

GIS-Based Network Analysis for Assessing Accessible Forest Areas Under Forest Fire Risk: A Case Study of Mangesh District

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Abstract

Wildfires threaten forest ecosystems and the rugged topography of Mangesh District in northern Iraq complicates fire response. The goal of this research was to evaluate access to available fire services, as well as to identify possible locations of high suitability for additional stations, using GIS-Network Analysis. The study utilized the Network Analyst extension in ArcGIS 10.8 to study the road network, response routes and service areas in the 487 km² study area of Mangesh District. The processed DEM reveals substantial topographic variation, with elevations ranging from 499 m to 1512 m above sea level. Road network data, topological data, and fire sensitive zones were utilized to identify the best travel routes, response coverage for emergency services within critical response times, and potential sites for a new fire station with the Closest Facility, Service Areas, and Location-Allocation models. The analysis indicated that the actual fire station (F1) has access to 25 of 39 potential fire zones, approximately 58% of the district, in the all-important 20 minutes response time. The other 42% of forested areas were outside of adequate coverage. The Location-Allocation model proposed two additional optimal fire stations (F2, and F3) and added to cover all 39 forest zones within or adjacent to the 20 minutes threshold, access, and emergency preparedness substantially improved. The GIS network analysis was a productive method for assessing and improving the fire response framework for the Mangesh District. The addition of the proposed fire stations also causes a substantial decrease in response time, coverage, and sustainable forest management. The results provide a model for enhancing improvements in wildfire management and emergency planning in other mountainous and ecologically sensitive regions.

Keywords: GIS; fire station accessibility; Location-Allocation Analysis; ArcGIS; network analysis.

1. Introduction

Forests are an extremely important ecosystem that maintains biodiversity, bolsters hydrology, stabilizes soils, and provides a major contribution to global carbon transport and cycling. Wildfires, however, are one of the most significant natural disturbances affecting forest resilience worldwide. Almost 500 million hectares of forest, savanna and open-forest landscapes across tropical and

subtropical landscapes are burned annually due to wildfires. Forest area degraded annually is estimated to be (10 – 15) million hectares in boreal and temperate forests and (20 – 40) million hectares in tropical forests [1]. These extensive disturbances negatively impact land degradation, greenhouse gas emissions and ecological disturbance at different scales. Wildfires are usually categorized as ground,

surface or crown fires. Surface and crown fires present the most risk due to fast spreading and destruction [2].

Wildfires can be ignited by a wide range of causes including accidents, human carelessness, arson, lighting, and other unknown causes. Fire behavior is shaped by fuel type, fuel availability, weather conditions, and topographic characteristics [3]. Seasonal fire patterns show two dominant peaks: spring fires commonly linked to agricultural residue burning and summer fires, which are often associated with increased human activity and tend to produce more severe damage [4]. In many regions, timely suppression is complicated by logistical challenges, delays in access, and the rugged terrain that increases travel times for response crews. Effective suppression depends heavily on adhering to critical response-time thresholds, where rapid intervention significantly reduces burned area [5]. Research shows that only 21.9% of fire suppression vehicles reach ignition sites within 15 minutes, and shortening response times to (15 – 20) minutes could reduce burned area by up to 70% [6]. Response times may be longer than (40 – 60) minutes in mountainous settings [7].

To effectively access locations of active fire feet, a detailed analysis, planning, and review process is needed incorporating Geographic Information Systems (GIS) and network analysis tools. For example, fire crews who are not officials and who are not familiar with roads may have trouble getting through a forest road in an emergency situation. Plus, as roads are blocked or damaged and fire conditions change, it becomes complicated for employees on the ground to route back to the fire. Network analysis methods utilizing GIS allow for the systematic review of the best paths of travel and reliable travel routes in relation to travel delays [8]. In forestry, GIS is increasingly used for fire prevention and protection, watershed management, management of forest operations, and planning transportation, as GIS provides effective means of collecting, storing and

manipulating data, and implementing spatial analysis [9,10]. Models, like Network Analyst in ArcGIS v. 9.2 and beyond, that can utilize GIS have demonstrated significant improvements in efficiency in transportation and other applications related to or during an emergency [11]. GIS-based fire analysis can also provide increased speed, lower operational costs, and increased accuracy in pertinent firefighter hub planning [12]. Improved spatial coverage and accessibility still require an optimized road network and possible additional fire access routes to access ignitions points within existing fire sensitivity classified timeframes [13]. Studies from Turkey and Greece are appropriate because they share similar climates, topography, and fire behavior to northern Iraq. They use GIS-network analysis methods that are required in this study, and their findings on response time, access, and station coverage strongly justify applying the same techniques to evaluate wildfire response in the Mangesh region.

In recent decades, the Kurdish Region of Iraq has experienced considerable forest loss attributable to the widespread effects of fires and outright deforestation. Between 1999 to 2018, the region has experienced the loss of nearly 2.2 million acres (approximately 890,000 hectares) of natural and planted forests, which affirms a 47% reduction in forest cover, of which about 526,000 hectares burned during the eight years preceding 2018, as fire intensity peaked between 2015 and 2018 [14]. Despite widespread documentation of forest loss and fires in other regions, few studies have assessed the accessibility and response-time performance and operational effectiveness of firefighting in the Mangesh region. Furthermore, no holistic GIS-based study has considered whether the current station is able to reach vulnerable forest areas within the critical response times proposed for different fire sensitivity levels. The lack of spatial analysis and operational analysis represents a significant gap in research knowledge in a region that is particularly

vulnerable to repeated and significant wildfire destruction.

The primary aim of the research is aimed to evaluate the current operational effectiveness of the firefighting station located in the Mangesh area by utilizing the Network Analyst extension in ArcGIS 10.8. The assessment incorporates two main analyses: (1) determining the optimum travel routes and minimum travel times from the firefighting station to 39, pre-identified zones that were considered potential areas for fire, and (2) analysis of service area coverage spatially within several emergency response time windows. The study then establishes potential alternative or additional locations for fire stations to improve coverage, minimize

response time, and provide enhanced capacity for managing wildfires.

2. Material and Methods

The study workflow is depicted in (Figure 1), which describes the steps taken to evaluate the accessibility of forest-fire response in the Mangesh District. The flowchart summarizes the preparation of spatial data, the creation of the network and travel-time dataset, and the integration of the geospatial layers. Subsequently, the flowchart illustrates the key analyses using Network Analyst Service Area, Closest Facility, and Location-Allocation that contribute to the operational framework of the study. The order of the flow of work provides a succinct summary of the analytical processes used to assess firefighting accessibility in the district.

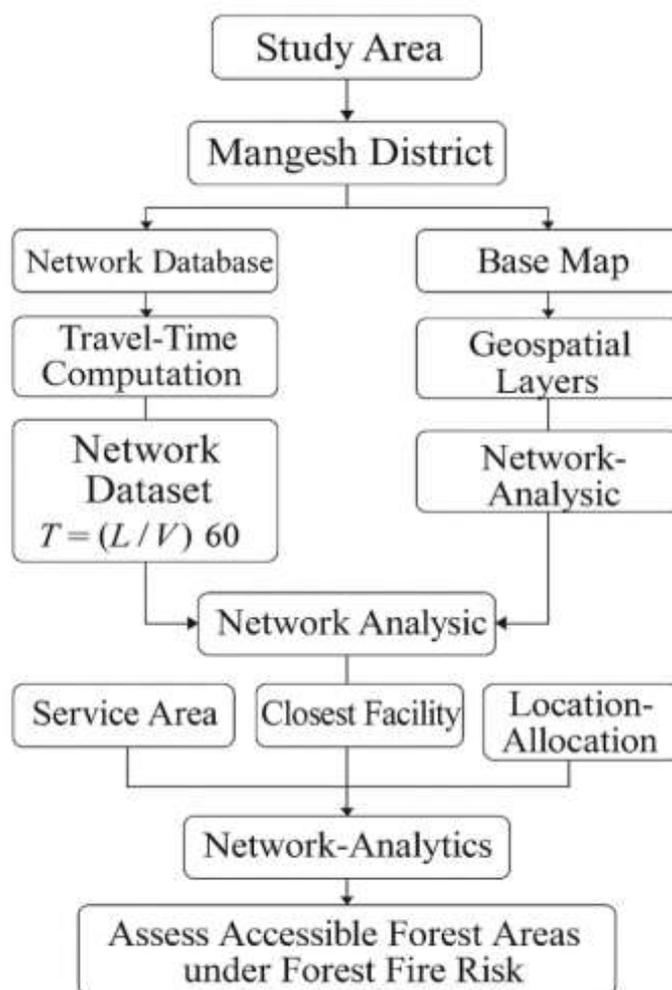


Figure 1. Methodological Workflow of the Network Analysis Process in proposed area.

2.1. Study Area

This study was conducted in the Mangesh District, which covers about 487 km² of the Duhok Governorate in the Northern of Iraq. The district is located approximately at 37°02'07" N and 43°05'29" E. The district is primarily mountainous and hilly as shown in (Figure 2). The climate in the region transitions between semi-arid and Mediterranean climate types, so there are hot, dry summers, with maximum temperatures often reaching (35 – 40) C°, and cold, wet winters. Rainfall is constrained to a period between November and April and total average rainfall throughout the district varies between 400 and 700 mm yearly (depending on elevation), but can be encountered unevenly due to orographic conditions. Snow typically occurs at and above the higher elevations of the district, while valley bottoms

generally have no snow cover. Vegetation cover is a heterogeneous mixture of woodlands, shrublands and grasslands. Hillslopes were dominated by drought-tolerant woodland species such as *Quercus Aegilops* L., *Pistacia khinjuk* Stocks., and *Prunus orientalis* Mill., and the valley systems contained more dense vegetation as well as a riparian community. At present, only one actual fire station (F1) (37°02'10" N, 43°05'37" E) Mangesh district (C22) is established to provide emergency fire services to the district. However, rugged landscapes, settlement patterns, limited road access, and long travel time all restrict the fire coverage area of the fire service. As a result, fire coverage area is lower in many parts of the district with some being km from timely response.

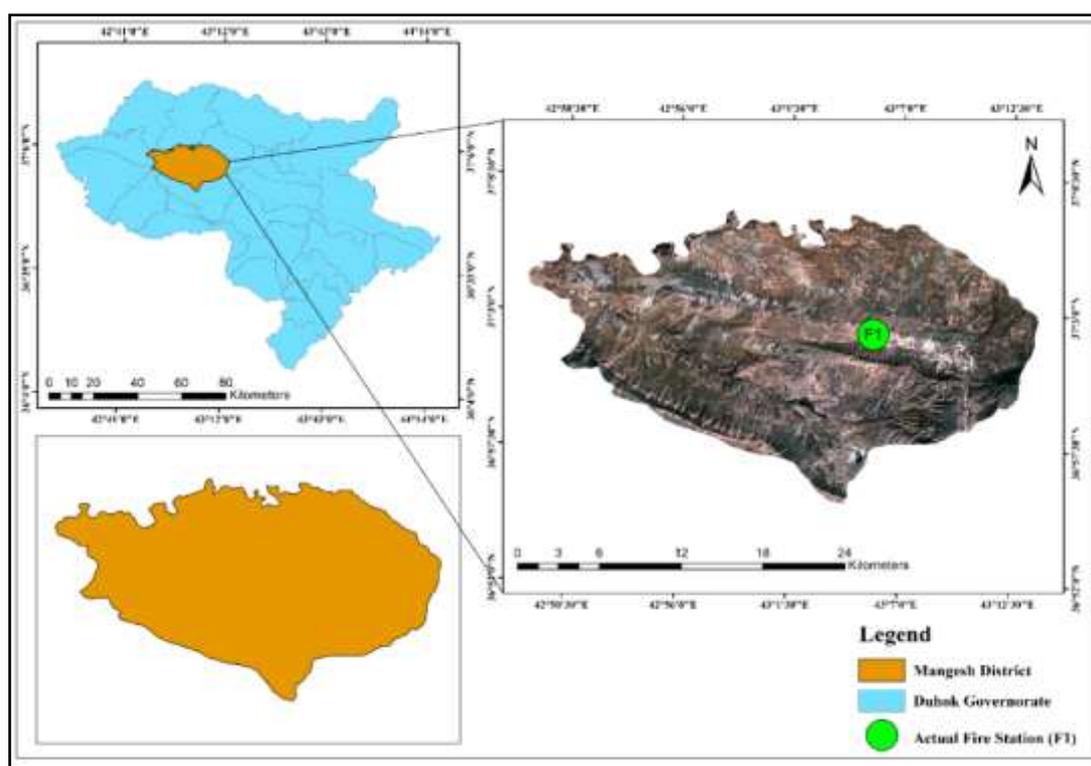


Figure 2. The Proposed Study Area.

2.2. Topographical Maps

To accurately represent the terrain characteristics of the study area, a 12.5m resolution Digital Elevation Model (DEM)

with radiometric corrections was obtained from NASA's Earth Data repository (Figure 3). The DEM tiles were mosaicked and clipped to the study-area boundary using a

masking procedure. For spatial consistency with Sentinel-2 imagery, the dataset was resampled to a 10m resolution using the nearest-neighbor method in ArcGIS 10.8. The processed DEM reveals substantial topographic variation, with elevations ranging from 499m to 1512m above sea level. While the landscape is primarily characterized by gentle to moderate slopes, steep and rugged areas are noticeable with slopes reaching a

maximum gradient of approximately 430%. Steep landforms exist in two types of geomorphic settings: linear and clustered along ridgelines and dissected valleys. The existence of these steep landforms indicates that although steep and rugged landforms cover a disproportionately smaller amount of the study area, they form an important part of the geomorphology in the study area.

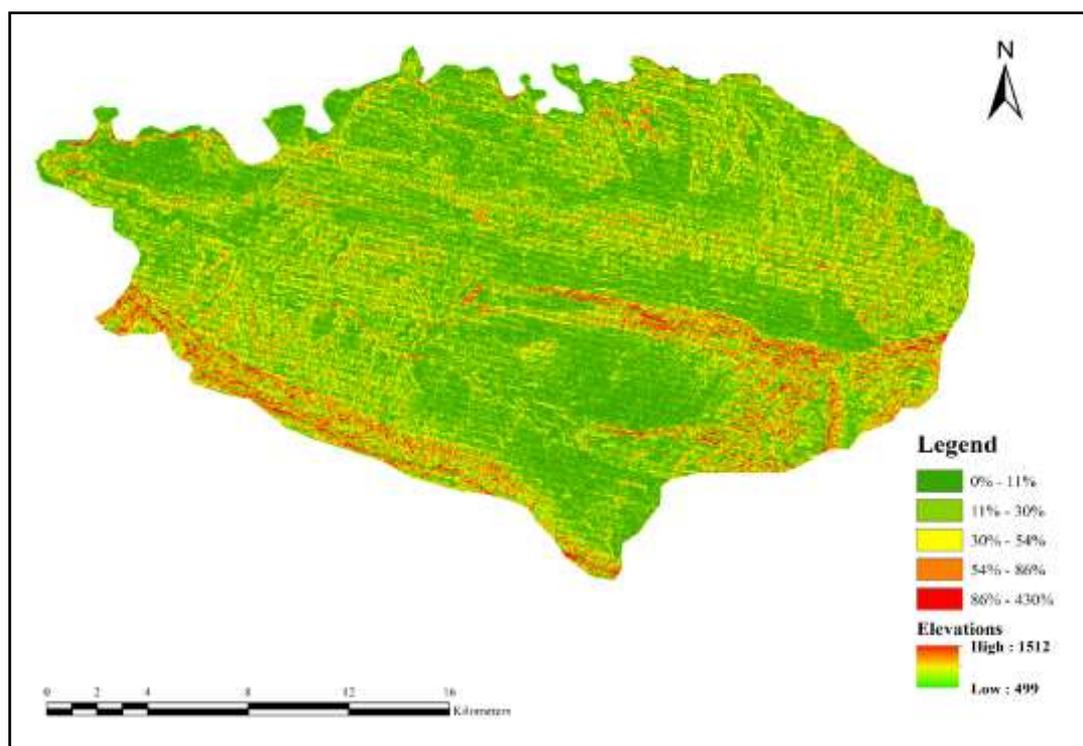


Figure 3. DEM of The Study Area.

2.3. Road Network

For network analysis, focused on the base map in ArcGIS 10.8 as a spatial foundation to utilize in the Mangesh District area. The base map was composed of geospatial layers of Mangesh District that provided specific details, like the road network, administrative boundaries, forest cover, water bodies, and other resources in a spatial resolution of 1:25,000. The road network layer was particularly important for defining nodes (or intersections) and edges (road segments), so we could analyze shortest paths, service areas, and optimized routing from the actual fire

station (F1) to the forest and natural resource areas. The combination of forest and water body layers provided an analysis of assess ability and response reach of fire services from the critical zones into the natural and resource areas. Using a base map and layers that were topologically consistent and attribute-rich, facilitated and allowed for an accurate and reliable network analysis suitable for planning forest fire management and emergency response for Mangesh District. The road network map was designed based of the topographical map of the study area.

From the network database, the average travel time of firefighting trucks for each road segment within the study area, was computed based on the road length and average speed of a firefighting truck. Firefighting truck speed was according to the type or location and condition of the road being traveled. The study area had two lanes of road: asphalt roads and forest roads.

The "Attribute Table" of the road network map included several fields for a number of parameters related to speed, road length, road condition, and travel time. Road length was determined within the Attribute Table using "Calculate Geometry." Road condition, or pavement surface type, was classified as either good, average, or poor as acquired from the information and data obtained through the Highway Department, the Forest and Rangeland Directorate in Duhok. Average speed for vehicles was determined by road type and condition whenever applicable. For asphalt roads, 60 km/hour was assigned the average speed with the good road condition. 30 km/hour was assigned as the average speed for forest road in good condition. Both estimates agree with previous studies from northern Iraq and other similar mountainous areas, where average traveling speeds were mostly influenced by the road surface type and

topography instead of legal speed limits [15,16]. Fire truck travel time for each section of the road was calculated using Equation (1), using the Field Calculator function in the attribute table of the road network map [17,18].

$$T = (L / V) * 60$$

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)

2.4. Network Analysis

The Network Analyst extension found in ArcGIS 10.8 functions according to a set of network analysis principles. It supports network analysis based spatial analyses such as routing, service area creation, closest facility analysis, and location-allocation modeling as shown in (Figure 4). Using an advanced model of a network the extension enables the user to quickly create networks from a GIS database. Network Analyst further allows for the dynamic simulation of a realistic network, including turn and height restrictions, speed limits, and traffic fluctuations.

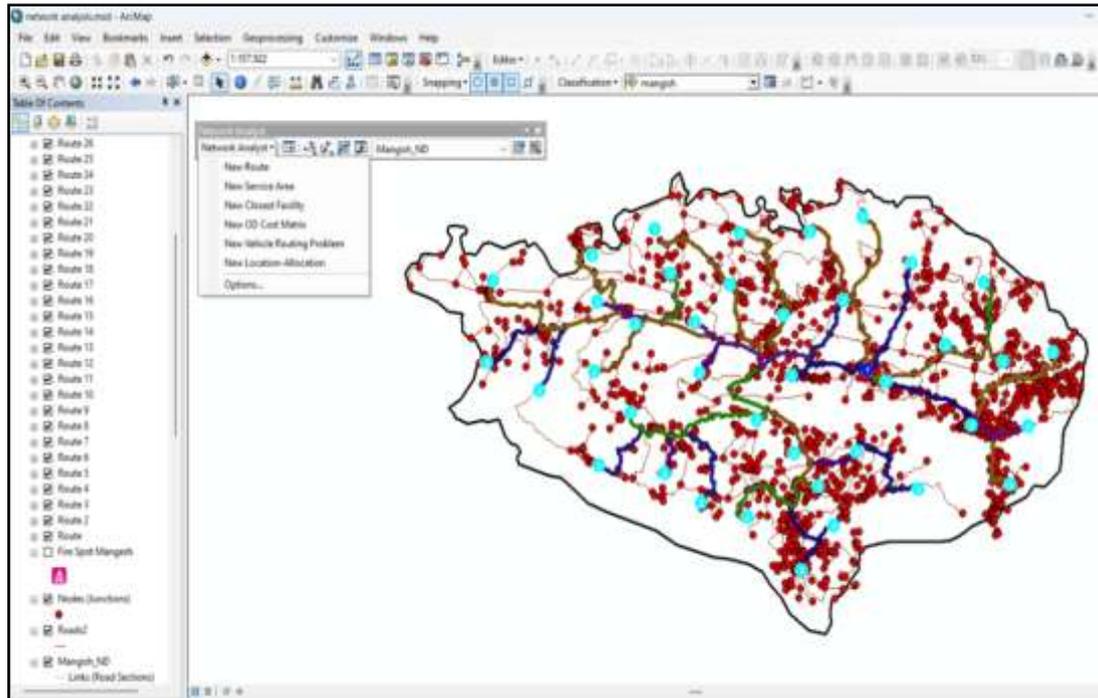


Figure 4. Network Analyst Toolset in ArcGIS 10.8.

To execute the analytical methods provided by the Network Analyst extension, a network database must first be created. In this study, a Personal Geodatabase was developed using the ArcCatalog module. Subsequently, a network dataset was constructed based on a road type map that included travel time

information for each road segment within the study area as shown in (Figure 5). Finally, the link (ND Edges) and node (ND Junctions) data layers were generated from the established network database.

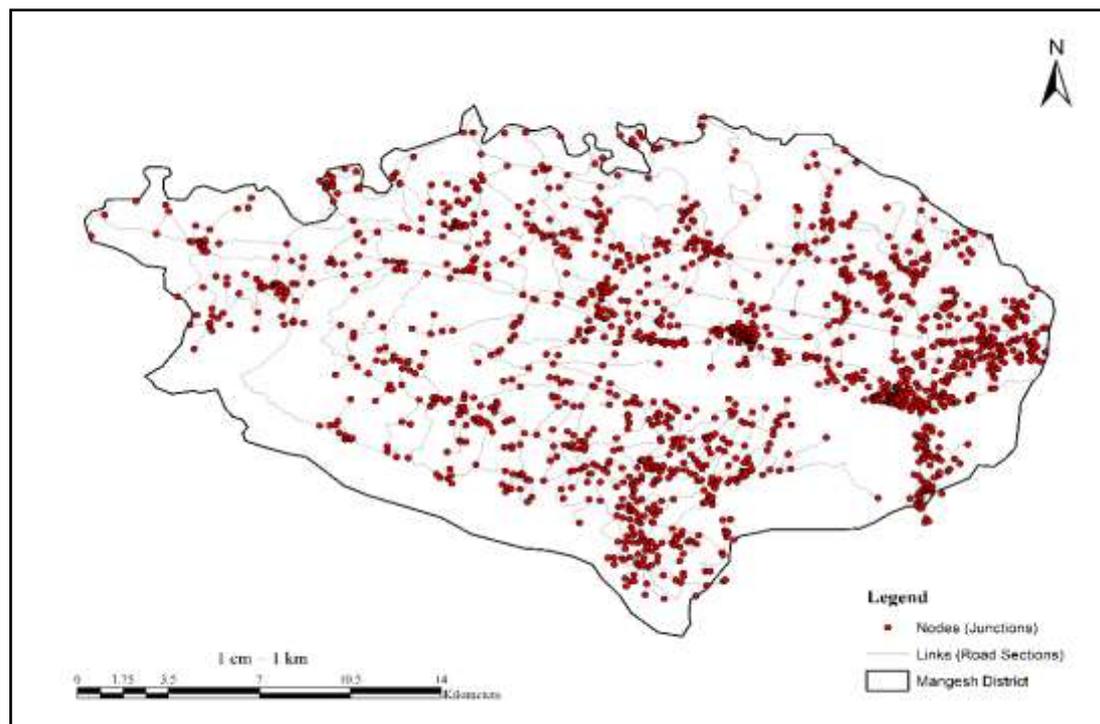


Figure 5. Link and Node Data Layers in Network Dataset.

Following the creation of the Network Dataset, the network analyses were carried out using ArcMap, which is the module of the ArcGIS software package. In this step, the tools “New Closest Facility”, “New Service Area”, and “New Location-Allocation” - all available in the Network Analyst extension were employed separately to assess spatial accessibility, optimal routing, and the allocation of fire stations.

2.4.1. New Closest Facility

The “New Closest Facility” approach was used to determine the optimal pathways between possible locations of fire occurrences in the analysis area and an actual fire station

(F1). First, travel times to assess the principles of the closest facility to each of the current 39 identified fire zones were determined for the fire services responding team. Under this approach, the geospatial data layers provided the positions of both the actual fire station (F1) and the potential fire zones in the analysis study area as exhibited in (Figure 6). This method is consistent with the previous studies that employed GIS-based Network Analyst Closest Facility analysis to improve emergency response routing and minimize travel time from the incident site to a response center [19,12].

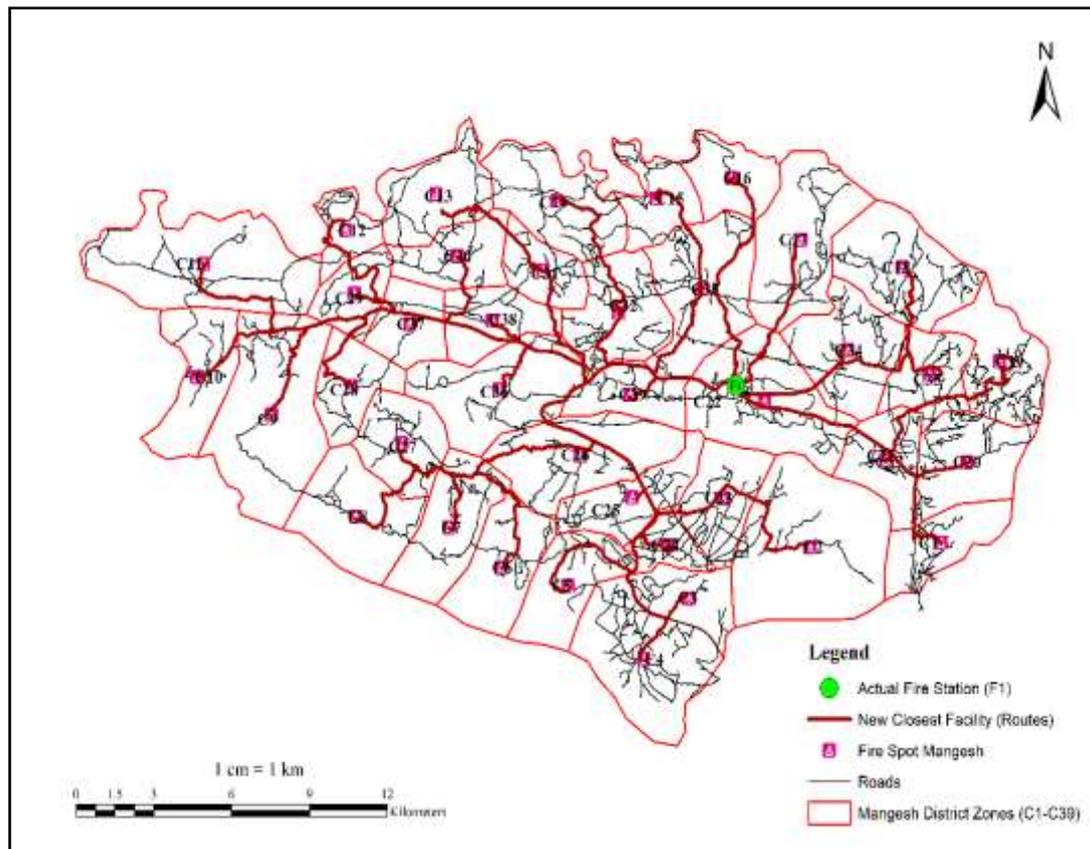


Figure 6. Optimum Routes to the Fire Point.

2.4.2. New Service Area

To make forest fire management more effective, it is important that firefighting team (i.e., think of them as operational unit) stationed as actual fire station (F1) respond to a fire on site within a critical response time. In this study, the New Service Area (NSA) method was applied to function map and assess the forest areas that could be reached in a critical response time. The NSA method is based on the same principles as Buffer Analysis; however, it takes place on a network-based system that utilizes actual roads to connectivity between locations, which also considers travel time as just a straight-line distance to drive to a location. The actual fire station (F1) is taken as a service point, with all

areas potentially reached based on time taken established by the user, mapped throughout the network. This method was used to determine forest areas that could be accessed by the firefighting team within a critical time response and beyond. A critical response time of 20 minutes was used based on the fire sensitivity and vegetation type of the study area and ecological vulnerability as shown in (Figure 7). Past research work has utilized comparable network-based spatial analyses, including the New Service Area and accessibility-related models, to evaluate response capacity for firefighting services and to efficiently allocate firefighting resources in forest landscapes [20,8].

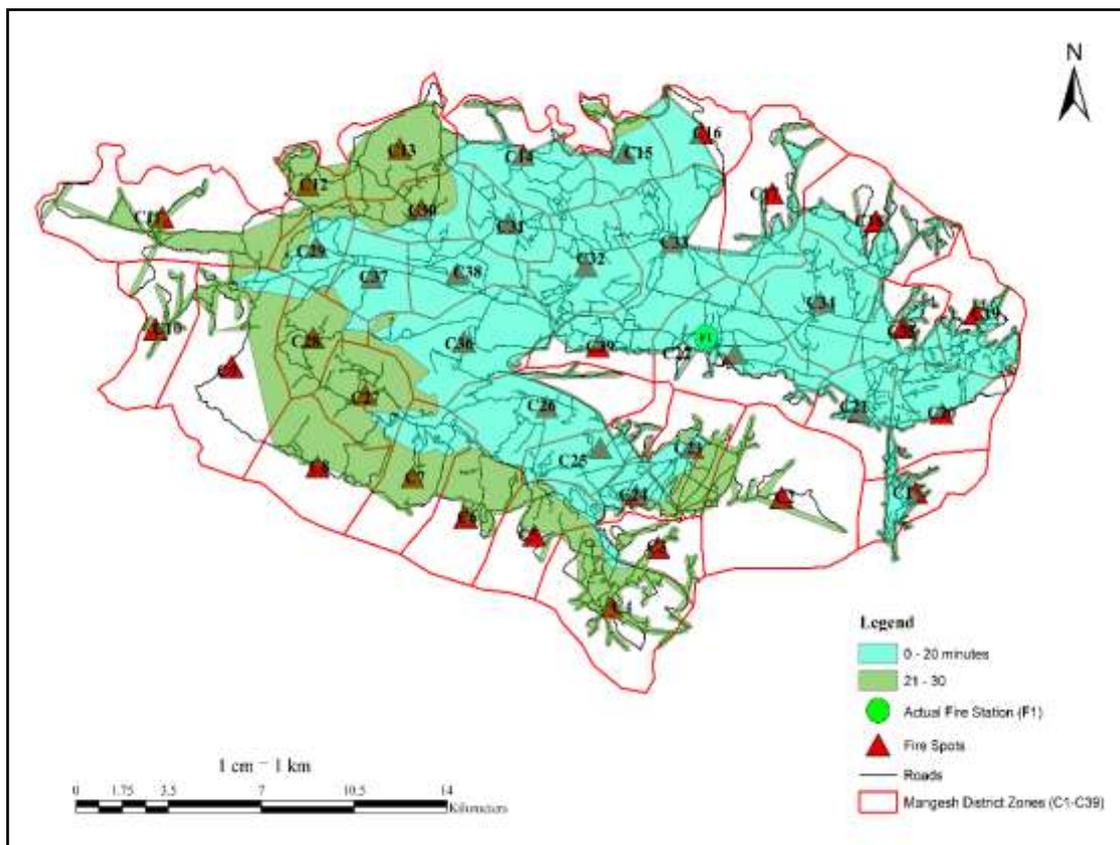


Figure 7. Coverage Areas of Actual Fire Stations (F1) within and beyond the 20 Minutes Critical Response Time.

2.4.3. New Location-Allocation Method

To enhance fire management of wildfires and reduce times under the current fire management program with incomplete fire station coverage (F1), the new location-allocation method was adopted in this study as shown in (Figure 8). This approach examines travel times, accessibility in the network, and spatial distribution of areas most at risk from forestry burns to determine potential placements of additional fire stations. Two new fire stations, (i.e., F2 and F3), were determined based on this method that may help cover forested areas not currently included in this study. (F2) is located at (36°58'33"N, 43°03'29"E) Beshinke rural

(C05), and (F3) is located at (37°03'01"N, 42°53'47"E) Ashanik rural (C09) were selected in both of these locations because they improve potential fire response for areas under coverage because every area is still covered in the desired response time. This strategy was followed in order to minimizing time and delay lost in the intervention and managing in order to potentially improve forest fire management. This method facilitates a more tactical planning of the fire service where actual fire stations and new placements could reach all of the area sufficiently, increase the ability to cover the entire forested area, and create a network of fire prevention and timely fire response.

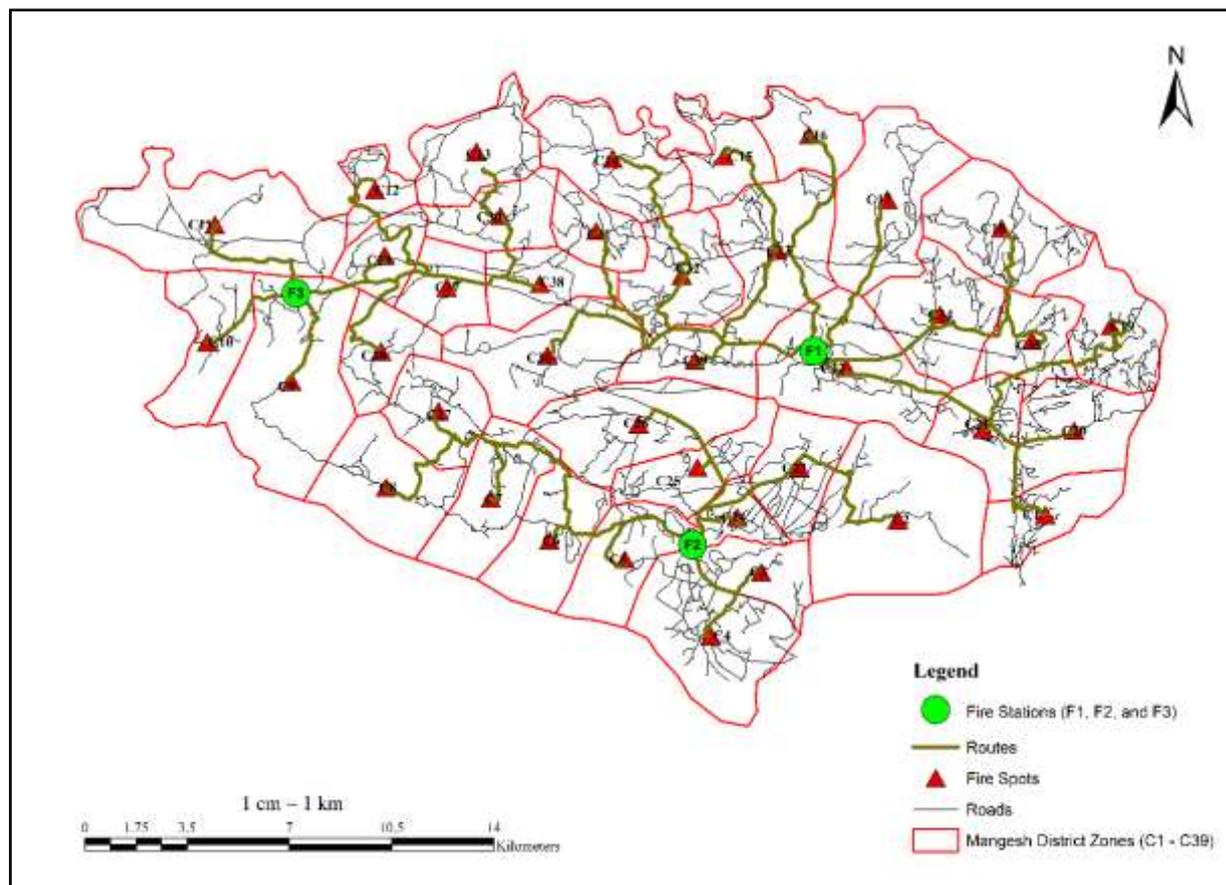


Figure 8. Location-Allocation Map of Fire Stations (F1, F2, and F3) and Fire Incidents Across Mangesh District.

3. Results and Discussion

3.1. Road Network

All the roads in the proposed study area (487 km²) cover a distance of 946 km of road. Forest roads comprise the majority of the road types at approximately 82% (772 km), while asphalt roads account for 18% (174 km) as shown in (Figure 9). This is equivalent to a total of about 1.94 km of road per km², with the forest roads having both the highest density and complexity. Forest roads are primarily local collector-level roads that

access remote or forested locations, while asphalt roads (i.e., although fewer in number) serve as the primary mode of transportation connecting major villages and the primary access locations. The structure and surface conditions of both types of roads were formally assessed and found to have suitable conditions for emergency vehicles including fire trucks to operate from. Forest roads, although not paved, were still assessed to have desirable conditions to access during an emergency.

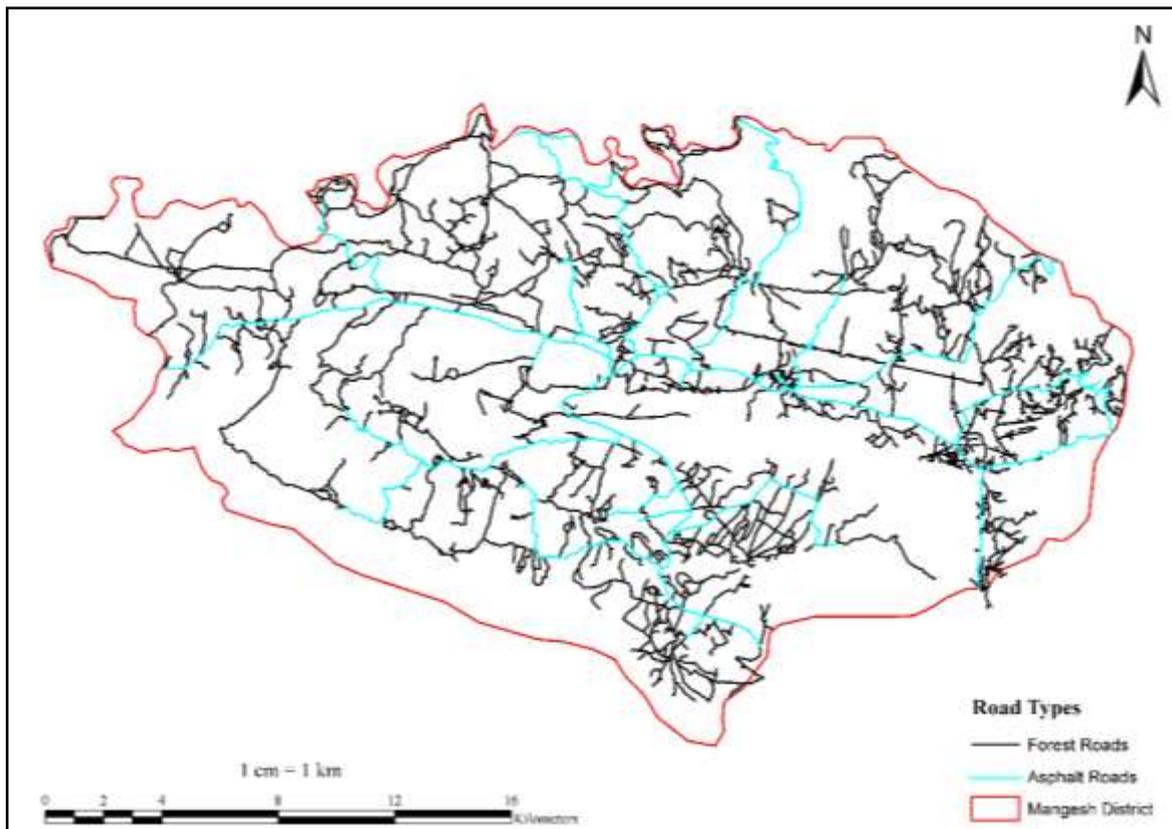


Figure 9. The Study Road Network Map.

3.2. Network Analysis

3.2.1. New Closest Facility

The "New Closest Facility model" has established that 25 out of the 39 sites for forest fires indicated in the study were reachable within a maximum of 20 minutes, indicating the critical response time based on data from the existing fire station (F1) as shown before in (Figure 6). In comparison, the study found that 14 of the forest fire sites were beyond the critical response time of 20 minutes, therefore

it indicates that the existing fire station (F1) provides limited coverage in that 20 minutes range as given in (Table 1), totaling 64% of the forest area within the 20 minutes of travel from the actual fire station (F1). [21], provides an interesting comparison from Tirana, Albania, which found that only 27% of forest area was accessible in the critical response time of 20 minutes, based on the spatial distribution of the existing initial response teams.

Table 1. Response Times (in Minutes) Coverage of Actual Fire Station (F1) Across Study Area Zones.

Category	Number of Zones	Zone Names & Times (Minutes)
≤ 20 minutes (□)	25	C01 (13), C14 (15), C15 (18), C16 (14), C17 (09), C18 (14), C19 (18), C20 (10), C21 (08), C22 (01), C23 (19), C24 (20), C25 (15), C26 (12), C29 (19), C30 (20), C31 (13), C32 (11), C33 (08), C34 (07), C35 (13), C36 (13), C37 (15), C38 (13), C39 (06)
> 20 minutes (□)	14	C02 (26), C03 (23), C04 (23), C05 (25), C06 (24), C07 (23), C08 (24), C09 (27) C10 (24), C11 (30), C12 (24), C13 (24), C27 (21), C28 (25)

3.2.2. New Service Area Method

The New Service Area method was utilized to determine areas served for actual fire station (F1) critical response times. Since some areas of the study are classified as first- and second-degree forest fire-sensitive areas, the road network was assessed for buffer areas of evidence based-access travel time of (0 - 20) minutes and (21 - 30) minutes. The assessment indicated that the primary response team in our study was able to access roughly 284 km² of the study area that encompasses 487 km² of forest area within the response time of (0 - 20) minutes, or 58.32% of the study area. An additional 203 km² (41.68%) could be accessed in (21 - 30) minutes of travel time as shown in (Figure 7). Similar findings were noted in the study conducted by [22] in Bursa, Turkey through GIS-based network analysis of the Sarnıç Forest Enterprise Chief firefighting teams, in which it was reported they located 26.18% of high forests and 60.29% of coppice forests that were accessed within 20 minutes of response time.

3.2.3. New Location-Allocation Method

Spatial optimization of fire service coverage was evaluated using a GIS-based location-allocation model for Mangesh District. The model produced three optimal sites for fire stations (F1, F2, and F3) that minimized the response times and maximized service coverage during the critical response window

of 20 minutes as shown in (Figure 10). The allocation results, shown in (Table 2), indicate that F1 is responsible for 17 zones, mainly in the northeastern and central areas, which had estimated response times of 1 to 18 minutes. F2 covered an additional 12 zones in the southern and southeast areas, with times ranging from 4 to 18 minutes. F3 covered ten zones in the western areas with response times of 4 to 20 minutes. This means that all of the 39 zones (C01 - C39) were either within 20 minutes or adjacent to the boundary at 20 minutes to the potential fire event, confirming that the distribution of the fire service currently provides optimal access to possible fire events across the Mangesh District. These findings are consistent with findings from previous GIS-based studies of emergency facilities that have emphasized spatial optimization for avoiding delays in response to emergencies. [23] for example found that taking into account both capacity and demand in location-allocation models is an important contributor to overall coverage of service. [24] found that spatial optimization along with accessibility analysis improves the effectiveness of urban fire station placement, and [21] assessed the placement of initial response teams in Tirana, Albania, and found that only 27% of forest areas under existing conditions were reachable in terms of critical response time, whereas accessibility improved

to 65% with added optimally deployed initial response teams.

Table 2. Estimated Arrival Times (minutes) of Fire Stations (F1, F2, and F3) to Potential Fire Locations within the 20 Minutes Critical Response Period.

Fire Stations	Number of Zones	Zone Names & Times (Minutes)
F1	17	C01 (13), C14 (15), C15 (18), C16 (14), C17 (09), C18 (14), C19 (18), C20 (10), C21 (08), C22 (01), C31 (13), C32 (11), C33 (08), C34 (07), C35 (13), C36 (13), C39 (06)
F2	12	C02 (12), C03 (05), C04 (05), C05 (07), C06 (07), C07 (17), C08 (18), C23 (05), C24 (05), C25 (04), C26 (07), C27 (15)
F3	10	C09 (08), C10 (04), C11 (10), C12 (13), C13 (20), C28 (12), C29 (06), C30 (14), C37 (07), C38 (11)

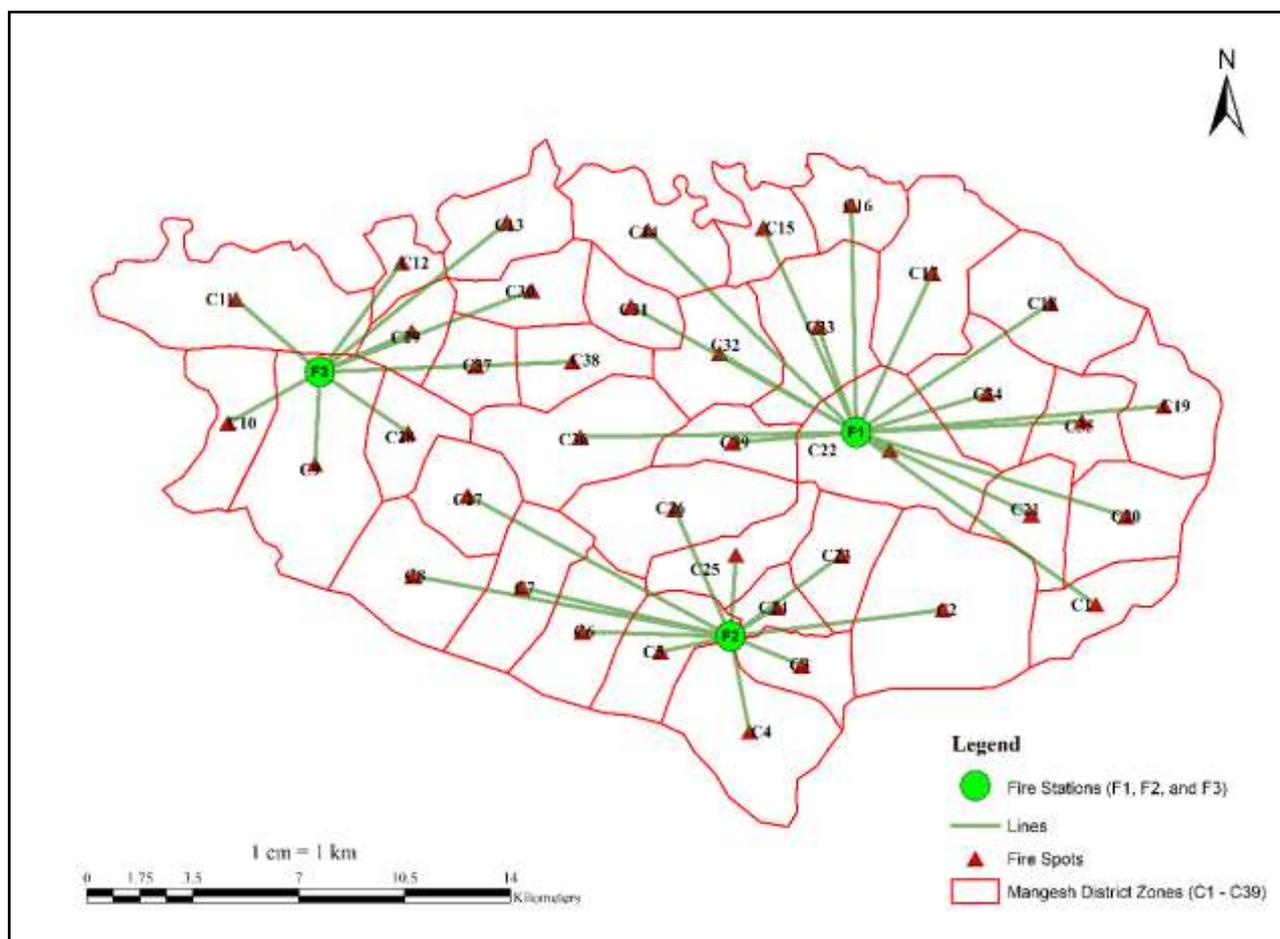


Figure 10. Accessible Areas within a 20 Minutes from Fire Stations F1, F2, and F3 Across the Whole Study Area.

4. Conclusion

This study used geographical information system (GIS) based network analysis to analyze and improve the accessibility of fire stations in the Mangesh District of the Duhok Governorate in Northern Iraq. The study indicated that the actual fire station (F1) covers only about 58% of the study area within the critical 20minutes response timeline, thus leaving a significant amount of "under covered" less populated forested area. A location-allocation model identified 2 additional proposed optimal fire stations (F2 and F3) which increased the overall service area coverage, covering all of the identified fire zones (39) all of which were located west of the critical 20 minutes travel time.

These results suggest that GIS-based spatial analysis has substantial promise as a decision-support tool in planning for more efficient emergency response operations to all hazards in mountainous and ecologically sensitive areas. Not only does optimizing the station network improve response times, but it also helps in minimizing environmental degradation, loss of biodiversity, and key forest resources in areas already feeling the effects of climate and topographic vulnerability.

The larger implication of this study provides a replicable, data-driven framework for fire management planning which could be implemented in other districts across the Northern of Iraq, or in similar landscapes around the world. Incorporating spatial optimization techniques, such as demonstrated in this study, into fire management systems, will ultimately improve preparedness, reduce environmental and economic losses, and facilitate sustainability of forest landscapes increasingly challenged by wildfire potential.

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