CLARIFYING EVACUATION OPTIONS THROUGH FIRE BEHAVIOR AND TRAFFIC MODELING

Carol L. Rice
Wildland Resource Management, Inc.
carollrice@aol.com

Ronny J. Coleman
FireForce One

Mike Price
Entrada/San Juan Inc.

Abstract.—Communities are becoming increasingly concerned with the variety of choices related to wildfire evacuation. We used ArcView with Network Analyst to evaluate the different options for evacuations during wildfire in a case study community. We tested overlaying fire growth patterns with the road network and population characteristics to determine recommendations for evacuation routes. We were able to develop time- and distance-based transportation models to identify preferred and alternate evacuation corridors. We also defined and applied network accumulation models to inventory, queue, and route evacuees using private and public transportation via the safest and fastest routes, without overloading the transportation system. The output from this type of modeling can be used as a decision support tool. Knowing the pace of the evacuation provides decisionmakers with information about the consequences of timing the decision to evacuate. The analysis can also quantify the effect of including additional residences or neighborhoods on the total evacuation time. This analysis makes it possible to identify information that is of vital importance to communities, such as specific routes and intersections that are appropriate and effective for evacuation and others that should be avoided.

1.0 INTRODUCTION

Evacuations during wildfires or other natural disasters can involve large and somewhat unpredictable numbers of private citizens, both informed and uninformed, traveling largely in private vehicles. An evacuation is often an immediate or nearly immediate event and successful outcomes depend on careful prior planning, proper notification, safe and timely community response, and much more. Defining, understanding, and anticipating traffic behaviors are key to a safe and efficient evacuation.

Ample information is available for homeowners or residents about how to prepare for and safely carry out an evacuation during an emergency or disaster (International Association of Fire Chiefs 2010, University of California Agriculture and Natural Resources 2010, University of Nevada Cooperative Extension 2010). However, there are few guides for evacuation decisionmakers and there are even fewer analysis tools to help fire or community planners make good decisions about when to call for evacuation and which evacuation routes to recommend. Time-based evacuation modeling can help provide this information. Evacuation modeling is an important component of any disaster plan when large numbers of affected citizens may be required to assemble, relocate to safe areas, or simply leave their community.

This paper presents a generic overview of the process of conducting a time-based analysis of wildfire evacuation scenarios, but we also tested this analysis on the case study town of Angwin, CA. The scenarios combined fire growth modeling, population density, and traffic flows in order to learn about the potential outcomes. This approach yielded information regarding how many cars would be expected to pass through each intersection, how long it would take to evacuate the community, preferred routes, and appropriate spatial triggers for evacuation.

The combination of population density data with fire growth modeling and traffic conditions modeling represents a new analysis approach for developing a workable community evacuation plan. It allows the user to determine, for example, whether a location can be evacuated prior to being included in the fire perimeter or whether it will be blocked by spot fires. The user can also see where choke points develop so that alternate evacuation routes can be designated. Planners can use different likely fire growth scenarios to evaluate evacuation routes and timing under different wildfire conditions.

1.1 Case Study Community of Angwin, California

Examples from the Angwin, CA, analysis are presented in several figures in this paper. Angwin is a largely forested wildland-urban interface community of about 3,300 people located 70 miles north of San Francisco in Napa County (http://www.city-data.com/city/Angwin-California.html). The town is home to Pacific Union College, a few independent vineyards, and a number of seasonal or retirement houses (http://www.angwincouncil.org). Community growth and in-migration are limited by a dearth of local employment, a long-range county plan that discourages housing growth throughout Napa County, and very limited public utilities that force most new homes to dig their own wells and septic systems (http://www.angwincouncil.org). Angwin's residents are aware of the community's wildfire risk and the town has the largest volunteer fire department in the county (http://www.angwincouncil.org). Proposed development in Angwin prompted an analysis of how added traffic could affect a wildfire evacuation.

2.0 METHODS

2.1 Time-based Evacuation Modeling with ArcGIS Network Analyst

Developed and supported by Environmental Systems Research Institute (ESRI; Redlands, CA), ArcGIS Network Analyst provides an excellent tool for mapping and modeling time- and distance-based travel using properly prepared street datasets. The Closest Facility (CF) solver tool was designed to locate the service or care facility closest to a specific event. For example, an automobile accident (the "incident") may require patient transport to a medical care facility and a towing company to remove damaged vehicles from the scene. The CF solver maps the accident location and searches for one or more nearby medical facilities using a travel time solution. Since a tow truck may not be needed in a time-based sense, the CF solver might identify several facilities that are a short travel distance from the accident.

To model wildfire evacuations with the CF solver, the at-risk households become the "incidents" and the evacuation centers, outside gates, or other points of egress become "facilities." If several shelters or gates are available, models can consider several destinations for each evacuee. Network Analyst's Closest Facility solver routes each evacuee from his or her starting point to each identified shelter or egress point; for whole communities, it aggregates this information and calculates the optimal travel time and distance for many evacuees to one or more safety points. In ArcGIS 10, point, polyline, and polygon barriers may be used to restrict and reroute travel on roads closed by flooding, wildfire, earthquake, toxic plumes, and more. Evacuation routes with available lane counts can be modified to include both responding and evacuating traffic. High-traffic intersections and corridors are readily identified and may be mitigated by traffic control and/or diverting some evacuees to a secondary route. The solver returns an arrival time and distance for each evacuee at each destination (shelter) and calculates the arrival order at each destination as well. The solver also identifies evacuees and other residents who may become trapped by an expanding emergency.

2.2 Input Data

Input data can be obtained from a number of sources (see Table 1 for some examples). First and foremost, time-based travel modeling requires complete, accurate, and current street data. The street dataset must perform well in a network modeling environment and it must have correct information about proper impedance (speed and distance), connectivity, directionality, crossing geometries, and turn modifications. For more information about street

Table 1.—Possible sources of data.

Evacuation Candidates	
Existing	*Proposed*
Census block-level data	Site plans
Assessor parcels	Tentative tract maps
Residence counts - use class, zoning designation; building footprint or effective area	Estimated points
Network Streets	
Existing	*Proposed*
Local jurisdiction	Site plans
Commercial streets	Tentative tract maps
	Estimated centerlines
Evacuation Destinations, Shelters	
Existing	*Proposed*
Local or regional jurisdiction(s) having authority	Site plans
Emergency response plans	Tentative tract maps
Local or regional mapping datasets	Estimated locations
Evacuation Hazards	
Recognized, Existing Hazards	*Anticipated Hazards*
Local or regional jurisdiction(s) having authority	Modeled natural hazards – Slope, vegetation/fuels, geologic hazards, flooding, wind damage, ice storm
Emergency response plans	Transportation concerns – Roads, bridges, terrain, blockage
Local or regional mapping datasets	

networks, refer to "It's All about Streets" on ESRI's support site (ESRI 2011). It is advisable to compare streets to current aerial imagery, checking alignments for accuracy and completeness. Good quality, up-to-date aerial imagery is very helpful for mapping obscure and private access points.

The next step is to identify potential evacuees and locate them on a map. For existing residents, County Assessor parcels and actual building footprints are often the most useful. Aerial images can also be used to locate and count individual occupied structures. With good aerial imagery and no building polygons, it may be possible to add points (dots) on individual structures on the geographic information systems map. As Census 2010 block-level data become available, dwelling counts can be verified. Community-level mapping and structure vulnerability assessments are also valuable.

Proposed and future at-risk populations may be identified using development plans, neighborhood as-built drawings, and population projections from growth plans. Proposed transportation corridors can also be determined from transportation plans and growth management information. These corridors must be added to a separate (future) version of the street network discussed above. Future scenarios can help show how added population in a particular part of town or the addition, extension, or expansion of a road could change evacuation rates or overall evacuation routes. Regional evacuation corridors can also be added from local and regional emergency response plans. The carrying capacity of evacuation corridors should be integrated into the street dataset.

Finally, essential facilities such as fire stations, hospitals, and evacuation shelters must be represented in mapped data.

2.3 The Closest Facility Solver

After the above data are obtained, standardized, and mapped, a preliminary evacuation model is prepared. First, an ArcGIS network is created and tested for connectivity and performance. Next, evacuation shelters and/or egress portals are added to the map. Finally, residence points are added; each point represents one occupied structure, not one individual or one vehicle. If available, commercial or institutional facilities are added along with attributes describing their occupancy.

Once input data are loaded, an initial Closest Facility solver is constructed. Shelters and egress points load as “Facilities” and the occupied structure points load as “Incidents.” Multiple potential Facilities may be modeled, routing evacuees to closest and alternate destinations. Travel direction is set from the Incidents to the Facilities. In most evacuation models, a maximum travel time is not specified. Routes are constructed to follow the street network. Both travel time and distance accumulate as the scenario plays out. The CF solver will now execute.

Upon completion (a large model requires significant time to run), results are inspected and verified. Superimposed routes are tabulated and the route count is joined to the underlying street dataset. Polyline symbols of varying width and color represent the accumulation of evacuees along optimal routes. Stacked routes at street intersections are summarized to provide counts of all vehicles that will pass through them. If certain routes or intersections are overloaded, secondary evacuation routes may be assigned to selected evacuees. Routes and intersection events are recounted and the model is optimized.

If the model is to be modified with closed or restricted egress, the base case CF model is saved and replicated. Point, polyline, or polygon blocks representing road closure or blockage are added to the model. With recently released ArcGIS 10 software, fire progression shells, expanding flood corridors, and mobile toxic plumes may be included. The CF model may be run multiple times, testing the effect of an expanding or moving hazard.

This type of computation is analogous to studies of hydrology. Roads are like little tributaries of cars with various flow rates. The cars accumulate at junctions, which act like minor dams, creating short delays. A car accident may create a longer delay and a more serious logjam. Law enforcement officials directing traffic could be seen as historical loggers riding down the river on a log, breaking up logjams.

2.4 Adding Fire Growth Modeling to Evacuation Planning

This analysis also used the FARSITE fire growth prediction model (Finney 1998), which allows managers to locate where a fire might spread over time under various weather conditions and ignition locations. Inputs to the model are presented in Table 2.

We compared fire growth time with the time it takes to evacuate to illustrate the risks to life and/or the need for additional traffic control. Visual inspection of the fire perimeter and dwellings indicates which roads are blocked at each time step. The delineation of the fire perimeter allows calculation of the number of dwellings blocked by fire in each time step and the number of cars that can leave an area before the fire blocks it off. In some cases, roads can be blocked in one time step, become engulfed in the fire perimeter in a subsequent time step, and be cleared again in another time step as the fire passes by. This scenario should be noted, as it represents a potentially dire outcome. Figure 1 shows one potential fire footprint in the Angwin community case study.

3.0 RESULTS AND PRODUCTS OF THE ANALYSIS

3.1 Accumulations and Critical Intersections

Several different specific types of information are produced by this analysis. First, we get a count of how many cars pass through a certain section of road (for example, a hairpin turn) or the number of residents that feed from narrow routes to larger arterials over the course of the evacuation. We can also identify critical intersections or choke points. For example, in one simulation in the Angwin case study, we discovered that 500 cars would need to pass through

Table 2.—Input parameters for two FARSITE fire behavior scenarios

Input Parameter	Value or Units	Value or Units
	1st Scenario - SW Winds	*2nd Scenario - NE Winds*
Fuel Model (LANDFIRE)	1 - 13, 98, 99	1 - 13, 98, 99
Elevation	Feet	Feet
Slope	Degrees	Degrees
Aspect	Degrees	Degrees
Canopy Cover	Percent	Percent
Stand Height	meters * 10	meters * 10
Canopy Base Height	meters * 10	meters * 10
Canopy Bulk Density	kg/m3 * 100	kg/m3 * 100
Temperatures	77 max/50 min	97 max/70 min
Relative Humidity	60 max/ 30 min	30 max/16 min
Wind Speed	10 mph max	25 mph max
Wind Direction	south to south west	north to north east
Foliar Moisture Content	120%	100%
Fuel Moisture Percent		
1hr	8	3
10hr	9	4
100hr	10	5
Live Herbaceous	110	60
Live Woody	110	70
Ignition Point	SW shrubby area	NE grassy area
Duration (31st of August)	10am to 4pm	10am to 4pm

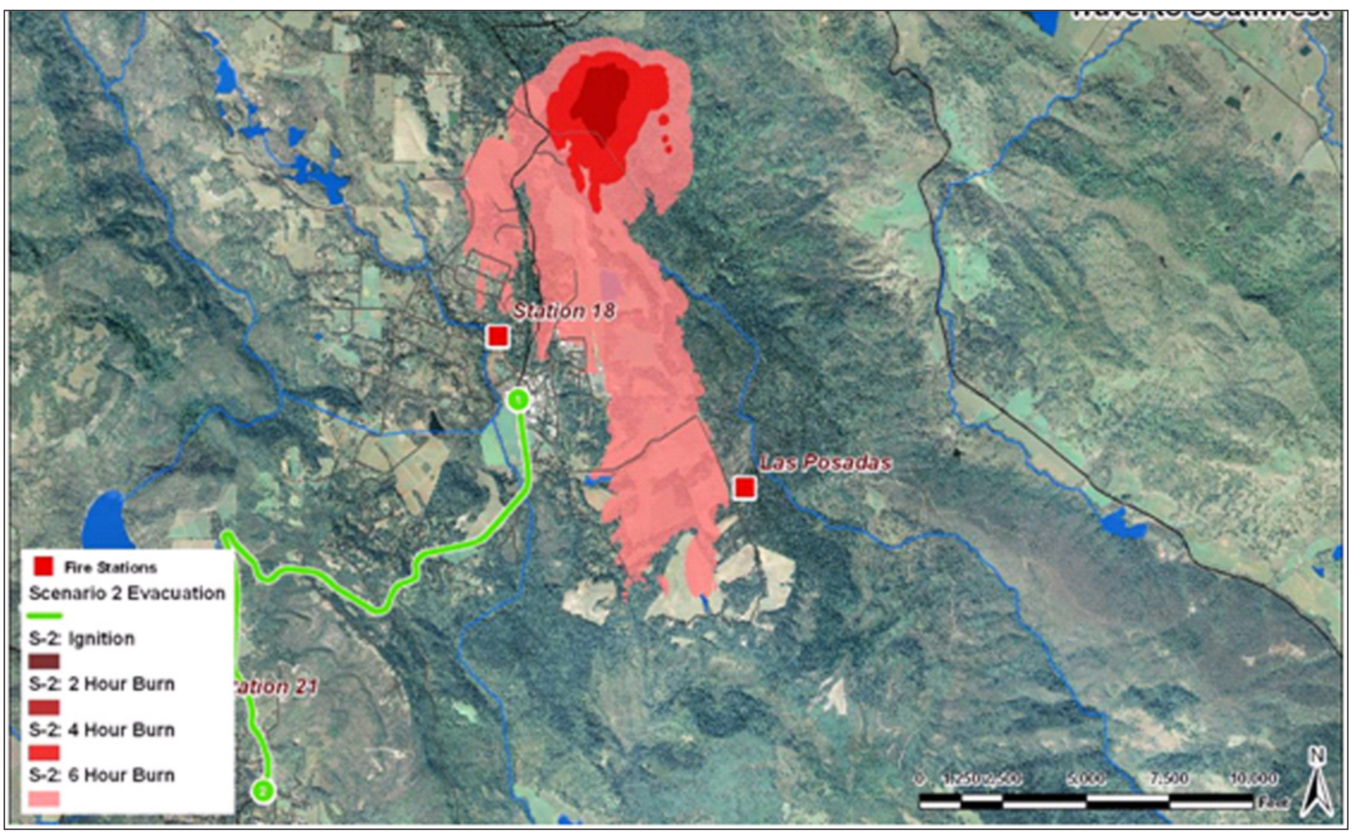

Figure 1.—Map of footprints from a hypothetical fire starting in the northeast portion of the Angwin, CA, community. It assumes extreme wind conditions with wind from the east driving the fire in a southwesterly direction. The map provides perimeters in 2-hour increments. The green line illustrates the route the community evacuation must follow.

one intersection in the downtown area of a community. This information can be used to make critical refinements to the community's evacuation plan. In Angwin, for example, someone could be assigned to monitor and direct traffic at this critical intersection. In all cases, once such a refinement is identified, the involved decision makers can allocate the needed resources ahead of time.

Once a simulation is conducted, an analysis of identified choke points may suggest the need to identify alternative routes. For example, Figure 2 illustrates a scenario in which residents could get farther away from the incident faster by traveling on a western route; in this case, the rerouting could also relieve traffic on the congested route, helping the rest of the community travel faster to the downtown area. If the community practices the evacuation, the residents in this neighborhood could practice using the alternate route.

3.2 Clearance Time

This type of analysis provides information about the total time required to move all evacuees through the road network—the length of time between the first and the last car leaving the area. Clearance times do not reflect how long it takes for an individual vehicle to go from a residence to any specific destination.

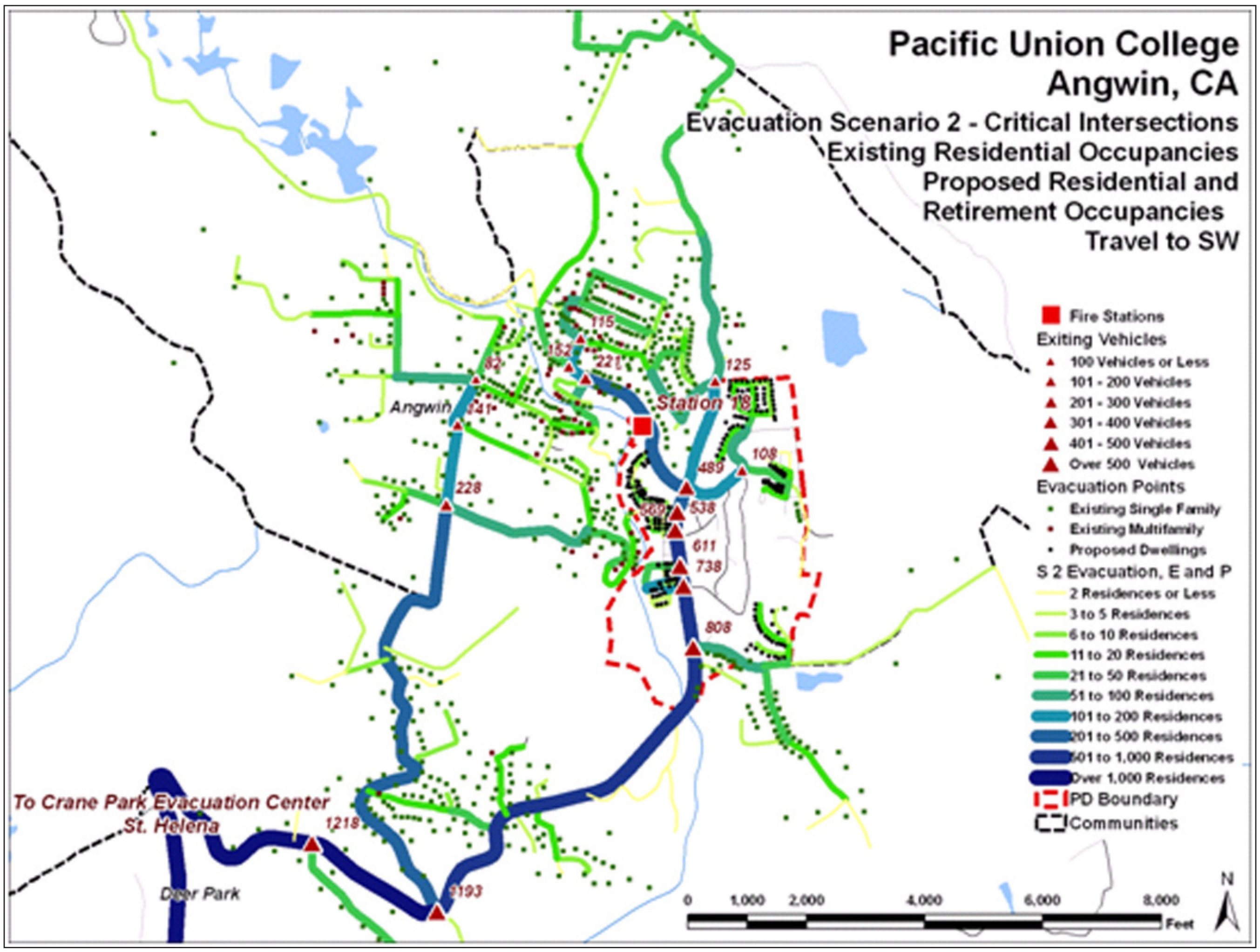

Figure 2.—Map of one Angwin community evacuation scenario with traffic counts for roads along the evacuation route. In a scenario where a fire burns to the northeast of the Angwin community, evacuation traffic is concentrated on Howell Mountain Rd. All intersections south of College Avenue experience more than 500 vehicles during the evacuation process. The intersection of Howell Mountain Rd. and Cold Springs Rd. experiences 808 vehicles, with 70 cars contributed from Cold Springs Rd. Farther to the west, Crestman Drive contributes 25 cars onto Howell Mountain Rd for a total of 1,218 cars at that intersection.

Different levels of background traffic are assumed in different model scenarios. For example, under optimum conditions in the Angwin case study, all dwelling units can travel through the road network to Howell Mountain Road in order to exit the community. If there are two lanes available on all roads and 1,000 cars per lane can flow per hour, the entire community can evacuate in about 90 minutes (assuming no car accidents). See Figures 2 and 3.

By comparing fire location and growth rate with clearance time, the evacuation planner can know whether any residents may be caught in the approaching fire. This information can be used for determining evacuation triggers.

This type of analysis also allows planners to conduct 'what if' scenarios, for example by adding car accidents to assess the impacts on clearance times and reverberations at critical intersections, or increasing the number of residents in a particular part of town to see whether the clearance time is slowed or choke points are added.

4.0 CONCLUSIONS

The analysis of wildfire evacuation scenarios underscores the importance of having a well thought-out evacuation plan that accounts for a range of contingencies. It is important for communities to have a specific evacuation plan with a target destination (or several destinations) that is shared with, understood by, and practiced by the community.

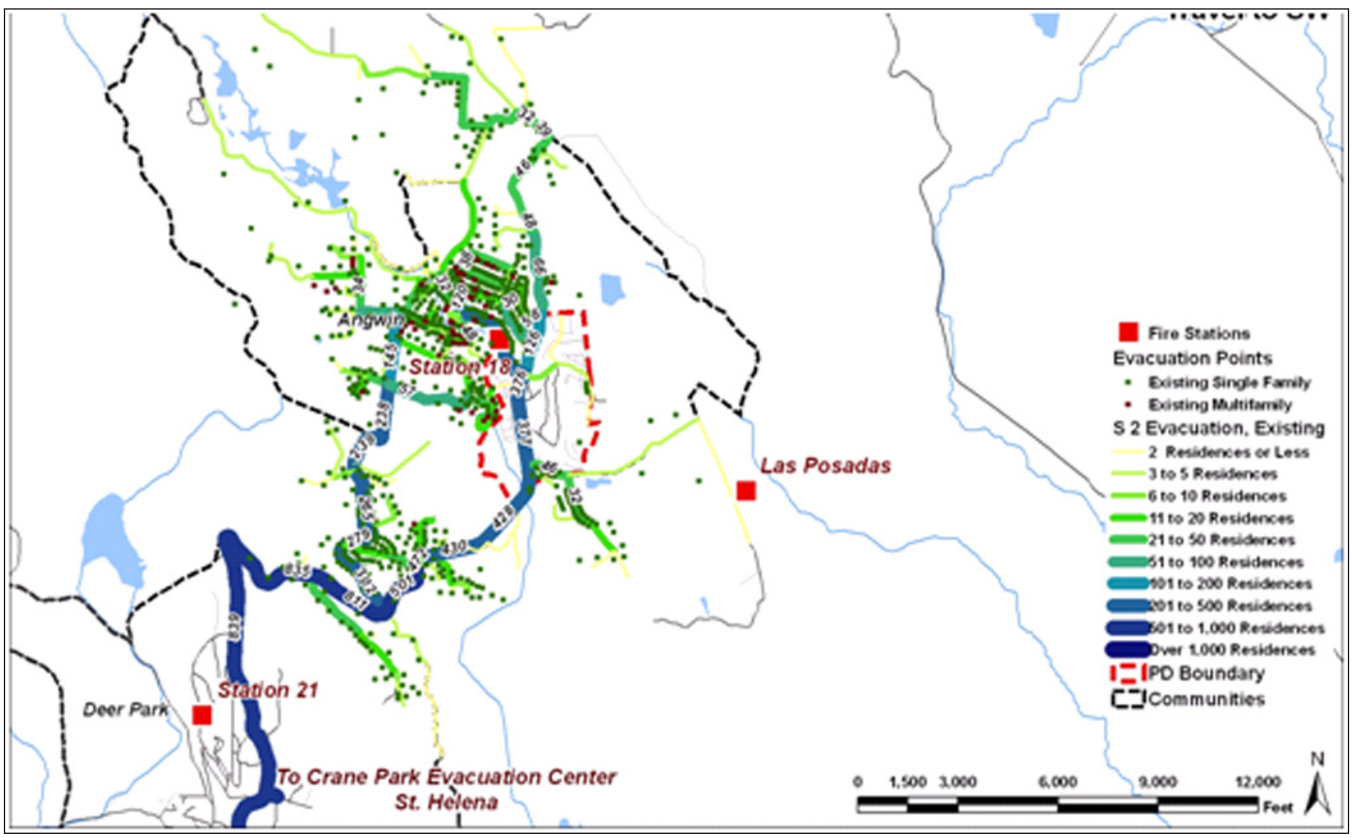

Figure 3.—Map of traffic accumulations and direction of evacuation for the Angwin community in one evacuation scenario. This map illustrates the theoretical accumulation of individuals on the transportation network in an evacuation to the southwest. Each residential unit is a dot on the map. The number of vehicles required to move the population along each route is indicated by the color coding on the street network. The lighter colors indicate very few vehicles (low traffic) and the dark blue color illustrates the maximum number of vehicles (heavy traffic). The arrow points to Howell Mountain Road, the main road out of the community to the southeast.

The combination of fire behavior modeling and traffic modeling for analyzing a proposed wildfire evacuation can be a valuable decision support tool. This type of analysis offers insights into:

- The timing necessary to get people to safety under various evacuation scenarios
- The likely choke points and troublesome routes
- How unforeseen events like car accidents or fire behavior may affect the evacuation in real time
- Possible alternative routing scenarios

We also found that analyzing the evacuation process provided valuable information about the trigger points that call for action, as well as the thresholds for and impacts of alternative scenarios. This type of analysis is a new tool for building better community wildfire response plans.

5.0 LITERATURE CITED

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