PREDICTING WILDFIRE IMPACTS ON MOBILITY USING GIS AND FIRE SIMULATION

FINAL PROJECT REPORT

by

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16. Abstract

The USDOT Strategic Plan underscores the importance of improving the mobility of people and goods through its focus on infrastructure. This is particularly important in times of natural disasters. Oregon's status as the largest timber producer in the United States, combined with the dry climate during fire season and myriad other factors, has resulted in large-scale forest fires that threaten the many logging towns east of Interstate 5. Many of the towns that are vulnerable to wildfires are accessible by roadways that fires could easily cut off, thus blocking aid to and evacuation from these towns. The spread of wildfires can significantly affect the roadway network through damage to infrastructure and the accumulation of roadway debris, preventing access for first responders and the evacuation of people. This project provided a framework to quantify the damage sustained by roadways in terms of the lengths and sections of roadways affected and to identify routes around impacted sections of roadway. A simulation-based methodology was used to model wildfire spread, and geospatial analysis was used to identify roadway sections that would be affected by the fire. This methodology was implemented for a case study of the Archie Creek Fire that occurred in Oregon in 2020.

It is expected that this project will help improve the decision-making process by enabling the analysis and estimation of roadway sections and their lengths impacted by wildfires. The results of this project can also help with resource allocation before fires by identifying particularly critical and vulnerable towns and the roadways connecting them. Finally, the developed framework can also be used to estimate evacuation times and to estimate recovery operation durations after wildfires.

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List of Abbreviations

ASCII	American Standard Code for Information Interchange
BLM	Bureau of Land Management
BTU	British thermal unit
CWFIS	Canadian Wildland Fire Information System
DFPA	Douglas Forest Protective Association
FEMA	Federal Emergency Management Agency
FIRMS	Fire Information for Resource Management System
GIS	Geographical Information Systems
IFTDSS	The Interagency Fuel Treatment Decision Support System
LCP	Landscape (file)
MTT	Minimum travel time
ODOT	Oregon Department of Transportation
PacTrans	Pacific Northwest Transportation Consortium
UTM	Universal Transverse Mercator

Abstract

The USDOT Strategic Plan underscores the importance of improving the mobility of people and goods through its focus on infrastructure. This is particularly important in times of natural disasters. Oregon's status as the largest timber producer in the United States, combined with the dry climate during fire season and myriad other factors, has resulted in large-scale forest fires that threaten the many logging towns east of Interstate 5.

Many of the towns that are vulnerable to wildfires are accessible by roadways that fires could easily cut off, thus blocking aid to and evacuation from these towns. The spread of wildfires can significantly affect the roadway network through damage to infrastructure and the accumulation of roadway debris, preventing access for first responders and the evacuation of people.

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Chapter 1 Introduction

The ability of roadway infrastructure to serve the mobility needs of people and vehicles is particularly important in times of natural disasters [1]. Oregon's status as the largest timber producer in the United States (U.S.), combined with the dry climate during fire season and myriad other factors, has resulted in large-scale forest fires that threaten the many logging towns east of Interstate 5 (I-5). Several of these towns that are vulnerable to wildfires are accessible by roadways that fire could easily cut off, thus blocking aid to and evacuation from these towns. Table 1.1 provides national annual wildfire statistics and their impacts between 2017 and 2021 in terms of acres burned. The spread of wildfires can significantly affect the roadway network through damage to infrastructure and the accumulation of roadway debris, preventing access to first responders and evacuation of people.

Table 1.1: Wildfire statistics in the United States [2]

Year	Number of Fires (thousands)	Acres Burned (millions)
2017	71.5	10.0
2018	58.1	8.8
2019	50.5	4.7
2020	59.0	10.1
2021	59.0	7.1

While only about 1 percent of wildfires in the U.S. become conflagrations, they cause catastrophic destruction. For example, the 2020 wildfires in Oregon burned over 1 million acres and resulted in the deaths of 11 people and the evacuation of more than 40,000 residents [3]. They also caused nearly 120 miles of highway to be closed because of hazardous conditions. Furthermore, the debris created by the wildfires adversely affected both rescue operations and evacuation efforts. Such fires have highlighted the need for better preparedness by transportation agencies, particularly related to their maintenance of rural roadway networks, to serve the twin purposes of enabling rapid evacuation of affected populations and enabling access to affected areas by first responders and firefighters. However, the spread of fires can significantly affect the roadway network through damage to infrastructure, the accumulation of roadway debris, the presence of "hazard trees" that threaten to block roadways, and low visibility due to smoke [4]. These impacts on roadway infrastructure severely affect the mobility of travelers and first responders.

While current knowledge enables decision-makers to simulate the spread of wildfires and separately establishes the impacts of closed roads on mobility, currently unknown are the impacts of wildfires on transportation infrastructure and potential methods to mitigate their impacts. This study aimed to fill these gaps by using a simulation-based approach to model the impacts of wildfires on road networks to facilitate decision making regarding the allocation of debris clearance, firefighting, and recovery equipment to address the impacts of wildfires.

This study contributes to PacTrans' mission by improving transportation mobility for evacuation, rescue, and recovery for rural communities, as well as the safety of communities by enabling first responders to have access to them. Specifically, this project proposed the use of wildfire simulation and geospatial analysis to evaluate the impacts of wildfires on roadway networks, thereby facilitating the optimal allocation of resources to enable speedy recovery of roadway assets.

This study pursued the following tasks to enhance understanding of the impacts of wildfires on Oregon's transportation network:

1. Identify areas of damage using wildfire simulation: Wildfire simulation software was used to create realistic simulations of wildfire spread through Oregon's forests under

changing environmental conditions. The wildfire simulation outputs can be easily integrated into any Geographical Information Systems (GIS) software in future studies.

2. Assess the road network affected by wildfires by using GIS: This was done by integrating a wildfire minimum travel time map and the Oregon road network into ArcGIS Pro to assess the road network.
3. Find the shortest alternative routes: The Network Analyst tool in ArcGIS Pro was used to identify the best alternative routes to use during wildfire road closures to optimize first responders' activities and equipment operations.

The major outcome of this study was a roadmap that can be used to evaluate the impacts of wildfires on transportation networks, with the goal of mitigating their adverse impacts. Specifically, this study was expected to create new knowledge in the following areas: (1) quantification of the impacts of wildfires on road networks; (2) quantification of the impacts of reduced capacity networks on travel times; and (3) evaluation of recovery times to clear and repair roadways.

The proposed simulation-based framework will enable comparisons among multiple what-if scenarios to obtain a holistic understanding of possible disaster scenarios, with the goal of minimizing road repair and travel times. The outcomes of this study are also expected to enable policymakers at the state level to incorporate external considerations related to natural disasters when considering the need and effects of capacity building and thus to provide support to numerous rural communities that rely on rural roadway networks to ensure their safety and livability.

This report is organized as follows. Chapter 2 presents the relevant literature in the fields of wildfire behavior modeling, geospatial analysis, and debris estimation. Chapter 3 introduces the methodological framework that integrates wildfire behavior and GIS to analyze wildfire impacts on roadways. Chapter 4 details the case study to which the developed methodology was applied, and Chapter 5 presents the conclusions of this research project.

Chapter 2 Literature Review

This chapter provides a review of previous research on wildfire behavior modeling, the use of geospatial analysis for evacuation models, and debris estimation methods.

2.1 Fire Behavior Models

Large fires are landscape-level events because of the large areas that they typically affect. They are also considered to be spatial events because the movement and behavior of wildfires depend upon the location of fuel relative to the fire progression [5]. Various characteristics of wildfires such as timing, location, intensity, and duration can be analyzed by carrying out simulations of multiple fires at local and landscape levels [6].

Fire modeling refers to use of computer models to simulate the spread of fires based on a variety of factors such as windspeed, fuel availability, and topography. While this may seem like a difficult task because of the sheer number of variables that must be considered, such as types of deadwood, terrain, weather, and moisture content of leaves and grass, computer models that predict wildfire spread are becoming increasingly sophisticated and can help land managers and fire commanders make decisions to save lives and property. For instance, in 2006, fire simulations were used for the first time to determine where fire crews and equipment needed to be deployed. Most recently, they have been utilized to help fight early-season fires in Florida, Georgia, and California [7].

There have been significant advances in fire modeling since its conception in 1940 by Wallace Fons, who built wind tunnels and crib fires to investigate fire behavior and characteristics [8]. Currently, multiple software applications are available for predicting and simulating fire behavior and properties. These include applications such as NEXUS, FlamMap, FARSITE, and BehavePlus. In addition to these, numerous software programs can be utilized to estimate weather, fuel moisture, and other input variables needed to develop fire behavior models. An overview of these tools is provided in the following section.

2.1.1 Software Used for Fire Behavior Modeling

This section provides an overview of the major software applications used in wildfire behavior modeling, with a focus on FlamMap, the software application that was used in this project.

Papadopoulos et al. [9] performed a comprehensive review of wildfire simulators used in forecasting forest fire propagation. Table 2.1 summarizes the features of the major software applications that they reviewed to provide general background on the capabilities of wildfire modeling software.

Table 2.1. Overview of fire modeling software [9]

Software Name	Software Features
FARSITE [10]	• Models the growth of fire in two dimensions (2D) by considering weather, fuel data. • Provides output in terms of fire size, direction, and time to reach location.
FireFamily Plus [11]	• Merges multiple other fire modeling programs into one integrated user-interface. • Calculates fuel moistures and fire danger indices by using hourly and daily fire weather data.
Rare Event Risk Assessment Process [12]	• Computes the probability of fire reaching a specific location. • Estimates fire travel and spread events depending on historical weather data and professional knowledge.
WindNinja [14]	• Simulates microscale, terrain-influenced wind speed and direction to improve accuracy of fire models. [15] [16]. • Outputs ASCII Raster grids of wind speed and direction that can be used by spatial fire behavior models and a GIS shapefile to plot wind vectors.
AceFuels [6]	• Streamlines the fuel management planning process and provides tools for quantitative wildfire risk assessment in ArcMaps. • Enables design and testing of fuel treatment programs in fire-prone wildlands.
FlamMap [19]	• Fire simulation software widely used for fire behavior research. • Integrates various GIS data inputs such as fuel moisture, canopy, slope, elevation, aspect, weather, and wind, which are used together to determine the potential fire behavior.

After a review of the literature and existing fire simulation software, FlamMap was chosen to be used in this project because of its documented capabilities and wide use in research. The following section provides more detailed information about FlamMap software.

2.1.2 FlamMap Inputs and Outputs

Fuel models are primary inputs for FlamMap, and they can be either collected in the field using guides or attained from data sources such as Landfire [6] or The Interagency Fuel Treatment Decision Support System (IFTDSS) [18]. The spatial inputs acquired from the previously mentioned data sources are usually eight GIS raster layers that describe fuel and topography characteristics that are combined into a landscape (LCP) file.

The input data necessary to operate a FlamMap simulation must have identical resolution and equal extent, and they must be co-registered into an LCP file constructed from ASCII grid files [19]. Model outputs including flame length and fire intensity are in ASCII grid and shapefile (vector) formats and are used to determine the outputs shown in table 2.2 to quantify the level of danger in a given area during a fire [20].

Table 2.2: FlamMap outputs [19]

Fire Behavior Value	**Output Type**	**Units**
Fireline Intensity	Raster	kW m^{-1} or BTU ft^{-1} sec^{-1}
Flame Length	Raster	meters or feet
Rate of Spread	Raster	M min^{-1} or ft min^{-1} or ch hr^{-1}
Heat per Unit Area	Raster	kW m^{-2} or BTU ft^{-2} sec^{-1}
Horizontal Movement Rate	Raster	M min^{-1} or ft min^{-1} or ch hr^{-1}
Midflame Windspeed	Raster	mph or kph
Spread Vectors	Vector	m min^{-1}
Crown Fire Activity	Raster	Index, 0 1 2 or 3
Solar Radiation	Raster	W m^{-2}
1-hr Dead Fuel Moisture	Raster	Fraction (0.0-1.0)
10-hr Dead Fuel Moisture	Raster	Fraction (0.0-1.0)

Minimum travel time (MTT) is an algorithm [21] employed by FlamMap software to calculate fire growth between the cell corners at a given resolution [19]. The MTT feature in FlamMap contains a different suite of outputs than the basic products listed in table 2.1, since it considers the area within the parameters of the fire as well as the area that is affected by the direction of fire movement, revealing flanking, heading, and backing spread [19]. These outputs are provided in table 2.3.

Table 2.3: Outputs of fire behavior from the minimum travel time feature in FlamMap [19]

Fire Behavior Value	Output Type	Units
Rate of Spread	Raster	kW m^{-1} or BTU ft^{-1} sec^{-1}
Influence Grid	Raster	meters or feet
Arrival Time Grid	Raster	M min^{-1} or ft min^{-1} or ch hr^{-1}
Heat per Unit Area	Raster	kW m^{-2} or BTU ft^{-2} sec^{-1}
Horizontal Movement Rate	Vector	M min^{-1} or ft min^{-1} or ch hr^{-1}
Midflame Windspeed	Vector	mph or kph
Spread Vectors	Vector	m min^{-1}
Crown Fire Activity	Raster	Index, 0 1 2 or 3

One limitation associated with fire growth computation using the MTT algorithm is that MTT depends on spatial patterns of fuels and topography, with the assumption that environmental conditions are constant and do not change with time. This can lead to dismissing time-varying winds or moisture content. Therefore, in the case of a frequently changing fire environment, such as changes in wind speed or direction and fuel moisture, the algorithm does not produce very reliable results under static conditions [19] [21].

FlamMap uses spatial information about topography and fuels to calculate fire behavior characteristics for a single set of environmental conditions. While this can be considered a limitation, it was one of the reasons to choose FlamMap for this study because changes in environmental conditions during a wildfire event were not the focus of this project. The next section details the integration of wildfire models with geospatial data analysis to identify the impacts of wildfires on transportation networks.

2.2 Integration of Wildfire Models with Geospatial Analysis

This section focuses on previous studies that have proposed to integrate wildfire models with GIS for various purposes such as evacuation and rescue. A particular focus is given to implementations that have used Network Analyst—a widely used tool within ArcGIS Pro—to solve transportation problems that have required identifying the optimal route under various conditions.

Akay et al. [23] detailed research conducted in Turkey to develop a GIS-based decision support system utilizing the Network Analyst extension within ArcGIS Pro to help first responders to take the shortest and safest route when driving from their headquarters to wildfire-affected areas. The study used a fire sensitivity map of the country to produce a spatial database of fire sensitivity degrees, given both forestlands and fire sensitivity. It then combined the two within GIS using the overlapping processing tool to establish the fire sensitivity of forest areas in the study area. A fire coefficient reflecting the number of fire incidents and burned areas per year was used to determine the fire sensitivity level of that area. This study considered several roads in Kahramanmaras Forestry Regional Directorate in Turkey that might be blocked by a wildfire. It then developed a simulation using the Network Analyst tool in the ArcGIS Pro software. Depending on the type and status of the road, road length and average speed were used to compute the travel time for first responders' vehicles [23].

Rise et al. [24] developed a time- and distance-based model to determine preferred and alternative wildfire evacuation paths by overlaying fire growth patterns over road network and population density layers. They used the ArcGIS Network Analyst tool for mapping, modeling, and testing the connectivity and performance of the case study. For fire growth modeling, the FARSITE fire growth prediction model, now part of FlamMap, was utilized to predict where the wildfire might spread with time and under different weather conditions and ignition positions. To determine which roads were blocked at a certain time, they visually inspected the fire perimeters overlaid over the road network and compared fire location and growth time against evacuation time. Using this approach, they were able to demonstrate risk levels and determine whether additional traffic control was needed [24].

Khan et al. [25] conducted a study in which they coupled traffic modeling, pedestrian behavior, and fire behavior to improve wildfire evacuation modeling. They created numerous traffic-modeling scenarios to model fire spread through closed roads by using a software program called PTV VISSIM for traffic modeling. They used geospatial satellite data from the Canadian Wildland Fire Information System (CWFIS) and NASA's Fire Information for Resource Management System (FIRMS) to predict fire growth. However, they concluded that a lack of historical data was a key limitation when these integrated models were used. Another limitation that the study faced was related to the shape files in ArcGIS that used separate polygons with no data acquisition time information, which led to assuming that the greatest temporal resolution was one day [25].

While previous studies have used methods and tools similar to the ones utilized in this project, none of them have dealt with predicting the impact of wildfire debris on mobility by using GIS and wildfire simulations.

2.3. Debris Spread and Other Damage Estimation

There is limited literature on wildfire debris, its estimation, and how to clear roadways of it. However, there is an abundance of research on the topic of debris-flows, which refers to high-density slurry of rock fragments, soil, woody debris, and mud, which can cause fast-moving landslides that are hazardous to life and property in the presence of rain [26]. Wildfire debris, especially on and near road networks, can block those networks, leading to disruption of rescue and evacuation operations during wildfire disasters and in their aftermath of. One of the first steps to enable recovery planning is to estimate debris volumes. According to the Federal Emergency Management Agency (FEMA) Debris Estimating Field Guide, there are several methods for estimating debris amounts, and these should be selected on the basis of the required accuracy, precision, and schedule of the operation, and also on the availability of resources such as personnel and equipment [27].The first method involves ground measurements, referring to visual observations and detailed data collection in the field using measuring tapes and GPS units. The second method is aerial estimation that compares aerial and satellite photographs of targeted areas taken before and after the wildfire to estimate debris quantities and types, depending on the structures, features, and debris observed in the images [27]. The third method is the use of computer-assisted simulation models that use historical information about debris quantities produced by similar disaster events, GIS data including topography and land use, other information related to the disaster such as the extent of flooding or hurricane category, and formulas that mathematically combine the data to generate an estimate. A software application called HAZUS-MH developed for this purpose contains models for estimating potential damage and losses, including debris generated by floods, earthquakes, and hurricanes but not from wildfires. When estimating debris, a combination of methods can be used if necessary [27].

The abovementioned methods can be used to estimate wildfire debris on road networks. The Field Guide for Hazard-Tree Identification and Mitigation on Developed Sites in Oregon and Washington Forests [28] noted that when hazardous trees are surveyed, all the tall trees in the area should be examined to determine whether they would block the road if they were to fall. Hence, the width of the survey area adjacent to roads should be equivalent to the height of the tallest trees [28], which was taken into consideration in this project when assumptions were made about wildfire debris volume calculations.

Chapter 3 Methodology

This study aimed to identify the sections of roadway affected by wildfires by using a simulation-based approach. This was accomplished by creating a framework that implements multiple software applications with unique functionalities wherein each software program produces an output that is essential for the next software application. This process requires format conversions to fulfill software requirements as needed. Figure 3.1 shows the proposed framework that interconnects the different software programs, data sources, and data format conversions used in this project.

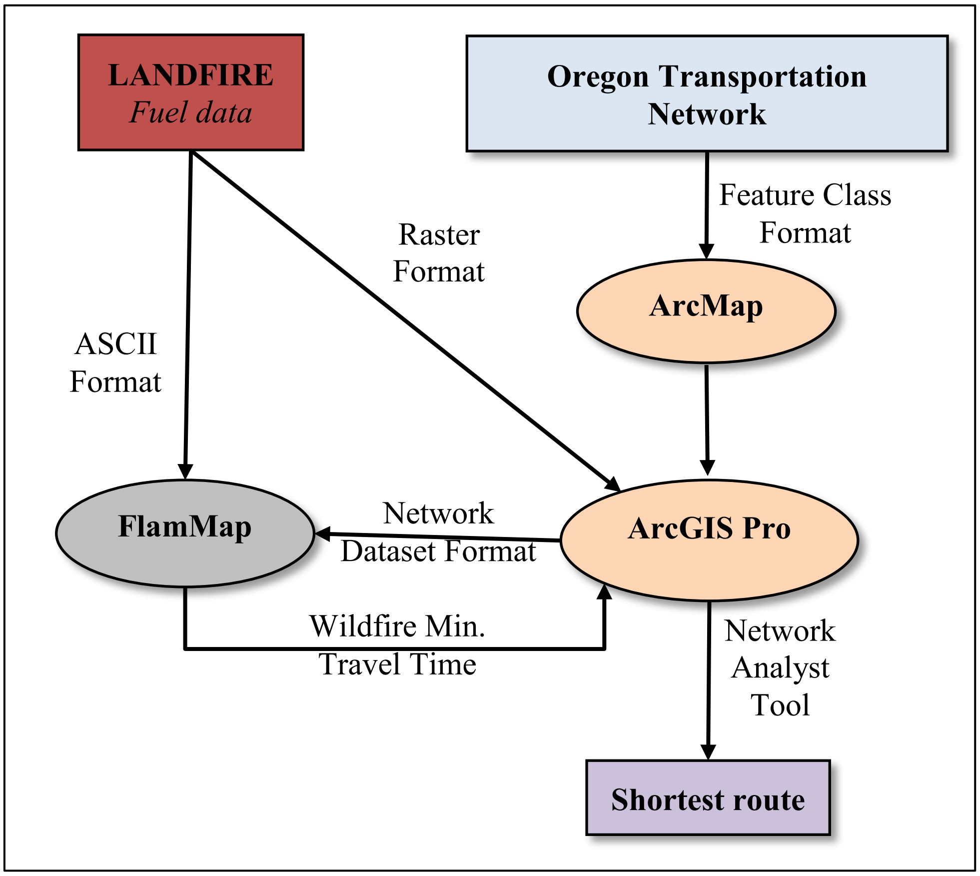


Figure 3.1: Overview of the proposed framework

The primary components of the framework are fire modeling and geospatial analysis, which are enabled by FlamMap and ArcGIS Pro software, respectively.

3.1. Fire Modeling

The first step toward determining the impact of a fire on the road network is to predict the behavior of the fire itself and simulate possible scenarios of spread. This project utilized the software FlamMap to achieve that goal. FlamMap is a widely used landscape fire behavior model for both researchers and fuel treatment planners in U.S. federal land management agencies [6], as described in Chapter 2. FlamMap requires multiple inputs to run a successful simulation, and the primary input is contained in a "Landscape" file that is constructed from ASCII grid files that are of identical resolution, co-registered, and of equal extent [19]. These files can be acquired from LANDFIRE Landscape Fire and Resource Management Planning Tools, which is a multi-partner project that produces consistent and comprehensive maps and data describing vegetation, wildland fuel, fire regimes, and ecological departures from historical conditions across the U.S. [29].

The landscape file consists of seven layers that are necessary for simulating wildfires: (1) elevation, (2) slope, (3) aspect, (4) fuel model, (5) canopy height, (6) crown base height, and (7) crown bulk density. The raster format of the native LCP file must be converted to ASCII format in ArcGIS Pro before the LCP files can be imported into FlamMap. Figure 3.2 shows how FlamMap reads the LCP files of an area in northeast Oregon.

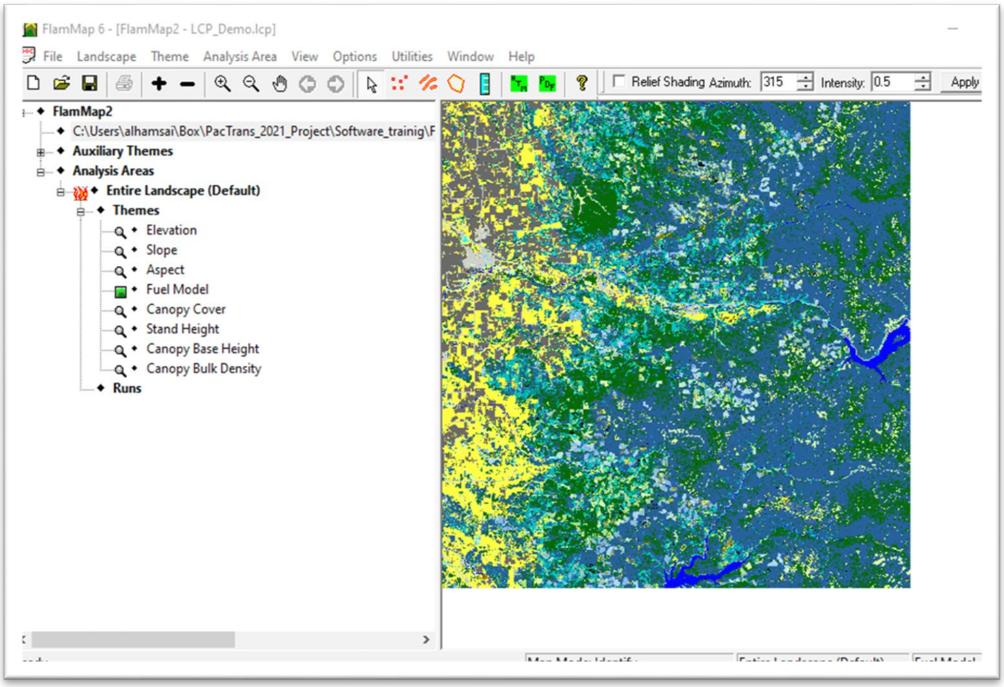
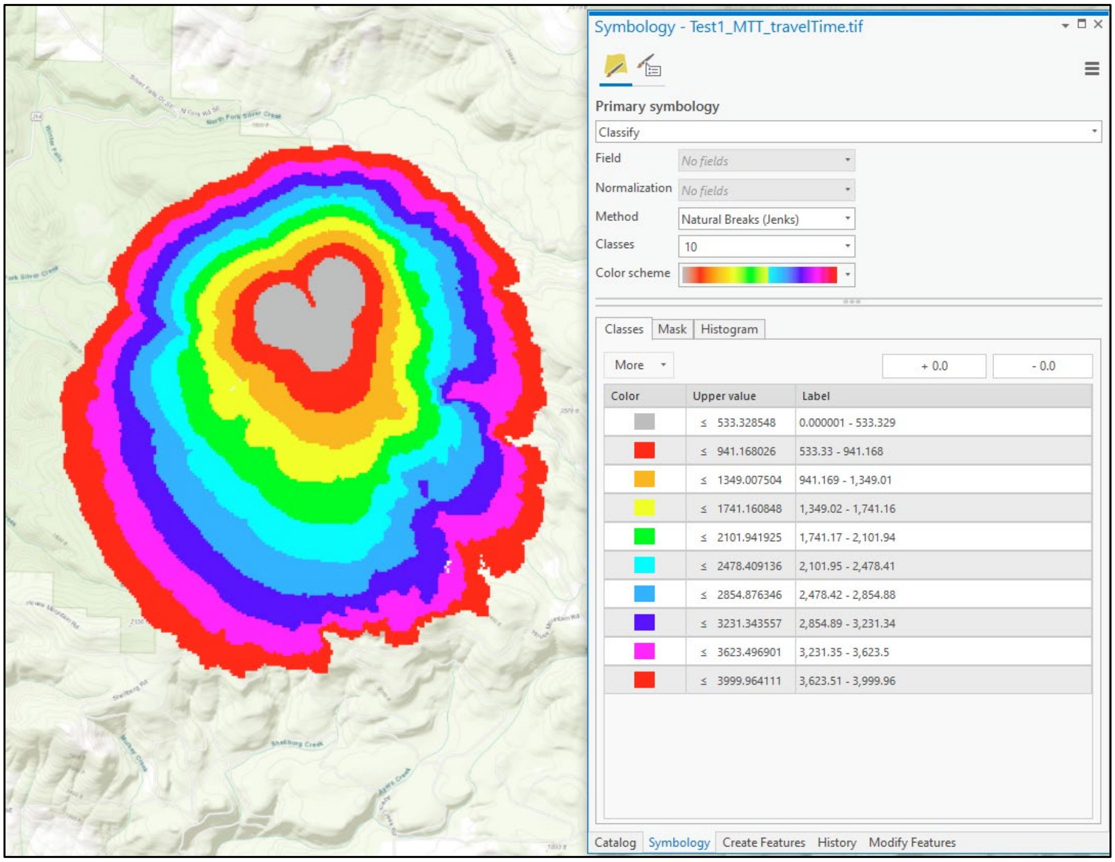


Figure 3.2: LCP files in FlamMap

To run a basic wildfire simulation in FlamMap, several pieces of information must be available, including those listed below:

- <u>Moisture fuel:</u> A default file was used in this project, but future implementations can create this file by using the software FireFamilyPlus to incorporate hourly or daily fire weather observations in their simulation.
- <u>Wind speed and direction:</u> Fixed speed and direction were used in the simulation. In future work, these data can be exported from WindNinja software to develop a more accurate wildfire simulation.
- <u>Ignitio:</u> Point, line, or polygon ignition files can be created by using FlamMap to show the source of the wildfire.

After the simulation has been run, different outputs describing various aspects of wildfire behavior can be obtained from FlamMap, such as flame length, crown fire activity, and fire intensity. The most relevant information to this project was the study of wildfire growth, which could be attained from minimum travel time (MTT). As mentioned in Chapter 2, MTT is an algorithm for modeling fire spread in complex landscapes that computes the minimum time for fire to travel among nodes in a two-dimensional network [21]. This algorithm can provide the status of a fire at different points in time, enabling the modeling of its spread, as shown in figure 3.3. This figure shows the total duration of a fire simulation that lasted 4,000 minutes, in which each color represents a time interval during the wildfire simulation.



Symbology - Test1_MTT_travelTime.tif

Primary symbology: Classify

Field: No fields

Normalization: No fields

Method: Natural Breaks (Jenks)

Classes: 10

Color	Upper value	Label
⬜	≤ 533.328548	0.000001 - 533.329
🟥	≤ 941.168026	533.33 - 941.168
🟧	≤ 1349.007504	941.169 - 1,349.01
🟨	≤ 1741.160848	1,349.02 - 1,741.16
🟩	≤ 2101.941925	1,741.17 - 2,101.94
🟦	≤ 2478.409136	2,101.95 - 2,478.41
🟦	≤ 2854.876346	2,478.42 - 2,854.88
🟪	≤ 3231.343557	2,854.89 - 3,231.34
🟪	≤ 3623.496901	3,231.35 - 3,623.5
🟥	≤ 3999.964111	3,623.51 - 3,999.96

Figure 3.3: Fire progression

3.2. Geospatial Analysis

ArcGIS Pro was used to predict the effects of wildfire on the road network by integrating Oregon road network information and FlamMap output to study their interaction. Public road network datasets were obtained from the Oregon Department of Transportation (ODOT) for use in this research.

These data were used to build a road network dataset that was compatible with the Network Analyst tool in ArcGIS Pro. They consisted of a set of edges that represented the links over which agents would travel and a set of junctions that connected edges and facilitated navigation from one edge to another [30]. The road network dataset was built with ArcMap software after the data had been exported from the feature class to a shapefile. Since the original data did not include information regarding speed limits, a fixed speed of 25 mph was assumed for all roads.

FlamMap' s MTT output was provided in ASCII format. Since this format was incompatible with ArcGIS Pro, it had to be converted to raster format in ArcMap before the data could be used in ArcGIS Pro.

The Network Analyst tool is a powerful extension of ArcGIS Pro that provides network-based spatial analysis, including route analysis, travel directions, closest facility analysis, and service area analysis [31]. It enables users to dynamically model realistic road network factors, such as turn restrictions, speed limits, and traffic conditions at different times of the day. The Network Analyst Extension uses the standard Dijkstra's algorithm [23] to calculate the least accumulated cost between the destination node and every other node in the network [30]. This is implemented in Network Analyst by combining links (arcs) and intersection points of links (nodes) to construct a network system database that can describe possible pathways between features across a landscape. In the solution procedure, various parameter values such as length, cost, and travel time are assigned to each network link. The shortest, or optimal, path is selected by determining the route that minimizes the sum of the total link parameter values [32].

This tool was used to determine the shortest route between points of interest in the analysis. The fire's impact on various routes was determined by defining the fire's perimeter as a barrier in ArcGIS Pro. This action can be performed either manually or automatically. The manual method requires the user to draw polygon barriers using the "create feature" function in ArcGIS Pro around the fire parameter for any given time. The second method imports the MTT raster map as a multiple-line barrier by converting the raster into a point feature class and then into a line feature class. Both methods simulate the interaction of the wildfire with the road network resulting in road blockage, which is considered by the Network Analyst tool in identifying the shortest route. Thus, the framework created identifies the shortest route possible between all points of interest while avoiding wildfire-affected road segments.

Chapter 4 Case Study

The framework presented in Chapter 3 was applied to a case study of the Archie Creek Fire that occurred in Oregon in September 2020 to demonstrate the framework's applicability and showcase the results that can be obtained. This chapter provides a description of the wildfire, followed by wildfire modeling and its integration into GIS to determine the fire's impact on roadways.

4.1 Archie Creek Fire

The Archie Creek fire started on September 8, 2020, and became one of the most expansive and expensive emergency disaster events in Oregon history. Conditions preceding the wildfire in the region included gusty winds that drove dry air from the east down the western slopes of the Cascade Mountains. The prevailing dry conditions, combined with high wind speeds, fanned the flames of existing wildfires, resulting in more than a million acres of mostly forest land burning in Oregon by late September [33].

The Archie Creek wildfire was east of Roseburg in the North Umpqua National Forest and affected both private and government-owned land [34]. Extreme weather conditions preceded the wildfire, and on September 4, 2020, the National Weather Services in Medford issued fire weather watch after detecting 15 to 25 mph wind speeds with gusts of up to 35 mph and relative humidity as low as 10 percent. On September 5, 2020, the fire weather watch was upgraded to a red flag warning after an increase in wind speeds (20 to 25 mph with gusts of up to 40 mph) and a decrease in relative humidity to 10 percent with low overnight recoveries.

The Archie Creek fire started on September 8, 2020, as a grass fire on the north side of the North Umpqua River near Glide and grew to 100,000 acres within one day [33]. After what was described as explosive fire activity during this first 24 hours, the Archie Creek Fire continued to expand but at a slower rate. While the fire wasn't contained until October 31st, with a burned area of 131,542 acres, the prime activity was contained during the first 11 days, between September 8 and September 18, 2020. Figure 4.1 shows an image of the conflagration, while table 4.1 shows the extent of the area affected through the course of the fire.

Figure 4.1: Archie Creek Fire, September 9, 2020, from Highway 138 [34]

Table 4.1: Progression of the Archie Creek Fire [33]

Date	Events
September 8	Fire Reported at 7:37 AM PDT
September 8	72,000 acres (8:00 PM PDT Estimate)
September 9	Nearly 100,000 acres (Morning Estimate)
September 10	107,000 acres (Morning Estimate)
September 11	115,857 acres (Evening Estimate)
September 12	115,857 acres (Afternoon Estimate)
September 13	121,379 acres (Afternoon Estimate)
September 14	121,379 acres (Morning Estimate)
September 15	125,498 acres (Evening Estimate)
September 16	125,498 acres (Morning Estimate)
September 17	128,020 acres (Evening Estimate)
September 18	130,429 acres (Evening Estimate)
October 31	131,542 acres (100% Contained)

4.1.1 Losses and Damage

The fire resulted in the loss of one human life and 109 homes, a majority of which were located in the Highway 138 East corridor and along Rock Creek Road. Additionally, the Rock Creek Fish Hatchery, a Douglas Forest Protective Association (DFPA) fire lookout on Mount Scott, and a DFPA guard station east of Swiftwater Park were lost to the fire [35]. According to a soil burn severity report released by the FEMA Erosion Threat Assessment/ Reduction Team in December 2020, 43,251 acres (33 percent of the fire's total area) were classified as a high severity burn area, while 59,700 acres (44 percent of the fire's total area) were classified as a moderate severity soil area [36].

Moderate severity soils are more vulnerable to erosion in post-fire rain events because of a loss of protective surface cover. Additionally, these soils may have less surface stability because of dead roots while the structure of the ground soil remains unchanged. Meanwhile, high severity soil areas have had all their pre-fire surface ground cover and organic matter (litter layer, duff and fine root) burned up by the fire [37].

4.1.2 Impact on the Road Network

The fire forced the closure of lands east of I-5 managed by the Bureau of Land Management (BLM). This closure included the Oregon Highway 138 East between Glide and U.S. 97, where hazardous situations caused by heavy winds and local fires, including fallen trees, debris, and rocks on the roadway, blocked accessibility in some areas affected by the fire [39][40].

4.1.3 Wildfire Recovery and Debris Removal

The wildfire recovery operations were divided into two phases. Phase 1 comprised the immediate response efforts and included firefighters' efforts to contain the fire and the ODOT's hazardous waste removal and initial roadway cleanup by pushing trees and other debris off to the side to provide roadway access for essential personnel and equipment. Note that ODOT did not remove debris from the corridors during Phase 1. Also, the amounts of debris and trees moved by ODOT in this phase were not measured [40].

After two weeks of Phase 1 operations and resulting road closure to the public, Highway 138 was reopened. Some areas, such as between the Oregon 230 junction (milepost 23-83) and Swiftwater Park, had only a single lane open, resulting in an approximately 45-minute delay. Meanwhile, hazardous rocks and burned trees remained that could fall onto the roadway. During the Phase 1 recovery operations, and in preparation for Phase 2, ODOT surveyed the damage in areas that were accessible along the roadway corridor and reported on the several hazardous trees that needed to be removed [41]. Those operations were performed in Phase 2.

Figure 4.2: Photos of damage in the Susan Creek area by ODOT [40]

The Phase 2 operation consisted of right-of-way hazardous tree removal and private property debris removal. The hazardous tree removal included the removal of fallen trees, slash, and debris caused by the wildfire along the 120-mile corridor of the affected roadway . It also included identifying and cutting hazardous trees along public roadways that would affect travel safety, where ODOT right-of-way ranged between 80 to 200 ft wide. However, the actual distance of ODOT's work zone from the road varied depending on the slope of the terrain and height of trees. Accordingly, the actual work zone for the recovery operations during Phase 2 went beyond ODOT's right-of-way in some areas [40]. Manual methods were used to remove hazardous trees along the roadway, while heavy equipment removed trees and rocks from the roadway.

4.2 Fire Modeling

This section describes the project's efforts to model the Archie Creek Fire, along with the data used and assumptions made. Specifically, the following assumptions were made regarding the data related to various aspects of fire modeling, including fuel data, ignition point, wind direction and speed, fuel moisture, and foliar moisture content.

- Fuel Data: The landscape (LCP) file of the impacted area was acquired from the U.S. government website called LANDFIRE. The LCP file included the necessary data to run the fire simulation in FlamMap, such as elevation, slope, canopy cover, canopy base height, and canopy base density.
- Ignition Point: According to incident reports, the coordinates of the fire ignition point were (43.334 latitude, -122.788 longitude) or (517185.88 UTM Easting, 4797927.83 UTM Northing) in Universal Transverse Mercator (UTM) coordinates. While these coordinates are considered to be the known origin point of the Archie Creek Fire, noted that the Star Mountain Fire merged with this fire, causing explosive fire activity in the first 24 hours [42]. Because of a lack of data available for the Star Mountain Fire, the merging of the two wildfires was not modeled, and only the original Archie

Creek Fire with its ignition point was modeled in FlamMap. This resulted in differences in spread between the actual fire and the model.

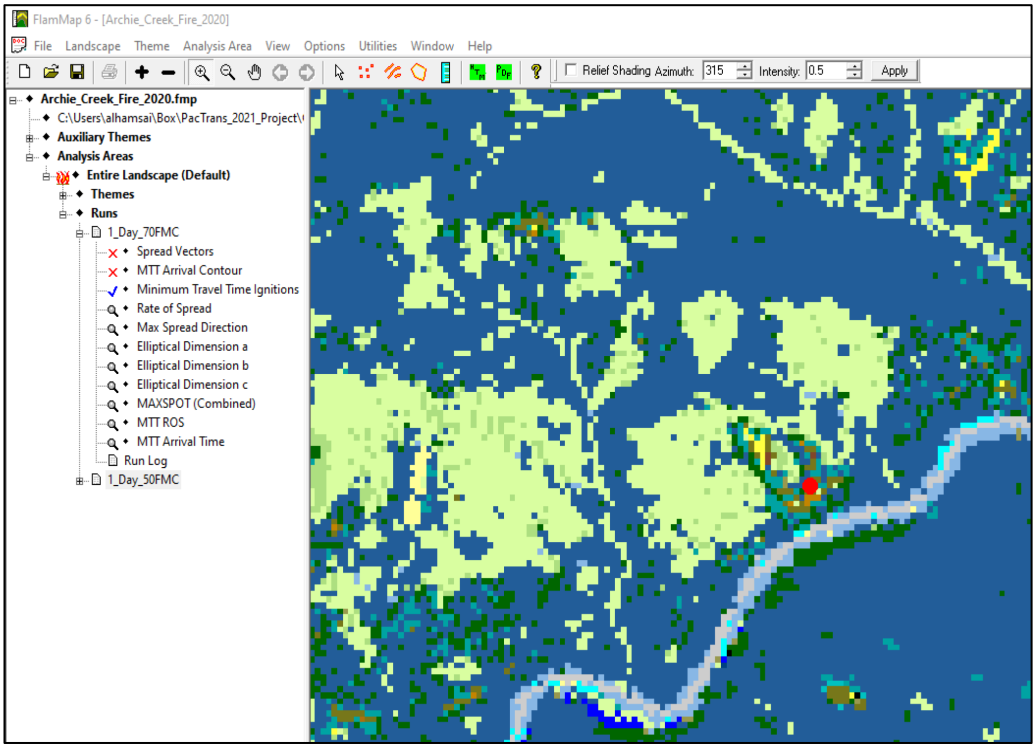


Figure 4.3: FlamMap screenshot showing the ignition point of the Archie Creek Fire

- <u>Wind Direction and Speed:</u> There were two distinctive wind condition phases during the fire, with gusty winds in the early days of the fire [43] [44] and breezy winds for the remainder of the fire [45]. Because FlamMap considers variables such as wind speed and direction constant in time, two separate simulations were conducted. The first one was for the first 1,440 minutes (one day) with 60 mph wind speeds to capture the explosiveness of the first day of the Archie Creek fire. The second simulation was for the maximum duration available in FlamMap, 10,000 minutes, which was close to seven days with 30 mph wind speeds to capture the average wind speed during the active fire. A constant value of 90 degrees (azimuth) was used to model the wind direction.

- Fuel Moisture: A default file was created to simulate dry fuel conditions with the assumption that fuel moisture did not change over time.
- Foliar Moisture Content: Foliar moisture dontent values used for crown fire risk assessment vary between 75 percent to 130 percent [46]. Because the Archie Creek fire had record-breaking dry conditions [43], the minimum value of 75 percent was used here.

As mentioned before, two fire model runs were performed with identical data values except for wind speed. For the first run (one-day duration), a 60-mph wind speed was used, and a 30-mph wind speed was used for the second run (seven-day duration). These are shown in figures 4.4 and 4.5, respectively.

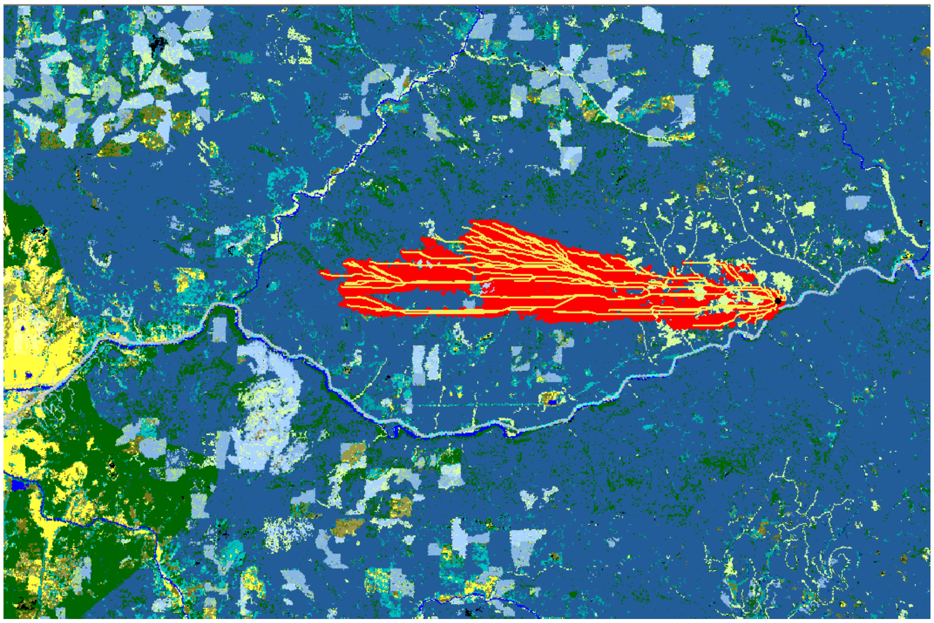


Figure 4.4: Fire model spread after one day

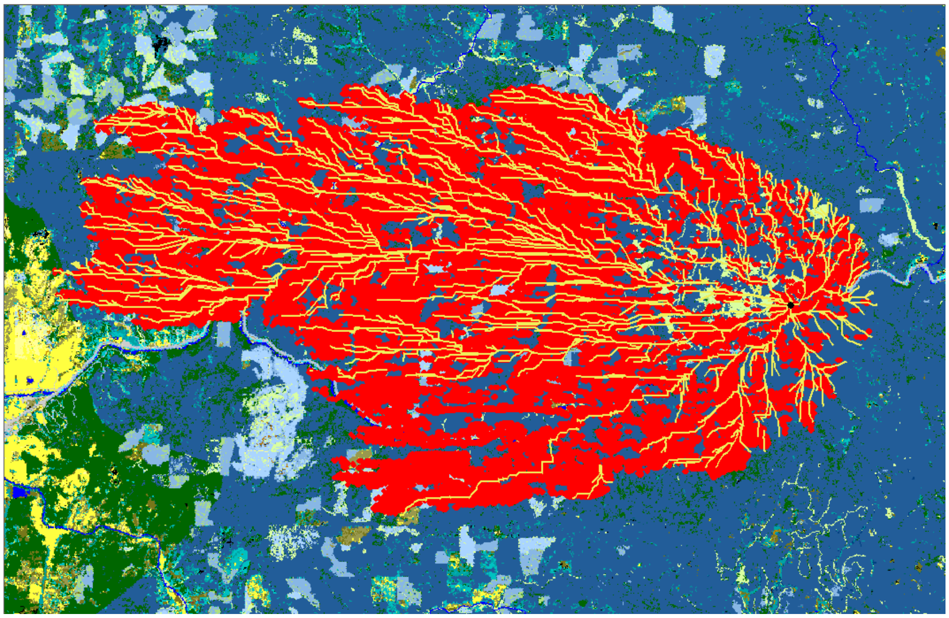


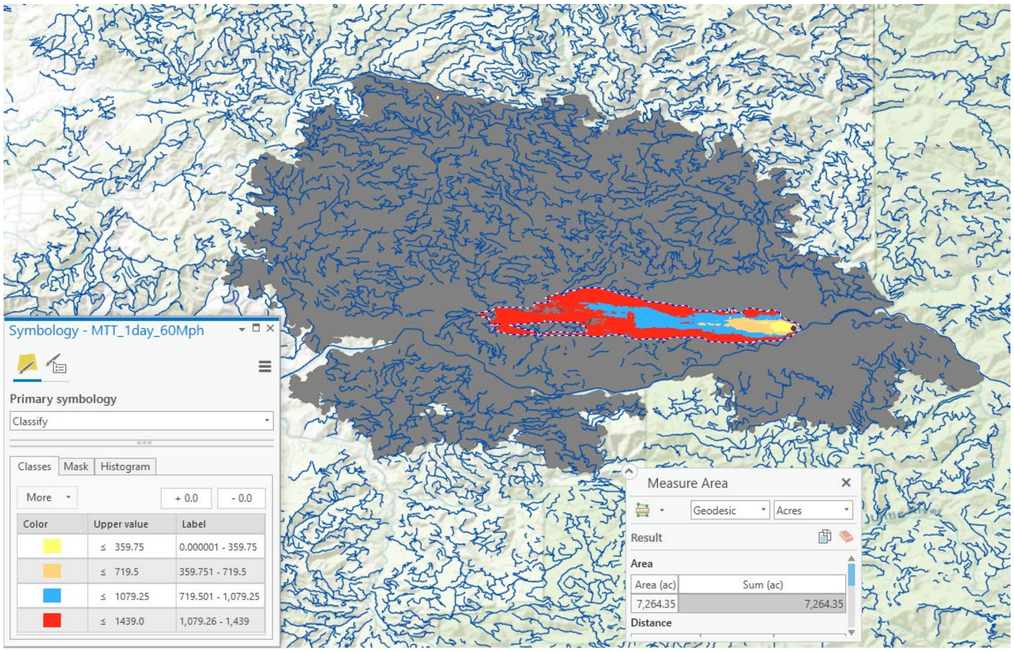
Figure 4.5: Fire model spread after seven days

To understand the fire models in comparison with the actual Archie Creek Fire, the FlamMap outputs showing the fire spread with time were imported into ArcGIS Pro for geospatial analysis, as described in the next section.

4.3 Geospatial Analysis

The outputs obtained from FlamMap were transferred into ArcGIS Pro for geospatial analysis as per the framework discussed in Chapter 3. For validation purposes, these results were compared to a GIS map of the Archie Creek Fire that was obtained from the National Interagency Fire Center. This map displayed only the final parameters of the fire and not the spread of the fire with time. In addition, Oregon road network GIS data were acquired from the ODOT website and integrated into ArcGIS Pro for analysis with the Network Analyst tool.

The fire model output MTT, shown in figures 4.6 and 4.7, was divided into four classes with equal intervals of 360 minutes (six hours). The direction of fire spread in the model was westward, similar to the actual Archie Creek fire (the gray colored area). Since no GIS map of the Archie Creek Fire progress with time was available, the spread patterns could not be more closely compared.



Primary symbology: Classify

Color	Upper value	Label
🟨	≤ 359.75	0.000001 - 359.75
🟧	≤ 719.5	359.751 - 719.5
🟦	≤ 1079.25	719.501 - 1,079.25
🟥	≤ 1439.0	1,079.26 - 1,439

Geodesic
Acres

Area

Area (ac)	Sum (ac)
7,264.35	7,264.35

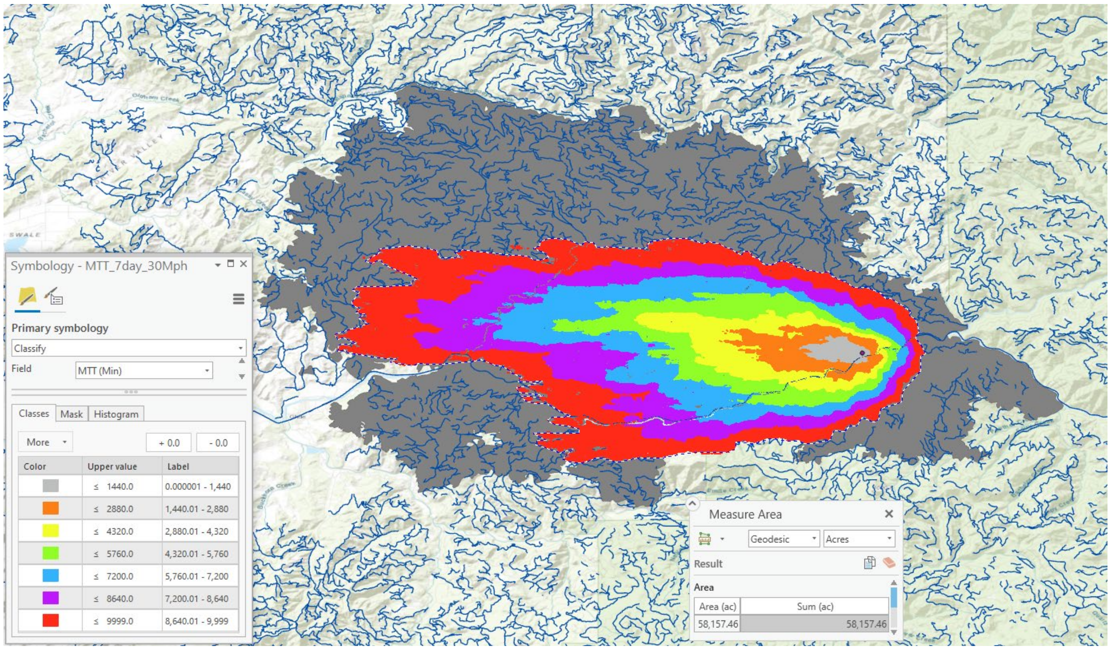
Figure 4.6: MTT output after one day

The modeled fire spread area was roughly 7,250 acres, which was only about 7.25 percent of the actual size of the first day of the Archie Creek fire. This difference can be attributed to the following factors:

- <u>The Star Mountain Fire:</u> The Star Mountain Fire north of Highway 138 East and Susan Creek Road was not integrated into the fire model because of a lack of available data. The Star Mountain Fire reportedly reached the size of 300 acres [47] before merging with the Archie Creek Fire at around 11:50 am on September 8, 2020 (four hours into the Archie Creek Fire), and it eventually grew to 8,000 acres [48]. It is unknown how much of the total 100,000 acres (the size of the Archie Creek Fire at 24 hours) can be attributed to the Star Creek Mountain Fire. However, given the explosive growth of the Labor Day fires in general and the Archie Creek Fire in particular, it could be assumed that the Star Mountain Fire accounted for a significant portion of the size difference between the fire model and the actual fire.

- Fuel Moisture: The model run conducted in this project used the default fuel moisture file, which did not accurately capture "the extremely dry fuels" [49] that were a major factor in the explosiveness of the Archie Creek Fire.

The 24-hour fire model run, shown in figure 4.6, had a reach close to 9.5 miles, affecting multiple roadways in its path, including a small portion of Highway 138 East.



Symbology - MTT_7day_30Mph

Primary symbology

Classify

Field MTT (Min)

Color	Upper value	Label
⬜	≤ 1440.0	0.000001 - 1,440
🟧	≤ 2880.0	1,440.01 - 2,880
🟨	≤ 4320.0	2,880.01 - 4,320
🟩	≤ 5760.0	4,320.01 - 5,760
🟦	≤ 7200.0	5,760.01 - 7,200
🟪	≤ 8640.0	7,200.01 - 8,640
🟥	≤ 9999.0	8,640.01 - 9,999

Measure Area

Geodesic

Acres

Result

Area

Area (ac)	Sum (ac)
58,157.46	58,157.46

Figure 4.7: MTT output at seven days

The seven-day fire model run, shown in figure 4.7, was divided into seven intervals. The first six intervals had equal values of 1,440 minutes (one day), while the seventh interval was 1,359 minutes (0.95 day). The spread of the fire during the first 24 hours was much smaller than that of the first fire model (24-hour duration) because of the use of an average wind speed of 30 mph.

The direction of fire model spread was westward. Since environmental conditions remained constant in FlamMap, any change in wind direction during the first seven days of the fire was not captured in the fire model. This could be the reason for the difference in the fire spread direction, as the real fire expanded more toward the northwest. A closer comparison of the fire spread patterns could not be performed because there was no available GIS map of the Archie Creek Fire's progress with time,

The model fire spread covered about 58,000 acres after seeven days, which was about 48 percent of the actual size of the Archie Creek fire on its seventh day. This difference could have been due to the same factors previously mentioned. The seven-day fire model's farthest reach was 14 miles from the ignition point toward the west and 1.7 miles toward the east. Table 4.2 shows the fire model's impact on Highway 138 East with time.

Table 4.2: Affected length of highway due to the Archie Creek Fire

Time (days)	**Affected Length of Highway 138 E (miles)**
1	0.5
2	1.9
3	3.6
4	5
5	7.5
6	9.5
7	14

4.4 Recovery Operations Analysis

The recovery operations analysis for the roadway network after the Archie Creek fire included estimating debris and hazardous trees, determining the shortest route for evacuation and first responder access, and supporting debris removal operations. These two analyses are discussed in this section.

4.4.1 Debris and Hazard Tree Estimation

Wildfire debris can be quantified through field observations after a wildfire event. Although no existing historical data about wildfire debris on roads or reliable figures for Phase 1 debris removal emergency efforts [40] were available, an ODOT report mentioned that the number of trees falling on the highway during the Archie Creek Fire was more than a hundred, with some of them having a diameter of more than 3 feet [50]. Therefore, to plan for debris removal operations, the following assumptions were made:

- The total number of trees fallen on the highway was assumed to be 200. Therefore, each mile of the 20 miles affected by the wildfire was impacted with ten fallen trees of the length and diameter shown in table 4.3.
- The previous assumption was also applied to the inner road network.
- Fallen rocks and smaller branches and brush were not considered in this estimate.

Table 4.3: Tree characteristics

No. of trees	Length (ft)	Diameter (ft)
3	30	1
2	50	2
3	70	3
2	90	4

The trees being removed were hazardous and within striking distance of the road. Different factors, such as the height of the tree and slope of the terrain, impact how far from the roadway that trees need to be removed to make the roadway safe. An estimated 140,000 hazard trees needed to be removed after the fires in 2020, of which Archie Creek was a part [40]. To plan for immediate tree removal and debris operations, the shortest route for first responders needs to be determined, which is described in the following section.

4.4.2 Responder Travel Alternative Analysis

After the Archie Creek Fire map was studied, the Smith Springs Campground area was chosen as the destination for the first responder rescue operations. Smith Springs Campground is north of Highway 138 E, as shown in figure 4.8.

Figure 4.8: Location of the Smith Springs Campground

The campground is surrounded by forest lands. According to the fire model of the Archie Creek Fire, the fire reached the Smith Springs Campground on the seventh day of the fire, as shown in figure 4.9.

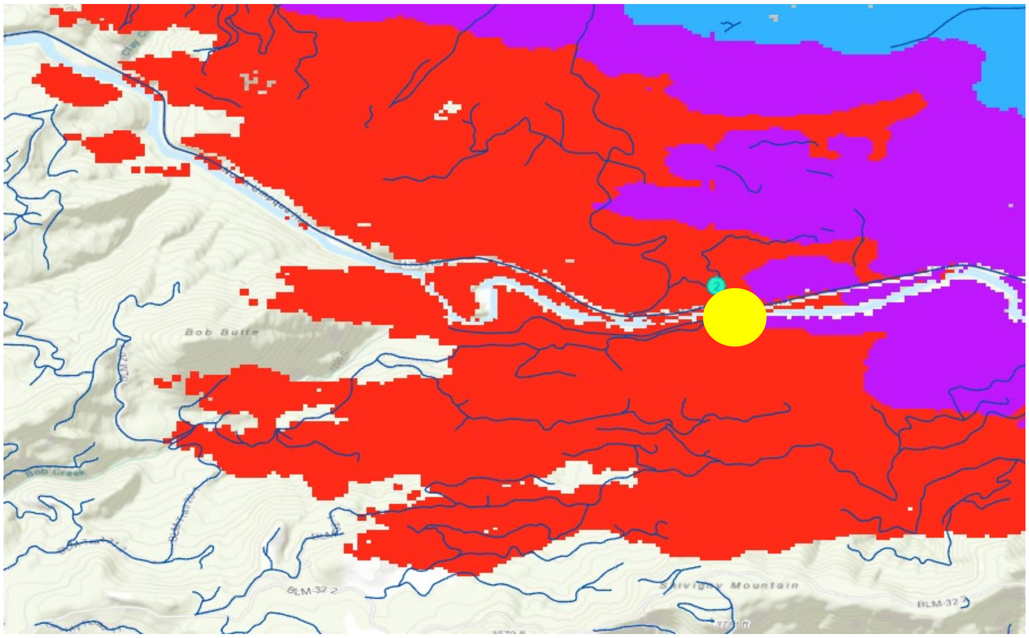


Figure 4.9: Smith Springs Campground location in the fire model

The location, highlighted in yellow in figure 4.9 and located north of the Smith Springs Campground, was the assumed destination for the rescue and evacuation operations. Using the Network Analyst tool in ArcGIS Pro, the fastest path, referred to as Path #1 in figures 4.10 and 4.11, between the Glide fire station and the Smith Springs Campground, was calculated. Path #1 was 11.4 miles, which means that at an average speed of 35 mph [51], first responders could reach their destination in about 20 minutes.

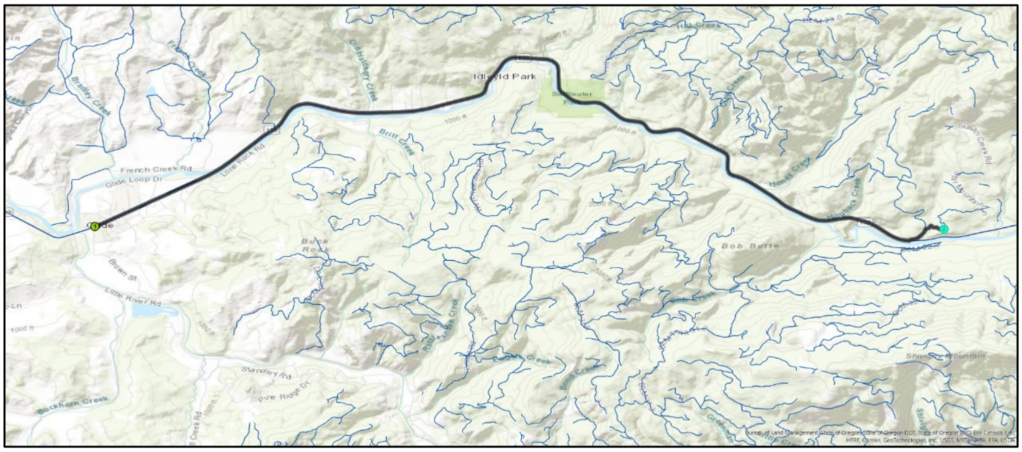


Figure 4.10: Path #1 between the Glide fire station and the campground

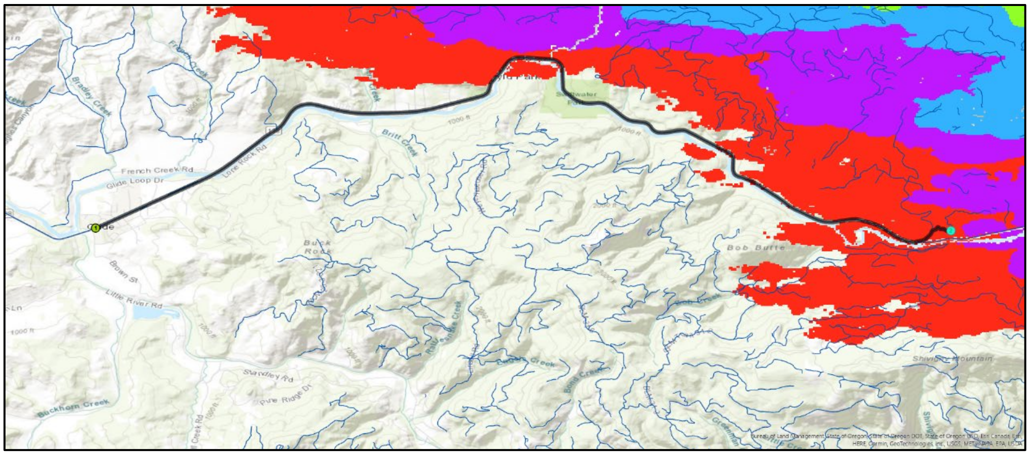


Figure 4.11: Shortest Path #1 affected by the fire

As seen in figure 4.11, parts of Path #1 were impacted by the wildfire. Using the measurement tool in ArcGIS Pro, the lengths of the affected sections of Path #1 were calculated as shown in table 4.4.

Table 4.4: Roadway impacts of the fire

Type of road	**Blocked Segment**	**Effected length (miles)**	**No. of fallen trees**
Highway 138 E	Segment A	1.1	11
Highway 138 E	Segment B	0.23	2
Highway 138 E	Segment C	0.27	3
Highway 138 E	Segment E	0.95	10
BLM Rd 26-2-22.2	Segment F	0.55	5
Total		**3.1**	**31**

Following the hypothesis that every mile of the road that was affected by the wildfire had ten fallen trees, it could be assumed that Path #1 was blocked by 31 trees, spread over five road segments (see figure 4.12).

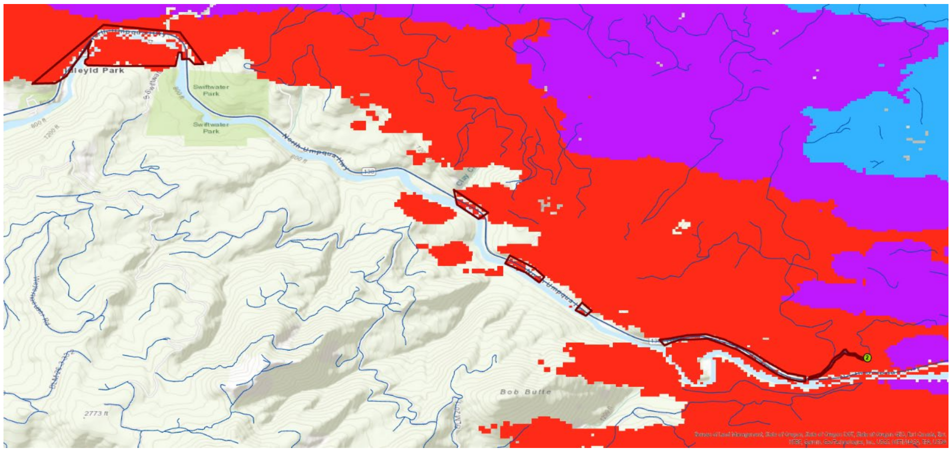


Figure 4.12: Blocked segments A to F in Path #1 from left to right

As an alternative to using Path #1 for rescue operations, first responders could also use an alternative path, as shown in figure 4.13. After line barriers had been created around the blocked parts of Path #1 in the GIS map, an alternative shortest path (Path #2) was calculated with the same tools in ArcGIS Pro (see figure 4.14).

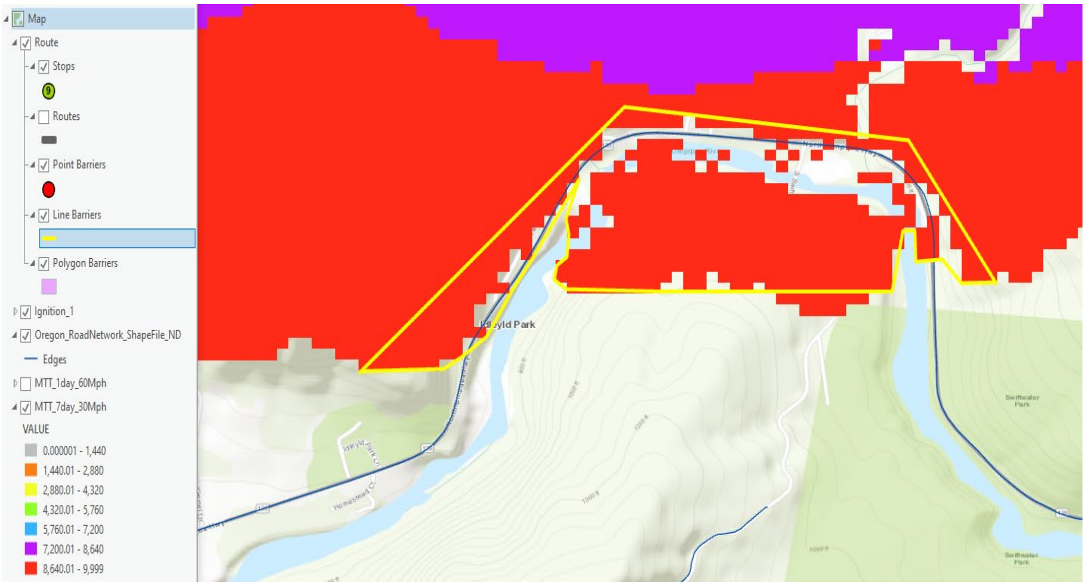


Figure 4.13: Line barriers around Segment A on Highway 138 East

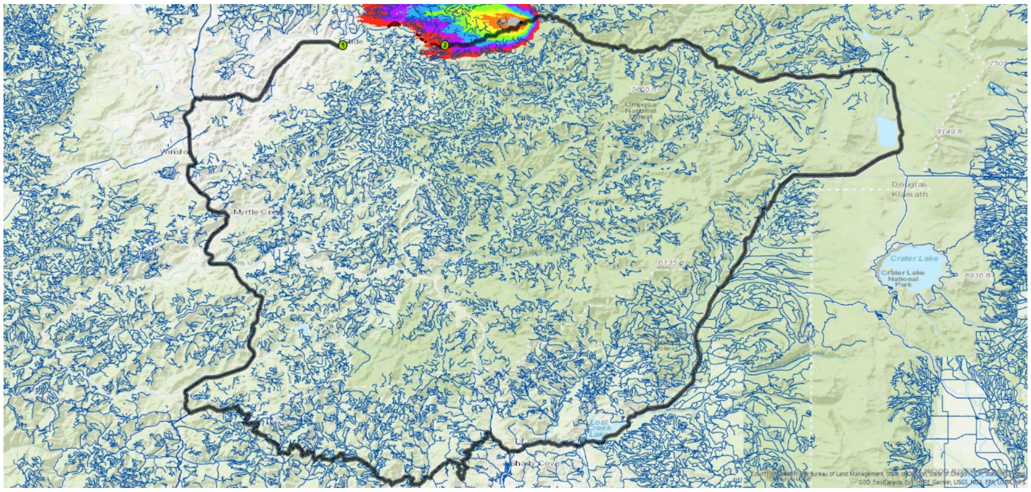


Figure 4.14 Shortest Path #2

Path #2 would provide the possibility for first responders to circumvent the blocked route. However, in this particular case, the best alternative route was 233.8 miles, which could take up to six and a half to seven hours for first responders to reach their destination at the same average speed of 35 mph as on Path #1.

Furthermore, there as a 1.35-mile section on Path #2 that was impacted by the fire model's seventh-day activities (figure 4.15). This would require some time to clear the road of 13 to 14 trees.

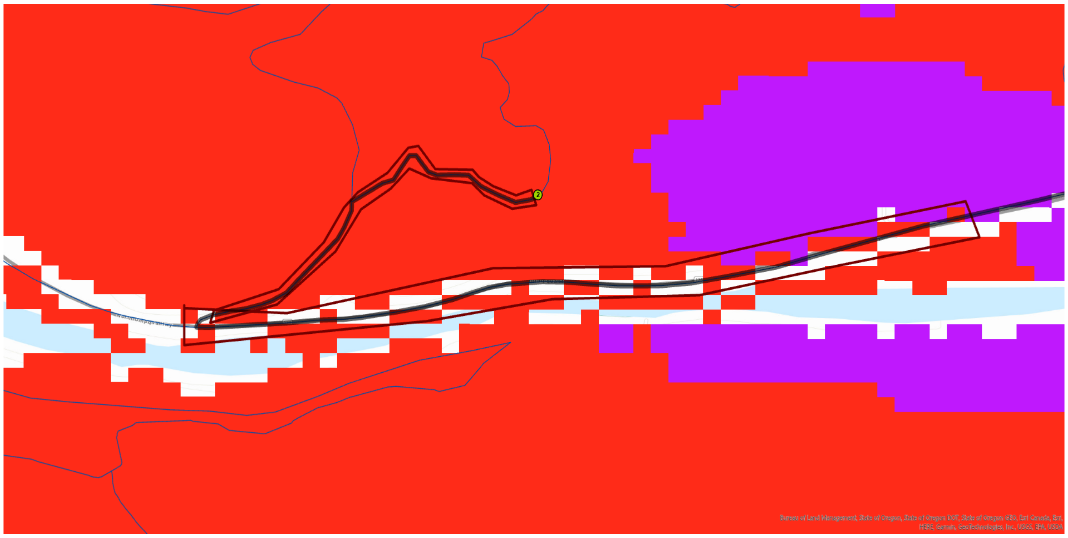


Figure 4.15: Impacts of portions of Path #2

Looking at the results obtained from these simulations, it was clear that Path #1 would be the best route in this case. However, there could be situations in which choosing the longer alternative route, with no or little damage from wildfire debris, would lead to shorter travel times to achieve optimal rescue and evacuation operations.

This case study was conducted to showcase how the geospatial analysis could be integrated with fire simulations to help identify the best route for first responders to use to reach affected areas after wildfires.

Chapter 5: Conclusions

This report describes the development of a simulation-based framework that aims to quantify the damage to roadways from wildfires to help first responders and emergency managers find the fastest and safest route to affected areas. To this end, the framework includes a fire-simulation component that was implemented with FlamMap software, and a geospatial component that was implemented using ArcGIS Pro. Following the development of the framework, it was tested using information obtained for the 2020 Archie Creek Fire in Oregon to demonstrate its applicability.

FlamMap simulates the spread of wildfires by considering a variety of variables such as local topography, fuel availability, wind direction. It provides outputs in terms of the areas affected by the fire as it spreads. While not all of the variables were accurately used in the simulation, the results did generally track the real-world fire based on a GIS-based comparison using available data. The results indicated that fire simulation can provide valuable insight to decision-makers about emergency planning.

Once the fire simulation was completed, the results obtained were overlaid upon the road network map in the affected area to identify which road segments were within the fire-affected areas. This process provided information related to the lengths and locations of damaged roadways, along with estimates of debris amounts for clearance and hazard tree counts to be harvested. These results can inform the calculation of recovery operations that need to occur before the affected roads can be fully opened to the public. This analysis can also provide travel time estimates for first responders and evacuees by considering the impacts of road blockages that are caused by fires.

This project accomplished its major goals of simulating wildfires in Oregon and integrating the obtained results with geospatial analysis to identify the impact of a fire on the local transportation infrastructure. While a simulation of recovery operations was not performed because of a lack of data for the case study, that is a future effort that will be pursued by the research team. Future work will also focus on resource allocation before a disaster to minimize recovery times and evacuation times in the aftermath of wildfire events. It is anticipated that the developed framework can provide insights that can help with decision-making for evacuees, first responders, emergency managers, and debris contractors during and in the aftermath of wildfires.

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