Drinking water distribution problem for assembly areas after earthquake: A case study in Sakarya, Turkey

Deprem sonrası toplanma alanlarına içilebilir su dağıtım problemi: Sakarya, Türkiye için bir uygulama

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ABSTRACT

Objective: The objective of the study is to minimize the latest arrival time to assembly areas in a determined region. The novel mathematical model is proposed for this problem handled. In the region, taking into account the four different scenarios that may occur as a result of the earthquake, the most suitable plan for drinking water distribution is created under each scenario.

Methods: The problem addressed in the study is analyzed as a vehicle routing problem. Optimization techniques are generally used in solving the vehicle routing problem. Optimization can be expressed as "searching the best" regarding the purpose of the decision maker under certain conditions (constraints). Thus, the phrase "finding the most suitable route" can be used for the vehicle routing problem. In this study, using the mathematical modeling approach, which is one of the optimization techniques, the best route that provides minimizing the latest arrival time to the assembly areas is proposed for decision makers.

Results: Within the scope of the study, different damage levels that may occur after the earthquake are examined in the different scenarios for Sakarya, Turkey.

ÖZET

Amaç: Çalışmanın amacı, belirlenen bir bölgede toplanma alanlarına en son varış süresini en aza indirmektir. Ele alınan bu problem için yeni matematiksel model önerilmiştir. Bölgede, deprem sonucu oluşabilecek dört farklı senaryo dikkate alınarak her bir senaryo altında içme suyu dağıtımı için en uygun plan oluşturulmuştur.

Yöntem: Çalışmada, araç rotalama problemi ele alınmıştır. Araç rotalama probleminin çözümünde genellikle optimizasyon teknikleri kullanılmaktadır. Optimizasyon, belirli koşullar (kısıtlar) altında karar vericinin amacına yönelik, "en iyiyi aramak" olarak ifade edilmektedir. Böylece, araç rotalama problemi için "en uygun rotayı bulma" ifadesi kullanılabilmektedir. Bu çalışmada, optimizasyon tekniklerinden biri olan matematiksel modelleme yaklaşımı kullanılarak, karar vericiler için toplanma alanlarına en son varış süresini en aza indirmeyi sağlayan en iyi rota önerilmiştir.

Bulgular: Çalışma kapsamında, deprem sonrası oluşabilecek farklı hasar düzeyleri, Sakarya için farklı senaryolarda incelenmiştir. Deprem sonrası meydana

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The latest arrival times to assembly areas increase as the damage that may occur after the earthquake increases. The arrival times to the assembly areas are also different according to scenarios, because the optimum routes change for these scenarios.

Conclusion: In this study, the drinking water distribution problem to assembly area is handled. The proposed mathematical model is run for different scenarios and the latest arrival times for each assembly area are determined. The optimum routes obtained are compared for these scenarios. It has aimed that, the proposed method will be used by organizations' aims to improve their disaster strategies.

Key Words: Assembly area, water distribution, earthquake, vehicle routing problem

gelebilecek hasar arttıkça, toplanma alanlarına en son varış süreleri de artmaktadır. Toplanma alanlarına varış süreleri de senaryolara göre farklı olmakta, çünkü bu senaryolar için optimum rotalar da değişmektedir.

Sonuç: Bu çalışmada, önerilen matematiksel model farklı senaryolar için çalıştırılmış ve her toplanma alanı için en son varış zamanları belirlenmiştir. Elde edilen optimum rotalar bu senaryolar için karşılaştırılmıştır. Önerilen yöntemin, kuruluşların afet stratejilerini geliştirmeleri amacıyla kullanılması hedeflenmiştir.

Anahtar Kelimeler: Toplanma alanı, su dağıtımı, deprem, araç rotalama problemi

INTRODUCTION

Natural or unnatural events that disrupt the social functions of societies and cause economic and environmental losses are defined as disasters. These disasters, which are caused by natural factors such as earthquakes, floods, hurricanes, landslides or terrorist attacks, chemical leaks are the result of the tremendous ecological collapse in the relations between people and their environment. It is estimated that more than 500 disasters occur every year in the world, about 75 thousand people die, and more than 200 million people are affected by these disasters (1).

In Turkey, natural disasters such as floods, landslides, fires, and earthquakes, which lead to loss of life and property in the country, are frequently encountered. Earthquake, one of these disasters, causes significant damage to the country. The probability of an earthquake is also very high in the country where two-thirds of its territory is located in the first and second seismic zones (2).

In order to reduce the impact of the earthquake that causes great losses, societies need to prepare their pre/post-earthquake emergency management plans systematically. The emergency management plan has four main stages: mitigation, preparedness, response, and recovery (3). While mitigation and preparation are pre-disaster prevention stages; intervention and recovery are the stages related to post-disaster emergency responses, which are also the subject of this study.

The responses to be carried out post-disaster are directed to two main purposes to minimize the suffering and death of people. These purposes are: (i) to evacuate people from areas at risk and to place them at safer assembly areas determined (ii) to deliver emergency aid materials such as drinking

water, food, medical supplies to those who are gathered at these points (4-6).

The assembly areas are safe places where people can reach quickly during and after the earthquake considering the risk that the earthquake may occur again (7). Until the victims settle in temporary shelters or safe spots, they often remain in the assembly areas for a few days or less, which can also be considered pre-evacuation areas. (8). It is essential to provide people with the most basic needs in these areas as quickly as possible.

Disasters often result in enormous demands that quickly deplete resources (9). Therefore, it is necessary to plan the flow of scarce resources effectively. The effective distribution planning of drinking water, which is among scarce resources, to post-disaster victims has always been a major concern. Delivering water late or not to the assembly areas can have fatal consequences.

Effective and efficient distribution of drinking water to people affected by earthquakes is critical for emergency response. Therefore, emergency management attracts the increasing attention of practitioners as well as academicians. Altay and Green (10) examined disaster operation management and studies on this subject. In order to better explain disaster operations, they elaborate on the studies on two disciplines as operations research and management science. Anaya-Arenas et al. (11) systematically analyzed the literature on the subject and classify the articles such as location, transportation, combined location and transportation, and aid distribution. Abounacer et al. (12) addressed the site selection problem and transportation in post-disaster response in their articles. Regarding the addressed problem, they aim to determine the number and location of the necessary humanitarian aid distribution centers in the disaster area. In terms of transportation, they deal with distributing aid to disaster victims from Humanitarian Aid Distribution Centers to demand points. In their study, they focus on three objectives:

operating the selected distribution centers, minimizing the transportation time of the aid to the demand points from the distribution centers, and minimizing the unmet demand at the demand points. Dündar et al. (13) created a Disaster Water Management Plan to establish a water resource and shipping structure that can be used in a disaster situation for the region they have determined in their studies. This specified region is Turkey's province of Zonguldak. In their work, they show the different types of distribution for various water sources and mention the management of drinking and usable water in case of disaster. Smadi et al. (14) focused on the amount of drinking water to be supplied to the Zaatari refugee camp for Syrian refugees and the location of water resources. They also consider the risks and distribution costs of water, such as dirty and insufficient water. In the short term, they propose a coverage model for the distribution plan of drinking water. They suggest that the most convenient transportation source is tankers. Tatham et al. (15) aimed to provide decision-makers with the appropriate routing plan for the supply of drinking water after a disaster. They propose a multi-objective decision-making model for the problem, in which different transportation sources are taken into account and solved the model using metaheuristic.

In this study, the distribution of drinking water to the assembly areas after the earthquake is discussed. A novel mathematical model is proposed for this problem. Considering the different scenarios that may occur as a result of the earthquake, the most suitable water distribution plan is created under each scenario.

MATERIAL and METHOD

The Proposed Methodology

When the disaster management is focused on, the effective and efficient delivery of assistance to people affected by disaster is critical to emergency response. After the disaster; The distribution plan of emergency supplies such as food, medical supplies, disposable,

and drinking water needs to be well managed. In this context, the drinking water distribution problem from depots to assembly areas after the earthquake is discussed within the scope of the study.

Distribution problems attract researchers day by day. In the literature, such problems are generally examined under the heading Vehicle Routing Problem (VRP). The VRP is a combinatorial problem defined as product distribution or collection between nodes on a graph. The first study on this subject is done by Dantzig and Ramser (16). After this study, the problem is handled in different structures and different models and algorithms are developed for the problem. Optimization techniques are generally used in solving the VRP, which can be associated with almost any subject such as health, energy, education, and disaster management.

Optimization can be expressed as "searching the best" regarding the purpose of the decision maker under certain conditions (constraints). Thus, the phrase "finding the most suitable route" can be used for the VRP. In this study, using the mathematical modeling approach, which is one of the optimization techniques, the best route that provides the fastest distribution to the assembly areas is proposed for decision makers.

The Proposed Mathematical Model

It is aimed to minimize the time of delivery of drinking water to the assembly areas in the handled problem. The problem is defined on a non-directional graph, expressed as G = (N, A), where N is the set of nodes on the graph, and A is the set of arcs between the nodes. Each assembly area and each warehouse are expressed as a node, and the arcs between the nodes are defined in the set A = {(i, j): ∀i, j ∈N, i ≠ j}. In the current situation, it is assumed that all the arcs can be used. It is assumed that the transition time (tij) between the nodes of the vehicles cannot be negative and tij = tji. Each assembly area has a drinking water demand Di and a service time Si that vehicle spent at the assembly area to supply drinking

water. It is assumed that the total water requirement is no greater than both the total capacity of the tanks (WCi) and the total capacity of the vehicles (Ck). In addition, it is assumed that each vehicle leaving the warehouse must return to the warehouse by completing the operations. The mathematical model prepared within the scope of the study is given below.

Sets

"I"   Set of all nodes

T   Set of assembly areas (T⊂I)

W   Set of warehouses (W⊂I)

K   Set of vehicles

Parameters

t_{ij}:   Transition times between nodes

D_i: Drinking water demand of the assembly area

S_i: Service time to assembly area

C_k: Vehicle capacity

WC_i: Warehouse capacity

M: Big number

Decision Variables

A_i: Arrival time to assembly area

A_{max}: Arrival time to the last assembly area

L_i: Leaving time from assembly area

Xijk :   {(1,if arc (i,j) used by vehicle (k)

{0,otherwise

Formulation

$$\min A_{max} \tag{Eq. 1}$$

Subject to:

$$t_{ij} \leq A_j - L_i + M(1 - X_{ijk}); \ \forall i, j \in I \text{ and } \forall k \in K \tag{Eq. 2}$$

$$t_{ij} \geq A_j - L_i + M(X_{ijk} - 1); \ \forall i, j \in I \text{ and } \forall k \in K \tag{Eq. 3}$$

$$\sum\sum X_{ijk} = 1; \ \forall j \in T \tag{Eq. 4}$$

$$\sum\sum X_{ijk} = 1; \ \forall i \in T \tag{Eq. 5}$$

$$\sum X_{ijk} - \sum X_{jik} = 0; \ \forall j \in I \text{ and } \forall k \in K \tag{Eq. 6}$$

$$\sum\sum X_{ijk} \leq C_k; \ \forall k \in K \tag{Eq. 7}$$

$$\sum\sum X_{ijk} \leq C_i; \ \forall i \in W \tag{Eq. 8}$$

$$A_{max} \geq A_i; \ \forall i \in T \tag{Eq. 9}$$

$$A_i, A_{max}, L_i \geq 0; \ \forall i \in T \tag{Eq. 10}$$

$$X_{ijk} \in \{0,1\}; \ \forall i, j \in I \text{ and } \forall k \in K \tag{Eq. 11}$$

The objective function (Eq. 1) minimizes the arrival time to the last assembly area. Constraints (Eq. 2) and (Eq. 3) ensure that the arrival time of vehicles to nodes and leaving times of vehicles from nodes are related to the traveling times between nodes. Constraints (Eq. 4) means that each assembly area must be visited by only one vehicle, and Constraints (Eq. 5) means only one vehicle must leave each assembly area. Constraint (Eq. 6) is the balance constraint for all nodes in the network, including assembly areas and warehouses. In Constraints (Eq. 7), each vehicle's capacity can not exceed the sum of the water demand for assembly areas assigned to the vehicle. In the Constraints (Eq. 8), the sum of water demand for the assembly areas assigned to each warehouse must be less than the capacity of that warehouse. The Constraints (Eq. 9) is added to the model to determine the arrival time to the last assembly area. Constraints (Eq. 10) and (Eq. 11) are non-negativity constraints and binary constraints for the decision variables, respectively.

The Numerical Application

In the study, Sakarya/Serdivan district was chosen for the drinking water distribution problem to the assembly areas after the earthquake. The fact that the region is located in the first-degree risky earthquake zone and the settlement spreads over a relatively large area played an important role in the selection of the district. In the district where there are 11 different nodes as the assembly area, it is assumed that drinking water can be supplied to the assembly areas from Sakarya Metropolitan Fire Department and Adapazarı Fire Department. In the handled problem, fire departments are considered as warehouses. The assembly areas (TA) and fire departments (I) in the district covered in the study are shown in Figure 1. In the figure, the locations of the assembly areas are expressed in yellow, while the locations of the fire department are shown in red.

The amount of drinking water that could be sent to the assembly areas after the earthquake is 10 thousand liters for the water tank (I-1) in Adapazarı Fire Department and 15 thousand liters for the water tank (I-2) under the Sakarya Metropolitan Fire Department. Information about the assembly areas determined by Sakarya Provincial Disaster and Emergency Directorate for Serdivan district was given in Table 1. Assuming that the average amount of
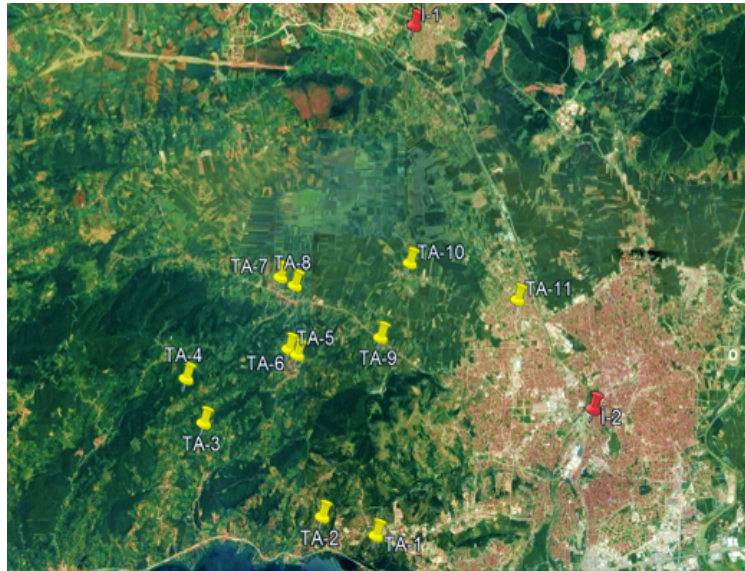

Figure 1. Assembly areas and fire stations

water a person consumes daily is 3 liters, the water demand for each collection area was determined by multiplying the population of the region and 3 liters. The service period that the vehicle would provide to the victims in the assembly areas was determined by using Equation 12.

$$S_i = 15 + \frac{D_i}{500} \qquad (Eq. 12)$$

When the proposed mathematical model was run for assembly areas in the Serdivan district, the optimum routes were shown in Figure 2 with different colors. Vehicle arrival times for each assembly area were given in Table 2.

As can be seen from Table 2, the first assembly area (Esentepe), and the eleventh assembly area (Köprübaşı) have the highest arrival times as 146 minutes.

Table 1. Demands and service periods of assembly areas

	Assembly Area	D_i	S_i(min)		Assembly Area	D_i	S_i(min)
TA-1	Esentepe	3506	19	TA-7	Kazımpaşa-1	530	7
TA-2	Aşağıdereköy	1157	10	TA-8	Kazımpaşa-2	531	7
TA-3	Yukarıdereköy	501	7	TA-9	Selahiye	1151	10
TA-4	Dağyoncalı	445	7	TA-10	Aralık	1600	11
TA-5	Çubuklu-1	404	7	TA-11	Köprübaşı	10903	49
TA-6	Çubuklu-2	404	7				
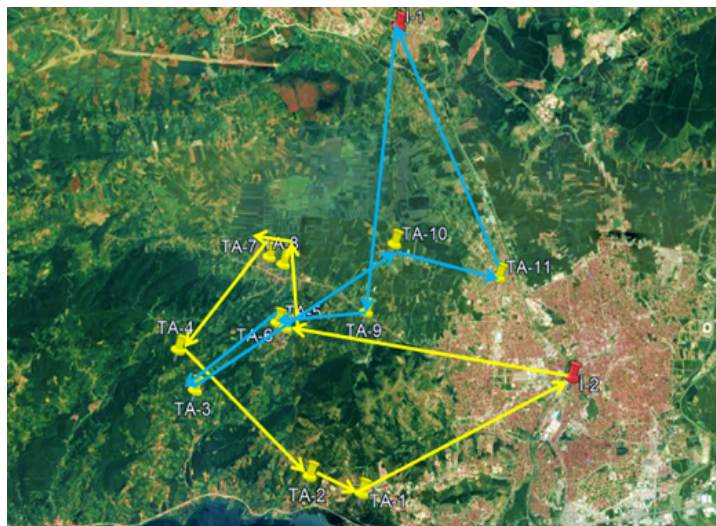
Figure 2. Optimum water distribution routes .

Table 2. Arrival times to the assembly areas

Assembly area	Arrival times (min)	Assembly area (min)	Arrival times (min)
1	146	7	40
2	113	8	60
3	72	9	15
4	86	10	113
5	17	11	146
6	41		

Scenario Analysis and Findings

Different scenarios may occur after the disaster. Negative factors such as damage (demolition) of transportation roads, damage to water tanks can make it more difficult to provide water to victims in the assembly areas. Different scenarios were handled within the scope of the study, considering such negative factors. These scenarios are explained in the sub-titles, and the optimum distribution routes are determined according to the scenarios by the proposed mathematical model.

Scenario 1: Damaged 18 Arcs

18 of 77 arcs between nodes (assembly areas and warehouses) are assumed to be damaged after the earthquake and these arcs cannot be used for transportation in the first scenario. These damaged arcs are given in Table 3.

59 arcs are still usable for transportation on the network after 18 arcs are damaged. Optimum routes for drinking water distribution routes are determined using these 59 usable arcs by the proposed mathematical model. These routes can be seen in Figure 3 in different colors. Arrival times to each assembly area are given in Table 4.

The assembly area 3 (Yukarıdereköy) has the highest arrival times among all assembly areas. The vehicle can reach this assembly area in 180 minutes. So, the latest arrival time to the assembly area is increased 34 minutes because of damaged arcs according to Scenario 1.

Table 3. Damaged arcs for Scenario 1

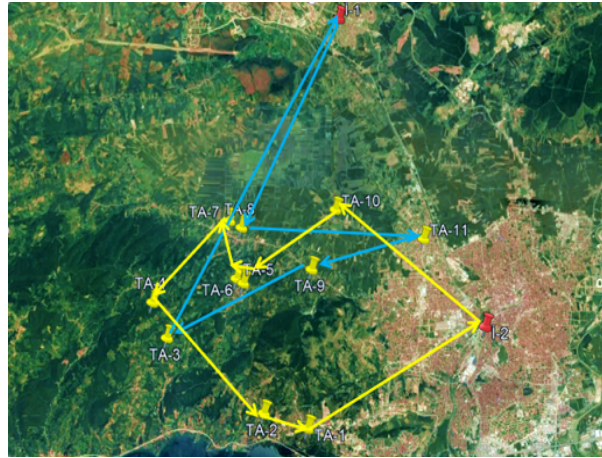| İ2-TA1	İ2-TA7	İ1-TA2	İ1-TA10	TA3-TA11	TA5-TA10
İ2-TA2	İ2-TA9	İ1-TA5	İ1-TA11	TA4-TA8	TA7-TA9
İ2-TA4	İ2-TA11	İ1-TA7	TA2-TA6	TA4-TA11	TA10-TA11

Figure 3. Optimum water distribution routes for Scenario 1

Table 4. Arrival times to the assembly areas for Scenario 1

Assembly area	Arrival times (min)	Assembly area	Arrival times (min)
1	176	7	89
2	143	8	21
3	180	9	141
4	116	10	14
5	66	11	50
6	48		

Scenario 2: Damaged 37 Arcs

As the second scenario, it is assumed that 37 of the 77 arcs are damaged after the earthquake. These damaged arcs are randomly selected and given in Table 5.

Optimum drinking water distribution routes are determined using 40 available arcs by the proposed mathematical model. These routes can be seen in Figure 4 in different colors. Arrival times for each assembly area are given in Table 6.

Table 5. Damaged arcs for Scenario 2

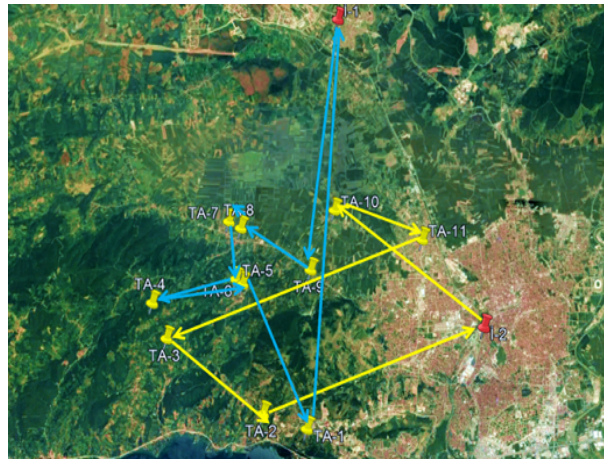| İ2-TA9	İ1-TA5	TA1-TA3	TA1-TA6	TA1-TA9	TA2-TA4	TA8-TA10
TA2-TA7	TA3-TA6	TA3-TA8	TA3-TA10	TA4-TA7	TA4-TA9	
TA4-TA11	TA6-TA8	TA6-TA10	TA7-TA9	TA7-TA11	TA9-TA10	
İ2-TA2	İ1-TA4	İ2-TA4	İ2-TA5	İ2-TA6	İ2-TA13	
İ1-TA3	İ1-TA7	İ1-TA13	TA1-TA2	TA1-TA7	TA1-TA10	
TA2-TA5	TA2-TA8	TA2-TA10	TA5-TA6	TA5-TA8	TA6-TA9	

Figure 4. Optimum water distribution routes for Scenario 2

Table 6. Arrival times to the assembly areas for Scenario 2

Assembly area	Arrival times (min)	Assembly area	Arrival times (min)
1	191	7	68
2	189	8	48
3	152	9	15
4	130	10	14
5	159	11	47
6	96		

The assembly area 1 (Essentepe) has the highest arrival times among all assembly areas as can be seen in Table 6. The vehicle can reach this assembly area in 191 minutes according to the results. So, the latest arrival time to the assembly area is increased by 45 minutes from the current situation (there is no damaged arc), increased by 11 minutes from Scenario 1.

Scenario 3: Damaged 47 arcs

In the third scenario, it is assumed that 47 of the 77 arcs are damaged after the earthquake and only 30 arcs are usable for the distribution of drinking water. These damaged arcs are randomly selected and given in Table 7.

Table 7. Damaged arcs for Scenario 3

İ2-TA9	İ1-TA5	TA1-TA3	TA1-TA6	TA1-TA9	TA2-TA4
TA2-TA7	TA3-TA6	TA3-TA8	TA3-TA10	TA4-TA7	TA4-TA9
TA4-TA11	TA6-TA8	TA6-TA10	TA7-TA9	TA7-TA11	TA9-TA10
İ2-TA2	İ1-TA4	İ2-TA4	İ2-TA5	İ2-TA6	İ2-TA13
İ1-TA3	İ1-TA7	İ1-TA13	TA1-TA2	TA1-TA7	TA1-TA10
TA2-TA5	TA2-TA8	TA2-TA10	TA5-TA6	TA5-TA8	TA6-TA9
TA8-TA10	İ2-TA1	TA4-TA8	İ1-TA10	TA9-TA11	TA3-TA9
TA1-TA5	TA5-TA10	TA8-TA11	TA3-T79	İ1-TA10	

Optimum routes for drinking water distribution are determined using 30 available arcs by the proposed mathematical model. These routes can be seen in Figure 5 in different colors. Arrival times to each assembly area are given in Table 8.

The assembly area 1 (Esentepe) has the highest arrival times among all assembly areas as can be seen in Table 6. This result is the same as Scenario 2. The vehicle can reach this assembly area in 193 minutes. So, the latest arrival time to the assembly area is increased by 47 minutes from the current situation (there is no damaged arc), increased by 2 minutes from Scenario 2.
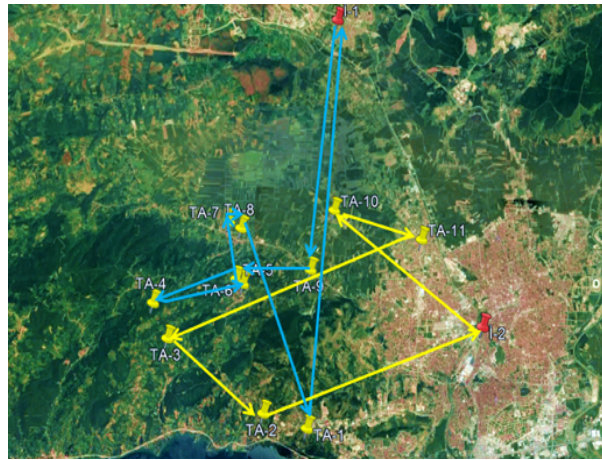

Figure 5. Optimum water distribution routes for Scenario 3

Table 8. Arrival times to the assembly areas for Scenario 3

Assembly area	Arrival times (min)	Assembly area	Arrival times (min)
1	193	7	132
2	189	8	152
3	152	9	15
4	70	10	14
5	42	11	47
6	105		

Scenario 4: Damaged water tank in Adapazarı Fire Department

In the last scenario, it is assumed that only the water tank in Sakarya Metropolitan Fire Department is still usable after the earthquake. In this case, it is necessary to distribute drinking water from the only water tank in Sakarya Metropolitan Fire Department with a single vehicle. The optimum route for drinking water distribution to assembly areas is determined and shown in Figure 7. The arrival time of the single vehicle to assembly areas is given in Table 9.
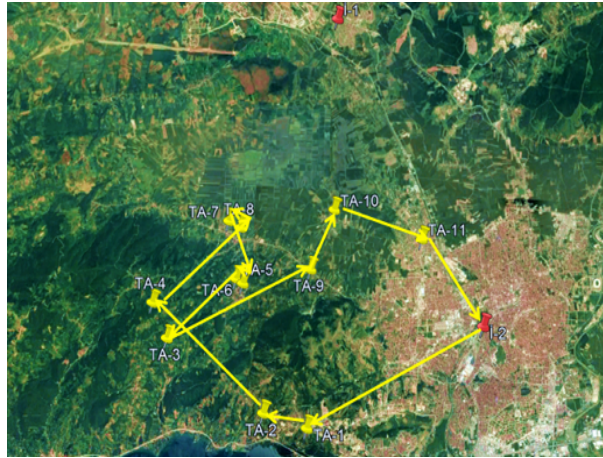
Figure 6. Optimum water distribution routes for Scenario 4

Table 9. Arrival times to the assembly areas for Scenario 4

Assembly area	Arrival times (min)	Assembly area	Arrival times (min)
1	15	7	139
2	62	8	119
3	212	9	247
4	93	10	274
5	163	11	307
6	181		

As can be seen from Table 9, when the drinking water distribution is made with only one vehicle from a single warehouse, the eleventh assembly area (Köprübaşı) has the highest arrival time as 307 minutes. Due to the use of only one warehouse, the time to reach all assembly areas has increased by 161 minutes compared to the current situation (there is no damaged water tank and arc).

RESULTS

Within the scope of the study, four different scenarios are discussed to better analyze the proposed mathematical model. Different damage levels that

may occur after the earthquake are examined in the discussed scenarios. The latest arrival times of the vehicles that distribute drinking water to all assembly areas are compared in Figure 7.

As can be seen in Figure 7, the latest arrival times increase as the damage that may occur after the earthquake increases. When focusing on scenario 4, it is seen that the latest arrival times are more than five hours. As a solution to this situation, water tanks should be made more resistant to possible earthquakes. The arrival times to each assembly area under all the discussed scenarios in the study are also given in Figure 8.
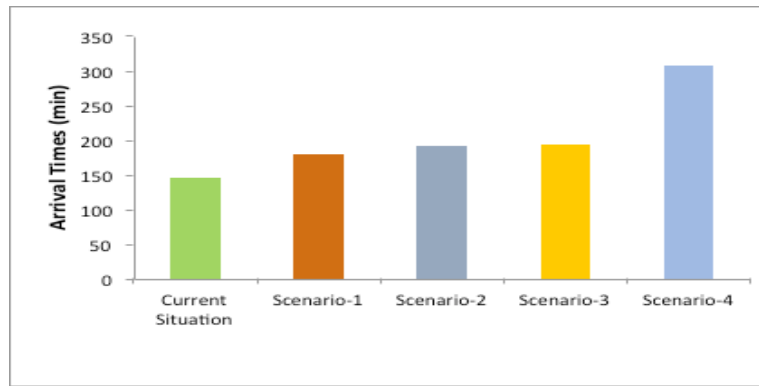
Figure 7. The latest arrival times to assembly areas under different scenarios
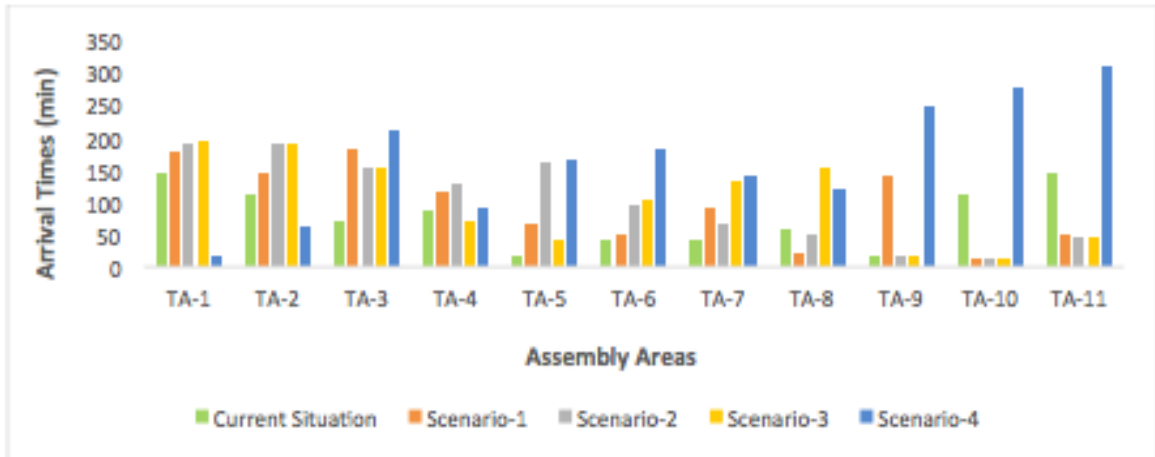

Figure 8. Arrival times to each assembly area under different scenarios

The arrival times to the assembly areas are also different according to scenarios because the optimum routes change for these scenarios. For example, when focusing on the eleventh assembly area (Köprübaşı) the arrival times change between 47 minutes and 307 minutes. This assembly area can arrive in 307 minutes for Scenario 4. Therefore, the water tanks should be more resistant to possible earthquakes to arrive at assembly areas faster.

In the study, the drinking water distribution problem area that needs to be made to the meeting areas where disaster victims gather as emergency shelters are handled. After the earthquake, the victims gather at the assembly areas as emergency shelters before moving to camps. The consumption of water is increased even more in case of a disaster. Considering this situation, a novel mathematical model is proposed to distribute drinking water as quickly as possible. The proposed mathematical

model is run for Sakarya/Serdivan district that first degree earthquake zone and results are gained. Firstly, the water distribution route is determined for the assembly areas after the earthquake for the current situation in the region. Then, four different scenarios are discussed to better analyze the proposed mathematical model. Different damage levels that may occur after the earthquake are examined in the discussed scenarios. Evaluations are made by comparing the scenario results.

The contribution of the study to the literature can be defined as follows: (i) the drinking water distribution problem to assembly area is handled; (ii) the optimum routes to reach the assembly areas are determined; (iii) arrival times for each assembly area are determined; (iv) real population data is used when determining drinking water requirement; (v) the proposed mathematical model is run for different scenarios and the optimum routes obtained are compared; (vi) it is aimed that, the proposed method will be used by organizations' aims to improve their disaster strategies.

As a future direction, bigger and/or combined regions can be selected as the application area for the problem. Heuristic or metaheuristic algorithms can be developed to handle complexity. The problem can be modeled as stochastic or robust structures.

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