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Research Article

Setting Wildfire Evacuation Trigger Points Using Fire Spread Modeling and GIS

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Abstract

Warning communities in the path of an advancing wildfire is a challenging problem. Decision makers need the most current information available to determine who should evacuate, when they should leave and what type of order to issue (e.g. mandatory, recommended, voluntary). This paper presents a new method for delimiting wildfire evacuation trigger points using fire spread modeling and GIS. Using data on wind, topography, and fuel in conjunction with estimated evacuation time, a trigger buffer can be computed for a community whereby an evacuation is recommended if a fire crosses the edge of the buffer. A case study is presented for the Corral Canyon section of the 1996 Calabasas Fire near Malibu, California, USA. The paper concludes with a discussion of the strengths and weaknesses of this approach.

1 Introduction

Recent large wildfires in the western United States have drawn attention to the growing threat that this hazard poses to people and property in many communities. In 2002, the Hayman Fire (Colorado), Rodeo Fire (Arizona) and Biscuit Fire (Oregon) set the record for the largest fire in each state's history. The devastating 2002 fires were followed by the 2003 Southern California Fire Complex, a set of large fires in Southern California that resulted in 24 fatalities, the loss of 3,710 homes, and the evacuation of over a hundred thousand people (Blackwell and Tuttle 2003). One of these fires, the Cedar Fire

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in San Diego County, was the largest fire in California's history. The recent increase in the occurrence of large fires in the western United States is generally attributed to fire suppression and accumulated fuel, although long-term climate patterns (Whitlock et al. 2003) and short-term extreme fire weather events (Moritz et al. 2004) are important factors in many areas. In any case, decades of steadily increasing exurban development in fire-prone areas greatly exacerbated the human impact of these fires (Cova et al. 2004).

Warning communities in the path of an advancing wildfire is a challenging problem. Emergency responders arriving on the scene of an event must rapidly acquire and synthesize information from a variety of sources to protect people and property. Decisions are generally made based on personal judgment using limited information about fire location and threatened communities. An incident commander needs the most current information available to determine who should evacuate, when they should leave, and what type of order to issue (e.g. mandatory, recommended, voluntary). Although evacuating everyone would seem to be the safest approach, it is important to not "over evacuate" and send too many vehicles onto often low-capacity roads (Cova and Church 1997). Ideally, evacuations should be orderly and proceed from the most threatened residents to the least threatened. Changing winds and capricious fire behavior can complicate this straightforward goal.

Emergency responders face many decisions in fighting a wildfire, but three important questions arise when formulating evacuation orders: who is at risk, how long will it take to evacuate, and how much time is available? These questions are often addressed together using a concept called an *evacuation trigger point*. A trigger point is an agreed-upon landmark whereby an evacuation is recommended if an advancing fire crosses this point. Roads, ridgelines, and rivers make good trigger points, but any prominent landscape feature will suffice. Trigger points are generally determined on-the-fly at the time of an event, but comprehensive emergency plans may identify candidate points in advance. In cases when there is not enough time to set trigger points in front of an advancing wildfire, evacuation orders may be issued immediately upon assessing the situation.

Determining who is at risk and the estimated time to evacuate (the first two questions above) represent a significant hazards research focus, but little work exists on determining how much time is available to evacuate a community in the face of an advancing wildfire (Kim et al. 2006). Research on this topic would aid in systematically deriving wildfire evacuation trigger points using a geographic information system (GIS). *HURREVAC* is one example of a GIS-based system that is used to set evacuation trigger points for coastal areas threatened by hurricanes (FEMA 2000). Although this approach has not been applied in a wildfire context, systematically deriving evacuation trigger points using GIS could improve community safety in fire-prone areas. In general, integrating physical and social process models to aid in managing emergencies represents a current application challenge in GIScience (Radke et al. 2000, Cutter 2003).

This paper describes a new method for delimiting wildfire evacuation trigger points using fire-spread modeling and GIS. The first section of the paper provides background on evacuation trigger points, evacuation time estimation and fire-spread modeling. The next section presents a method for deriving wildfire evacuation trigger buffers around a location or community given data on wind, topography and fuel. A case study is presented for the 1996 Calabasas Fire. The paper concludes with a discussion of the strengths and limitations of this approach.

2 Background

2.1 Setting Evacuation Triggers Using GIS

As noted, the best example of setting evacuation triggers using GIS is the Federal Emergency Management Agency's *HURREVAC* (FEMA 2000). This system relies on a simple equation to determine the radius of an evacuation buffer for counties along a coastline. This circular buffer (referred to as a *decision arc*) is based on a prior evacuation time estimate (ETE) for each county in conjunction with real-time meteorological data on a hurricane's speed and direction. A buffer is computed for each county's centroid by multiplying the speed of the hurricane toward the county by the estimated evacuation time plus an additional hour for safety. The result is a buffer radius in nautical miles as follows:

$$r = (t + 1) \cdot s \tag{1}$$

where r is the radius of the evacuation buffer, t is the time required to evacuate the county in hours, and s is the speed in nautical miles per hour of the hurricane toward the county. The additional hour (e.g. $t + 1$) allows for uncertainty in the estimated evacuation time. For example, if a hurricane is moving toward a county with an estimated evacuation time of 3 hours at a speed of 20 nautical miles per hour, the buffer would have a radius of 80 nautical miles. If the outer edge of a hurricane touches a county's buffer, an evacuation order is recommended for that county.

Although there is currently no system for setting wildfire evacuation triggers analogous to *HURREVAC*, the concept of a "decision arc" (or buffer) may have application in a wildfire context. A key difference is scale, as wildfires result in much smaller evacuations, generally on the order of a neighborhood or community. However, large fires can result in numerous evacuations over the course of the event. An *evacuation trigger buffer* is defined here as a set of points (or arc) that circumscribes a community whereby an evacuation order is recommended if a wildfire crosses the buffer's edge. In theory, a wildfire evacuation trigger buffer could be centered on a structure, community, town or other asset.

Another difference between hurricanes and wildfires is the geometry of the trigger buffer. In high winds, complex topography and heterogeneous fuels, wildfires can spread in a very irregular manner. This would lead the shape of a trigger buffer to be very irregular, as it might follow a ridgeline, extend into the wind, or have holes where there is insufficient fuel. In addition, evacuation is not always the best protective action in a wildfire (Krusel and Petris 1992), and it is easy to imagine nested buffers in a wildfire context where an outer buffer triggers an evacuation, but an inner buffer triggers a "shelter-in-place" recommendation because there is insufficient time to safely evacuate and residents should seek the best available shelter.

2.2 Evacuation Research

A second related area of research is evacuation modeling. Evacuation research is an interdisciplinary field that can be divided into two principal foci stemming from a behavioral and engineering perspective. The concern of the behavioral perspective is studying how people behave under different warning and hazard conditions. This area has advanced significantly over the last 20 years, and evacuation researchers now understand "warning and response" with a high degree of confidence (Sorensen 2000). The principal concern from an engineering perspective is estimating the time it will take to evacuate a defined area given traffic generation, trip distribution, vehicle routing and supporting transportation infrastructure. Simulation modeling is the principal approach in this perspective (Southworth 1991), and studies are performed by traffic engineers for many hazards. Current research in this area focuses on incorporating findings from the behavioral perspective into simulation models and analyzing the benefits of traffic routing strategies (Wolshon 2001, Cova and Johnson 2003).

2.3 Fire Spread Modeling

Fire spread modeling is the most relevant research area in developing a GIS-based wildfire evacuation-trigger method. Fire spread models estimate the rate of spread of fire through surface fuels based on conservation of energy. The rate of spread of fire is related to the ratio of the energy received by unignited fuel ahead of the fire over the energy required to ignite fuel at the leading edge of the fire (Williams 1976). Rothermel (1972) created a model that combined conservation of energy and empirical measurements of fire spread in wind tunnel experiments. Current operational fire spread models (e.g. Finney 1998) rely on the rate of spread equation developed by Rothermel (1972). The rate of spread of a fire through a fuel bed in the heading direction is calculated as:

$$ROS = \frac{I_R \xi (1 + \Phi_w + \Phi_s)}{\rho_b \varepsilon Q_{ig}} \quad (2)$$

where *ROS* is the rate of spread in m/s, I_R is the reaction intensity in $J/m^2 \cdot s$, ξ is the propagating flux ratio, Φ_w is the wind factor, Φ_s is the slope factor, ρ_b is the oven-dry bulk density of the fuel in kg/m^3, ε is the effective heating number of the fuel, and Q_{ig} is the heat of preignition of the fuel, in J/kg.

Van Wagner (1969) established the use of an ellipse to model two-dimensional fire spread. Starting from an ignition point at one of the foci of an ellipse, the rate of spread in any direction can be described using the following two equations:

$$x = a \sin \theta \quad (3)$$

$$y = b \cos \theta + c \quad (4)$$

where y is parallel to the direction of the heading fire, x is perpendicular to the direction of the heading fire, and θ is the angle with respect to the direction of the heading fire. The dimensions a, b, and c are shown in Figure 1. Anderson (1983) developed relationships between wind speed, slope, and the ratio of b to a in a semi-ellipse. These relationships were adapted to the single ellipse by Finney (1998), with an adjustment to the b-to-a ratio to create a circular fire spread shape for no slope and no wind conditions.

3 Methods

This section describes the method for delimiting an evacuation trigger buffer around a point, line, or area given data on wind, topography and fuel. The method does not rely on forecasting fire position for a specific event, as our goal was to delimit a trigger buffer that would have value prior to (or during) any wildfire. As such, a given buffer has value for any wildfire that might ignite (outside the buffer) under the given conditions.

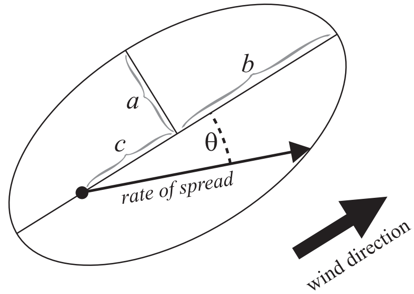


Figure 1 Elliptical parameters for calculating two-dimensional fire spread parallel to a slope. The parameters *θ, a, b,* and *c* correspond to variables in equations 3 and 4. The rate of spread for angle *θ* is displayed. The maximum rate of spread is *b* + *c* when *θ* is equal to 0

The approach has three steps: (1) compute the rate of spread for every cell (in eight directions); (2) create a rate of spread network that represents the shortest time for fire to spread from a cell to an adjacent cell; and (3) calculate an evacuation trigger buffer using an evacuation time estimate as input. This section reviews these three steps in more detail and provides theoretical examples of computing trigger buffers given wind, fuel and topographic conditions.

3.1 Step 1: Fire Spread Modeling

The *FLAMMAP* software package developed by the USDA Forest Service Fire Sciences Lab is ideally suited for our purposes. *FLAMMAP* is based on the *FARSITE* model (Finney 1998) and computes the maximum rate of spread, the azimuth of the maximum rate of spread, and the elliptical parameters *a*, *b*, and *c* in equations 3 and 4. In the context of our method, these five parameters are calculated for each cell in a raster, given data on slope, aspect, fuels and wind. Maximum rate of spread, the azimuth of the maximum rate of spread, and the elliptical parameters are then read into the Interactive Data Language (IDL) environment and used to calculate rate of spread in eight directions (N, NE, E, SE, S, SW, W, NW) for each cell using equations 3 and 4. An IDL script is also used to adjust the rate of spread in each direction from vectors parallel to the slope of each cell to vectors parallel to the plane. Figure 2 depicts the results of this calculation for one cell where the spread rate in each direction is in meters per minute.

3.2 Step 2: Creating a Fire-Spread Network

The results of step 1 are converted into a network-based representation of fire spread (Finney 2002). The network arcs depict the minimum time (in terms of rate of spread) that it would take for fire to travel between adjacent cell centers in eight directions (Moore's neighborhood) for every cell under the given wind conditions. This is accomplished by converting the rate of spread in meters per minute for each cell into the time for fire to travel between adjacent cell centers using the resolution of the raster:

$$t_{ij} = \left(\frac{d_{ik}}{r_{ik}} + \frac{d_{jl}}{r_{jl}} \right) \qquad (5)$$

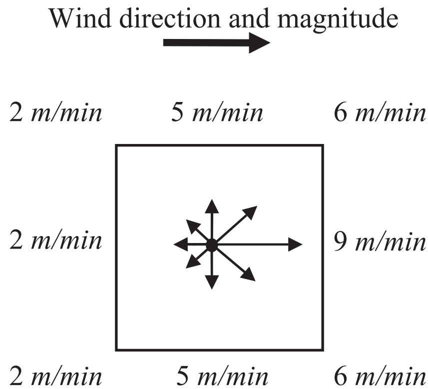
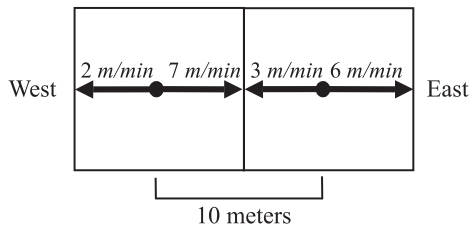


Figure 2 Example rate of spread calculation in eight directions based on wind speed, wind direction, and a cell's fuel type and slope

where t_{ij} is the time for fire to travel from cell center i to cell center j, d_{ik} is the distance from cell center i to the edge of the cell in direction k, r_{ik} is the rate of spread for cell i in direction k, d_{jl} is the distance from cell center j to the edge of the cell in direction l, and r_{jl} is the rate of spread for cell j in direction l. The travel-time for fire to spread between two adjacent cells is thus a composite of the rate of spread across part of one cell and the rate of spread across part of the other cell as shown in Figure 3. This calculation is asymmetric because fire spread-rates vary by direction. For example, fire spreads slower downhill or upwind and faster uphill or downwind. For this reason, the network is "doubly linked" between cell centers. This step also takes into consideration the fact that the diagonal distance from a cell center to a corner point (d_{jk}) is 1.414 times the distance from the cell to one of its edges in the four cardinal directions.

3.3 Step 3: Deriving a Wildfire Evacuation Trigger Buffer

The third step of the procedure is to determine the trigger buffer given an estimated evacuation time. This is accomplished by computing the shortest path tree for every cell using a shortest path algorithm. However, to get the shortest time for fire to spread *to* a cell (or community), the travel time for every link in the network computed in step 2 must be reversed (Figure 3). This allows one to calculate the reverse shortest time (and path) for fire to move across the landscape *toward* a cell, or set of cells, from any other cell. We use Dijkstra's (1959) shortest path algorithm with a modified terminating condition to generate the shortest path tree. Thus, for a given origin cell (community), rather than terminating when a destination cell is reached (e.g. a shortest path), the algorithm terminates at the first cell that exceeds the original evacuation time estimate. At this point, the entire shortest path tree is recorded. This tree represents the set of cells where fire could reach the original cell in less than the time it would take to evacuate (Figure 4a). An evacuation trigger buffer is then defined as the outer edges of these cells (Figure 4b). It is important to note that the edge of the buffer represents the cells where the fire "could" reach a given cell in less than the available time to evacuate rather than cells where the fire "will" reach the target cell. In other words, the path to the target cell is the shortest path that fire might travel and not necessarily the most likely path.



$$\text{East: } 1.5 = \left(\frac{5}{7} + \frac{5}{6}\right)$$

$$\text{West: } 4.2 = \left(\frac{5}{3} + \frac{5}{2}\right)$$

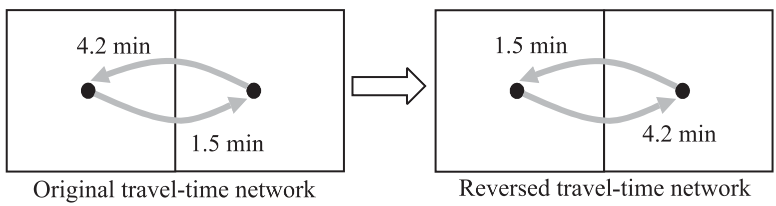


Figure 3 Calculating wildfire travel-time between adjacent cells in each direction and reversing the network

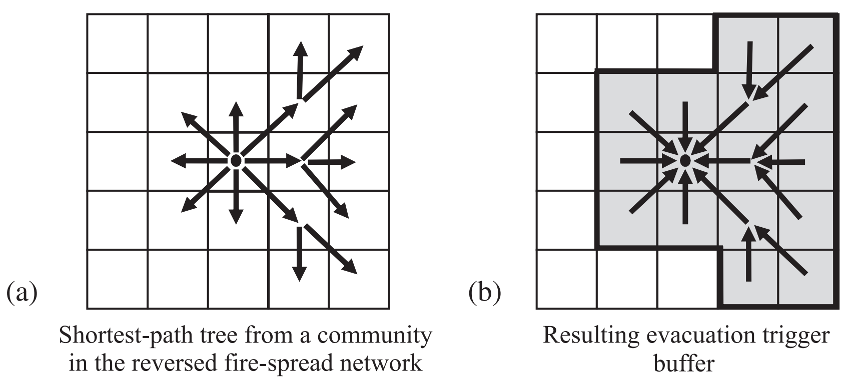


Figure 4 An evacuation trigger buffer in bold (right) derived from a reverse shortest-path fire-spread tree from the center cell (left).

The trigger buffer is also only valid for the given wind speed and direction, so it would have to be recomputed as wind conditions change.

Figure 5 depicts examples of computing an evacuation trigger buffer for a cell under a uniform fuel assumption while varying wind and slope conditions. The required warning time in all of these examples is 10 minutes. An Anderson (1982) system fuel class 1 (short grass) was used as the uniform fuel. The wind speeds in these examples are assumed to be at a height of 6.1 m (20 feet) above the terrain, in keeping with standard

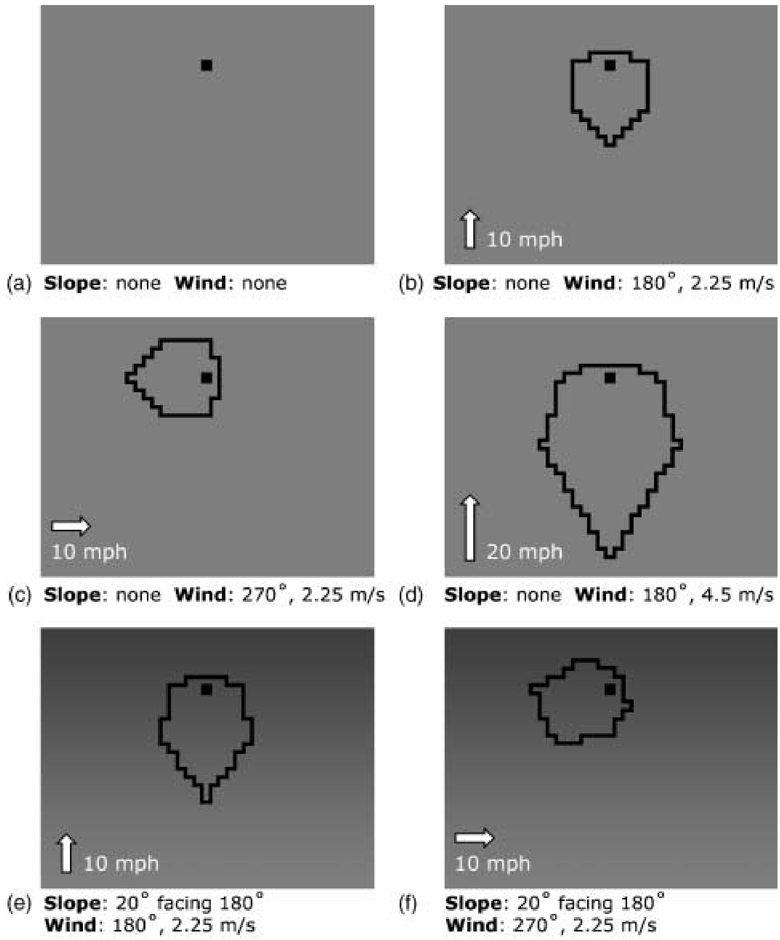


Figure 5 Computing 10-minute evacuation trigger buffers under varying wind and slope conditions in a 10 m raster

wind inputs for fire spread models. Dead fuel moisture for the example scenarios was set at 10% (mass of water/dry mass of vegetation). In figure 5a, there is no wind, and the terrain is flat. For this reason, fire spread rates are very slow (0.8 m/min) and the resulting trigger buffer is only one cell (10 m). In figure 5b, a 2.25 m/s (10 mph) southerly wind is introduced which serves to stretch the buffer into the wind, as a wildfire would be able to spread faster in a northerly direction. Figure 5c shows the buffer if the wind was from the west at 2.25 m/s. Figure 5d depicts the buffer given a southerly wind at 4.5 m/s (20 mph), or twice that of Figure 5b. In this case, the buffer is much larger, reflecting the increased rate of spread produced by higher wind speeds. Figure 5e introduces a 20 degree south-facing slope to the same wind condition as in Figure 5b. The buffer is slightly longer because a fire from the south could be rapidly driven upslope with a 2.25 m/s tailwind. Figure 5f shows an asymmetric buffer given a south-facing slope of 20 degrees but a 2.25 m/s westerly wind. In this case, the wind and slope are not working together to advance the fire, so the shape of the resulting buffer is skewed towards the southwest (lower left corner).

4 Case Study: Corral Canyon in the 1996 Calabasas Fire

To demonstrate the method in a more realistic context, evacuation trigger buffers were derived for a section of the 1996 Calabasas Fire in the Santa Monica Mountains of Southern California. This fire was ignited at approximately 1100 PDT on 21 October 1996 and quickly spread south under extreme Santa Ana conditions (i.e. strong, hot and dry winds). On 22 October after 1200 PDT, the fire burned northward due to a reversal in wind direction, rapidly climbing the side of Corral Canyon and overtaking a firefighting crew protecting a community at the top of the canyon (Bossert et al. 2000). Three crew members suffered burns and smoke inhalation; one was burned critically. Bossert et al. (2000) modeled this scenario using a 1.28 by 1.28 km landscape with 10 m resolution cells.

Trigger buffers for three hypothetical scenarios were derived based on the simulation landscape used by Bossert et al. (2000). All simulations used a 128 by 128 grid with a resolution of 10 m. This cell size matches the highest resolution digital elevation model (DEM) available for the area, a 10 m U.S. Geological Survey (USGS) DEM. Fuels were mapped at 20 m resolution using data from the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) acquired on 17 October 1996. To reconcile the resolutions of the DEM and fuels map, the fuels map was resampled to 10 m resolution.

The case study scenarios were created to closely approximate the topographic and meteorological conditions present when the canyon burned in the Calabasas Fire. In the first scenario, a uniform fuel bed of short grass was used, where Bossert et al.'s (2000) fuel map was used for the second and third scenarios. In all of the scenarios, the wind speed was set at 4.5 m/s (20 mph) from 180° (South), the approximate direction of the wind when the Calabasas Fire burned through Corral Canyon. Dead fuel moisture was set at 10% (mass of water/dry mass of vegetation), based on remote automated weather-station fuel-stick measurements in the area of the fire. Live-fuel moisture for the second and third scenarios was set at 60%, the critical live-fuel moisture for chamise (*Adenostoma fasciculatum*) as designated by the Los Angeles County Fire Department (LACFD) (Dennison et al. 2005). LACFD live-fuel moisture samples from this time period show that the live-fuel moisture in the region was close to 60%.

Figure 6 depicts 10-minute evacuation trigger buffers using a uniform fuel assumption for a sample of locations (black cells). Although the fuel in this scenario is uniform, the southern wind and topographic effects are evident in the shape of the buffers. To provide a 10-minute warning buffer, the buffer extends into the wind in all cases with the variation in buffer shape owed solely to topography. A fire would pose much less risk if it was to the north (top of figure) of these locations, so a buffer does not need to extend as far in that direction.

Figure 7 shows an example of generating nested trigger buffers in complex topography and fuel for a fire crew (white square) located along a road. The buffers represent 15, 30, and 45 minutes of evacuation warning time. It is clear from this figure that a fire can spread most rapidly to the fire crew's location from the south and southeast. The darkest cells in this raster represent "no fuel" and thus perforate the evacuation zone. It would only take a few contiguous, no-fuel cells to comprise a safe zone where

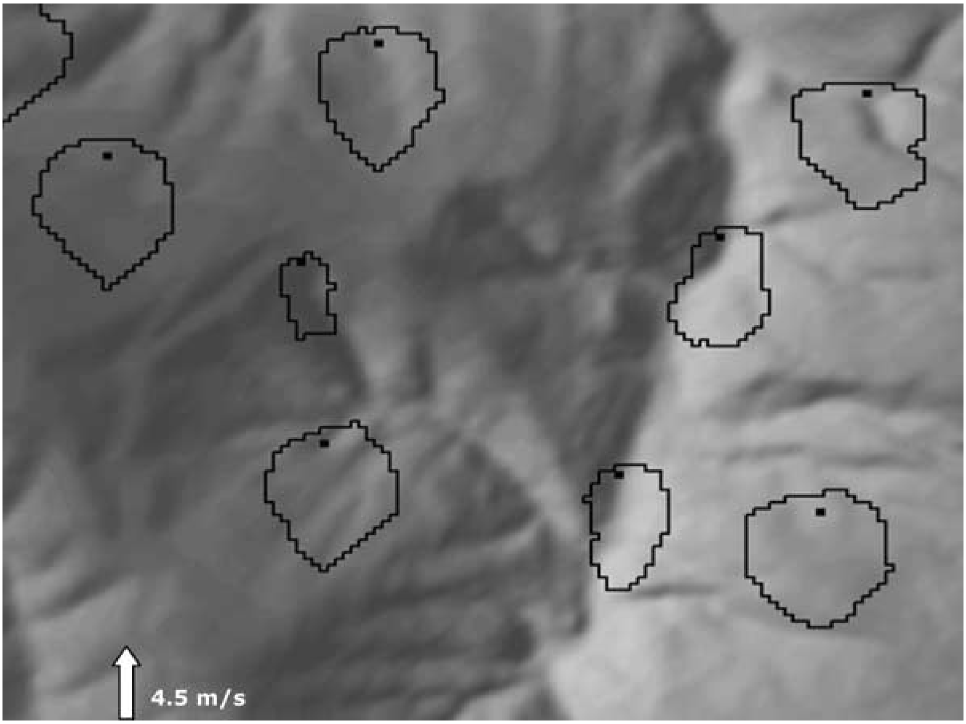


Figure 6 Evacuation trigger buffers (10 minute) for various locations (black dots) in complex topography, uniform fuel (grass), and a 4.5 m/s (20 mph) wind from the south

one could seek shelter rather than evacuate. In Figure 7, the "no-fuel" cells are largely isolated, and given that the resolution of the fuels map is 20 m, these areas would not provide good fire shelter.

The buffers generated in Figure 7 are for a fire crew's location, but in most cases it would be more valuable to generate a trigger buffer for a corridor or area (set of cells). The set of cells might represent a road, neighborhood, canyon or other geographic feature. This can be accomplished with a union (i.e. logical OR) of the cells that comprise the buffers for every cell in a defined area. For example, if a fire crew was located on a road as in Figure 7, it would be valuable to generate a trigger buffer for all points along the road leading out of the canyon rather than just for the location itself. Although the crew may have 30 minutes before the fire reaches them, the fire may block their exiting road in less time. A trigger buffer generated for every location along the exiting road from a crew's current location would grow to include areas where a wildfire might reach any point along the exiting road in the given evacuation time.

Figure 8 shows nested trigger buffers for a crew's location and all the cells along the exiting road that would be traversed in leaving the canyon. Each buffer is a superset of the buffer for the same evacuation warning time in Figure 7. This figure shows that to protect the entire road, it is important to address the fact that fire can approach from either side of the road. Furthermore, fire can advance more quickly toward the upper section of the road than the lower section, as demonstrated by the wide buffers to the southeast of the upper section of the road (i.e. location of buffer times).

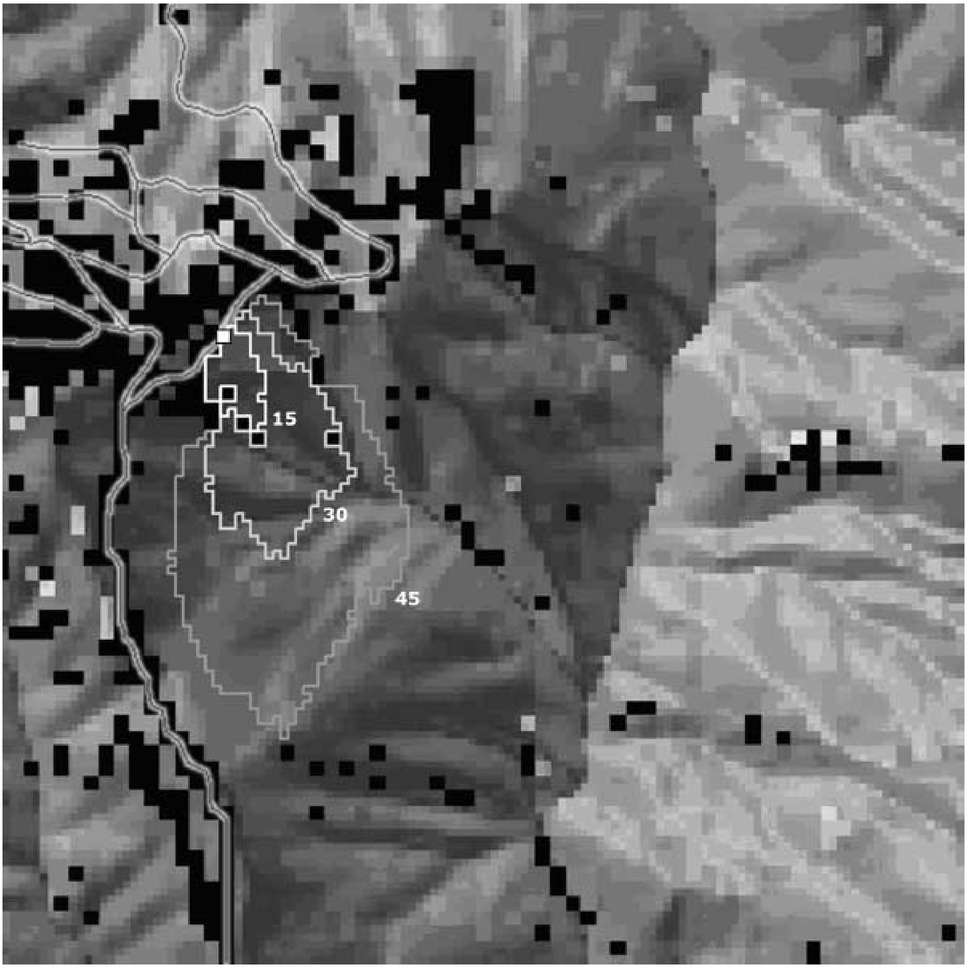


Figure 7 Nested evacuation trigger buffers (15, 30 and 45 minutes) in complex topography and fuel for a location along a road in Corral Canyon

5 Discussion

A key strength of this method is that generating a trigger buffer does not require information on any particular fire's location. A given trigger buffer generated with this approach would have value for any fire that might ignite outside the buffer. This means that the method could be used in a strategic (long-term) or operational (short-term) planning context to generate trigger buffers around communities. In a strategic context, fire managers could study the average, or likely, winds in a given area to generate trigger buffers and identify good landmark trigger points with lasting value. In an operational setting, emergency managers could use the method given current or forecasted weather conditions to delimit short-term trigger buffers on demand. The main hurdles in this time frame are uncertainty, real time data collection, and trigger point definition.

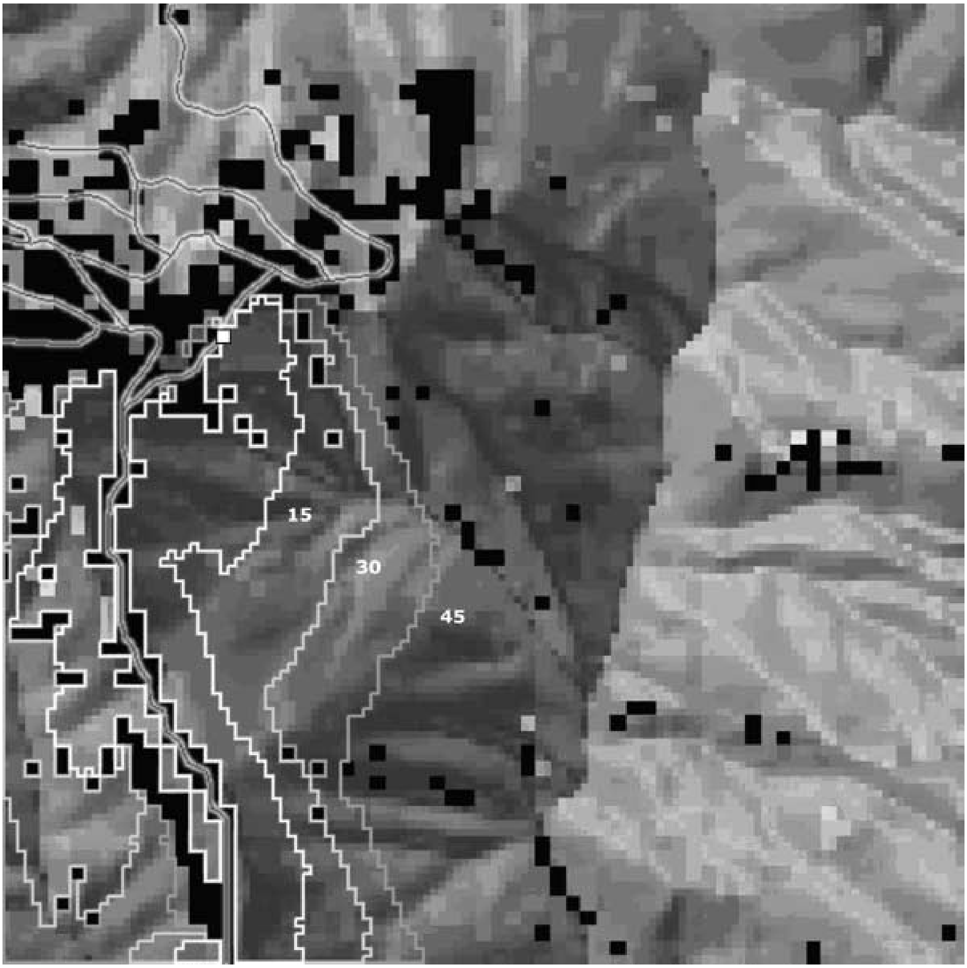


Figure 8 Nested evacuation trigger buffers (15, 30, 45 minutes) in complex topography and fuel for all points along an exiting road in Corral Canyon

Uncertainty is present in all modeling, and this topic has received significant attention in the GIS community (e.g. Zhang and Goodchild 2002). In the context of the method presented herein, uncertainty in an evacuation trigger buffer can creep in via the modeling of fire spread, the estimation of evacuation time, or through any of the inputs (e.g. wind direction and speed, fuel, topography). Given perfect weather, topographic and fuel data (a theoretical extreme), significant uncertainty would exist in the *FLAMMAP^{tm}* output of maximum rate of spread. For example, *FLAMMAP^{tm}* does not incorporate spotting (the ability for embers to be blown significantly ahead of a fire's front) into the rate of spread output. In addition, the Rothermel (1972) model does not account for interactions between fire and wind. Fire can alter its environment and produce a "chimney" effect, which funnels wind through a canyon and drives the fire forward at high rates of spread. For these two reasons alone, a fire in extreme wind conditions is likely to behave differently than predicted. However, validation of this fire spread model (and similar ones) is an ongoing research focus and the next generation of fire-spread models will likely address these issues (Linn et al. 2002).

Another significant area of uncertainty is the evacuation time estimate. As noted, this is also a significant research topic, but in most cases this input would be derived from expert judgment on the part of an experienced public official. To err on the safe side, the evacuation time could be increased as it is in *HURREVAC* (i.e. plus one hour). This is a general strategy that could be used to deal with all forms of uncertainty; increasing the estimated evacuation time. For example, in Figures 7 and 8, if 30 minutes of warning time is the goal, then the 45-minute buffer could be used instead to allow for uncertainty in the edge of the 30-minute buffer.

A second challenge in moving this method into an operational context is real-time data collection. Because wind can change direction and speed frequently, a given buffer might be highly dynamic in reality. It is important to restate that the buffers derived in Figures 4 through 8 are for set wind conditions. One approach for dealing with this issue is to test how sensitive a buffer is to changes in wind direction and speed in a given fuel and topographic context. If it is very sensitive, then the most conservative approach would be to union together (i.e. logical OR) a number of buffers calculated using different wind conditions. This would lead to a more circular trigger buffer that would offer protection in all directions. However, the size and shape of the buffer would still be based on the speed that fire is likely to travel across a given fuel bed and topographic setting.

A third challenge in moving this method into an operational context is determining the location of the buffer for a given evacuation trigger-zone on the landscape. Even if a buffer was "true" and perfectly represented the point at which an evacuation should be triggered, it may be difficult to locate the buffer edge on the landscape. One approach to this problem is to identify prominent landmarks that are clearly outside the trigger buffer and designate them as the working trigger point for an evacuation. For example, the GIS-derived trigger buffer may be located somewhere on a hillside in uniform vegetation, but the hill may have a prominent transmission line which would make a more easily identifiable trigger point.

6 Conclusions

This paper presents a novel method for delimiting wildfire evacuation trigger buffers using fire-spread modeling and GIS. This approach draws from existing research areas including GIS-based trigger point modeling for hurricanes and fire-spread modeling. The method allows an analyst to derive wildfire evacuation trigger buffers around a location or community for various wind and topographic conditions. A key strength of the method is that it does not rely on the location of any particular fire. For this reason the method can be used in a short or long-term planning context. A case study was presented for the 1996 Calabasas Fire where nested buffers were computed both for a location on a road and for all points along the exiting road.

The method described in this paper is limited by the accuracy of the fire-spread model. For this reason advances in fire-spread modeling will improve the derivation of the buffers. Three key challenges in moving the method into operation include uncertainty, real-time data collection and trigger point definition. Uncertainty can be managed in the short term by increasing the evacuation time estimate by a percentage or absolute amount. An important aspect of the method presented in this paper is that the derived trigger buffers are only for the given weather conditions, which may change on very short time scales. Finally, to deal with trigger buffers that may be difficult to locate on the landscape, one can identify prominent landmarks that are clearly beyond the buffer generated using this method.

Acknowledgements

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