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Examining the Road Networks and Locations of Firefighting Teams by Using GIS Techniques

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For effective response to forest fires, the period of time necessary for the firefighting team to reach the fire site should not exceed the critical response time, where the fire is more likely to be taken under control. For this reason, the optimum route that allows the team to reach the fire site by a fire truck within the shortest time possible should be determined. Computer-aided methods such as the road network analysis are widely used in the solution of such transportation problems that require the shortest path analysis. In this study, the locations of the existing road networks and firefighting team were examined using GIS techniques in order to determine the optimum route that will provide the promptest access to the fire site. The study was carried out in the Adana Forest Enterprise Directorate, where first degree fire-sensitive forests are located. There are three firefighting teams located in the boundaries of the study area. The sites in the study area where previously occurred forest fires (15), which burned 1 ha or more forest areas, were evaluated as potential fire sites. The analysis results showed that 64,12% of the forest areas in the study area was reached by the firefighting teams within 20 minutes, which is the critical response time for first degree fire sensitive forests. It was found that the teams could reach 12 potential fire sites within the critical response time. This result revealed the necessity to establish new firefighting teams in the study area. In addition, it is thought that improving the road network density in the study area by building new roads or increasing the truck travel speed by improving the conditions of existing roads will help to solve the problem.

Key words: Forest fire; Optimum route; Shortest path; Network analysis; Fire access road; Fire trucks; Travel speed; Critical response time; Adana; Turkey.

Introduction. The number of forest fires, as one of the main source of forest destructions, have increased in many regions of the world, as well as in the Mediterranean countries (Littell, Peterson, Riley, Liu,

& Luce, 2016; Bathrellos, Skilodimou, Chousianitis, Youssef, & Pradhan, 2017). In Turkey, 5.5 million hectares of forests along the coastline starting from Kahramanmaraş to the Marmara region in the east

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of the Mediterranean region are fire sensitive at the first degree (Akay, Wing, Zengin, & Köse, 2017). In order to combat forest fires effectively, fire must be suppressed as soon as possible. For this reason, it is of great importance to identify detect and locate forest fires as soon as they start and to report them to the firefighting teams without delay (Akay, Karaş, & Kahraman, 2018).

In order to combat forest fires effectively, the time to reach the fire site, especially in the first degree fire sensitive forest areas, should not exceed the critical response time in which the fire is more likely to be brought under control. For this reason, the firefighting teams should be placed in a suitable location from which most of forest area can be reached in critical response time (Sakar, 2010). After the fire alarm is received, the optimum route that allows the firefighting team to reach the fire site in the shortest time should be determined as soon as possible.

Considering some restrictive factors, computer-aided methods (e.g. network analysis, linear programming, dynamic programming, heuristic methods) are used in the solution of such problems, which searches for the optimum route with the shortest transportation time among alternatives (Sun, Lang, & Wang, 2015; Liu & Chen, 2016; Seyedhosseini, Makui, Shahanaghi, & Torkestani, 2016). Network analysis method is widely used in the solution of transportation problems aimed at determining the optimum route (Hashemi, Karimi, & Tavarna, 2015; Chiang, Chen, & Ho, 2016). Developments in computer technology and Geographic Information Systems (GIS) allow the use of modules based on the network analysis method of GIS software to solve transportation problems (Ford, Barr, Dawson, & James, 2015; Gheshlaghi, 2019; Yıldırım & Bediroğlu, 2019; Das, Ojha, Kramsapi, Baruah, & Dutta, 2019).

The fire sensitivity rate of a zone is determined based on the number of fires in that zone, the ratio of the burning area to the forest area of the forest enterprise and the fire constant (Erdoğan, 2019). In order to combat forest fires effectively, the concept of fire sensitivity has been developed to rank the sensitivity of the forest enterprise and to show the status of a forest enterprise with a known sensitivity rate compared to other forest enterprises. The most important factor in determining the degree of sensitivity is the archive information about the forest fires that occur (Küçük & Ünal, 2005).

The degree of fire sensitivity, which represents enterprises with a certain degree of sensitivity, actually constitutes the fire sensitivity class. The degree of fire sensitivity varies according to the size of burning area and the number of fires per unit area. As the number of annual fires in the burning area and unit area decreases, the sensitivity decreases, and as it increases, the sensitivity to the fire increases (Akay et al., 2017). Fire constant values are used to determine the fire sensitivity levels of the forest enterprises. Figure 1 shows the fire sensitivity map of the forest enterprise directorates in Turkey.

In order to effectively fight forest fires, the firefighting team must reach the fire site within the critical response time. Table 1 indicates the critical response times according to the degree of fire sensitivity (GDF, 2008). For effective fight against forest fires, the arrival time of the firefighting team should not exceed these time limitations. In this study, the locations of the existing road networks and the firefighting team in a sample forest enterprise were evaluated using GIS techniques in order to determine the optimum route that will provide the fastest access to the fire site.

Fig. 1. The fire sensitivity degrees of Forest Enterprise Directorates in Turkey

Table 1

Critical response times (minutes) to fire sensitivity ratings

	Fire Sensitivity Degrees				
	I	II	III	IV	V
Response Time	20	30	40	50	50

Material and Methods. 1. Study Area. The study was carried out within the boundaries of the Adana Forestry Regional Directorate (FRD), Adana Forestry Enterprise Directorate (FED), Sarıçam Enterprise Chief (FEC) (Fig. 2). The tree species that dominate the area are Brutian pine, Stone pine and other coniferous species. The area of the Sarıçam FEC is approximately 70,000 hectares, and approximately 9,000 hectares are covered with forests. There are three firefighting teams within the boundaries of the study area. The sites in the study area where previously occurred forest fires (15), which burned 1 ha or more forest areas, were evaluated as fire-prone sites.

2. GIS Database. Within the scope of the study, GIS database was produced to apply GIS techniques in ArcGIS 10.4 program. To generate this database, road network map, forest stand map and location information about potential forest fires and firefighting teams were used (Fig. 3). Information about the fires that occurred at the working area boundaries and where the burned area is 1 ha and above is given in Tab. 2. A data layer showing forest areas was produced using the stand map

to evaluate the transportation of the firefighting teams to the forest areas in the study area.

Fig. 2. The map of the study area

Fig. 3. Road network, firefighting teams and fire locations in the study area

3. Network Analysis. Network analysis method is widely used in the solution of transportation problems requiring the optimum route (Chiang et al., 2016). In the network analysis method, links (arc) and nodes where the links intersect form a network system. In order to determine the optimum route that provides access to the fire site in the shortest time possible, the average transportation time of fire truck to be spent on each road section was determined. Transportation time

was calculated based on the length of the road and the average speed of the fire truck. The average vehicle speed varies depending on the type of road (asphalt, gravel, forest road) and condition (good, average, poor). The average vehicle speed assigned for each road section according to the type and condition of the road is given in Tab. 3 (Bilici, 2009).

Table 2
Information on forest fires (≥ 1 ha) within the study area (2009-2019)

Fire No.	Date	Cause	Burned Area (ha)	YIL
1	24.07.2009	Stubble	1.0	2009
2	11.08.2009	Stubble	1.0	
3	21.08.2009	Stubble	2.0	
4	19.10.2009	Stubble	10.5	
5	22.09.2011	Other Fire Use	1.8	2011
6	1.10.2011	Other Fire Use	1.3	
7	12.11.2011	Shepherd's Fire	1.0	
8	10.06.2013	Stubble	1.0	2013
9	11.07.2013	Stubble	2.0	
10	11.07.2013	Piece of broken glass	20	
11	11.07.2013	Unknown	1.6	
12	29.05.2014	Machine burning accident	1.5	2014
13	15.08.2015	People	2.5	2015
14	17.10.2016	Unknown	2.9	2016
15	5.10.2017	Unknown	1.03	2017

Table 3
Average vehicle speeds for road type and road condition (km/hr)

Road Types	Road Condition		
	Good	Average	Poor
Asphalt	60	50	40
Gravel	50	40	30
Forest Road	30	25	20

Finally, the transportation time for each section was calculated using Equation 1. Thus, attribute fields with length (km), road type, road condition, vehicle speed (km/hr) and travel time (minutes) are generated in Attributes Table of the road data layer.

$$t_i = \frac{l_i}{v_i} 60, \quad (1)$$

t_i – travel time (min)
 l_i – section length (km)
 v_i – vehicle speed (km/hr)

Network Analyst Application. The advances in GIS and computer technology enable the use of network analysis method within GIS software for solving transportation problems (Yıldırım & Bediroğlu, 2019). In this study, Network Analysis (Network Analyst) plugin available in ArcGIS 10.4 program was used to determine the optimum route that will provide the fastest access to a possible fire site from firefighting headquarter.

In order to apply the network analysis method with the Network Analysis plugin, a Personal Geodatabase was first produced in the ArcCatalog module of ArcGIS 10.4 program. Later, Network Data (Network Dataset) was developed by making use of the road network data layer containing the values of the links (travel time) that constitute the road network in the study area. Finally, link (ND_Edges) and node (ND_Junctions) files were produced using Network Dataset.

After completing the Network Data set, the «New Service Area» and «New Closest Facility» methods under the Network Analysis plugin were applied. Firstly, how much of the forest areas on the site can be reached during the critical response period was evaluated by the New Service Area method. In the New Service Area method, which is similar to the Buffer Analysis (Buffer) method, a service point determined on the network system is accepted as the start and the regions within a total link value (access time) determined by the user are determined on the network

system. In this study, with the help of the «New Service Area» method, it is aimed to determine the forest areas that can be reached within 20 minutes, with critical response times for the first degree fire sensitive forests, by centering the locations where the first firefighting teams are located. Using the «New Nearest Facility» method, it was aimed to determine the optimum route between the potential fire areas in the study area and the first firefighting teams. In the study, the first firefighting teams that could reach each fire site as soon as possible were determined. In addition, optimum routes that will allow all the first firefighting teams in the study area to reach each fire site have been determined.

Results and Discussion. 1. GIS Database Results.

According to the results obtained, the total length of the road network in the study area was calculated as 592.00 km. A large part of these roads is forest road (57,57%), followed by gravel road (22,47%) and asphalt paved road (19,96%) (Tab. 4). Considering the condition of road networks in the study area, 65,28% of roads are classified as good, 26,74% as average and 7,98% as poor (Fig. 4). All asphalt paved roads are considered to be in good condition in terms of traffic flow. When the gravel roads are taken into consideration, it is determined that a large part of the roads are in good condition (93%), 5% are in the average and the remaining roads are in poor condition (2%). As to the forest roads, 45% of them are average, 42% – good, and 13% – poor.

Table 4

Length information about roads in the study area

Road Type	Total Length (km)	Length by Road Conditions (km)		
		Good	Average	Poor
Asphalt	118.15	118.15	-	-
Gravel	133.03	124.28	6.10	2.65
Forest Road	340.82	144.02	152.19	44.61
Total	592.00	386.45	158.29	47.26

Fig. 4. Road network map of the study area

According to the land use type map developed for the study area, a total of 10 different land use classes have been identified (Fig. 5). It was found that the type of land use with the largest area was agriculture (71,90%) followed by forest areas (16,39%). Burned forest areas, forest soil and forest depots are considered under forest areas, total forest areas were calculated as 17,32% of the total area. The spatial distribution of land use types can be seen in Tab. 5.

Table 5

The areal distribution of land use classes

Land use classes	Alan (%)
1	2
Forest	16.39
Forest Soil	0.47
Water	4.13

Continuation of Table 5

1	2
Settlements	4.31
Forest Depots	0.01
Agricultural	71.90
Burned Areas	0.45
Power Line	0.01
Community Health	2.22
Cemetery	0.11

Fig. 5. Land use type map of the study area

2. *Network Analysis Results.* Network analysis application was carried out by using two basic data layers

produced in Network Database. These are data layers; the link data layer (Network_ND_Edges) representing the road sections on the road network and the node data layer (Network_ND_Junction) representing the points where these links intersect (Fig. 6). Using the «New Service Area» method, the locations of the firefighting teams were centered and the forest areas that can be reached in the study area within the critical response times were determined. The study analyzes fire response time for 3 firefighting teams to reach 15 fire sites. Table 6 shows that the firefighting teams were not able to reach all 15 fire sites within the optimal period of time (no more than 20 minutes).

Fig. 6. The link and node data layer in the Network Data Set

Table 6

Fire response time (min) of firefighting teams to reach each fire site

Team Name	Fires														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Y_Ekip_1	23	13	25	10	17	21	10	16	26	23	17	22	8	19	6
Y_Ekip_2	49	38	23	35	28	47	19	32	52	20	43	12	27	44	27
Y_Ekip_3	5	34	31	31	32	42	31	22	47	38	38	39	29	13	27

Since forests are first degree fire sensitive in the study area, areas which firefighting teams can reach on the road network within 0-20 minutes have been identified (Fig. 7). Later, forest areas that could be reached within 0-20 minutes were found. The results showed that 64,11% of forest areas in the study area were reached by fire crews within 20 minutes. The firefighting teams that reach potential fire site in the shortest time were identified by using «New Closest Facility» method. Figure 8 shows the optimum routes that provide access to each fire site in the shortest time. The optimum routes that allow all the firefighting teams in the study area to reach each fire site were determined (Tab. 7). It was found that the teams responded 12 fires within the critical response time (20 minutes) while 3 fires (3, 6 and 9) could not be reached on time (See Tab. 7). The results showed that there is a close relationship between the distance to fire sites, road types, and the transportation time.

Fig. 7. Accessible and inaccessible areas within the critical response time (20 minutes)

Fig. 8. The shortest routes providing access to each fire site in the shortest time

Table 7

Firefighting teams first reaching the fire sites and their response times (min)

Fire No	Team Name	Response Time (min) (dakika)
1	Y_Ekip_3	5.37
2	Y_Ekip_1	12.58
3	Y_Ekip_2	22.67
4	Y_Ekip_1	9.74
5	Y_Ekip_1	16.57
6	Y_Ekip_1	21.03
7	Y_Ekip_1	10.43
8	Y_Ekip_1	16.37
9	Y_Ekip_1	26.42
10	Y_Ekip_2	19.90
11	Y_Ekip_3	17.38
12	Y_Ekip_2	12.46
13	Y_Ekip_1	8.18
14	Y_Ekip_3	13.38
15	Y_Ekip_1	6.42

Conclusions. In this study, the firefighting teams were evaluated by using GIS techniques in order to determine the optimum route that provides the fastest access to the fire sites. Sarıçam FEC was selected within the borders of Adana FED. The forest areas in the Directorate are classified as first degree fire sensitive forests. Within the scope of the study, three firefighting teams available in the area and 15 fire incidences happened between 2009-2019 that affected 1 ha or more forests were taken into consideration. It

was determined that the existing firefighting teams in the study area could not reach three of the potential fire sites within the critical response time of 20 minutes. In the study, forest areas that the firefighting teams could not reach within the critical response time were also identified. According to the results, it was found that 35,99% of the forest areas could not be reached in 20 minutes. These results reveal the necessity of locating new firefighting teams in addition to the existing firefighting ones. Moreover, it is thought that improving the road network in the study area by building new roads or increasing the travel speed by improving the conditions of existing roads will also contribute to the solution of the problem.

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Вивчення дорожніх мереж і місцезнаходження пожежних команд за допомогою методів ГІС технологій

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Для ефективного реагування на лісові пожежі тривалість доступу пожежної бригади до місця пожежі не повинна перевищувати критичного часу реагування, впродовж якого загоряння з більшою ймовірністю може буде взято під контроль. З цієї причини доцільно визначити оптимальний маршрут, який дасть змогу команді дістатися до місця пожежі на пожежній машині в найкоротші терміни. Комп'ютерні методи, такі як мережевий аналіз, широко використовують під час вирішення таких транспортних завдань, які вимагають аналізу найкоротшого шляху. У цьому дослідженні розташування існуючих дорожніх мереж і пожежної команди було оцінено з використанням методів ГІС технологій, з метою визначення оптимального маршруту, який забезпечить найшвидший доступ до місця пожежі.

Дослідження здійснювали в Управлінні лісового господарства Адани, де розташовані ліси переважно першої категорії, найбільш уразливі до пожеж. У межах досліджуваної території розташовані три пожежні команди. Ділянки в досліджуваній зоні, де раніше траплялись лісові пожежі (15) і в яких вигоріло 1 га або більше лісової площі, оцінювали як потенційні осередки виникнення лісових пожеж. Результати показали, що 64,12% лісових площ на досліджуваній території були охоплені пожежними командами протягом 20 хвилин, що є критичним часом реагування для лісів першої категорії, які є найбільш чутливими до пожеж. Було встановлено, що впродовж критичного часу реагування команди могли досягти 12 місць можливих загорянь. Цей результат показав необхідність створення нових пожежних команд у досліджуваній зоні. Крім того, можна підсумувати, що збільшення щільності дорожньої мережі в досліджуваній області за рахунок будівництва нових доріг або збільшення швидкості руху на відрізку шляху за рахунок поліпшення стандартів існуючих доріг допоможе вирішити проблему.

Ключові слова: лісова пожежа; оптимальний маршрут; найкоротший шлях; мережевий аналіз; пожежний доступ; пожежні машини; швидкість по-дорожі; критичний час відгуку; Адана; Туреччина.

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Исследование дорожных сетей и местонахождения пожарных команд с помощью методов ГИС технологий

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Для эффективного реагирования на лесные пожары продолжительность доступа пожарной бригады к месту пожара не должна превышать критическое время реагирования, на протяжении которого возгорание с большей вероятностью может быть взято под контроль. По этой причине следует определить оптимальный маршрут, который позволит команде добраться до места пожара на пожарной машине в кратчайшие сроки. Компьютерные методы, такие как сетевой анализ, широко используются при решении похожих транспортных задач, которые требуют анализа кратчайшего пути. В этом исследовании расположение существующих дорожных сетей и пожарной команды было оценено с использованием методов ГИС технологий, с целью определения

оптимального маршрута, который обеспечит самый быстрый доступ к месту пожара.

Исследование проводилось в Управлении лесного хозяйства Аданы, где расположены леса первой категории, наиболее чувствительные к пожарам. В границах исследуемой территории расположены три пожарные команды. Участки в исследуемой зоне, где раньше случались лесные пожары (15) и в которых выгорело 1 га или более лесной площади, были оценены как потенциальные очаги лесных пожаров. Результаты показали, что 64,12% лесных площадей на исследуемой территории были охвачены пожарными командами в течение 20 минут, что является критическим временем реагирования для лесов первой категории, которые являются наиболее чувствительными к пожарам. Было обнаружено, что за критическое время реагирования команды смогли достичь 12 мест возможных возгораний. Этот результат показал необходимость создания новых пожарных команд в исследуемой зоне. Кроме того, можно сделать вывод, что увеличение плотности дорожной сети в исследуемой области за счет строительства новых дорог или увеличения скорости движения в пути за счет улучшения стандартов существующих дорог поможет решить проблему.

Ключевые слова: лесной пожар; оптимальный маршрут; кратчайший путь; сетевой анализ; пожарный доступ; пожарные машины; скорость путешествия; критическое время отклика; Адана; Турция.

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