Iranian Journal of Forest
Vol. 17, No. 4, Winter 2026
pp. 581-596
Research Article

DOI: 10.22034/ijf.2026.543401.2065

GIS-Based Evaluation of Fire Station Accessibility in Zawita, Duhok

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(Received: 26 August 2025; Accepted: 13 October 2025)

Abstract
Wildfires present a major threat to the ecologically valuable forests of the Zawita District in northern Iraq, where anthropogenic activities (human-caused) and limited firefighting capability create additional threats. While there is an actual fire station (F1) in the district, its coverage is limited. Thus, this study sought to test whether the addition of a new fire station (F2) in the center of the district would improve suppression efficiency. Using GIS-based network analysis software (ArcGIS 10.8), we modeled road accessibility and travel time to 33 forest zones based on assumptions regarding asphalt and forest road conditions. Travel times for firefighting trucks were calculated for both F1 and F2 conditions under a critical response time of 15–20 min. We developed a third-degree polynomial regression model and validated the relationship between response time and burnt area, with excellent fit (R^2 = 0.9999 calibration; R^2 = 0.9984 validation). Predicting burnt areas for both F1 and F2 scenarios for all forest zones enabled quantifying their relative effectiveness. F1 covered 72% (305 km^2) of the study area over the 20-minute time frame, while F2 covered 70% (293 km^2). While F1 had one more zone in the critical time frame compared to F2 (27 vs. 26), our regression model shows that F2 produced quicker responses in the key central zones, which led to a net reduction of 288000 m^2 of burnt area in the district. The polynomial model demonstrated that brief delays in response time had an exponential effect on fire damage, emphasizing the need for better and strategically placed stations. The suggested model incorporates both stations (F1 + F2) to achieve the best trade-off in overall geography and improved accessibility from a central location. This recommendation corresponds to increased capacity for wildfire suppression, less loss of forests, and serves as a precedent for disaster planning in similar ecologically sensitive, resource-poor areas.

Keywords: ArcGIS, Fire station accessibility, GIS, Network analysis, Optimal route analysis.

1. Introduction

In the last hundred years, the rapid increase in the number of humans and the increased demand for consumer products have created more pressure on forests, an important renewable natural resource. Most of the pressure has been due to forest destruction, illegal logging, and an increased number of wildfires (Ertugrul, 2005). Each year, billions of dollars of economic, environmental, and social harm are inflicted upon largely unconnected and expansive areas of forest by wildfire (Thomas et al., 2017). The sustainability of forest resources is negatively impacted by anthropogenic effects of wildfire, and wildfires also produce unprecedented environmental disturbances within forest ecosystems (Pompa-García et al., 2012). Most scientists recognize wildfire as a result of two types of influences: natural causes, such as lightning and high temperature, and human-induced causes, such as cooking, burning, and smoking. Wildfire can ignite when the oxygen concentration exceeds 16% (Belcher et al., 2010; Belcher et al., 2013). Fire dynamics are shifting globally as rising temperatures intensify heat and drought, alter precipitation patterns, and substantially increase the risk and frequency of forest wildfire (Jolly et al., 2015; Abatzoglou & Williams, 2016).

To effectively combat wildfire, the initial response team must reach the fire site within

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the critical response time, during which the likelihood of controlling the fire significantly increases. Therefore, identifying the optimal route that minimizes the travel time of firefighting trucks from fire headquarters to the affected area is essential. According to Turkey's wildfire sensitivity map, which was developed by the General Directorate of Forestry (GDF), the Kahramanmaraş FED consists of first-degree fire-sensitive forest areas, and the critical response time is determined to be 20 minutes (Akay & Şahin, 2019). Consequently, the identification of an optimal real-time route is crucial for assessing the fire-fighting teams' performance promptly and directly for fire-fighting and extinguishing operations. This is accomplished through advanced technologies, including Geographic Information Systems (GIS), Global Positioning Systems (GPS), and real-time monitoring systems for reported traffic situations, to determine the safest and fastest way from the fire station to the location of the fire (Akay & Süslü, 2017). When creating effective forest transportation plans, various technical factors must be thoroughly evaluated to ensure the efficient movement of vehicles, especially firefighting and forest management vehicles. These factors include forest road length, types of forest roads, forest road conditions, and vehicle speed (Lugo & Gucinski, 2000). The type and condition of forest roads affect vehicle speed, which consequently impacts transportation time (Boston, 2016). Furthermore, greater distances lead to longer transportation times. Studies show that the average initial response time for fire suppression in Greece is around 33.4 minutes. In high-risk fire areas, this time is usually between 20 to 30 minutes, while in mountainous regions, it can range from 40 to 60 minutes (Ranabhat et al., 2022). Only 21.9% of wildfire suppression vehicles arrive at the fire site within 15 minutes. If the response time for the first intervention were reduced to under 15 to 20 minutes, it could lead to a substantial reduction in the burnt area, potentially cutting it by up to 70% (Psilovikos et al., 2011). Additionally, research has established ten zones accessible to firefighting units within critical response times. Analysis of six documented fire incidents has shown that the quickest response teams did not depart from their stations until approximately 30 minutes after ignition, exceeding the threshold they established for an effective response. Thus, only four ignition points in the study area of Erbil were reachable within the acceptable response time. These findings highlight the need for additional fire stations to increase spatial coverage, improve forest accessibility, and improve existing roads. It will also take new fire access roads, along with speed improvements on current roads, to get the units there quickly (Akay & Aziz, 2015).

The Zawita sub-district, located in Duhok, experienced multiple wildfire events from 2001 to 2023. Based on local perceptions, wildfires were the first-ranked factor in forest loss, followed by land conversion and harvest practices (Eklund et al., 2021). Over these years, there were multiple extensive fires, and the Zawita fire that started in late July 2021 was one of the largest, burning more than 10,000 dunums of woodland, according to civil defense, and it lasted four days despite considerable firefighting efforts. The heat of the fire also caused landmines to explode, greatly complicating wildfire suppression efforts (Mosa, 2016).

Satellite imagery showed a clear stratified concentration of vegetation-fire "hotspots" throughout northern Iraq from 2016 to 2022. This analysis also indicated that Zawita experienced an increased frequency of fires prior to 2023 (Eklund & Dinc, 2024).

This research explores the operational performance of firefighting units in the field in Zawita District, utilizing the Network Analyst module in ArcGIS. The analysis was conducted in three phases: (1) the shortest path to the fire location from both the actual fire station (F1) and the proposed new fire station (F2); (2) the predicted burnt area per zone across the study site as a function of arrival times of the firefighting teams; and (3) the area that firefighting teams can effectively reach within a critical response time.

2. Materials and Methods

2.1. Study Location

This study is focused on the Zawita District, which is a sub-region of the Duhok Governorate in the north of Iraq. Zawita is located to the northeast of Duhok city, and it is strategically important for several reasons, as it is located relatively close to urban areas in addition to containing ecologically rich forested areas. These ideas are well illustrated in Figure 1, which shows the location of Zawita in this context. Zawita is located between approximately 36°52′ and 36°58′ North latitude and 42°58′ and 43°04′ East longitude. Zawita is characterized by a diverse topography, which includes mountainous areas and valleys, further contributing to the variation and ecological diversity of the area. In general, Zawita is characterized as having a Mediterranean climate, distinguished by long, dry summers and mild to cold winters with reasonable precipitation. Summer temperatures usually range from 30°C to 40°C, and winter temperatures frequently fall below the freezing point (0°C). From year to year, at the higher elevations, occasional winter snowfalls may accumulate in the nearby valleys. Climatic data from the Duhok meteorological station between 2012 and 2024 show that Duhok receives an average of about 619.49 mm of rainfall annually. Rain typically occurs from November through March (Miho & Rekany, 2023). The precipitation in the region ranges from 600 mm to 1000 mm per year, depending on local microclimatic variation.

From a biological standpoint, the district has a dense variety of native vegetation, made up primarily of *Quercus aegilops* L. and *Pinus brutia* Ten., as well as shrubland and herbaceous grasslands. The forests play a very important role in managing hydrological processes, protecting against soil erosion, protecting biodiversity, and sequestering carbon from the atmosphere. However, for decades, the district has increasingly lost forest cover due to anthropogenically induced changes, including illegal logging, pasture or cultivation expansion, and infrastructure expansion, as well as natural wildfire events.

Zawita has an area of about 421 km², encompassing an area roughly equivalent to 6.42% of Duhok Governorate's total land area of 6,553 km². The land use of the district consists of agricultural lands, dispersed rural settlements, forest areas, and peri-urban expansion near the city of Duhok. Zawita is characterized by a variety of villages and small towns mixed in with a patchwork of human and natural systems.

Although Zawita has significant ecological importance and a strategic role, there is still very limited firefighting capability within the area. The actual fire station (F1), located at 36°53′0.6″ N, 43°1′5.88″ E, serves as the primary wildfire emergency response location, especially in the hot and dry summer months. To improve the logistics of fire service coverage, it would be advisable to develop a new station (F2) in a location that serves as a hub within the study area, such as Bade Village (36°54′28″ N, 43°5′13″ E). Choosing this location, which is almost directly near F1, was the result of a detailed spatial analysis of coverage conducted to ensure maximal and balanced service throughout the study area. Other areas were investigated, but they only provided partial coverage, which means that many areas would still not be served. While location F2 is close to the middle of the study area, the combination of F1 and F2 will provide the greatest coverage, which will lead to improved response times, enhanced efficiency of fire crews, and improved overall community protection (Figure 2). It is the intended location that will provide the most effective and supportive service coverage for the study area, ensuring all areas are accessible by the stations.

2.2. GIS Database Generation

A GIS-based network analysis was employed to determine forested areas that can be reached within a defined critical response time. This analysis was based on the development of digital data layers representing land use and transportation networks. The land use dataset was generated using high-resolution imagery acquired from Space Imaging Middle East (SIME). This system supplies data captured by various Earth observation satellites and aerial platforms, with spatial resolutions between 15 cm and 20 m. The imagery utilized in this study, with a resolution of 15 cm, was sourced from the Statistics Directorate of Duhok Governorate (SDDG).

The road network in the study area is made up of two main types: asphalt roads and forest roads. All road segments were determined to be in generally good condition. Average vehicle speeds were established from previous studies (Pompa-García et al., 2012; Akay et al., 2012) and official amounts provided by the Highway Departments and the Forest Directorate in Duhok. As a result, we estimated mean travel speeds of 60 km/h for asphalt roads and 30 km/h for forest roads, while

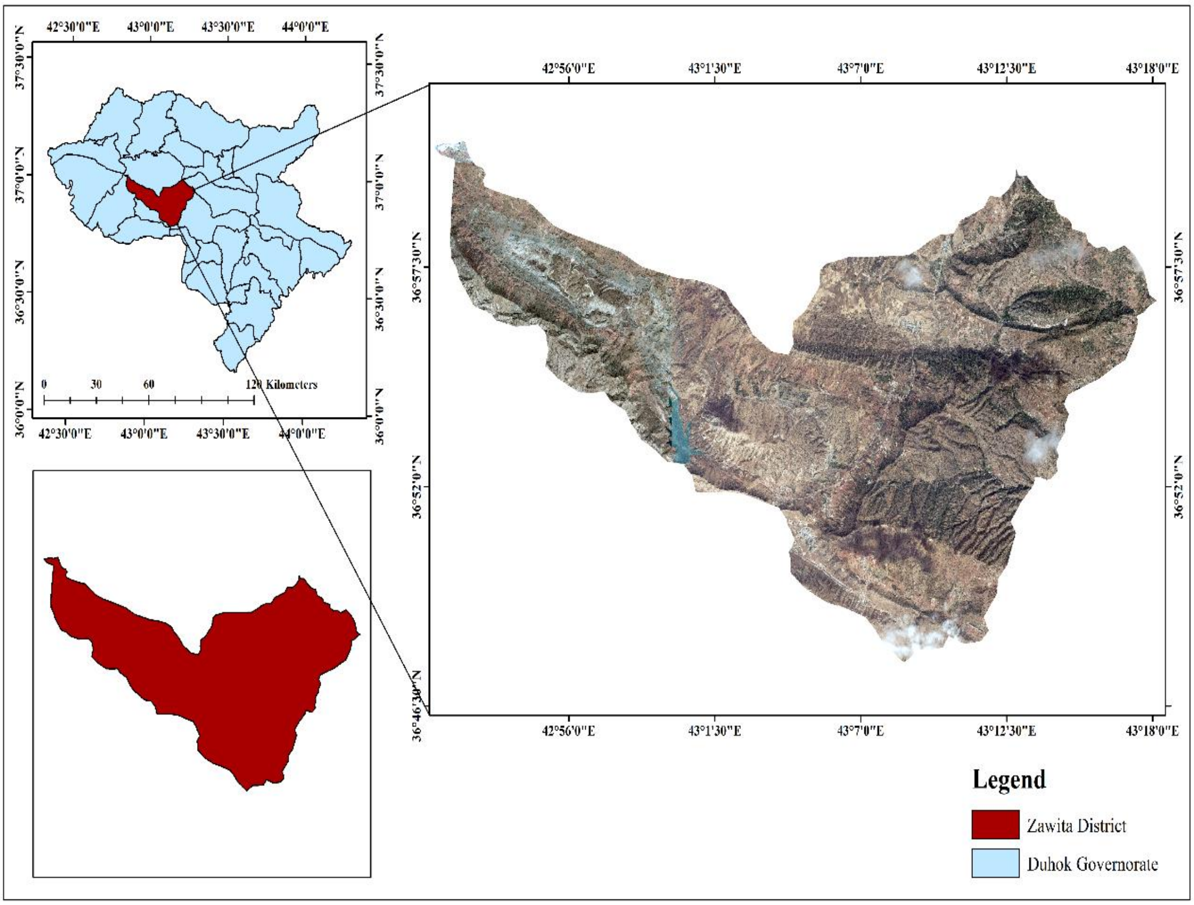

Figure 1. The Proposed Study Area

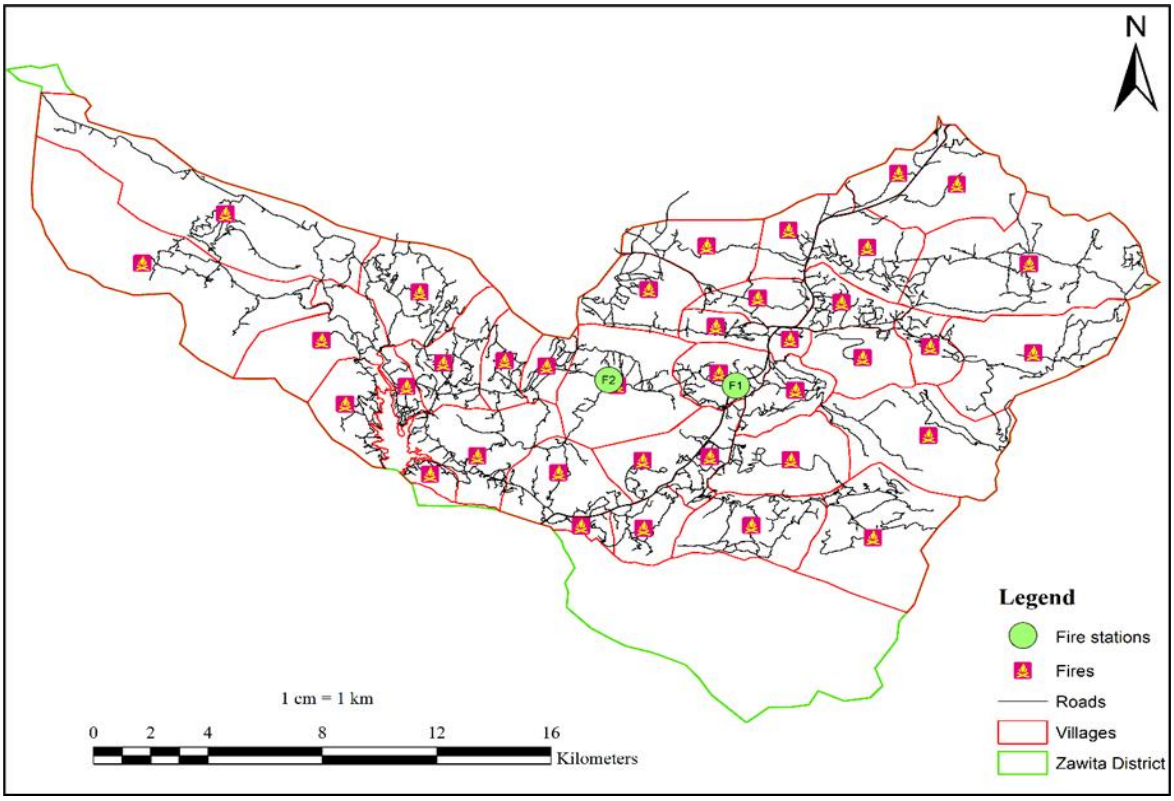

Figure 2. The map of the study area indicating the positions of the two fire stations

accounting for conditions typical of the Duhok region. These speeds reflect reasonable estimates, based on informed assumptions derived from local travel practices, regional topography, and the general state of existing infrastructure; we did not conduct direct field reconnaissance. The asphalt roads in Duhok consist of both longer urban routes that link urban centers with community centers, and shorter routes that connect urban centers with community centers. Regardless of the route, asphalt roads in Duhok typically traverse moderate hills and are in adequate repair. By considering dynamic factors and road geometries such as curvature, elevation change, stopping and braking behaviors, and driving behaviors, a mean travel speed of 60 km/h is a reasonable average travel speed representative of local area conditions.

The forest roads in the region are generally unpaved, with narrower widths, and are often partially or fully obstructed by natural impediments to driving, like rocks, vegetation, or undulations from erosion features. These are inherent limitations to any travel speed, even under normal or emergency use situations. Overall, the estimated average speed of 30 km/h represents the best estimate of the travel limitations on forest roads. Both estimates correspond to findings of other studies conducted in northern Iraq and in similar mountainous regions, where average travel speeds are determined by road surface types and topography, rather than legal limits (Mohammed, 2024; Hamawandy et al., 2025). Fire truck travel times for each road segment were calculated using Equation 1, applied through the "Field Calculator" within the attribute table of the road network map (Akay & Aziz, 2015; Demir & Akay, 2024):

$$T = (L / V) * 60 \quad (1)$$

where:

T = Travel time (minutes)

L = Length of the road segment (km)

V = Average speed of the fire truck (km/h)

60 = Conversion factor to express time in minutes (from hours)

2.3. Network Analysis

In order to assess changes in accessibility and efficiency of firefighting response, a network analysis was conducted for the 33 identified forest zones. The purpose of the network analysis was to estimate whether, and by how much, travel time from the firefighting stations to each identified zone changed using two scenarios based on updated standards for forest road conditions. For Scenario 1, travel times were calculated using the actual fire station (F1), and for Scenario 2, travel times were calculated with a proposed new fire station (F2) located more centrally within the study area (Figure 3). Network analysis is a commonly used GIS analysis technique to determine the best route based on cost (i.e., travel times, distances, etc.) (Hayati et al., 2013). This analysis was completed using the "New Route" tool from the Network Analyst extension in ArcGIS 10.8 (Figure 4). A personal geodatabase in ArcCatalog was used to create a network dataset with a classified road map with travel time attributes. The road network was then divided into feature classes—edges (ND Edges) and junctions (ND Junctions)—and used to create a functional transportation network to help the New Route tool determine the least-cost travel paths from F1 and F2 to all 33 fire-prone zones, as seen in Figure 2. The Network Analyst engine employed Dijkstra's algorithm for the identification of the shortest travel-time path while incorporating road restrictions such as speed limits, turning restrictions, and surface condition.

This method allowed a comparison of coverage from the actual fire station (F1) and the new fire station (F2), and also provided planners with insight into which units could achieve the most effective response to each fire-prone zone. The analysis also took into account thresholds and burning conditions derived from topography that are critical when assessing the ability of fire departments to respond to wildfires, specifically where fire stations are located on the landscape. The analysis demonstrated the applicability of network analysis to validate planning activities and improve the planning of emergency response capacity in forested regions.

3. Results

3.1. GIS Database

The total length of the road network in the study area was estimated to be 755.2 km, of which forest roads represented approximately 73% (550.66 km) and asphalt roads represented 27% (204.54 km) (Figure 5).

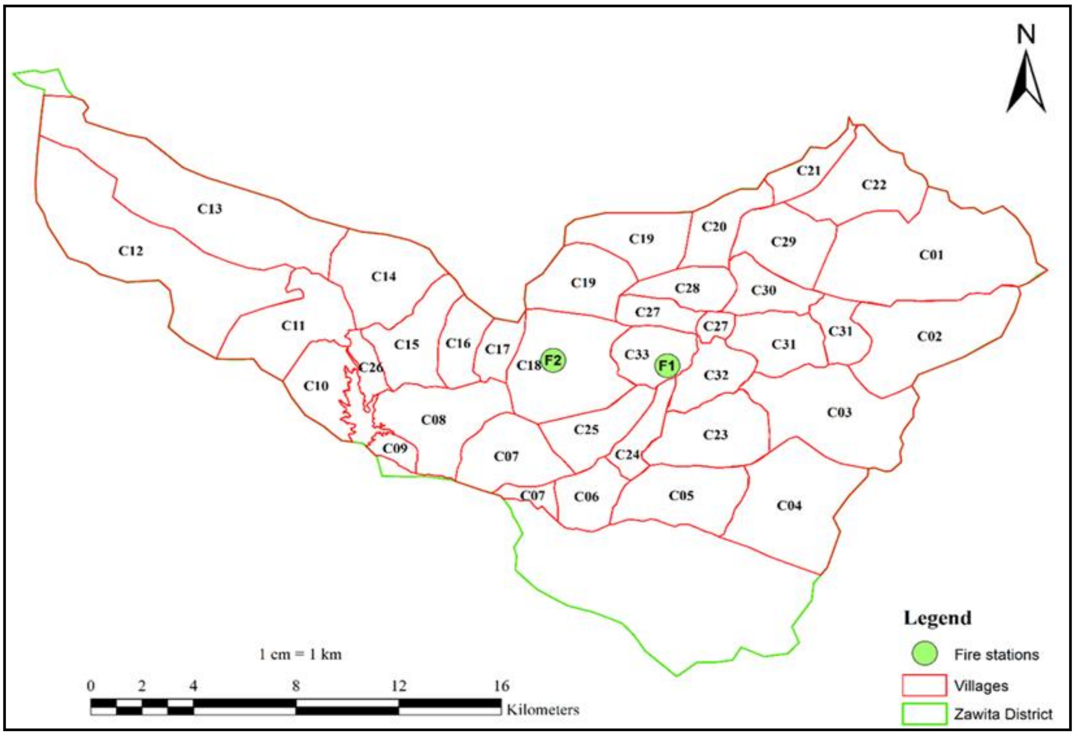

Figure 3. Spatial subdivision of the study area into 33 zones

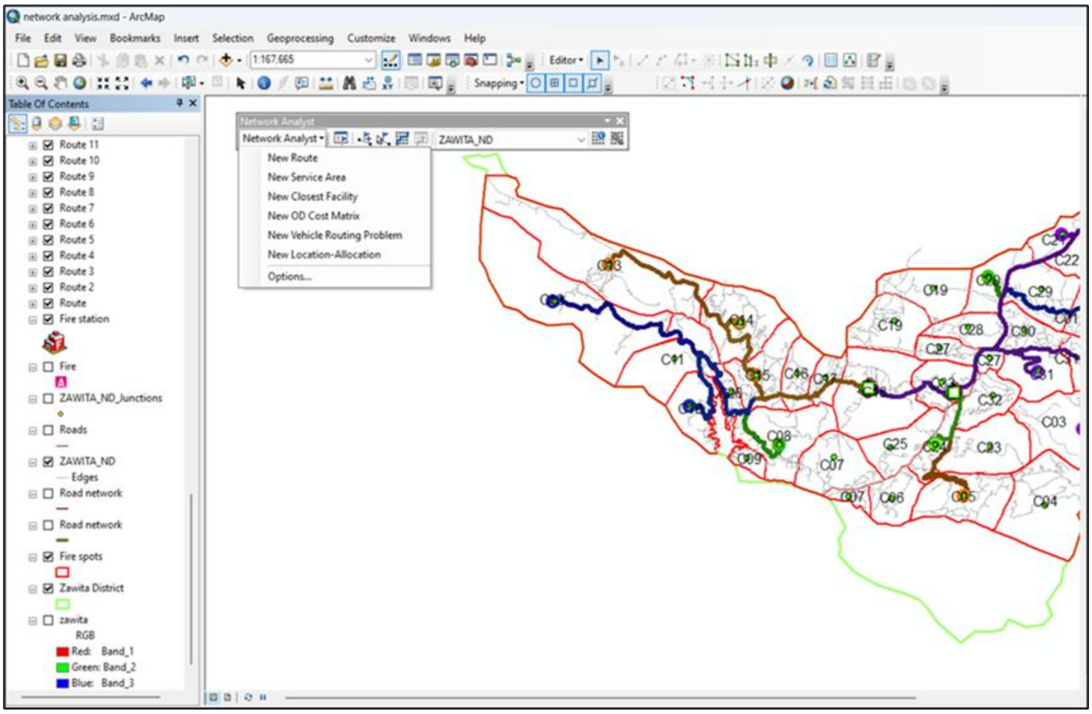

Figure 4. Network analyst toolset in ArcGIS 10.8

Overall, forest roads represented the largest component of the road network as well as the largest number of segments. These roads, which were generally at a local collector level, had the greatest density and complexity and were intended to provide access to remote or forested areas. Asphalt roads, while fewer in number, were ultimately the most important roads, as they provided the greatest transportation linkage between major villages and access points in the study area.

The structural integrity and surface conditions of both forest and asphalt roads were systematically evaluated and found to be adequate to support emergency vehicle operations, particularly for fire trucks.

Although forest roads were unpaved, their maintenance status was sufficient to ensure accessibility under emergency conditions.

3.2. Network Analysis

3.2.1. New Route

In each routing evaluation, the New Route tool generated route layers that represented the most efficient travel routes from the current fire station (F1) or the new fire station (F2) to each of the 33 identified forest zones. Cumulative travel times for all routes were extracted and compared to a critical response time threshold of 15–20 minutes, which is a standard practice used nationally and internationally, as well as aligned with the operational guidelines of the Duhok Forest Directorate. This threshold was also corroborated by existing literature (Psilovikos et al., 2011; Ranabhat et al., 2022) and similarly outlined the response-time criteria for mixed wildfire emergencies, which in turn supported its use in this study.

The analysis led to the identification of areas within and outside the identified response time and revealed spatial variability in emergency response coverage. For each fire scenario, the number of areas inside the 20-minute response time was computed, and comparative performance measures were created for F1 and F2. The evaluation and comparison of emergency response times for the actual fire station (F1) and the new fire station (F2) for the 33 forest zones were conducted using the "New Route" tool, currently located in the Network Analyst Extension of ArcGIS 10.8, following a workflow that is outlined in (Table 1).

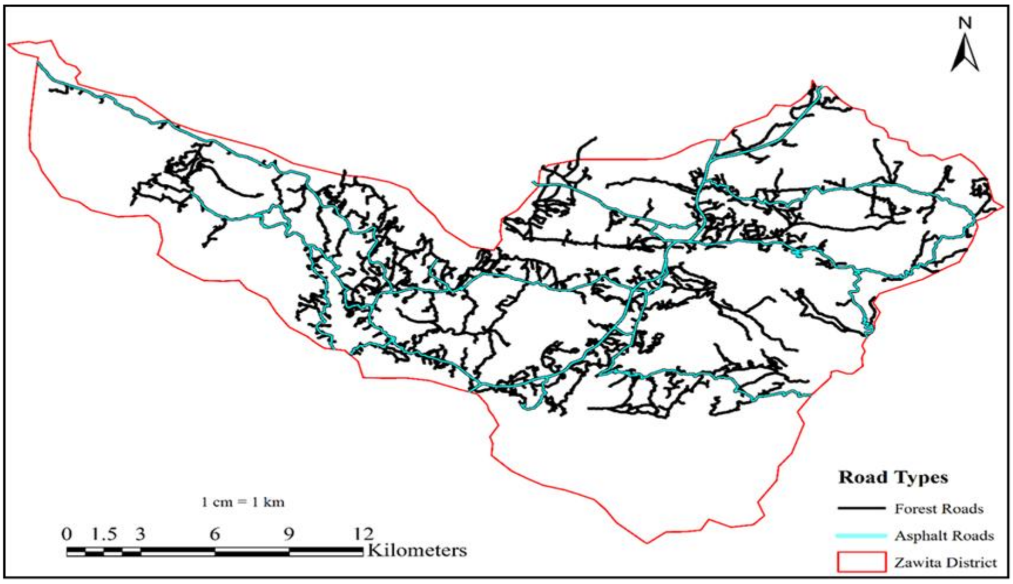

Figure 5. The study road network map

Table 1. Step by step workflow for analyzing emergency response routes using the "New Route" tool in ArcGIS 10.8 network analyst extension

Step	Description
1	**Prepare Your Data:** Import your road network (with travel time along network) and your fire station points (F1 & F2) and your 33 forest zone center points (C01 – C33); be sure are using the same coordinate systems.
2	**Enable Network Analyst Extension:** From the Customize menu, check to enable the Network Analyst toolbar and load the network dataset.
3	**Create a Route Analysis Layer:** In the Network Analyst toolbar, click **Network Analyst > New Route.**
4	**Add Facilities and Incidents:** Add F1 and F2 as Facilities. Add the 33 forest center points as Incidents. It will perform two analyses, one for F1 and one for F2.
5	**Solve Routes:** Iterate the Route solver twice once for F1 and once for F2 to get the travel time from each facility to the 33 zones.
6	**Export and Compare Results:** Export the route results for each facility and compare them to the (15-20 minute) critical response time standard.
7	**Visualize on Map:** You can symbolize routes or use service areas to visualize coverage for each station.

The tool calculated the shortest travel-time paths from each station to all zones and provided detailed route layers. From this, response times were extracted and compared to the defined Critical Response Time Threshold (15–20 minutes). This resulted in two output tables: Table 2 for F1, and Table 3 for F2, which indicated which zones would be included within the threshold and which zones would not.

This approach allowed for a clear spatial and numerical comparison of the coverage potential of the stations. Through a review of these tables, it could also be determined whether F2 would improve emergency response coverage and where the greatest benefit to coverage could be derived from the proposed new station.

The comparative analysis between the actual fire station (F1) and new fire station (F2) revealed notable shifts in response performance, as shown in Table 4.

3.2.2. New Service Area

Using the New Service Area Tool, the locations of the two fire stations (F1 and F2) were mapped to identify which forest areas could be reached within the critical response time of 20 minutes. The mapping identified areas that could be reached by firefighting teams and areas beyond the 20-minute threshold (Figure 6). The results showed that F1 could cover 305 km² of the total study area, which is 421 km², representing 72% of the service area, while F2 could cover 293 km² of forest area, which is 70%. However, 116 km² of F1 forest area (28%) and 128 km² of F2 forest area (30%) could not be accessed within the 20-minute time period. (Akay and Kılıç, 2015) used a GIS-based network analysis for a study in Bursa, Turkey, and reported that Sarnıç FEC firefighting teams could access 26.18% of high forests and 60.29% of coppice forest areas in the same 20-minute response time.

Table 2. Response times (in minutes) coverage of actual fire station (F1) across study area zones

Category	Number of Zones	Zone Names & Times (Minutes)
≤ 20 minutes (✅)	27	C01 (19), C02 (17), C04 (15), C05 (13), C06 (14), C07 (13), C08 (15), C09 (17), C15 (14), C16 (12), C17 (11), C18 (6), C19 (15), C20 (10), C21 (14), C22 (17), C23 (11), C24 (7), C25 (11), C26 (17), C27 (7), C28 (5), C29 (11), C30 (8), C31 (11), C32 (4), C33 (2)
> 20 minutes (❌)	6	C03 (23), C10 (28), C11 (24), C12 (34), C13 (29), C14 (21)

Table 3. Response Time (in Minutes) Coverage of New Fire Station (F2) Across Study Area Zones

Category	Number of Zones	Zone Names & Times (Minutes)
≤ 20 minutes (✅)	26	C04 (19), C05 (17), C06 (18), C07 (11), C08 (13), C09 (13),C11 (18),C14 (15), C15 (8), C16 (6), C17 (5), C18 (1), C19 (19), C20 (16), C21 (20), C23 (15), C24 (11), C25 (15), C26 (10), C27 (13), C28 (10), C29 (16), C30 (13), C31 (16), C32 (9), C33 (8)
> 20 minutes (❌)	7	C01 (24), C02 (22), C03 (29), C10 (21), C12 (27), C13 (22), C22 (22)

Table 4. Comparative analysis summary

Criteria	F1 (Actual)	F2 (New)
Zones within or less 15 – 20 min	27	26
Zones exceeding 20 min (at risk areas)	6	7
Fastest Response Time	2 min (C33)	1 min (C18)
Slowest Response Time	**34 min (C12)**	**29 min (C03)**

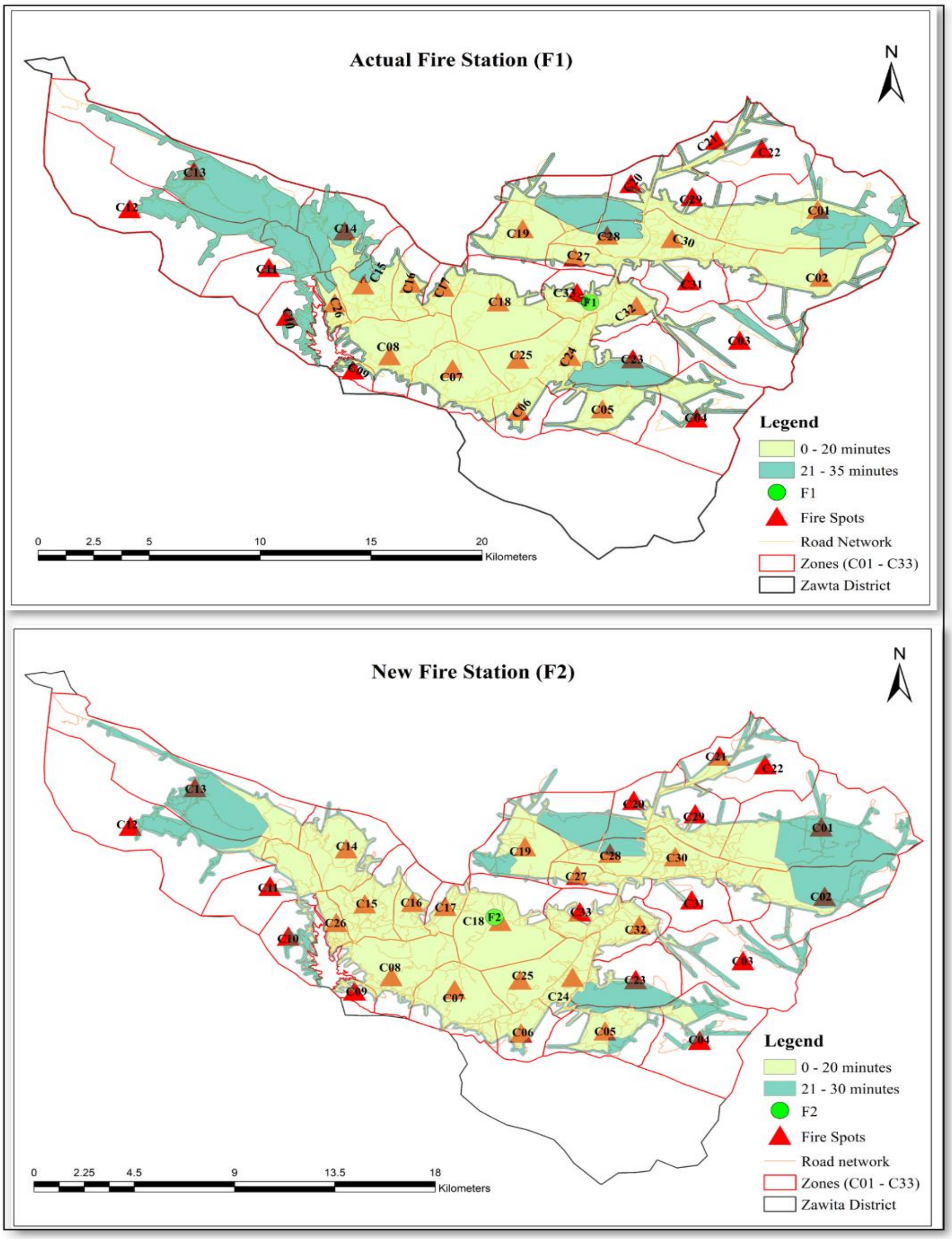

Figure 6. Coverage areas of fire stations (F1 and F2) within and beyond the 20 minutes critical response time

Before constructing this equation, the scatter plot of Time versus Burnt Area was first evaluated to look for potential outliers and to look for a general trend among the variables (Figure 7). It showed a well-defined, smooth relationship with no significant outliers, and therefore, it justified trying a polynomial model. Based on 33 observations, the fitted third-order polynomial produced an R^2 value of 99% with a very small Standard Error of Estimate (0.259) and Mean Absolute Error (0.212), indicating that all predictive values were very close to the observed data (see Equation 2). Both Statgraphics 19 and CurveExpert 1.3 software packages were used to develop this equation, further confirming that the outcome is reliable. This strong deterministic relationship, rather than random variability, is the reason the model is so predictive. Validation using 9 separate observations also took place, and this portion is discussed in the validation section of Table 5.

$$Y\ (\text{Burnt area}) = -0.401312 + 0.429221X - 0.000518601X^2 + 2.00815E^{-7}X^3 \quad (2)$$

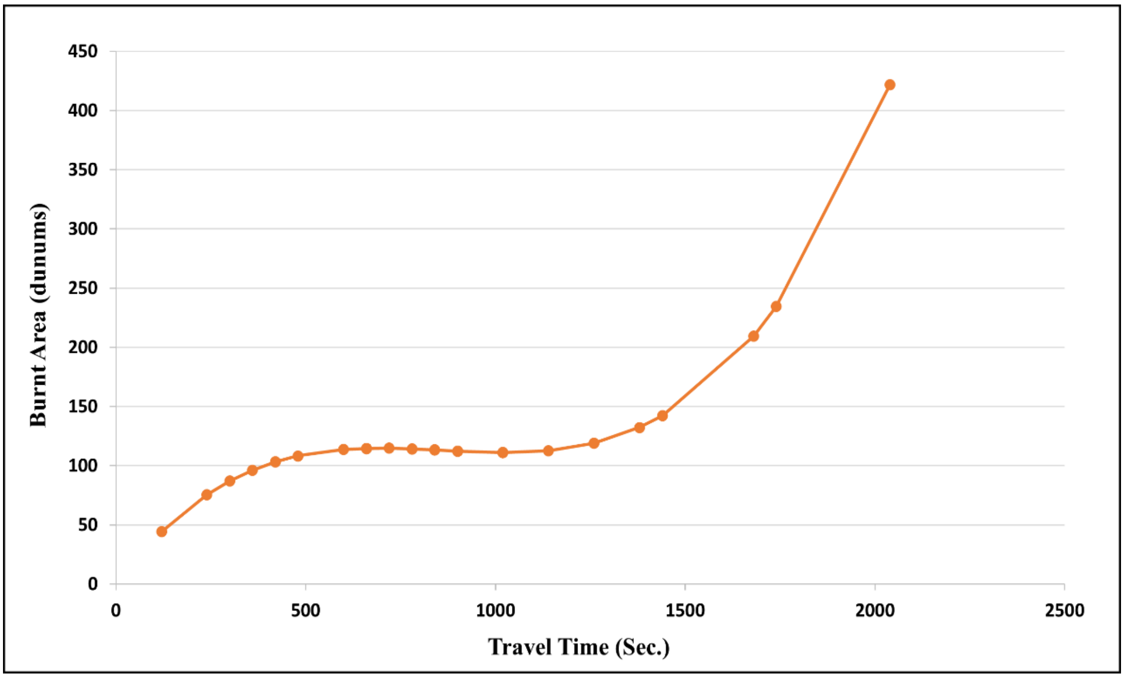

Figure 7. Scatter plot illustrating the relationship between the studied variables

Table 5. Comparison between the developed calibration and validation equations for the Zawita District

Study Area	Equations	B1	B2	B3	R^2
Zawita District	Calibration Eq.	0.429221	-0.000518601	$2.00815E^{-7}$	0.9999
	Validation Eq.	0.491399	-0.000598812	$2.24861E^{-7}$	0.9984

The verification process involved a comparison of the calibration and validation equations for the Zawita site (Table 5). The coefficients of the two equations were very similar, and the R^2 values remained extremely high (99.9984% for calibration and 99.8457% for validation), confirming the robustness and predictive strength of the model developed.

The chosen equation summarizes the third-degree polynomial relationship between response time (X) in seconds and burned area (Y) in dunums. It stands to reason that as burned area increases, response time is longer; however, there are varying rates of change over time, as indicated by the quadratic and cubic components of the model. In the end, this is all meant to demonstrate how longer official response times can potentially become more problematic and increasingly exacerbate the consequences of wildfires.

Using this equation, expected burnt areas were computed for all 33 fire outbreak locations, considering the response times of both the actual fire station (F1) and the proposed new fire station (F2). Using Equation (2), the expected burnt areas were estimated for all 33 fire outbreak locations using the response times of the current fire station (F1) and the proposed new fire station (F2). Table 5 compares the area burnt (in dunums) for each site and the response scenarios related to F1 and F2. Using the expected burnt area approach in this analysis, the relative effectiveness of F1 and F2 was evaluated in controlling fire spread based on their respective response times and fire-spread dynamics.

Table 7 provides a statistical summary and the meaning of differences in fire extent (burnt area) between the actual configuration of fire stations (F1) and the new configuration (F2), using the scenarios set forth in (Table 6).

Table 6. The computed differences in burnt areas between scenarios (F1) and (F2) across all proposed locations

Name	Centers	According to time arrival		Difference (F2 - F1)	
		Burnt area by Dunums for Actual Fire station (F1)	Burnt area by Dunums for New Fire station (F2)	(+) F1 Bad	(-) F2 Useful
Bihere Forest	C01	113	143	30	
Baniye and Sariyah Forest	C02	111	125	14	
Benarinke Forest	C03	132	234	102	
Peda Forest	C04	112	113	1	
Kuzo Forest	C05	114	111		3
Eminke Forest	C06	113	111		2
Besere Forest	C07	114	115	1	
Bajilor Forest	C08	112	114	2	
Gre Qasroke forest	C09	111	114	3	
Piromara Forest	C10	209	119		90
Baxornif Forest	C11	142	111		31
Linawa Forest	C12	422	188		234
Butiya Forest	C13	234	125		110
Bakuze Forest	C14	119	112		7
Qarqarawa Forest	C15	113	108		5
Ekmala Forest	C16	115	96		18
Sindore Forest	C17	115	87		27
Bade Forest	C18	96	24		72
Mamane Forest	C19	112	113	1	
Bagera Forest	C20	114	111		3
Lomana Forest	C21	113	115	2	
Swaratoka Forest	C22	111	125	14	
Zawita Dense Forest	C23	115	112		3
Bablo Forest	C24	103	115	11	
Bare Bihar Forest	C25	115	112		3
Garmava Forest	C26	111	114	3	
Zawita Galy Forest	C27	103	114	11	
Kura Forest	C28	87	114	27	
Xrabia Forest	C29	115	111		4
Barushka Seve forest	C30	108	114	6	
Rashanke Forest	C31	115	111		4
Old Zawita Forest	C32	76	112	36	
New Zawita	C33	44	108	64	
Total				**328**	**616**

Table 7. Statistical overview and analysis of burnt area variation between actual (F1) and new (F2) Fire Station Scenarios

Metric	Value	Scientific Interpretation
Total Number of Forest Locations Assessed	33 centers	The study consists of 33 different forest areas (C01 to C33), each representing a unique locational point for assessing efficiency in response to fire damage.
Number of Locations with Increased Burnt Area under F2 (F2 > F1)	12 locations	These are areas where the new fire stations relocation resulted in a greater area burnt, indicating poor performance of the new location.
Total saved Area (Bad column) (F2 - F1)	328 dunums	This cumulative value reflects the total area (in dunums) where forest damage became worse due to slower or less effective response to fire risk in the new scenario.
Number of Locations with Decreased Burnt Area under F2 (F2 < F1)	21 locations	These also represent areas that saw improved fire suppression outcomes under the new fire station deployment, suggesting better spatial access and response time.
Total Saved Area (Useful column) (F2 – F1)	616 dunums	This represents the total reduction in burnt area due to improved fire station access and acceptable locations of fire stations in the scenario F2.
Net Difference in Burnt Area (F2 - F1)	288 dunums	This value confirms a net benefit; the reduced fire's total burnt is 288 fewer burnt dunums under F2, that evidence prompts confidence in the new fire station configuration effectiveness.
Maximum Area Reduction in a Single Forest (Best Improvement)	234 dunums (Linawa Forest – C12)	Linawa Forest exhibited the greatest decrease in burnt area under F2, implying that its coverage significantly benefits from improved spatial positioning of the new fire station which have indicated in Figure (5).
Maximum Area Increase in a Single Forest (Worst Degradation)	102 dunums (Benjarinke Forest – C03)	Benjarinke Forest experienced the largest negative impact, where the proposed location likely hindered prompt response time or accessibility which have indicated in Figure (5).
Mean Reduction per Benefited Forest (21 forests)	29.33 dunums	On average, each of the 21 forests that benefited from F2 saw a reduction of approximately 29.33 dunums in burnt area.
Mean Increase per Worsened Forest (12 forests)	27.33 dunums	Conversely, the 12 forests with increased damage had an average additional burnt area of 27.33 dunums per forest.

➞Mean Reduction indicates the average reduction in burnt area per forest location where the new fire station configuration (F2) displayed improved fire suppression performance.

- ✓ Mean reduction= Total reduction across 12 forests/12
- ✓ Mean reduction= Total reduction across 21 forests/21

4. Discussion

Road type proved to be a key element in the efficiency of wildfire response. Although forest roads made up 73% of the network, thereby providing access to remote areas, the unpaved surfaces and the topographic characteristics limited fire truck speeds to about 30 km/h. Asphalt roads could be driven faster than that, at 60 km/h, owing to their superior structural integrity, which allowed more efficient and reliable movement of the trucks. These estimates correspond with those reported by (Pompa-García et al., 2012; Akay et al., 2012), who used a similar methodology.

Although the present study focuses exclusively on time as the independent variable to predict burnt area, the results can still be meaningfully compared with previous works that incorporated multiple biophysical and climatic predictors. This study developed a time-based model to predict burnt area and improve fire-response efficiency. Since fire growth is directly influenced by elapsed time, time was made the only independent variable. The resulting third-order polynomial model showed an exceptionally high fit ($R^2 = 0.9999$ for calibration; $R^2 = 0.9984$ for validation), indicating a near-deterministic relationship between response delay and fire growth under controlled conditions. In comparison, broader-scale studies that included multiple environmental and climatic variables, such as (Abatzoglou & Williams, 2016), reported $R^2 \approx 0.72$; (Hawbaker et al., 2020) reported $R^2 > 0.70$; and (Parks et al., 2025) reported $R^2 = 0.61–0.63$, thus showing lower coefficients of determination due to spatial heterogeneity and environmental variability. Similarly, previous experimental polynomial models (Namba & Yasuno, 1986) yielded moderate fits with considerable interaction, reflective of experimental noise. These comparisons show that the high R^2 found here is not an artifact but a consequence of the strong causal relationship between time and burnt area. The current model is simplified on purpose, but it adequately represents the inherent temporal dynamics in fire growth. This does not imply that fire behavior is caused by time alone; rather, it identifies the time–area relationship as a base measure of the spread process itself. The model can be considered a strong, relatively robust baseline model, which, in future work, can be implemented with environmental variables, thereby enhancing the prediction and general application of the model.

The Zawita district demonstrates well the overall efficiency of road density and quality in relation to the effectiveness of wildfire response. In Zawita, there was 72% accessibility with the actual F1 station and 70% accessibility with the new F2 station within the critical response time of 20 minutes, mostly due to the density of roads and the road network covering the proposed location, which facilitated vehicle mobility. In contrast, Erbil's nine fire stations could only achieve 44% accessibility to all potential fire sites in 30 minutes of travel time, covering only 6.88% of the total land area, with 17.64% of the forested land (Akay & Aziz, 2015). Compared to Bursa, which had earlier reported (Akay & Kılıç, 2015) a 26.18% accessibility for the high forests and accessibility to coppice forests at 60.29% within the 20-minute response time, Zawita demonstrated higher efficiency, especially with respect to total area covered within that 20-minute response time. When considered in totality, these findings point to the Zawita case as the stronger case study, demonstrating how better initial placement of stations and higher-quality infrastructure connectivity facilitate greater accessibility to reach and suppress fire.

5. Conclusions

The GIS-based comparative network analysis between the present location of Fire Station F1 and Fire Station F2 suggests that both stations offer good coverage for the Zawita District, albeit with different characteristics. F1 currently has slightly greater coverage of forest zones (27 versus 26) in the allotted time of 20 minutes; however, F2 also achieved faster response times in some essential central locations, resulting in a net reduction of 288 dunums of burnt forest area throughout the study region. This means that while neither station can cover the region completely by itself, there is an improvement in overall capacity for emergency responses when both stations (F1 & F2) are considered together.

More generally, the results suggest that the effectiveness of wildfire suppression in mountainous ecosystems and sensitive environments is closely linked to the spatial distribution of firefighting resources. Furthermore, the analysis supports a two-station option in which the use of F1, the actual fire station, and F2, a proposed new fire station, would have greater operational efficiency: F2 would focus on deploying resources in high-risk areas, while F1 would ensure broader coverage of the entire geographic extent of the study area.

The results provide important implications for policy and planning. When supplemented by targeted investments in additional fire stations at strategic locations, the study suggests a significant reduction in wildfire damage, greater protection of biodiversity, and enhanced resilience against escalating threats from climate change. In addition, the analytical method used in this study provides a model that can be replicated by others under similar conditions of a limited resource pool in ecologically vulnerable landscapes. As such, future wildfire management approaches should consider dual-station configurations (F1 + F2) to benefit from greater spatial coverage and consider predictive fire-risk modeling in broader land-use planning and disaster risk reduction approaches. In areas where response time is over 20 minutes, the assessment indicates large gaps in accessibility to emergency response, especially in border forested areas and locations with limited road access. Addressing the gaps in accessibility may entail the need to place satellite substations in high-risk areas, upgrade existing road systems to minimize travel-speed delays, as well as deploy mobile and/or quick-deployment units to respond to remote areas. Expanding these specific initiatives in reactive wildfire management plans would hopefully lead to greater efficiency in public agency response and a reduction of risks.

6. Acknowledgments

I would like to thank everyone who helped or contributed to the completion of this work. I especially thank the Statistics Directorate of Duhok Governorate (SDDG) for information and data that were vital to the study. I would also like to thank the Duhok Forest Directorate for their cooperation and assistance in providing insights into the current forest management and protection system.

I also wish to mention the Firefighting Directorate of Zawita for their essential input relating to fire prevention and response actions and their willingness to share field experiences that proved invaluable to this research.

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مجلهٔ جنگل ایران، انجمن جنگلبانی ایران
سال هفدهم، شمارهٔ ۴، زمستان ۱۴۰۴
ص ۵۹۶-۵۸۱
مقاله پژوهشی

شناسه دیجیتال (DOI): 10.22034/ijf.2026.543401.2065

ارزیابی مبتنی بر سامانه اطلاعات جغرافیایی (GIS) از دسترسی‌پذیری ایستگاه‌های آتش‌نشانی در زاویته، دهوک

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(تاریخ دریافت: ۱۴۰۴/۰۶/۰۴ ؛ تاریخ پذیرش: ۱۴۰۴/ ۰۷/۲۲)

چکیده

آتش‌سوزی‌های جنگلی تهدیدی جدی برای جنگل‌های باارزش بوم‌شناختی منطقهٔ زاویتا در شمال عراق به شمار می‌روند، جایی که فعالیت‌های انسانی و توان محدود در مهار آتش، خطرهای بیشتری ایجاد می‌کند. با وجود استقرار یک ایستگاه آتش‌نشانی (F1) در این منطقه، پوشش خدماتی آن محدود است. از این‌رو، در این پژوهش بررسی شد که آیا افزودن یک ایستگاه آتش‌نشانی جدید (F2) در مرکز منطقه می‌تواند کارایی اطفای حریق را بهبود بخشد یا خیر. با استفاده از نرم‌افزار تحلیل شبکهٔ مبتنی بر GIS (ArcGIS 10.8)، دسترسی جاده‌ای و زمان سفر به ۳۳ ناحیهٔ جنگلی براساس فرضیه‌های مربوط به وضعیت جاده‌های آسفالته و جنگلی مدل‌سازی شد. زمان‌های سفر خودروهای آتش‌نشانی برای هر دو سناریوی F1 و F2 تحت بازهٔ زمانی بحرانی پاسخ‌دهی ۱۵ تا ۲۰ دقیقه محاسبه شد. یک مدل رگرسیون چندجمله‌ای از درجهٔ سوم توسعه داده شد و رابطهٔ میان زمان پاسخ‌دهی و مساحت سوخته‌شده با برازش بسیار عالی ($R^2 = 0.9999$ برای کالیبراسیون و $R^2 = 0.9984$ برای اعتبارسنجی) تأیید شد. پیش‌بینی مساحت‌های سوخته‌شده برای هر دو سناریوی F1 و F2 در همهٔ نواحی جنگلی امکان ارزیابی اثربخشی نسبی آنها را فراهم کرد. ایستگاه F1 در بازهٔ زمانی ۲۰ دقیقه‌ای حدود ۷۲ درصد (معادل ۳۰۵ کیلومتر مربع) از محدودهٔ پژوهش را پوشش داد، درحالی که F2 حدود ۷۰ درصد (معادل ۲۹۳ کیلومتر مربع) را پوشش داد. هرچند ایستگاه F1 یک ناحیه بیشتر از F2 را در بازهٔ بحرانی پوشش می‌داد (۲۷ در برابر ۲۶ ناحیه)، نتایج مدل رگرسیون نشان داد که F2 در نواحی مرکزی کلیدی پاسخ سریع‌تری ارائه داد و در نتیجه سبب کاهش خالص ۲۸۸ هزار مترمربع از مساحت سوخته در منطقه شد. مدل چندجمله‌ای نشان داد که تأخیرهای کوتاه در زمان پاسخ‌دهی تأثیری نمایی بر شدت خسارت آتش‌سوزی دارند که بر ضرورت ایجاد ایستگاه‌های بیشتر و جانمایی راهبردی آنها تأکید می‌کند. مدل پیشنهادی شامل پیکربندی هر دو ایستگاه (F1 + F2) است تا بهترین تعادل میان پوشش جغرافیایی و دسترسی از موقعیت مرکزی حاصل شود. این پیشنهاد سبب افزایش توان اطفای حریق، کاهش از دست رفتن جنگل‌ها و ایجاد الگویی برای برنامه‌ریزی مدیریت بحران در مناطق مشابه دارای حساسیت بوم‌شناختی و منابع محدود می‌شود.

واژه‌های کلیدی: تحلیل شبکه، تحلیل مسیر راه‌های جنگلی بهینه، دسترسی به ایستگاه آتش‌نشانی، سیستم اطلاعات جغرافیایی.

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