Rational Design of a Wildfire Evacuation Model

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1 Abstract

Extreme weather events affecting wildfires are increasing in intensity and frequency. NOAA reports 58,733 wildfires during 2021 alone. As populations encroach further into forests, the wildland-urban interface and the risk of wildfire damage increases. To better enable emergency services to mitigate damage done by wildfires, simple, efficient, accurate, and precise models of wildfire spread are necessary. This paper develops a simple design to model fire spread in an area with limited precipitation and design an evacuation plan for Apollopis. The promise of this simple simulation presented here suggests rapid and simple development of wildfire simulation can substantially improve the safety of forest communities.

2 Background

Climate change has been shown to increase the frequency and severity of wildfires by decreasing rainfall and snowpack, and increasing extreme heat events in forest communities These changes have immediate effects on communities at risk of burning [3]. Consider as a case study the California wildfires of 2021.

The state experienced 8,619 wildfires over the period of one year, which cumulatively burnt 2,569,009 acres, destroyed 3,629 buildings, caused 22 non-fatal injuries, and resulted in 3 deaths. The most severe of these fires burnt 963,309 acres alone, destroying 1,329 structures [1]. The total monetary cost of these disasters is difficult to estimate, but likely is on the order of billions of dollars.

Wildfire damages, particularly the cost to human life, may be decreased with rationally-designed evacuation protocols. Protocols will need to specify the spatial and temporal particularities of evacuation, that is, which regions must be evacuated and at what times. Unfortunately, such plans cannot be constructed with long-term projections of where wildfires will have spread by some time in the future.

The problem of predicting fire behavior is nontrivial, as the dynamics of fire are intrinsically chaotic and highly dependent on difficult-to-predict weather patterns over time [2]. Here, a highly-tunable method of efficiently simulating the dynamics of wildfire spread is developed and subsequently used to produce an evacuation plan on a model city, named Apollopis.

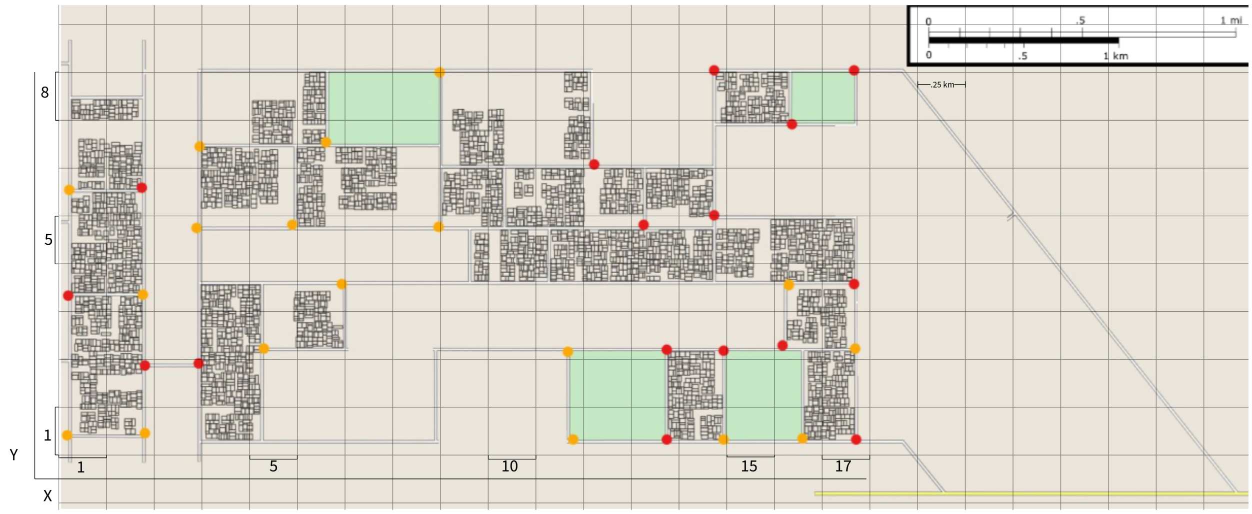

Figure 1: Map of Apollopis with 0.25km × 0.25km zones superimposed. Up is north.

3 Methods

3.0.1 Software

All work was performed using Python 3.7 with the `numpy`, `scipy`, and `matplotlib` modules. All code is available on github at `https://github.com/nicholscrawford/SIAM2022`.

3.1 Data Source

Data (Figure A) concerning historical temperatures, dew point, precipitation, wind, and atmospheric pressure as well as complete weather forecasts including temperature, precipitation, wind, and humidity for the two week following the start of the wildfire is provided.

3.2 Wildfire Model Setup

Apollopis and its surrounding forest were partitioned into squares of side length 0.25km. Apollopis measures 17 of these squares in East/West direction and eight of these squares in the North/South direction (Figure 1). In total, a simulation area running 50km East/West and 25km North/South was considered. Each zone was conceptualized as an entry in a matrix in $\mathbb{R}^{100\times 200}$, where the magnitude of each entry was a measure of 'fire intensity.'

Fire intensity varied from zero to one, with one being the most intense. Fire intensity values were used to simulate the growth of fire inside a given zone as well as the spread of fire to an adjacent zone. The rate of fire spread and growth was determined as a function of weather phenomena. Once an entry reached a fire intensity exceeding or equal to one, the corresponding zone was considered 'burnt out,' and no longer able to spread the wildfire.

Within this paradigm, a small fire (intensity=0.1) was initialized 17km west of the West-most zones designated to be part of Apollopis at 7:00am on day zero (Figure 2), and city zones were monitored to determine when the wildfire would reach them. Simulations were performed with a temporal resolution of one hour. The details of model construction follow.

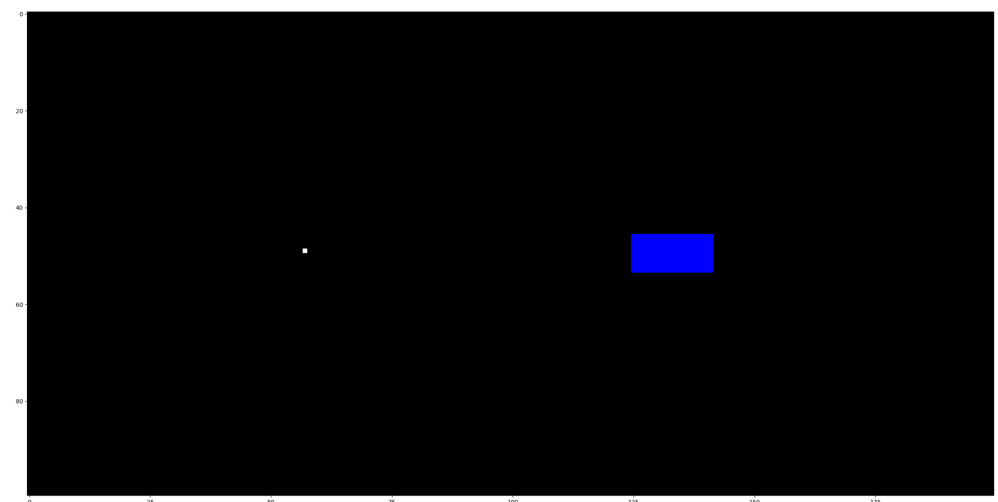

Figure 2: Initial state of the simulation. Black areas are unburnt, Apollopis is marked in blue, and the small initial fire is marked as a single white pixel. Each pixel is a 0.25km $\times$ 0.25km zone.

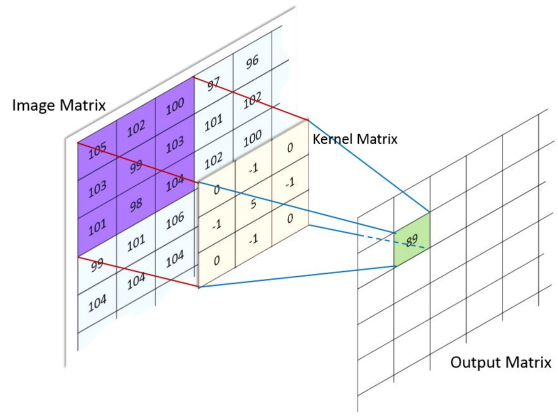

Figure 3: Illustration of convolution methods.

3.3 Masked Convolution

The fire intensity within a given zone at time t+1 was considered to be a weighted sum of the fire intensity in that same zone and its eight neighbors (four in the cardinal directions and four in the ordinal directions) at time t. This paradigm immediately lends itself to image convolution, wherein an output image is produced by adding each element of an input image to its local neighbors, weighted by a kernel matrix Ω. Convolutions were performed using the `scipy.ndimage.convolve()` method (Figure 3).

In the model presented here, $\Omega \in \mathbb{R}^{3\times 3}$ was used under the simplifying assumption that fire could not spread to a zone from any zone not immediately touching it. The weights included in this kernel were all calculated on an hour-to-hour basis in simulation as a function of weather conditions.

Because fire cannot be spread to or from a burnt out zone, the convolution operation was only applied to non-burnt out zones. This was done by keeping track of the boolean 'burnable' status of each zone in a mask matrix in $\mathbb{R}^{100\times 200}$ and by using the `nump.where()` method.

3.4 Weather Effects

To simplify the model, the forecasted high and low temperatures, wind speeds and directions, chances of precipitation, and humidities were considered exact. Similarly, the dew point was approximated to always be the three-month mean, despite existing on a distribution. Temperature was approximated to increase linearly each day from the daily low to the daily high from 7:00 to 15:00, then decrease linearly to the following day's low from 15:00 to 7:00. Precipitation events had the potential to begin each hour with probability equal to the forecasted probability and were maintained for an hour. Precipitation events are applied uniformly over the entire simulated region.

If a precipitation event occurs at the beginning of an hour or if the calculated temperature for that hour is below the dew line, the identity kernel is used:

$$\Omega = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

that is, fire does not spread whatsoever. This is predicated on the assumption that burning areas

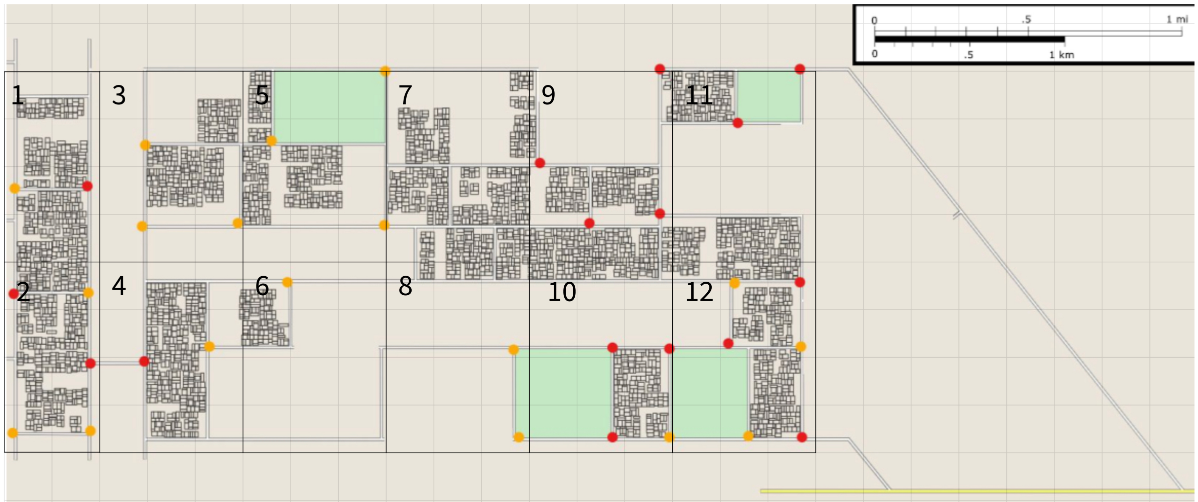

Figure 4: Division of Apollopis into 1km × 0.75km neighborhoods. Each neighborhood is numbered.

will remain dry through the event due to the heat of the fire, but nonburning regions will not begin to burn after becoming wet.

Otherwise, Ω_{11} is calculated as proportional to wind speed with a constant of proportionality manually adjusted to reflect the fire spread data for the first 10 hours of burn presented in Figure 12. All other kernel entries were manually determined such that the geometry of wildfire spread over time is reflective of the data for the first 10 hours of burn presented in the problem statement. The entire kernel is then multiplied by $(1 - h)$, where h is the relative humidity, predicated on the assumption that fire spread would be negligible at 100% relative humidity and completely unhampered at 0% relative humidity. All parameter optimization was performed assuming 3-month mean relative humidity.

3.5 Evacuation

A neighborhood-by-neighborhood evacuation plan was developed wherein evacuation is recommended for each neighborhood at a given time. Neighborhoods are defined as 1km × 0.75km zones within the city, each of which extends 4 zones in the North/South direction and 3 zones in the East/West direction. Two of these zones are 1km by 0.5km to fit the map evenly.4

The model makes several simplifying assumptions.

1. Dividing the city up into sections, each section has some number of people in it, and people flow out of that area through paths.

2. Paths have a maximum flow rate.

3. Sections and paths within sections of the city should be evacuated before any portion of that section begins to burn.

4. Section's roads can be modeled by a path, where the path connects each section to a nearby section in a vertical or horizontal direction, always towards the evacuation exit. This assumption is implementation specific, and our model generalizes to non-vertical/horizontal paths,

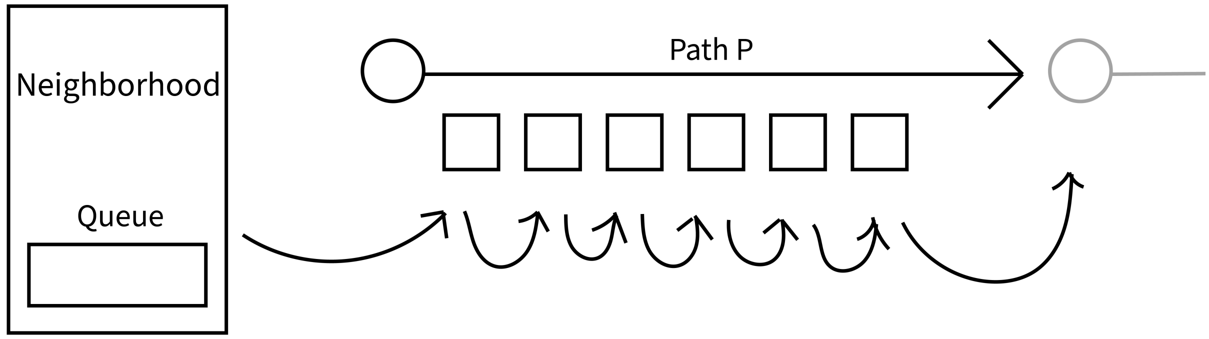

Figure 5: Diagram of the evacuation model, where the people leave the neighborhood, (and end up queueing to leave the neighborhood if unable), into a path. People move along the path each timestep, (given the path isn't above is capacity) spending the appropriate amount of time (rounded up) given the speed limit of the road. People leave the road to the next road if the next road has capacity at the same per timestep rate.

and more complicated path structures. Ideally, the math inclined DOT for the city could provide computerized maps that could be directly implemented into the system, and improve simulation resolution.

3.6 Evacuation Model

The evacuation model models street sections, with a given length and speed limit. The street has a carrying capacity for cars, which was modeled by discretizing the street into an array where each segment of the array has a maximum capacity for cars, based on our numbers for the maximum capacity of cars per unit length of street given a speed. The maximum capacity of cars per kilometers was calculated as

$$\lambda_{crit} = \frac{1}{vt_f + d_0},$$

where v is speed, t_f is following distance (assumed to be the DMV-recommended 3 seconds), and d_0 is the mean length of a car on the road, which was approximated to be $4.5m$.

In the model, given a time step, each car advances along the street it's on, and once at the end, moves to the next street, or the end evacuation zone. Each street may have multiple inputs, but each street only has one exit, due to there being a shortest time length path till to the evacuation zone.

Neighborhoods in the model have one exit onto a street, decided by the street intersecting with the border of the neighborhood with the shortest time length path to the evacuation zone. People attempt to exit the neighborhood according to the distribution of 'wait times' in Figure 4. The number of people inhabiting each neighborhood was calculated by manually counting the number of 0.25km $\times$ 0.25km squares which were more than half filled with structures, and assuming each of those squares had a typical suburban population density of around

$$\frac{2000}{mi^2} \approx \frac{781}{km^2} \approx \frac{195}{zone}.$$

1560	975	975	1560	1170	780
1560	780	390	0	585	1560

Table 1: Number of people per neighborhood. Table is organized such that the position of each table entry corresponds to the neighborhood position in Figure 11

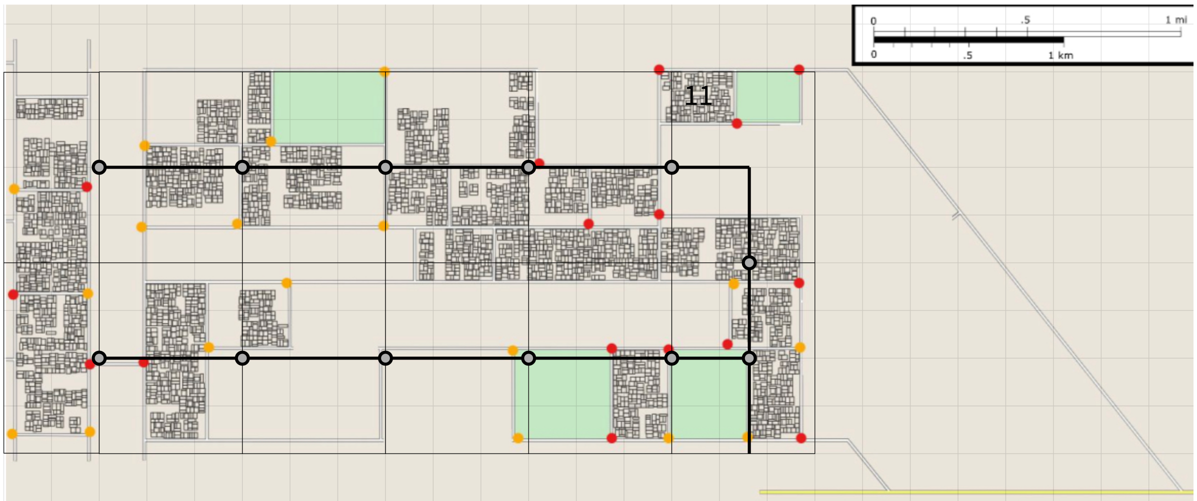

Figure 6: Map of the paths we used for simulation, though our model is generalizable. Grey centered dots represent points where neighborhoods and paths feed in to paths. Thick lines represent paths.

The model takes into account how long each neighborhood has until any portion of it begins to burn, and tests the validity of a given evacuation plan, and can also give estimates of how long any given plan will take. The model will consider any given plan a failure if the residents are not evacuated an hour before a section begins to burn. The time residents take to leave their neighborhood is distributed according to the data of Figure 11

For this implementation of the model we use horizontal/vertical paths, though our model is easy to generalize to precise paths with computerized maps. The model was used to generate times for evacuation for the sections, giving an expected evacuation time for the given section.

4 Results and Discussion

4.1 Wildfire Evolution

Within the modeling framework described in Section 3, the time evolution of a wildfire started at 7:00am on day 0 17km West of Apollopis was simulated. The characteristic elliptic fire front is clearly visible, and the burnt region evolves in time in a manner reflective of the provided 10-hour burn pattern (Figure 12).

4.2 Burn Times

The time evolution of the the wildfire was used to determine at what time each zone within Apollopis would begin to burn (Figure 8). These times represent the absolute latest that any person could

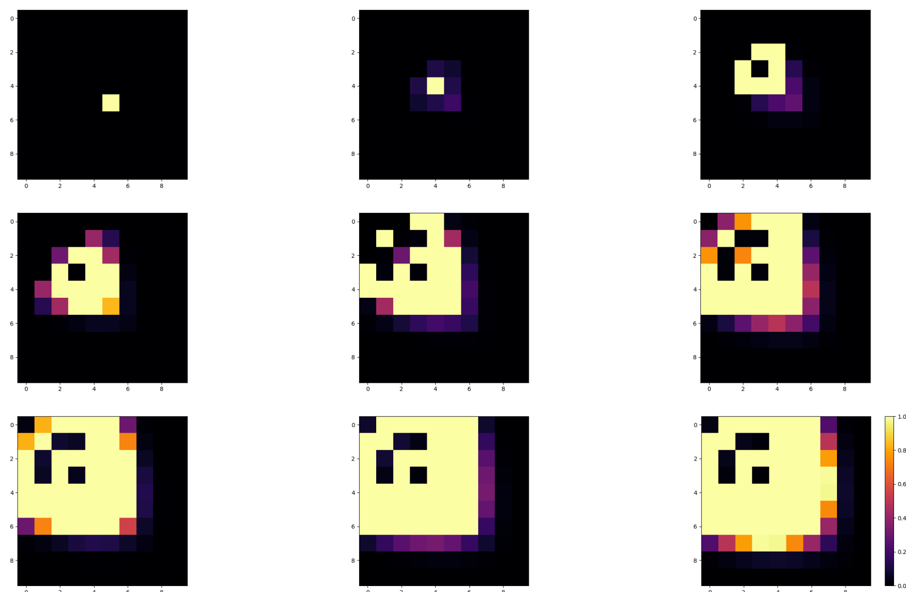

Figure 7: State of a small-scale wildfire simulation for the first nine hours of simulation (read left to right, then top to bottom). Burnt out areas are displayed as having fire intensity one for clarity, despite really having a value of zero.

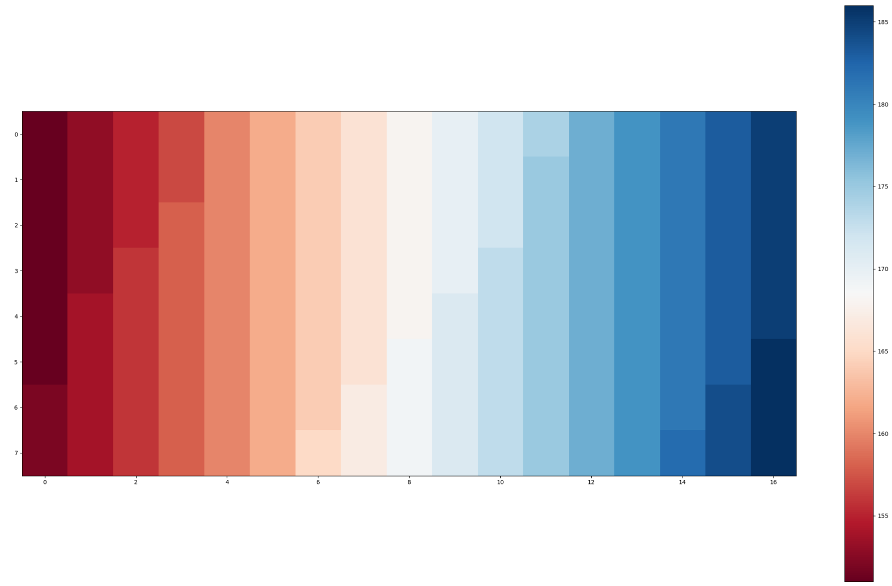

Figure 8: Time in hours for each zone in Apollopis to begin to burn. Up is North, such that this heatmap could be superimposed onto the image in the problem statement.

9.83	6.25	6.16	9.58	7.17	4.75
12.25	6.25	3.25	0.83	4.67	0.5

Table 2: Time for each neighborhood to evacuate in hours. Table is organized such that the position of each table entry corresponds to the neighborhood position in Figure 4

safely be in the zone, and is therefore used in evacuation plan design. In particular, an optimal evacuation plan allows each each neighborhood to be fully evacuated well before that neighborhood begins to burn.

4.3 Evacuation Duration

The time required for each neighborhood to evacuate is summarized in table 2.

This means that the total evacuation time is about 71.5 hours, or just under 3 days. Each numbered neighborhood must begin to evacuate, at the latest, at the times summarized below (after the fire began):

1. 5 days, 21.17 hours
2. 5 days, 18.75 hours
3. 6 days, 4.75 hours

4. 6 days, 5.75 hours
5. 6 days, 13.84 hours
6. 6 days, 16.75 hours
7. 6 days, 16.42 hours
8. 7 days, 2.17 hours
9. 7 days, 1.83 hours
10. 7 days, 4.33 hours
11. 7 days, 10.25 hours
12. 7 days, 14.5 hours

This gives the following neighborhood evacuation order:

$$2 \to 1 \to 3 \to 4 \to 5 \to 7 \to 6 \to 9 \to 8 \to 10 \to 11 \to 12.$$

Note that this differs at several points from the order in which the fire is expected to arrive at each neighborhood (Figure 8). To allow for a reasonable factor of safety, it is advisable to evacuate each neighborhood at least one day (24 hours) prior to the latest possible evacuation time.

4.4 Discussion

The method of wildfire simulation presented here allows for the rapid construction of models and efficient production of simulation results, making it well suited to inform the rational design of evacuation protocols.

While the method is validated by the limited fire spread data (Figure 12), there is not enough data available to prove that the system is accurate or precise in a variety of circumstances. Critical surveys of wildfire data through forests of different densities and under various weather conditions would be necessary to fully validate the model. The paradigm presented here may also scale poorly, as it is principally dependent on convolution, which is $O(n^2)$.

The evacuation simulation presented here also allows for the rapid construction of models and efficient production of simulation results, and interfaces with the wildfire simulation to calculate the number of people who are unable to escape the fire, if any.

As was the case with the wildfire simulator, the evacuation model makes several simplifying assumptions and is not validated on a substantive real data set, so further work in data collection may be needed to verify the model. Additionally, in situations with more complicated shortest paths, shortest path graph algorithms should be implemented to create paths for our simulator. Hand entering paths can be cumbersome, so procedurally entering computerized area maps for cities with non-trivial road system should be applied when attempting to use the model.

References

[1] Cal Fire, C. D. o. F., and Protection, F. Stats and events.

[2] Malarz, K., Kaczanowska, S., and Kulakowski, K. Chaotic Dynamics of Forest Fires.

[3] Stocks, B., Wotton, B., Flannigan, M., Fosberg, M., Cahoon, D., and Goldammer, J. Boreal forest fire regimes and climate change. In *Remote sensing and climate modeling: Synergies and limitations*. Springer, 2001, pp. 233–246.

A Problem Statement Data

Temperature (℉)	Max	Average	Min
Max Temperature	103	93.32	85
Avg Temperature	82.21	73.93	68.8
Min Temperature	65	57.19	0
Dew Point(℉)	Max	Average	Min
Dew Point	59	51.61	0
Precipitation (Inches)	Max	Average	Min
Precipitation	0	0	0
Snow Depth	0	0	0
Wind (mph)	Max	Average	Min
Wind	17	6.82	0
Sea Level Pressure (“Hg)	Max	Average	Min
Sea Level Pressure	30	29.84	29.68

Figure 9: Weather temperature in Apollopis area

Day	Max Temperature(℉)	Min Temperature(℉)	Precipitation (%)	Wind (mph)	Humidity (%)
1	94	60	0	15 nw	49.2
2	87	56	0	16 nw	57.1
3	86	55	0	12 nw	55.2
4	97	59	0	9 nw	41.5
5	98	61	0	13 nw	40.0
6	89	61	0	17 nw	44.1
7	92	57	0	12 nw	45.1
8	96	58	0	15 nw	42.5
9	98	59	0	10 nw	45.3
10	99	64	0	12 nw	38.1
11	103	65	0	10 nw	34.3
12	103	64	0	9 nw	35.3
13	97	62	0	14 nw	50.0
14	91	57	0	13 nw	56.9

Figure 10: Apollopis weather forecast for next 14 days

		Amount of time it took individuals to leave after being asked to evacuate (in minutes)							
		0<t<5	5<t<15	15<t<22	22<t<25	25<t<33	33<t<45	45<t<51	t>51
Number of Individuals per Evacuation	Evacuation 1	2109	3136	1623	573	1205	1277	408	1689
	Evacuation 2	22712	34864	17599	6119	13332	13400	4636	17850
	Evacuation 3	76165	115761	57483	20105	43531	44517	15493	58874

Figure 11: Proportion of citizens who waited given amount of time before evacuating in three past evacuations.

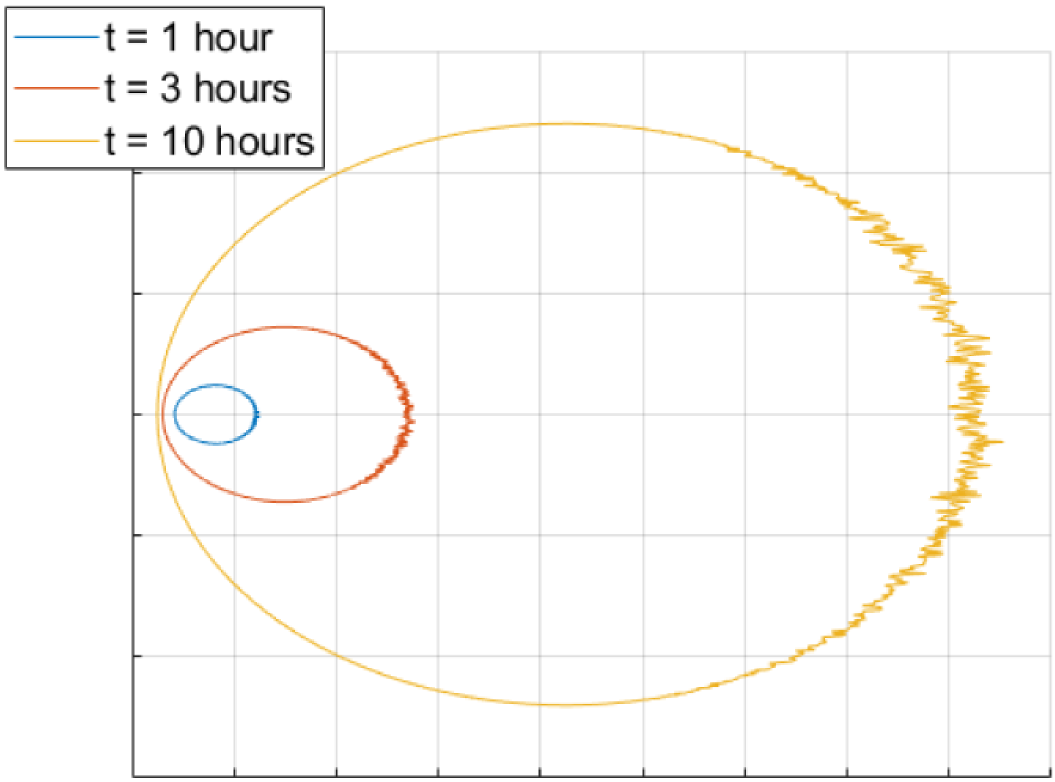

Figure 12: Measured growth of the burn area over the first 10 hours.