GIS-Based Forest Road Network Model for Forest Protection Purposes

Abdullah Akay 1 and Barzan Aziz 2

1 Professor, Forest Engineering Department, Faculty of Forestry, Bursa Technical University, Turkey
2 MS student, Bioengineering and Sciences Department, Faculty of Forestry, Kahramanmaraş Sütçü İmam University, Turkey

Arrival of the fire truck and ground team into the forest fire area in the shortest time period possible is very crucial in order to effectively fight with forest fires in time. In this study, GIS (Geographical Information System) based system has been developed to decide the route which minimizes the arrival time to the forest fire areas. The study area was city of Erbil, located in the north of Iraq. In the study area, there are nine fire stations for firefighting teams. In this study, firstly, the road network, locations of the headquarters, and possible fire locations were digitized by using ArcGIS 10.0 software. Then, network database were generated based on the digitized data by using Arc Catalog module. Finally, the optimum route, providing the fastest transportation from fire stations to possible fire areas, was determined by using Network Analyst working under Arc Map module. Also, the areas that can be reached by firefighting teams in critical response time were determined. It was found that six of these fires were not accessible by the teams within the critical response time. Thus, only four of the potential fire areas were reached within the critical response time. These results indicated that new fire stations should be established in the study area to provide sufficient firefighting response to all forested lands. Besides, new fire access roads and increasing the design speed on current roads should be considered to increase firefighting response capabilities.

Keyword: forest road network, network analysis, shortest path, GIS, fire protection

1. Introduction

Forest resources are subject to many risk factors such as illegal land use changes, illegal harvesting of trees and wild forest fires (Ertugrul, 2005). Wildfires seriously damage forest resources, threaten sustainability of forest resources, which leads to biological and ecological impacts on forest ecosystem (Bilici, 2009). Besides, forest fires are important sources of greenhouse gasses (CO2, CH4, etc.) emitted to the atmosphere (Guido et al., 2004). After forest fires, the volume and value of forest trees, fire-killed or fire-damaged trees can be affected by deterioration agents such as insects and fungus, which reduce the volume and value of forest trees (Akay et al., 2006).
Forest fires are considered to be one of the most detrimental factors affecting forest resources throughout the world and, in particular, Mediterranean countries (i.e. France, Greece, Italy, Portugal, Spain, and Turkey) due to their climate and other factors (Demir et al., 2009). A typical firefighting crew is divided into 5 groups: initial response team, reserved fighting team, mobile team, fire truck team, and aerial support team (Akay et al., 2010). In order to fight forest fires effectively, the arrival time of the initial response team at a fire area should not exceed the critical response time in which the probability of controlling the forest fires rises markedly (GDF, 2008). Therefore, it is crucial to determine the optimum route that minimizes the travel time of the initial response team from fire headquarters to the fire areas using firefighting trucks.

To develop an adequate transportation planning, many alternative routes should be evaluated so that an optimum route can be selected. There are number of studies where computer-based methods, using computer technology and optimization techniques, have been employed to assist planners in evaluating high number of alternative routes (Ichihara et al., 1996; Akay and Sessions, 2005; Aruga et al., 2005; Akay et al., 2012a).

Solving transportation problems such as shortest path, maximum flow, and optimum task allocation, computer-based network analysis method provides accurate and quick solutions (Akay et al., 2012b). In the solution process of network method, various parameters such as cost, travel time, and length are assigned to the network links and then the shortest or optimal path is selected by searching the alternatives (Zhan, 1997). A network analysis approach is a potentially powerful approach to solving transportation and routing problems.

Suitable plans for forest transportation should involve some technical factors such as road length, road types, road conditions, and vehicle speed, (Tucek, 1999). Road types and road conditions effect vehicle speed which then reflects transportation time (Akay and Erdaş, 2007). Besides, longer distance increases transportation time.

In recent years, GIS-based decision support systems have been utilized to improve the efficiency of fire management stages including planning, managing, and decision making (Burgan et al 1998; Sampson et al 2000; Kucuk et al., 2005). Advances in computer and GIS technology have also made it possible to use GIS-based network analysis based modules such as Network Analyst in ArcGIS software for solving transportation problems (Akay and Sakar, 2009). ArcGIS Network Analyst is a powerful extension that provides network-based spatial analysis including routing, travel directions, closest facility, and service area analysis.

In this study, a GIS-based decision support system utilizing the Network Analyst extension within ArcGIS 10 was developed to assist fire managers in determining the fastest travel routes to fire areas. The decision support system was applied in the city of Erbil, located
in the north of Iraq. The study area was classified as second degree sensitive to forest fire. Multiple network analyst simulations were conducted to identify the optimal travel route and associated response times of nine fire response teams to 10 fire areas that were generated using historical data. The simulations accounted for road surface and condition, and sensitivity of forest areas to fire.

2. Material and Methods

2.1. Study area

Study area is the city of Erbil, which is located about 350 km north of Baghdad in northern Iraq. The city of Suleimanya is located at the southeast of Erbil, Dohuk and Mosul are at the west, and Kirkuk is located at the east. There is an international border of Turkey and Iran along the north and northeast of Erbil (Figure 1).
The study area is located within 35°28’46”-37°19’4” North and 43°18’23”-45°5’15” East coordinates. The study area covers about 1.5 million ha land. In the study area, the average elevation and ground slope is about 814 m and 22.46%, respectively. In the study, the optimum routes were investigated for 10 different potential fire locations, considering nine different fire stations including Erbil center, Dashty hawler, Shaqlawa, Khabat, Koya, Soran, Sidakan, Mergasor and Barzan. The locations of fires and fire stations were indicated in Figure 2.

The city center is laying on wide plain area, however, its districts and sub-district are in the hilly and mountainous areas. The height of the mountains increases to the direction of the north and north east. Halgurd top is the highest point of Hasarost mountain with the height of...
3607 m. The tree species in the area are Quercus infectoria Oliv., Quercus libani Oliv., Quercus brantii Lindl., Quercus aegilops., Pistacia eurycarpa Yalt., Pistacia khinjuk Stocks, etc.

There are nine different fire stations in the study area; Erbil center, Dashty-Hawler, Shaqlawa, Khabat, Koya, Soran, Sidakan, Mergasor and Barzan. All of the fire stations were visited, crew and equipment status determined and UTM (Universal Transverse Mercator) coordinates with the height were recorded by using handheld GPS. Figure 3 indicates some of the views from fire stations in the study area.

Figure 2. The study area map indicating fire stations
2.2. Road Network

The road network map was generated based on topographical map of the study area. In order to develop network database, average travel time of fire trucks on each road section was computed based on road length and average speed of a fire truck, which varies depending on road type and road status. Thus, “Attribute Table” of the road map included fields for these parameters. The road length was calculated by “Calculate Geometry” tool in “Attribute Table”. The road type in the study area was defined as asphalt roads. The road conditions (good, average, poor) were determined based on information obtained from Highway Departments. Then, the average vehicle speed was estimated based on road type and conditions as 60 km/hr, 50 km/hr, and 40 km/hr for good, average and poor condition roads, respectively. Finally, travel time of the fire truck for each road section was computed based on Equation 1 by using “Field Calculator” tool in “Attribute Table”:

\[
t_i = \frac{l_i}{v_i} \times 60
\]

- \( t_i \): travel time on road section \( i \) (minutes)
- \( l_i \): length of road section \( i \) (km)
- \( v_i \): vehicle speed on section \( i \) (km/hr)
- 60: coefficient to convert time from hours to minutes

2.3. Landuse Classification

The landuse types map was generated based on LANDSAT 8 ETM image acquired in 2013. The systematic geometric and radiometric corrections have been done by the provider (the U.S. Geological Survey) to a quality level of 1G before delivery. Landsat’s thermal band has
a resolution of 60 m while the rest has 30 m, except the panchromatic band which has a resolution of 15 m. ERDAS Imagine software was used to classify the satellite imagery by supervised classification technique. Bands 1-5 and 7 of Landsat 7 ETM were used, while Thermal band (band 6) and panchromatic band (band 8) were excluded from the classification. In the image of the research forest, there was a high frequency of data variability due to background vegetation and ground materials. To reduce spatial frequency, “Convolution” function in ERDAS Imagine was used by applying 7X7 low-pass filter.

Supervised Classification method was then performed based on a set of user-defined classes, by obtaining the appropriate spectral signatures from the data. “User-Defined Polygon” function was employed to lower the chance of underestimating class variance since it involved a high degree of user control. Once a set of reliable signatures were created, supervised classification was performed using the Maximum Likelihood (statistically-based classifier) technique. After classification, the landuse types were divided into five main classes including forest, shrub, urban, water, and others. In the recoding process, open grounds, agriculture, etc. were assigned into the class of “others”. Finally, the accuracy assessment of the supervised classification was performed by systematically selecting 250 sample points from the recoded image. Forest and shrubs are combined into a single class called forest, considering that they are subject to fires.

2.4. Network analysis

Network Analyst extension in ArcGIS software works based on the methodology of network analysis. It provides network-based spatial analysis including routing, service area, closest facility, travel directions, and new location-allocation analysis (Figure 5). Using a sophisticated network model, users can easily build networks based on GIS database. Network Analyst also enables users to dynamically model realistic network conditions such as turn and height restrictions, speed limits, and traffic conditions.
In order to run methods of Network Analyst extension, a network database should be generated. In this study, firstly, a Personal Geodatabase under ArcCatalog module was generated, and then, network dataset was produced based on road types map containing travel time information for each road section in the study area. Finally, links (ND_Edges) and nodes (ND_Junctions) data layers were generated by using network database.

After having network database, the New Closest Facility and New Service Area methods under Network Analyst extension was used to explore routing solutions. The New Closest Facility method was used to find the fastest access routes from each initial response team to the potential fire areas in the study area. Then, the response team with the minimum travel time was determined for each potential fire area. In addition, other initial response teams with the second or third shortest arrival time and their access routes can be identified in a case
where an initial response team with the minimum travel time is not sufficient in terms of equipment or number of firefighting personnel.

The New Service Area method was also used to evaluate accessible and inaccessible forest areas by the initial response teams according to the critical response time. As mentioned before, the critical response time varies depending on the fire sensitivity degree. The study area was classified as the second degree sensitive area, which requires critical response time of 30 minutes.

The New Service Area method works similar to a GIS buffer analysis. A service area point is first located in the network system and is considered as a center point from which other portions of the network can be reached given a user-defined total link value threshold. This reachable area comprises the service area. In this study, the locations of the initial response teams were considered as service area points and service areas are then the forest areas that can be reached within the total link value as defined by the critical response time. Therefore, the locations and numbers of initial response teams that are capable of reaching a fire area within the critical response time were evaluated through this approach.

3. Results and Discussion

3.1. Road Network

The results indicated that total length of the road network in the study area was computed as 2502.92 km (Figure 5). All of the roads were asphalt roads. Considering road conditions in the study area, it was found that 57.06% of the road network was in good condition, while 29.75% and 13.19% of the roads were in average and poor conditions, respectively (Table 1).

3.2. Landuse types

The results of the classification process indicated that there were five different landuse types in the study area. The accuracy assessment of the supervised classification was also performed. The overall classification accuracy and kappa statistics were 92% and 0.89, respectively (Table 2). Table 3 indicates areal distribution of landuse types (Figure 6).
Table 1. The length information about road types in the study area

<table>
<thead>
<tr>
<th>Road Conditions</th>
<th>Total Length</th>
<th>Good</th>
<th>Average</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road Lengths (km)</td>
<td>2502.92</td>
<td>1428.16</td>
<td>744.66</td>
<td>330.10</td>
</tr>
</tbody>
</table>

Table 2. Accuracy assessment matrix table

<table>
<thead>
<tr>
<th>Class Name</th>
<th>Reference Totals</th>
<th>Classified Totals</th>
<th>Number Correct</th>
<th>Producers Accuracy</th>
<th>User Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrub</td>
<td>82</td>
<td>80</td>
<td>80</td>
<td>97.56</td>
<td>100.00</td>
</tr>
<tr>
<td>Forest</td>
<td>18</td>
<td>11</td>
<td>10</td>
<td>55.56</td>
<td>90.91</td>
</tr>
<tr>
<td>Urban</td>
<td>55</td>
<td>67</td>
<td>53</td>
<td>96.36</td>
<td>79.10</td>
</tr>
<tr>
<td>Water</td>
<td>50</td>
<td>48</td>
<td>46</td>
<td>92.00</td>
<td>95.83</td>
</tr>
<tr>
<td>Others</td>
<td>91</td>
<td>94</td>
<td>87</td>
<td>95.60</td>
<td>92.55</td>
</tr>
<tr>
<td>Totals</td>
<td>296</td>
<td>300</td>
<td>276</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

38th Annual COFE Meeting – Engineering Solutions for Non-Industrial Private Forest Operations
Table 3. The areal distribution of the landuse types in the study area

<table>
<thead>
<tr>
<th>Landuse Types</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrub</td>
<td>26.98</td>
</tr>
<tr>
<td>Forest</td>
<td>12.04</td>
</tr>
<tr>
<td>Urban</td>
<td>10.89</td>
</tr>
<tr>
<td>Water</td>
<td>7.44</td>
</tr>
<tr>
<td>Others</td>
<td>42.65</td>
</tr>
</tbody>
</table>

Figure 6. Landuse types

3.3. Network Analysis

New Closest Facility

The fastest access routes for each firefighting team to the potential fire areas in the study area were determined using the New Closest Facility method (Table 4). Results indicated that there is a close relationship between the travel time and road length, as well as between travel time and road condition. Firefighting teams that reached potential fire areas within the
minimum arrival time were identified considering fastest access route. Although the decision support system found the fastest access routes to the potential fire areas, six of these fires were not accessible by the teams within the critical response time. Since the potential fire areas were in areas sensitive to forest fires at the second degree, the critical response time was considered to be 30 minutes. Only four of the potential fire areas were reached within the critical time.

**New Service Area**

The areas that can be reached by initial response teams within a critical response time were determined by the New Service Area method. Since the study area consisted of areas sensitive to fires at the second degrees, the buffer areas that can be reached through the road network within 30 minutes were investigated. Results indicated that the teams could reach only 6.88% of the study area within 30 minutes (Figure 7).

The GIS tools were used to combine the reachable areas and forest land databases to determine forest areas that could be reached within critical response times (Figure 8). It was found that the firefighting teams can reach 17.64% of the forested areas within 30 minutes. The rest of the forest area (82.36%) could be reached by the teams within critical response time.

| Table 4. The arrival time (minutes) of firefighting teams to each potential fires |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|                                 | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
| Erbil                           | 146 | 132 | 138 | 91  | 100 | 36  | 45  | 27  | 34  | 15  |
| Dashty-Hawler                   | 164 | 150 | 157 | 110 | 119 | 54  | 25  | 47  | 53  | 34  |
| Shaqlawa                        | 105 | 91  | 97  | 51  | 60  | 32  | 67  | 74  | 44  | 58  |
| Khabat                          | 170 | 156 | 162 | 115 | 124 | 64  | 75  | 41  | 42  | 16  |
| Koya                            | 176 | 162 | 168 | 121 | 130 | 46  | 48  | 98  | 77  | 84  |
| Soran                           | 48  | 34  | 33  | 26  | 32  | 97  | 125 | 131 | 87  | 115 |
| Sidakan                         | 82  | 68  | 41  | 60  | 66  | 132 | 159 | 165 | 122 | 150 |
| Mergasor                        | 31  | 31  | 58  | 44  | 50  | 115 | 143 | 149 | 105 | 133 |
| Barzan                          | 34  | 57  | 87  | 73  | 78  | 144 | 172 | 178 | 134 | 162 |
Figure 7. The accessible areas within 30 minutes in whole study area
4. Conclusions

GIS (Geographical Information System) based system has been developed to decide the route which minimizes the arrival time to the forest fire areas. The study area was city of Erbil, located in the north of Iraq. In the study area, nine fire stations teams located in Erbil were considered in execution of the system. The network analyst method under “Network Analyst” extension of ArcGIS 10 platform was used to systematically search for optimum routes. In application, 10 potential fire locations were considered to run network analysis.

The total length of the road network in the study area was found as 2502.92 km. The roads were asphalt paved roads. It was also found that more than half of the road network was in good condition, while about 30% and 14% of the roads were in average and poor conditions, respectively. The topographical analysis indicated that about 62% of the study area was covered by land with low and very low ground slope, while rest of them was medium, high and very high slope.
Based on classification process, shrub lands covers about 27% of the study area, followed by forest (12%), urban (11%), and water (%7). About 43% of the area was covered by other landuse types. In network analysis application, forest and shrubs are combined into a single class called forest, which totally covers about 40% of the study area.

The fastest access routes for each firefighting team to the potential fire areas in the study area were determined using the New Closest Facility method. Six of these fires were not accessible by the teams within the critical response time of 30 minutes. Only four of the potential fire areas were reached within the critical response time. Results indicated that there is a close relationship between the travel time and road length, as well as between travel time and road condition.

The areas that can be reached by initial response teams within a critical response time were determined by the New Service Area method. Results indicated that the teams could reach only 6.88% of the study area within 30 minutes. Considering only forested areas, it was found that the firefighting teams can reach 17.64% of the forested areas within 30 minutes. About 82% could be reached by the teams within critical response time.

5. References


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