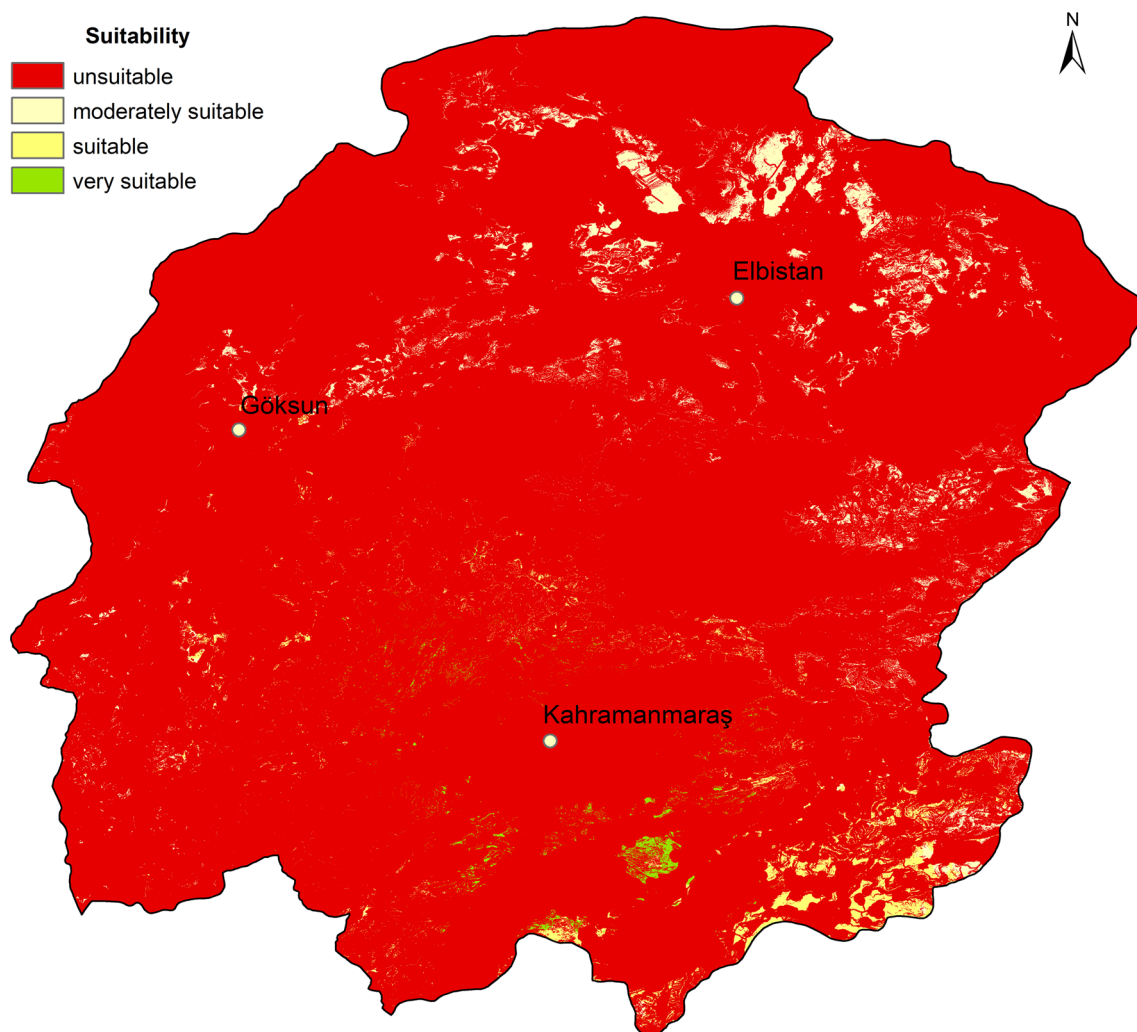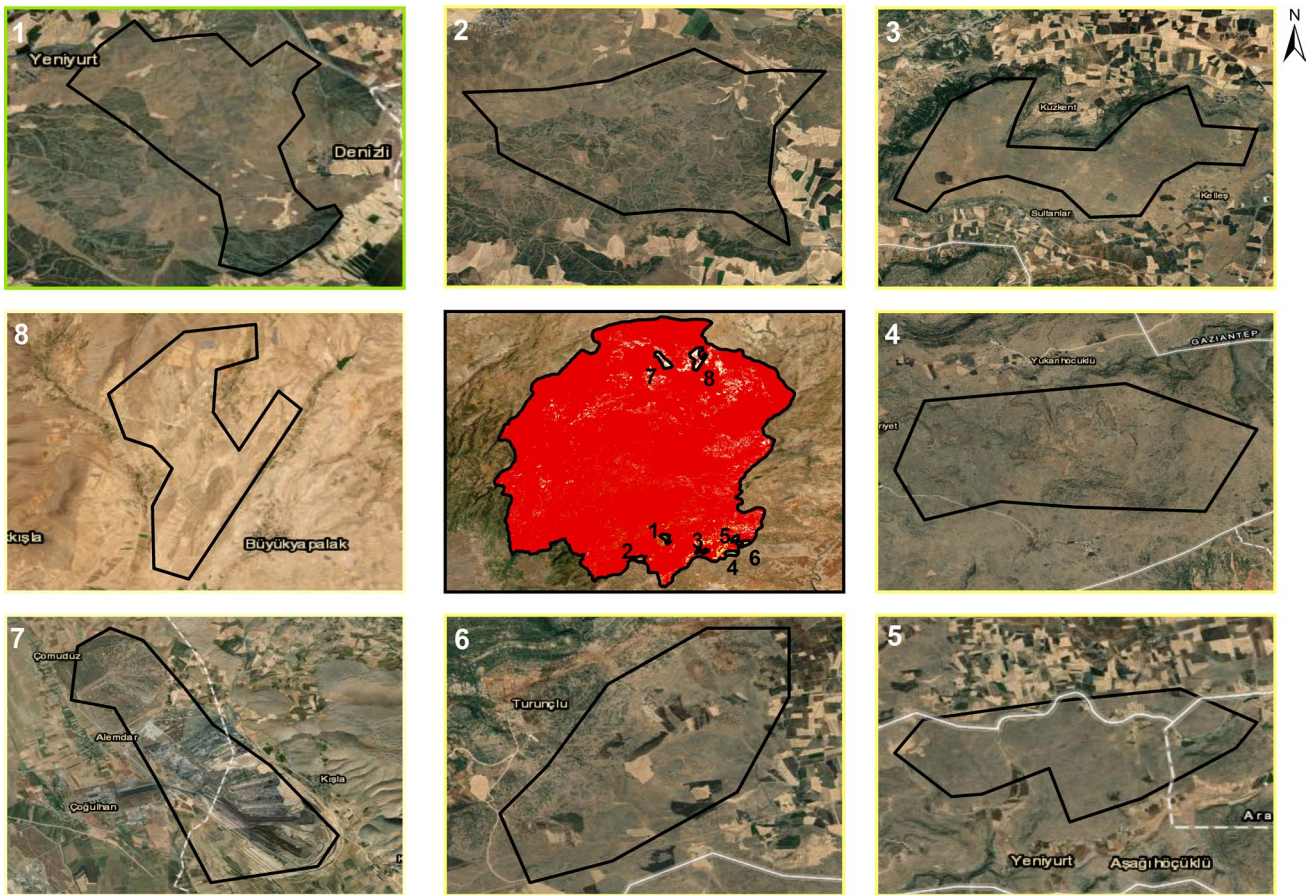

Fig. 7 Suitability map

Fig. 8 Suitable regions

Table 3 Transportation time of disaster waste from the heavily demolished area to the temporary disaster site and corresponding areas (40 km/h average speed of trucks)

Region	Area (km^2)	Owner	Transportation time of waste (day/1000 truck)
1	14.1	Municipality	98
2	13.2	Municipality	150
3	8.6	Private	206
4	13.3	Private	305
5	14.7	Municipality	328
6	7.7	Municipality	290
7	32	Half private half municipality	703
8	48.7	Municipality	750

Fig. 9 Suitability ranking of the temporary waste disaster sites

necessary area of 5.06 km^2. Additionally, the resultant area is close to a rectangle in shape, making it easier to work on.

Regions 7 and 8 are located on the north side of the demolished area, and they have a considerable distance from it. Therefore, the transportation time of the waste in these regions is about 7.0 to 7.5 times that of region 1, making them the least suitable for temporary site selection.

Regions three and four are located in the suitable region, but they are privately owned and are less attractive due to leasing costs (CBS 2023).

The sixth region is situated on the border of Kahramanmaraş and Gaziantep. Although it has the smallest area among all the alternatives, it exceeds the minimum
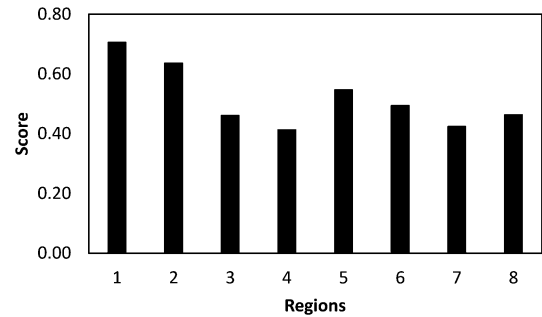
In summary, the most suitable region for the temporary site selection is region (1), located between Yeniyurt and Denizli villages. The other regions, while still suitable to varying degrees, have certain drawbacks such as longer transportation times, private ownership, or higher environmental burdens.

To prioritize the regions identified through the suitability analysis, the TOPSIS method was employed. The application of the method utilized the suitability rankings depicted in Fig. 7, along with the owner and area of each region. In the analysis, a score of 1 was assigned if a region belonged to the municipality, while a score of 0 was assigned if it was privately owned. For region 7, which is half-owned by the municipality, a score of 0.5 was assigned. The weights assigned to suitability, owner, and area in the analysis were 0.6, 0.3, and 0.1, respectively. Based on this analysis, Fig. 9 was generated, indicating the rankings. The figure highlights that Region 1 emerges as the most favorable area for the temporary disaster site. Although the distance between Region 8, and the heavily demolished area is greater than that of Regions 3 and 4, Region 8's higher suitability, attributed to its ownership by the municipality, slightly outweighs the distance factor.

Environmental impacts due to transportation

The results of the environmental burden due to the transportation of disaster waste in the heavily demolished area are presented in Fig. 10. The calculations considered the emissions from both the heavily demolished area to the temporary disaster site and from the temporary disaster site to recycling centers.

The lowest emissions were observed in region 1, where the CO_2, SO_x, NO_x, and PM emissions were approximately 88,000, 4.4, 7.6, and 47.7 tones, respectively. However, the emissions tended to increase with the total distance between the demolished area and the temporary disaster site, as well as between the temporary disaster site and recycling centers. For region 8, all the emissions were nearly 7 times those of region 1, indicating that this region is less suitable for the temporary site selection due to its higher environmental burden. Consequently, region 1 has the lowest environmental burden due to the transportation of disaster waste, while region 8 has the highest environmental burden.

Conclusion

The timely removal of waste from populated areas after a natural disaster is crucial, but it is important to consider additional technical and environmental factors for clean and sustainable disaster waste management. This study investigated the first steps in the management of disaster waste, the calculation of the waste amount and the selection of the temporary disaster sites, following the recent Kahramanmaraş Earthquakes on February 6th, 2023. The study estimated the total amount of C&D waste and household waste in the Kahramanmaraş province to be 15 million tons and 41,000 tons, respectively. A temporary site with an area of at least 5.06 km^2 was required to manage this waste. To select possible regions for temporary disaster sites, a code was developed to calculate CO_2 emissions and transportation time for waste transportation, taking into account the real road network. The novelty of the method is that both the emissions and transportation time were included in the temporary site

Fig. 10 Environmental impacts due to the transportation of the disaster waste. **a** CO_2, **b** SO_x, **c** NO_x and **d** PM emissions
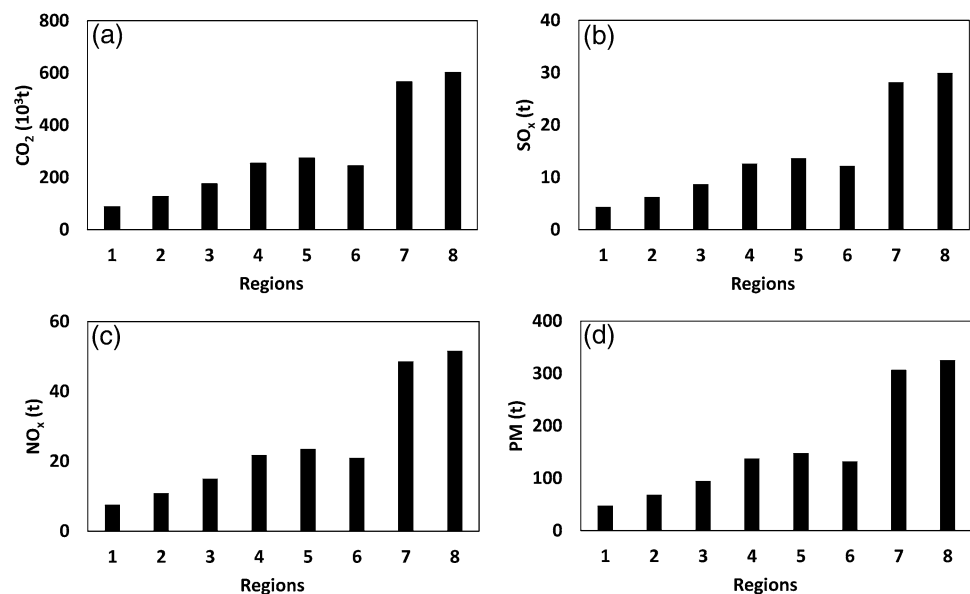
selection process in which the sites producing the minimum emissions and minimizing the transportation time are favorable. In addition, environmental and technical criteria such as distance to heavily demolished areas, slope, elevation difference, distance to rivers, distance to populated areas, and distance to roads were also considered in site selection as criteria in the AHP analysis. The results showed that 96% of the area is unsuitable for temporary disaster sites, emphasizing the importance of pre-planning for waste management. The study proposed eight suitable regions for temporary sites, with the southeast region of the city center found to be the most suitable. The TOPSIS method was also used to rank these 8 regions based on suitability rankings, owner information, and area. The most appropriate region found in this study belonged to the municipality, and the transportation time of the waste from the disaster area was estimated to be 98 days with 1000 trucks in operation. Additionally, the study calculated the CO_2, SO_x, NO_x, and PM emissions in this region, which amounted to approximately 88,000, 4.4, 7.6, and 47.7 tons, respectively.

It is common to hear reports of incorrect waste disposal after natural disasters, particularly in developing countries. Thus, there is a need for a pre-planned waste management strategy following such events. This study focuses on the clean and sustainable selection of temporary disaster sites for waste management. Further investigations on the amount of waste that can be recycled, reused, or incinerated, as well as the clean and sustainable recycling process for separated waste in the temporary site, could be the subject of a follow-up study. The methodology developed in this study can be applied to identify temporary disaster sites for waste resulting from any natural disaster.

Author contributions Both Ali Ersin Dinçer and Abdullah Demir contributed to all aspects of the study.

Declarations

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