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Management of Low Volume Roads: A Decision Support Tool for Sustainable Wildfire Prevention and Maintenance Resources Allocation Via GIS-Network Analysis

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Abstract

This study presents a GIS-based decision support system (DSS) for prioritizing forest road network maintenance to enhance wildfire prevention and suppression in Mediterranean forest regions. The research focuses on low-volume roads (LVRs), which play a critical role in fire response operations but often suffer from limited maintenance resources and accessibility constraints. Using GIS-based network analysis, the study integrates road hierarchization, wildfire risk modeling, and optimal route determination to develop a structured approach for forest road maintenance prioritization. The methodology involves segmenting and evaluating road networks based on travel time, slope, and fire risk exposure, enabling a data-driven ranking system that identifies critical access routes for emergency response. The study applies the Closest Facility method to determine optimal routes from firefighting vehicle stations to various locations within the network. Results indicate that a targeted maintenance strategy, prioritizing high-risk road sections, significantly improves fire response efficiency while optimizing resource allocation in financially constrained forest management frameworks. This approach introduces a sustainable and cost-effective framework for forest road infrastructure planning, offering a practical tool for decision-makers in fire-prone regions. By ensuring proactive maintenance scheduling, the proposed method enhances wildfire resilience, reduces emergency response delays, and supports long-term forest sustainability.

Keywords

Road maintenance, road hierarchization, forest management, optimal routes, spatial optimization, sustainability.

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Introduction

The term low-volume roads (LVRs) refer to road networks characterized by limited vehicular traffic flow. These roads typically include forest roads, agricultural roads, and, in many cases, rural connector roads that link settlements (Praticò et al., 2011). LVRs serve as permanent infrastructure elements, commonly found in mountainous and semi-mountainous regions, as well as in rural areas beyond urbanized zones (Selva et al., 2011; Kolkos et al., 2024). These roads play a crucial role in facilitating accessibility, economic development, and resource management in remote and sparsely populated areas (Arabatzis et al., 2010; Mavraki et al., 2020). Despite their limited traffic load, LVRs are essential for forest management, agricultural activities, emergency response, and rural mobility (Mavraki et al., 2020). Due to their location and function, they often exhibit unique geometric, structural, and maintenance challenges, requiring tailored engineering approaches to ensure sustainability, resilience, and cost-effectiveness (Ferenčík et al., 2019; Akgul et al., 2017). The design, maintenance strategies, and environmental impacts of LVRs is critical for optimizing their long-term performance and minimizing degradation, particularly in areas prone to erosion, extreme weather conditions, and limited funding for infrastructure maintenance (Yolmeh et al., 2021; Ghajar et al., 2013).

The prevention and suppression of wildfires are closely linked to the forest road network, which serves as the primary means of transportation for firefighting forces to reach affected areas efficiently (Cristan et al., 2016). Given the increasing frequency and severity of wildfires, the role of forest infrastructure in fire management has become more critical than ever. Adequate road networks not only facilitate rapid emergency response but also enable the strategic deployment of resources, minimizing the extent of fire damage (Thompson et al., 2021). Beyond their function as access routes, forest roads play a crucial role as a fundamental protective measure in wildfire management. Their presence significantly enhances the capacity for effective fire suppression, particularly in rugged and remote landscapes where ground-based firefighting operations rely on mechanized interventions (Dinca et al., 2025).

The effectiveness of forest roads in wildfire response is highly dependent on their design, maintenance, and strategic planning. Poorly maintained roads can hinder rather than aid suppression efforts, delaying response times and increasing the risk to both firefighters and forest ecosystems (Thompson et al., 2021). Therefore, an integrated approach that considers road network optimization, sustainable forest management, and technological advancements in fire monitoring is essential to enhance wildfire resilience (Arabatzis et al., 2024; Kolkos et al., 2023). The maintenance of forest road networks represents an urgent and fundamental challenge in forest infrastructure management (Riid et al., 2020). Insufficient attention and inadequate funding have led to a concerning deterioration of road conditions, directly hindering wildfire response efforts and compromising the overall sustainability of forested areas. As forest fires become increasingly frequent and severe due to climate change and land-use transformations, the condition of forest roads plays a decisive role in determining the efficacy of emergency interventions and resource accessibility (Ranyal et al., 2022).

The structural composition of road pavements consists of multiple layers of geotechnical materials, which enhance both strength and functionality. In many cases, forest roads are constructed using either a single base layer or a two-layer system comprising a base layer and a surface layer (Daigle, 2010). The majority of forest roads are designed as unpaved pathways, typically built using freely available coarse material. Furthermore, forest roads include a subset of LVRs, which are characterized by low traffic volumes (Chandak et al., 2019 ; Tsiotas et al., 2023). The design of a forest road is a complex engineering challenge, requiring the integration of economic and environmental considerations. In particular, construction and maintenance costs play a dominant role in the total cost of forest harvesting operations (Akay, 2003). Poor construction practices and inadequate maintenance can have significant environmental consequences, potentially causing greater ecological damage than other forestry-related activities (Anderson and Lockaby, 2011). Consequently, the alignment and placement of forest roads require careful evaluation to balance construction and maintenance costs while adhering to design requirements and environmental protection standards (Robinson et al., 2010).

The development of a Road Network Analysis System is essential for evaluating the connectivity, accessibility, and efficiency of transportation networks. This system integrates spatial data, network topology, and advanced analytical techniques to assess various factors such as travel time, route optimization, and network hierarchy. By leveraging geographic information systems (GIS) and network modeling, the system enables the identification of optimal routes, critical infrastructure, and areas requiring maintenance or upgrades (Comber et al., 2008). A well-structured road network analysis system enhances decision-making in transportation planning, emergency response, and infrastructure management (Neville et al., 2016). It allows for the evaluation of road performance based on key parameters such as travel cost, road classification, and environmental constraints. Moreover, the integration of real-time data can improve traffic flow prediction and disaster response planning. By systematically analyzing road networks, this approach contributes to more sustainable, efficient, and resilient transportation systems, supporting both urban and rural development.

A systematic and prioritized classification of forest roads is essential to enhance maintenance strategies and optimize resource allocation. Establishing a ranking system that evaluates and categorizes different sections of the forest road network based on their functional significance would facilitate efficient maintenance planning and targeted investment. Such a system would ensure that critical access routes for fire suppression, forest management, and conservation activities remain in optimal condition, thus reinforcing the resilience of forest ecosystems against natural disturbances. Beyond fire suppression, a well-maintained forest road network contributes to biodiversity conservation, erosion control, and the overall stability of forest landscapes (Tsiotas et al., 2024; Kantartzis et al., 2021).

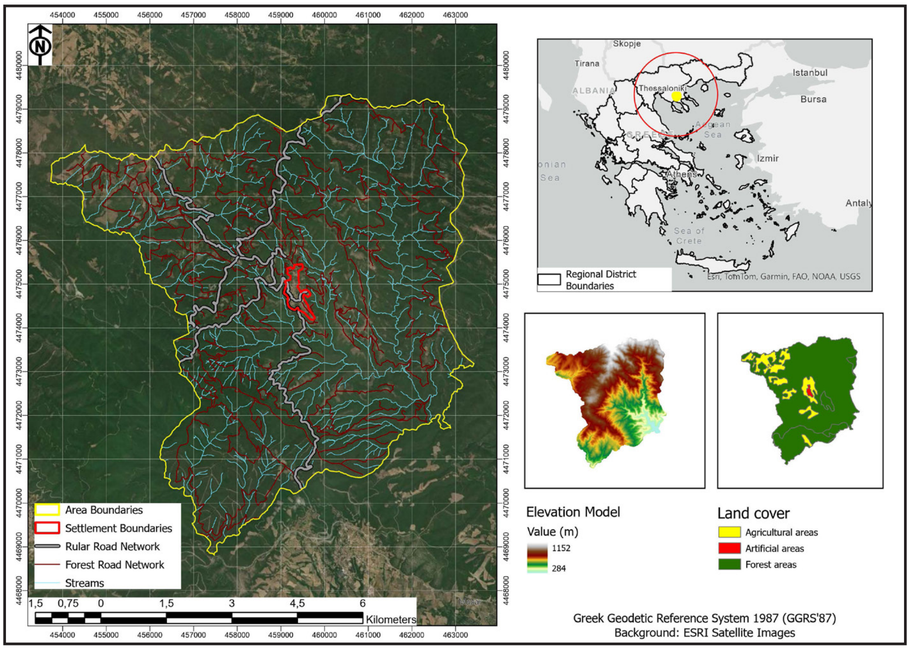
The implementation of a data-driven maintenance framework, integrating remote sensing technologies, geospatial analysis, and predictive modeling, would enable proactive infrastructure management and mitigate the risks associated with deteriorating road conditions (Mohajane et al., 2021; Bentekhici et al., 2020). To address these pressing concerns, policymakers and forest management authorities must prioritize long-term investment in road maintenance, adaptive infrastructure strategies, and interdisciplinary research. Strengthening the resilience of forest road networks is not only vital for effective wildfire suppression but also for ensuring sustainable forest management, ecosystem protection, and climate adaptation in fire-prone regions (Ferreira Da Silva et al., 2020).

This research aims to develop a comprehensive decision support system (DSS) that enables stakeholders to optimize resource allocation for the maintenance and improvement of forest road networks. The primary objective is to identify the most critical road segments by considering their role in ground-based wildfire suppression operations. By prioritizing these segments, stakeholders can enhance the efficiency of resource distribution and establish an optimal maintenance scheduling framework to ensure the functionality of vital access routes. By integrating wildfire risk assessment and optimal route analysis, this study proposes a systematic methodology for ranking different sections of the forest road network. This prioritization process involves evaluating fire-prone areas, access constraints, and infrastructure vulnerabilities, leading to a structured classification of road segments based on their significance in emergency response and fire containment. The outcome is a data-driven assessment that clarifies which road sections require immediate intervention and long-term investment to enhance wildfire resilience. The proposed decision-making tool will provide stakeholders with actionable insights to make informed, evidence-based decisions on forest road network management. By leveraging advanced spatial analysis, remote sensing technologies, and predictive modeling, this system will facilitate sustainable infrastructure planning and proactive maintenance strategies. Ultimately, this approach aims to strengthen wildfire protection, improve emergency response efficiency, and create a more resilient forest environment for future generations.

Materials and methodology

Research area

The study area selected for the present research is the Taxiarchis University Forest, located in the Regional Unit of Chalkidiki within the Region of Central Macedonia, Greece. The forest extends between the latitudinal coordinates 40°23' - 40°28' N and longitudinal coordinates 23°28' - 23°34' E. In accordance with the Greek Geodetic Reference System of 1987 (GGRS '87), its coordinates range from X: 452700 to 463875 and Y: 4466875 to 4480675. The elevation of the area varies between 320 and 1,165 meters above sea level, covering an approximate area of 5,870.50 hectares. Figure 1 presents the location of the research area, the digital elevation model and land cover classification.



Source: Greek National Cadastre, European Union Copernicus Land Monitoring Service, Geographical analysis

Figure 1: Location map of the Taxiarchis University Forest (study area), including digital elevation model (DEM) and land cover classification.

Since 1934, the forest has been granted to Aristotle University of Thessaloniki (AUTh) and has since been utilized for educational and research purposes. It serves as a site for the implementation of contemporary forestry and forest management programs. Both the management and administration of the forest fall under the jurisdiction of the AUTh Forest and Management Fund. A range of research projects conducted by the School of Forestry and Natural Environment at AUTh has yielded valuable scientific data concerning the region's topography, road network, and factors influencing forest fires. Within the area lies the settlement of Taxiarchis, which, according to the Hellenic Statistical Authority, has a population of 1,070 inhabitants. The region also hosts university facilities and tourist accommodations. Approximately half of the study area is designated as part of the Natura 2000 network (sites GR127001 and GR1270012), highlighting its ecological significance.

Data collection

The initial step in conducting this research involved the systematic collection of essential data. As a first measure, the road network of the study area was digitized to ensure accurate representation and analysis. According to the existing Greek legislation, the road network within the region is categorized into four distinct classes. These include the provincial road network, which is paved, and the forest road network, which is further subdivided into three classes (A, B, and C) based on its geometric characteristics. The classification criteria for the forest road network are detailed in Table 1. To achieve this classification, orthophotos from the Hellenic Cadastre and topographic field surveys were utilized, ensuring a comprehensive and precise assessment of the road network structure.

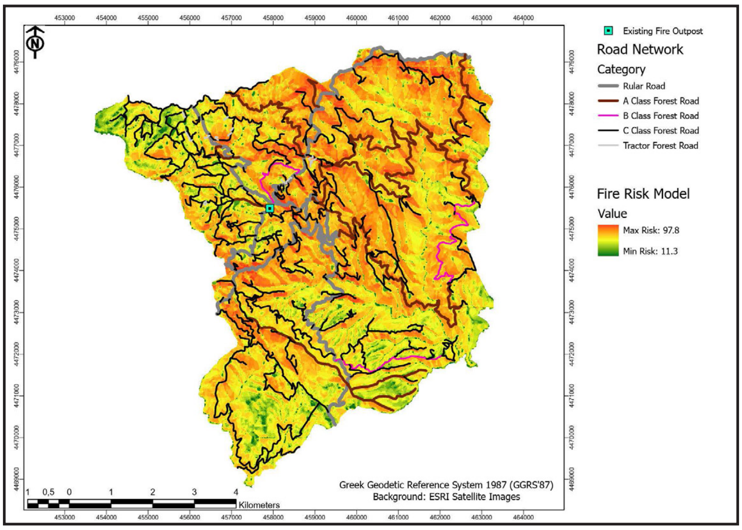
Subsequently, data related to wildfire hazard assessment in the study area were collected and analyzed. Kolkos et al. (2025) developed a wildfire risk model specifically for the Taxiarchis University Forest as part of a targeted fire risk assessment. The resulting output of that study is directly used in the present work. The model was developed using Geographic Information Systems (GIS), employing a weighted overlay technique to combine six critical spatial variables: elevation, terrain slope, vegetation type and density, distance from the road network, and proximity to anthropogenic infrastructure. Each variable was normalized and assigned a weight reflecting its relative impact on wildfire ignition and spread. Figure 2 presents the model output, as a high-resolution raster (5 × 5 meters) in which each pixel is assigned a wildfire risk score ranging from 0 (very low risk) to 100 (very high risk). This classification enables a detailed and precise evaluation of fire-prone zones within the study area.

Finally, the existing designated parking locations for firefighting vehicles were identified. According to local forestry authorities, the study area contains only one officially designated parking site for firefighting vehicles. This location, which serves as the primary dispatch point for emergency response operations in the event of a wildfire, is depicted in Figure 2. In case of a fire outbreak, firefighting vehicles are deployed from this designated parking area to reach the affected zones as efficiently as possible.

Technical Specifications	Categories of Forest Roads		
	A Class	B Class	C Class
Width (Earthy and Semi-Rocky Terrain)	6 - 8 m	4 – 6 m	4 – 5 m
Width (Rocky Terrain)	6 m	4 m	5 m
Minimum Curve Radius (Rmin)	30 m	25 m	20 m
Longitudinal Slope Smax	8%	8%	12%
(On the Downhill Section)			
Longitudinal Slope Smax	6%	6%	12%
(On the Uphill Section)			
Technical constructions	YES	YES	YES

Source: Greek legislation

Table 1: Classification and technical elements of forest roads according to the Greek Ministry of Agriculture.



Source: Author, Geographical analysis

Figure 2: Road network categorization and wildfire risk model of the study area. The map illustrates provincial and forest road classes (A, B, C) alongside the wildfire risk raster.

Methods

Development of road network snalysis system

The first and fundamental step in road network analysis for optimal route determination is the creation of a comprehensive and structured database. The primary objective is to model roads as a network system, enabling efficient route planning and analysis. A network system consists of interconnected elements, where edges (lines) and nodes (points) represent possible pathways between locations. This approach allows for the systematic representation of road connectivity, facilitating advanced spatial analysis. For the development of the network system, ArcGIS 10.8 software was utilized along with a vector dataset containing the categorized road network. This integration ensures accurate spatial representation and supports the subsequent analysis of optimal routes within the study area.

The process of constructing the road network dataset (Network Dataset) in ArcGIS 10.8 began with the importation of the vector line dataset representing the road network of the study area. Each record within the dataset's attribute table includes the classification of the forest roads, categorizing them as Provincial Roads or Forest Roads of Class A, B, or C. To ensure the proper functionality of the Network Dataset, topological consistency checks were performed. These checks were essential for identifying and correcting connectivity errors, such as disconnected road segments or structural inconsistencies within the dataset.

Subsequently, the road network was segmented into sections of 100 meters, creating the road sections dataset. This was achieved using the Generate Points Along Lines tool, which generated points at 100-meter intervals along the road network lines. Following this step, the Split Line at Points tool was executed to divide the road segments accordingly. Each road section was then assigned a unique identifier (Road Section ID) to ensure precise referencing and analysis. A new field was added to the attribute table of the road network segments to store the length of each section (road length). Due to the segmentation process in the previous step, most road sections have a length of 100 meters. However, in some cases, particularly at the endpoints of roads, the Split Line at Points tool generated shorter segments where the remaining distance was less than 100 meters.

In the next step, the longitudinal slope of each road segment was calculated. To achieve this, the coordinates of the start and end points of each segment were extracted and added to the attribute table. Based on these coordinates, a point layer was generated, to which elevation values were assigned using the Extract Values to Points tool from the Digital Elevation Model (DEM). The road sections dataset was then updated using the unique identifier (Road Section ID) to include the elevation values at both the start and end of each segment. Following this step, a new field was created to store the longitudinal slope of each segment, calculated using the following Equation 1:

$$\mathrm{LRSS} = \left|\frac{Z_A - Z_E}{L_S}\right| * 100 \tag{1}$$

Where LRSS: the longitudinal slope expressed as a percentage of each road segment (Longitudinally Road Section Slope), ZA: the elevation at the start of the segment (in meters), ZB: the elevation at the end of the segment (in meters), and LS: the length of the road segment (in meters).

The next step involved assigning the average travel speed for each road segment. The average travel speed of each segment is determined based on the classification of the forest road. Each road category reflects its geometric characteristics, including road width, pavement type, curvature radii, and other relevant attributes. For each road category, a base average speed was assigned, which was then adjusted according to the longitudinal slope of the segment. For segments with a longitudinal slope between 0% and 10%, the travel speed remained unchanged. For slopes ranging from 10% to 30%, the travel speed was reduced by 30%, while for slopes between 30% and 60%, the travel speed was reduced by 50%. Table 2 presents the travel speed values for each case. Based on these values, the attribute table of the road sections dataset was updated accordingly to reflect the adjusted travel speeds. The adopted speed reduction factors are consistent with findings from previous studies on unpaved and forest road networks in mountainous terrain (Akay et al., 2021; Cavalli and Grigolato, 2010), where slope significantly influences vehicular mobility and safe driving speed.

The next step involves calculating the travel time based on speed for both cases. Using the speed-time-displacement (Equation 2), the required travel time for each road segment was determined.

$$t = \frac{x}{u} \tag{2}$$

Where t: traveling time, x: travelling length, u: traveling speed

With the completion of the above steps, the database of the forest road network was finalized, which will be used for the optimal route analysis. Subsequently, the Network Dataset was created using the Network Analyst platform of ArcGIS.

Response time evaluation from fire outpost

Network analysis enables the calculation of travel time between two points by determining the optimal route that minimizes the traversal cost, which in this case is the travel time. This analytical approach was employed to assess the accessibility of all points within the road network based on their travel time from a designated location, identified as the parking site for firefighting vehicles. The primary objective of this analysis was to evaluate the efficiency of the parking location and to quantify the spatial coverage it provides in terms of response time. By integrating road network characteristics and travel speed variations, the analysis offers a data-driven assessment of how effectively emergency response vehicles can reach different areas within the study region.

This application utilizes the Closest Facility method from the Network Analysis package in ArcGIS. This method calculates the travel cost between Incidents and Facilities, determining the closest facility for each incident based on the defined travel constraints. Additionally, it generates the optimal routes between incidents and facilities, providing a detailed representation of the travel cost associated with each route. This approach enables an accurate assessment of response efficiency and accessibility within the study area.

To implement this method, points were generated at 20-meter intervals along the entire road network within the study area of Taxiarchis, Chalkidiki, using the Generate Points Along Lines tool in ArcGIS. The 20-meter interval was selected as a balance between spatial resolution and computational efficiency. This spacing ensures sufficient granularity to capture local variations in accessibility and fire hazard exposure along the road network, while maintaining a manageable processing load during network analysis.

Road class	Average Speed (km/h)	Speed Based on Slope (km/h)		
		Slope 0-10%	Slope 10-30%	Slope 30-60%
Provincial Road (Asphalt-Paved)	40	40	28	20
Forest Road Class A	30	30	21	15
Forest Road Class B	25	25	17,5	12,5
Forest Road Class C	20	20	14	10

Source: Akay et al. (2021); Cavalli and Grigolato (2010)

Table 2. Assigned passing speeds for different road categories under varying longitudinal slope conditions.

The designated study location for the analysis was the firefighting vehicle parking area near the Forest Service facilities. This location was assigned the role of Facility, while the points generated along the road network were designated as Incidents. Through this approach, an Optimal Route was established from the parking location to each point within the road network. The generated optimal routes were analyzed, and the road network segments were classified according to their respective travel time from the parking location. The road segments were further categorized based on their accessibility time, providing a comprehensive spatial representation of response time distribution across the study area.

Road network hierarchization

The purpose of prioritizing road network segments is to establish a structured system where road sections are ranked based on their significance in wildfire suppression operations. This prioritization aims to determine the relative importance of each road segment, facilitating more efficient planning and allocation of maintenance efforts.

The final ranking of road segments was determined through a two-step process that integrates both network centrality and wildfire exposure. Optimal routes were first computed from each firefighting vehicle parking location to all incident points placed every 20 meters along the road network. Each of these points was assigned a fire risk value based on the underlying wildfire hazard raster, which was then inherited by the corresponding optimal route. For each road segment, we calculated the total number of optimal routes crossing through it and summed the fire risk values associated with those routes. The final prioritization score, referred to as the Road Segment Fire Risk Score (FRS), was computed as follows:

$$Road\ Segment\ FRS = \sum_{1}^{i} Optimal\ Route\ FRS\ (i) \quad (3)$$

Where *i*: the optimal route that passes through road segment, *FRS*: Fire Risk Service

Overlapping of optimal routes within the same road segment was addressed by aggregating the wildfire risk values of all routes passing through that segment. The importance of each segment was thus determined by both the frequency of route overlap and the cumulative fire risk exposure, rather than route length alone.

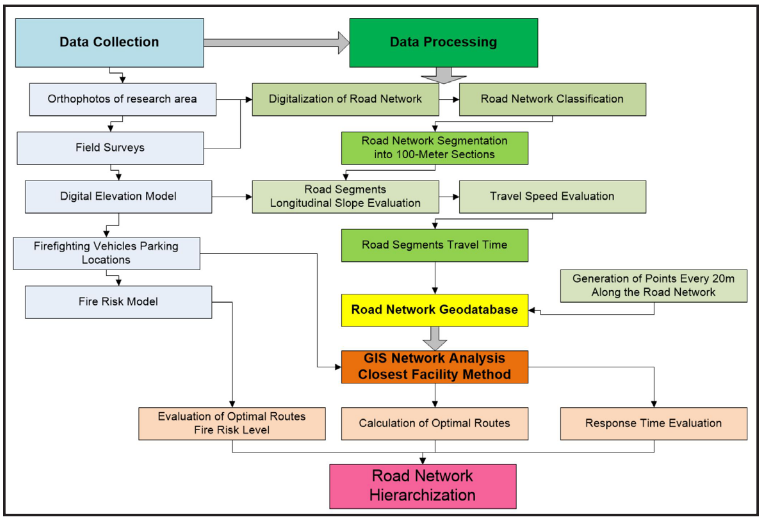
The hierarchical classification of the road network, based on its importance for ground-based firefighting, was carried out through the following methodology:

1. The raster model of fire risk was converted into a point layer, with each point representing the center of a pixel and assigned a fire risk value (0–100).
2. Road points were generated every 20 meters along the road network using ArcGIS 10.8, each with a unique ID and the corresponding road section ID.
3. A Spatial Join assigned to each fire risk point the road section ID of its nearest road point.
4. The Dissolve tool was applied to the fire risk points by road section ID, summing their fire risk values. The output was merged with the road points layer.
5. Each road point (every 20 meters) now contained the aggregated fire risk of nearby fire risk points, representing local hazard levels.
6. Using the existing parking location as the facility, the Closest Facility tool was used to generate optimal routes to all road points. Each route included the road section ID of its destination, linking it to the fire hazard it serves.
7. The road network was segmented into 100-meter sections. A Spatial Join and Dissolve between these sections and the routes layer allowed each segment to accumulate the number and fire hazard level of intersecting routes.

The final road sections layer consists of 100-meter segments containing attributes such as category, length, and aggregated values of optimal routes and the fire hazard they serve. Based on these, the segments were prioritized according to the level of fire hazard they address, from highest to lowest importance.

Figure 3 outlines the step-by-step process followed in the study, from data collection to final road network hierarchization.

The Closest Facility approach allows for real-time prioritization of access routes based on travel time rather than mere distance, offering a more practical and risk-responsive solution for wildfire emergency planning (Zhang et al., 2011). Compared to other GIS-based decision support models used in road maintenance



Source: Author

Figure 3: Methodological workflow diagram. The flowchart presents the sequential steps followed in the study: data collection (road network, DEM, fire hazard), road segmentation, slope and speed calculation, response time evaluation, wildfire risk integration, and final road network hierarchization.

and infrastructure planning (de Medeiros Pereira et al., 2024; Arampatzis et al., 2004), this study's methodology provides a fire-specific prioritization framework, ensuring that critical forest roads are ranked and maintained based on their role in emergency response. By integrating spatial analysis with wildfire risk modeling, this approach enhances resource allocation and proactive maintenance scheduling, leading to more effective wildfire mitigation strategies.

Results and discussion

Road network analysis

The network analysis was conducted using the provincial road network and forest roads classified into Categories A, B, and C. These road categories collectively cover a total length of 228,556 meters. Specifically, 33,808 meters correspond to provincial roads, 44,428 meters to Category A forest roads, 9,730 meters to Category B forest roads, and 140,857 meters to Category C forest roads. According to the adopted methodology, the forest road network was segmented into discrete sections to facilitate a more detailed analysis. A total of 2,427 road sections were generated, with the majority of these segments having a length of 100 meters. However, 316 sections were shorter than 100 meters, as they corresponded to terminal road segments. In terms of longitudinal slope, 195 road sections were calculated with a 0% slope, while 1,011 sections had slopes ranging between 1% and 6%. An additional 809 sections had slopes between 7% and 12%, whereas the remaining 412 segments exhibited slopes exceeding 12%, with the maximum recorded slope reaching 41%. This segmentation approach provides a structured framework for evaluating road accessibility and optimizing maintenance and emergency response planning within the study area.

Response time evaluation

The response time assessment method was applied to the existing firefighting vehicle parking location within the study area. The travel speed, in relation to the length of each road segment, was converted into travel time (in minutes), which served as the key parameter for route optimization. This travel time parameter was integrated into the network analysis as the minimization criterion for determining the optimal routes.

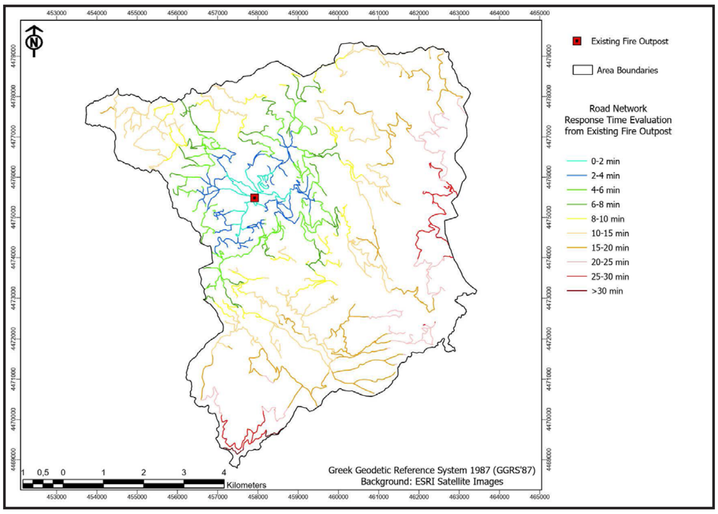
To implement this methodology, a total of 16,657 points were generated across the road network. On average, these points were placed every 20 meters, although in some cases they were positioned at shorter intervals, particularly at road network endpoints. These points were designated as Incidents in the network analysis process. From the designated firefighting vehicle parking location, which was assigned the role of Facility in the analysis, the Closest Facility tool from the Network Analysis package in ArcGIS was applied. This resulted in the generation of 16,657 optimal routes, each connecting the parking location to an Incident point. This approach provided a detailed assessment of response time distribution across the study area, facilitating the evaluation of accessibility and the effectiveness of the existing parking location in supporting emergency operations.

Figures 4 and 5 illustrate the response times across the road network from the existing firefighting vehicle parking location. The most distant point in this analysis, assuming an ideal road surface condition without deterioration effects, required a maximum travel time of 30.78 minutes. The analysis revealed that the existing parking location provides coverage to 43.63% of the road network within a 0–10 minute response time. Within 10–20 minutes, the coverage extends to 38.78% of the network, while an additional 16.76% of the road network is accessible within 20–30 minutes. Finally, 0.84% of the road network requires more than 30 minutes to reach from the designated parking location, assuming optimal road conditions.

Road sections Hierarchization

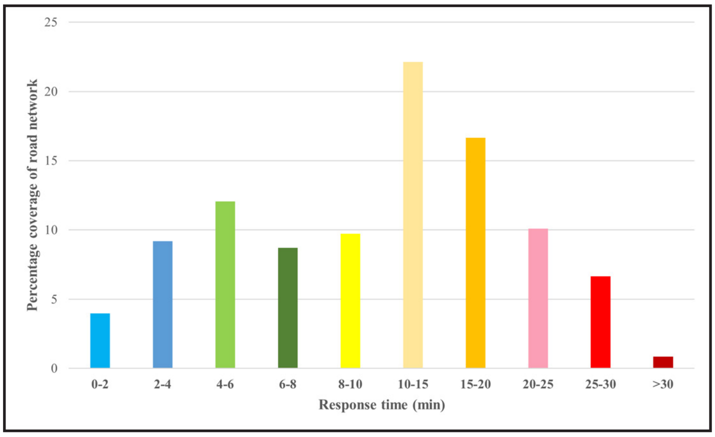
According to the applied methodology, a total of 16,657 optimal routes were generated from the existing firefighting vehicle parking location to a corresponding number of points placed at 20-meter intervals along the road network. For each of these points - and consequently, for each of the 16,657 optimal routes - the cumulative wildfire hazard score was calculated by summing the values of the nearest pixels from the previously developed Wildfire Risk Digital Model.

Furthermore, for each of the 2,472 road segments,



Source: Author, Geographical analysis

Figure 4: Spatial coverage of response times from the existing firefighting vehicle parking location. Road network sections are color-coded based on travel time (minutes) required to reach each point under optimal conditions.



Source: Author, Statistical Analysis

Figure 5: Percentage distribution of road network accessibility by response time intervals from the existing firefighting vehicle parking site.

two key metrics were computed: the number of optimal routes passing through each segment and the total wildfire hazard score accumulated along these routes. The final hierarchical classification phase involved ranking road segments based on the aggregated wildfire hazard scores, enabling a systematic evaluation of their relative importance in firefighting operations and emergency response planning.

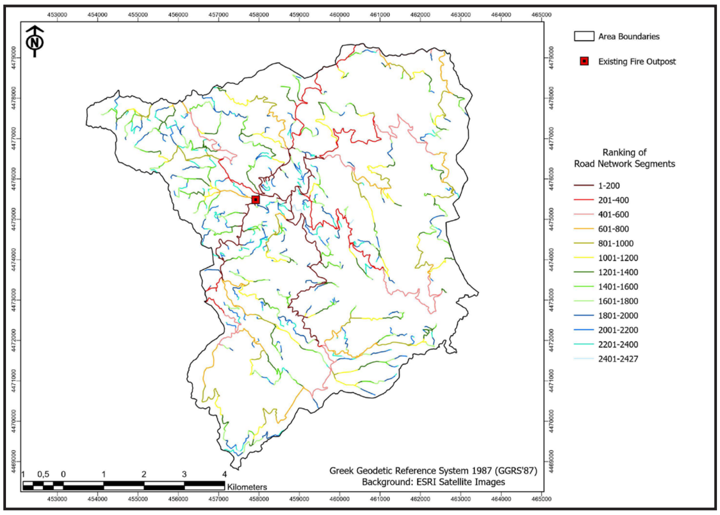
Figure 6 presents the final ranked map of the road network, resulting from the aggregation of optimal route frequency and wildfire risk exposure per segment. The darker the segment, the higher its criticality score, indicating roads that are both frequently involved in emergency access routes and associated with destinations of elevated fire hazard. This spatial outcome synthesizes the entire methodological framework and offers a clear decision-support tool for prioritizing interventions such as maintenance, clearing, or reinforcement.

The map reveals spatial patterns of priority - highlighting, for example, peripheral or remote segments that may not be central in road density but are crucial for reaching high-risk zones. Conversely, some centrally located roads may score lower due to limited exposure or route redundancy. This result can directly inform strategic planning for wildfire preparedness, ensuring that the most essential segments are identified for timely and reliable access during fire events.

Discussion

The findings of this study highlight the critical role of LVRs in wildfire suppression operations, aligning with previous research on rural road networks. While LVRs are often overlooked due to their limited traffic flow, their strategic importance in emergency response is undeniable, particularly in forest fire-prone regions (Zhang et al., 2020). The study's network-based prioritization approach reinforces the argument that well-maintained forest roads significantly enhance the efficiency of firefighting efforts, as suggested by Calkin et al. (2016). Poorly maintained LVRs can delay emergency vehicle deployment, increasing the likelihood of fire escalation and the subsequent environmental and economic costs (Stefanović et al., 2016). The results demonstrate that a data-driven road maintenance framework, focusing on wildfire risk and accessibility constraints, can optimize resource allocation, ensuring that critical access routes remain functional during fire emergencies. Inadequate infrastructure maintenance can lead to greater environmental degradation than other forestry activities. Therefore, integrating LVR-specific fire response strategies into broader forest management policies is essential for enhancing wildfire resilience and ensuring sustainable infrastructure planning.

The GIS-based network analysis used in this study differs from conventional GIS-based DSS by integrating fire risk assessment and accessibility constraints into road network optimization (Parsakhoo, 2016 ; Hosseini et al., 2012). Unlike traditional spatial analysis techniques, which often rely on static road classifications and distance-based shortest path models, this study employs the Closest Facility method to dynamically assess response



Source: Author, Geographical analysis

Figure 6 Final prioritization map of the forest road network, showing 100-meter road segments ranked according to their wildfire hazard exposure and frequency of use in optimal firefighting routes.

time and accessibility for wildfire suppression. The results support the advancement of data-driven decision-making in forest infrastructure planning, reinforcing the importance of adaptive road management in fire-prone regions.

The proposed road maintenance prioritization strategy in this study presents a cost-effective and sustainability-driven approach to wildfire management, diverging from conventional models that primarily focus on road deterioration and usage frequency. Unlike traditional maintenance frameworks, which allocate resources based on traffic load and infrastructure wear (Majstorović and Jajac, 2022), this study integrates wildfire hazard assessment into the prioritization process. By ranking road sections based on their role in fire suppression, the proposed model ensures that limited resources are directed toward high-risk areas, optimizing both fire response efficiency and road network resilience. Additionally, compared to generalized rural road management models, which emphasize economic and environmental trade-offs (Chamorro and Tighe, 2019), this study highlights the multifunctionality of forest roads, reinforcing their critical role in wildfire suppression, ecosystem protection, and sustainable forestry.

Conclusions

This study developed a hierarchical methodology for prioritizing forest road segments based on their contribution to wildfire suppression operations. The findings emphasize that the maintenance and optimal condition of forest roads are essential components of wildfire prevention and emergency response strategies. While the prioritization framework does not diminish the importance of maintaining any specific road segments, it provides a structured approach to guide maintenance scheduling and ensure that resources are allocated efficiently, particularly when funding is limited. By integrating network analysis and wildfire risk assessment, the proposed method enables a data-driven approach to forest road management, ensuring that key access routes remain operational before and during the fire season. The ranking of road segments based on their fire suppression significance allows for strategic planning, optimizing both resource distribution and infrastructure resilience. The study's approach is particularly useful in forested regions with looped or interconnected road networks, where network analysis techniques are essential for identifying optimal routes for emergency access and evacuation.

The proposed method successfully identified high-priority road segments based on a combined assessment of fire hazard and route frequency. For instance, segments located in the northeastern and central-western parts of the study area consistently appeared in the top 10% of critical links, reflecting both high fire exposure and strategic accessibility. These results demonstrate the model's ability to pinpoint roads that are operationally significant for emergency response, even in low-volume forest networks.

Despite the robustness of the proposed forest road network prioritization methodology, certain limitations should be acknowledged. The network analysis model relies on static road conditions and predefined wildfire risk factors, which may not fully capture real-time changes in road accessibility or evolving fire dynamics. Additionally, the study assumes optimal vehicle performance under varying road conditions, without incorporating potential vehicle mobility constraints due to severe terrain degradation, extreme weather conditions, or unforeseen obstacles. Another limitation is the resolution of the wildfire risk model, which, despite its high spatial accuracy, may still be subject to classification uncertainties affecting road segment prioritization. Finally, while the methodology is highly applicable to looped or circuit-like forest road networks, its adaptability to linear or fragmented road networks in more complex topographies requires further investigation.

Future research should focus on enhancing the adaptability of the methodology by integrating real-time road condition monitoring and dynamic fire behavior modeling to improve response efficiency. Further exploration of economic feasibility assessments and cost-benefit analyses could also strengthen the decision-making process, ensuring that sustainable infrastructure investments are aligned with long-term forest management goals. Finally, the incorporation of climate change projections would allow for adaptive road maintenance planning, ensuring resilience against future wildfire risks in a changing environment.

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