Community evacuation from wildfire events

By Dr Steve Gwynne, Dr Georgia Bateman, Dr Erica Kuligowski, Dr Max Kinateder, Afroza Mallick, Hannah Nevill, Dr Enrico Ronchi, Prof Guillermo Rein, Amanda Kimball

Executive summary: Wildfire evacuation events have been examined to demonstrate their complexity. As part of the wider project, data from a US wildfire exercise was used to configure a macroscopic evacuation model – to simulate evacuation scenarios and capture some of the complexity present. To complement this, this case study explores complexity by identifying event dynamics and examining how they unfold to form a narrative – given events/evacuee decisions compiled from real-world incidents.

Contents

Tags: Wildfire; Wildland-Urban Interface; Evacuation; Modelling; Complex System; Pedestrian; Traffic.

What is the subject and its context?

This work is based on several assumptions that are developed in the coming pages:

- *Wildfires pose a serious threat to community safety.*
- *This threat is expanding and increasing.*
- *New communities are becoming vulnerable to this threat as it affects new locations.*
- *New communities are becoming vulnerable to this threat as people move to wildland-urban interface locations.*
- *Communities historically threatened by wildfires are facing new and unfamiliar conditions.*
- *Given new locations and severity, wildfire conditions are diverging from the conditions faced in the recent past. This makes it harder to derive projections directly from historical fires.*
- *This makes it even harder to derive insights from 'similar' recent incidents given sensitivities to changes in the initial conditions and underlying dynamics (generated through interactions between factors and agents at multiple levels).*
- *Wildfire outcomes are formed from various elements (social, physical and environmental) that interact in complex ways.*
- *To understand the threat posed it is necessary to understand a community's capacity to cope with the conditions faced.*
- *New means to quantify community evacuation are needed – to capture interactions between the various elements and to cope with challenges in deriving projections from historical events.*
- *Modelling will assist in this.*
- *Such models would also be needed to support performance-based regulations or inform the development of prescriptive approaches, should one be employed.*

A wildland fire is defined as an "unplanned and uncontrolled fire spreading through vegetative fuels, at times involving structures" [1]. If it develops in a wildfire-prone boundary between structures and vegetation, then it can be considered as a wildland-urban interface (WUI) fire [2]. The development of the fire itself (see **Figure 1**) will be influenced by geography, weather patterns, and vegetation; the impact on affected structures by construction materials/techniques and land use planning; the capacity for communities to cope with an incident will be influenced by the resources available, the information available, and their ability to evacuate.

Each of these represents a system of interacting parts with varying degrees of local agency, for example, local planners, individual residents evacuating, regional emergency management.[1] These factors are managed by different

1 A key discussion in wildfire safety is the propensity of some residents to remain in place during a wildfire emergency. We here focus on the evacuation process (pedestrian and vehicular) rather than the decision-making process of the resident who decides to remain in place. The reader is referred here for a comprehensive discussion on such decision-making [3].

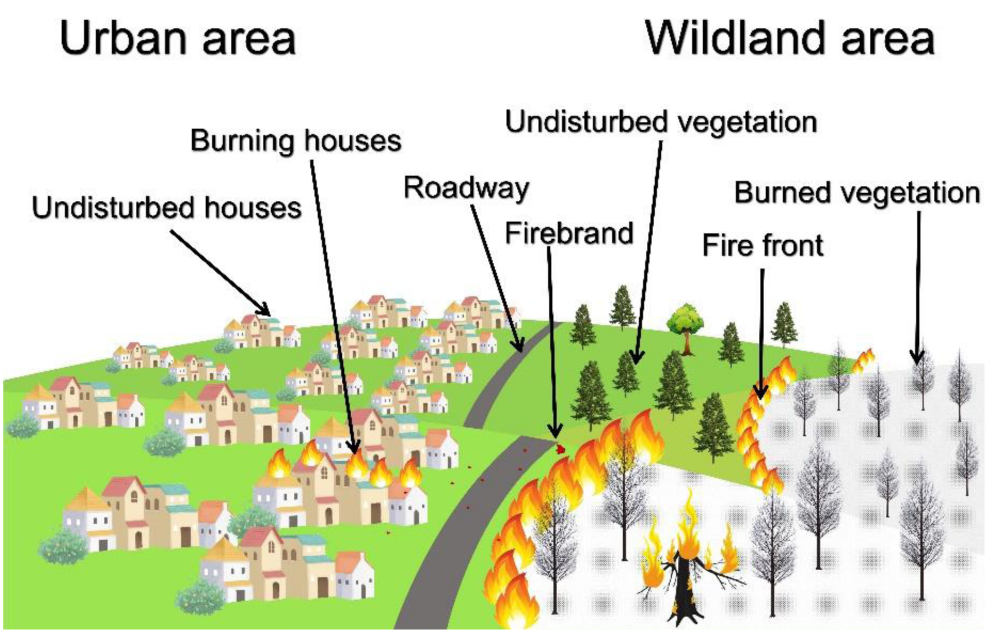

Figure 1: The interface between a wildfire and urban settlements, highlighting the ways in which the fire might affect the surrounding areas (courtesy of HAZELAB).

stakeholders, interact in complex ways and at different levels, and evolve quickly given decisions made at the individual, community, national, and even international levels.

Wildfires are an important safety issue in many regions of the world. Such fires can threaten both rural and urban areas – affecting the short-term (life safety, infrastructure and the economy) and long term (the environmental conditions, community health and well-being, tourism, and so on) status and viability of a community. The regions at risk of such events are expanding beyond those historically affected (see **Figure 2**).

The wildfire issue is likely to get worse and cause more concern in the future, due to climate change [4] and population growth in WUI areas [5].[2] The impact of wildfire is evolving and rapidly becoming more serious given several physical and environmental factors: (a) increased fire activity (more, larger and more intensely active fires), (b) hotter/drier summers affecting larger areas, (c) an increased number of severe thunderstorms – increasing the probability of lightning triggering new fires, and (d) stronger winds. Previous wildfire assessments are quickly becoming outdated giving the evolving conditions. Risk analysis based on probability and consequences are undermined given the speed of change of these conditions. Similarly, conclusions drawn from seemingly similar conditions from previous fires are now less relevant. This places extra pressures on local and national resources – making the availability of credible numerical evidence more important to justify budgetary decisions.

Other factors also impact the threat posed by wildfires. There is now a greater propensity for people to live in WUI areas, combining rural, and suburban conditions. Residential populations are therefore growing near/in the wilderness [5]. This means that there are a larger number of residents living in areas vulnerable to wildfires and that the number of people naïve to such threats is increasing. In addition, the population of many industrialised countries is ageing. This has an impact on a population's capacity to respond. Communities are also becoming more diverse making the social and cultural attributes of our communities more diverse and complex – along with their response.

The current situation may evolve towards more dangerous scenarios in areas which have a long history of wildfires [6,7]:

- The US WUI increased by 52% between 1970 and 2000, eventually constituting 12.5 million households and nearly 500,000 km² of land [8,9]. *More area is vulnerable to wildfires.*
- In the US, 46 million homes are in WUI areas (2012). The estimated conversion rate from wildlands to WUI is about 810,000 ha/year

2 The terms Wildland Urban Interface fires and Wildfires are used interchangeably here given that we are primarily concerned with wildfires that affect human communities.

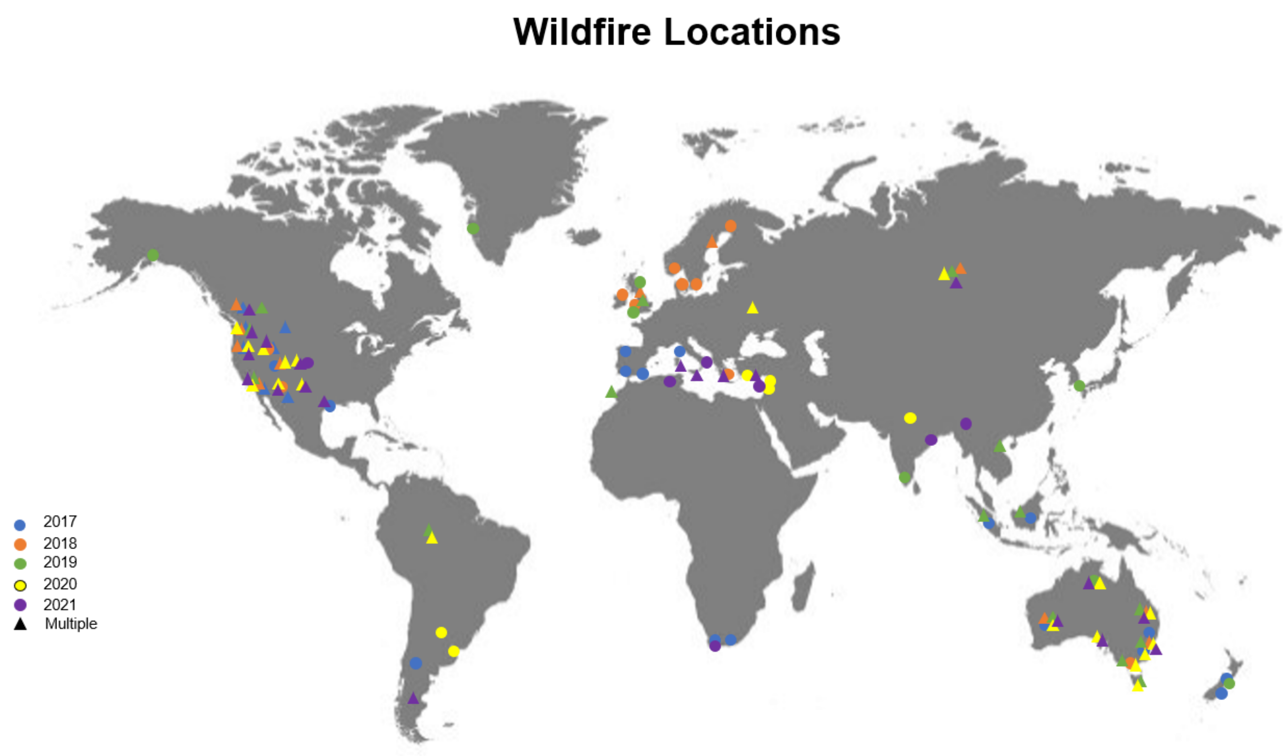

Figure 2: Internationally-noted wildfire events between 2017 and 2021.

since 1990. There are 8 million projected new homes in next 10 years [10]. State foresters have designated 89,000 ha as high-risk areas for WUI fires, with about 100,000 wildfires burning 2.8 million ha/year, and 2,970 homes/year lost on average since 2000 [10]. *More people are vulnerable to wildfires as they live in vulnerable locations.*

- In California alone the WUI area is estimated as 746,037 ha. There are estimated to be more than 5 million houses in the WUI area [11]. An average area of 1,272 km^2 is burned/year by wildfires (during the period of 2011–2015, according to the US Department of Agriculture, Forest Service).
- In Australia, more than 11,000 houses were lost in the period 1939–2007 (more than 60% in Victoria) [12].
- In New Zealand, the national average annual total area burned in the period 1991–2007 was 5865 ha, with the average number of wildfires having increased from 1,200 to 4,000 annually in the same period [13].
- France has approximately 4,000 fires/year, with 5.5 million ha of forests potentially exposed to fire risk [14].
- In Italy, in the first seven months of 2017, 74,965 ha burned with Sicily, Calabria and Campania being the worst affected [15].

However, other regions that have not been traditionally subject to wildfires are becoming more vulnerable and will continue to do so in future years, for example, South America, Africa and Northern Europe [4,16]. Examining media coverage of wildfires in 2021 outside of the US, Canada and Australia (where the occurrence, if not the recent severity, of wildfires is expected), we see the range of locations involved (see Appendix A). These were simply 'newsworthy' wildfires from 2021 that occurred in locations not historically associated with severe wildfire events (mapped in **Figure 2**).

Previous attempts to map the areas vulnerable to wildfires occurring are now in danger of becoming outdated – given the evolving wildfire landscape – affecting community planning and resource allocation. This requires a more fundamental understanding of the factors that contribute to the outcome of wildfire evacuations and the development of tools that can assess such events (for example, quantify them) and support regulatory structures that help ensure good practice in this domain.

Some jurisdictions have provided standards, codes, and guidelines to aid planning, prevention, and protection against wildfires. However, by their nature, WUI fires are often multijurisdictional,[3] multidomain,[4] multilayered,[5] potentially multiple in nature,[6] and exist over a protracted period.[7] As such, WUI fires are challenging to understand (challenging the siloed approach often employed by researchers and research organisations), difficult to assess, and difficult to address via regulatory structures given jurisdictional and subject matter issues – and given the innate complexity of wildfire evacuations.

Regulations and guidance

Intini et al. conducted a review of standards and guidelines for development in WUI areas deriving from North America, Europe, Oceania, and international codes [17]. The codes addressed several aspects of wildfire events: the definition of WUI hazards/risks used, land and environmental factors, suggested building materials, utilities, fire protection measures, and road access. Some commonalities were evident:

- the need to define WUI areas and establish severity classes
- the representation of land factors including the defensible space/ignition zones
- the prescription of requirements for buildings and access.

The main gaps highlighted included lack of requirements for resources, fire protection measures, and the consideration of environmental factors in detail.

It was apparent in the work of Intini et al. that the regulations available focused on [17]:

- mitigating the effect of the hazard through managing the land (for example vegetation, topographic terrain), building construction (for example roofing, walls, decks)
- accounting for environmental factors (such as the weather, fire history)
- managing the resources available (utilities, firefighters, access, planning, outreach).

In the material reviewed by Intini et al. there was little or no direct reference to the community involved and their capacity to respond. In more recent guidance produced in Canada (informed by the work of Intini et al.) there is explicit account of the community – the planning required, the factors that might affect their performance and communication strategies – although it still excludes many social and demographic considerations [17].

There are also regional efforts to provide guidance for residents and communities on how to enhance their protection against wildfire. For instance, the National Fire Protection Association (NFPA) FireSmart programme in Canada

3 They start on one person's property and affect many others.

4 Involve human, physical and environmental factors.

5 Affecting the individual, the group, the household, the community, the region and so on.

6 Involving several separate fire fronts that may evolve and merge.

7 Over days and weeks rather than the more typical hours for a building fire.

and FireWise programme in the US.[8] These provide resources for individual residents and for communities to address issues including property preparation, vegetation management, property design. It is more focused on prevention or reducing the impact of fire, should it occur, than on the need for evacuation. Similarly, the NFPA also provides codes and standards relating to land development, water supplies for firefighting, reducing structure ignition hazards, wildfire management, wildfire apparatus, wildfire protective clothing, and equipment.[9] Of course, all these are of fundamental importance. However, the nature and effectiveness of community response is not explicitly addressed. One of the most important contributions to wildfire planning is NFPA 1300 (Community Risk Assessment and Community Risk Reduction Plan Development) [18]. This is not specific to wildfires but identifies the need for coordinated community assessment of the risks faced given the population present and the provisions in place.

Implications of failure

The current location and possible future expansion of the WUI poses severe challenges to community safety from an evacuation perspective. Large wildfires are associated with severe negative consequences including mass community evacuation, property and livelihood losses, social disruption, damage to infrastructure, as well as evacuee and responder fatalities/injuries [19–21]. This has implications for the residents of such areas, community/safety planners, emergency managers, the construction industry, and the insurance industry – to name but a few.

The time for a community to reach a place of safety is an emergent property of its response, the infrastructure available, the information available, and the impact of the fire on the conditions experienced. It is not possible to extract an accurate estimate of the threat posed by an incident by examining any one aspect of a wildfire in isolation. It is similarly not possible to extrapolate from the performance of one community to another with any confidence, or to a different scenario or location, given that outcomes are extremely sensitive to local conditions. Any assessment or regulation requires a coupled approach to provide insights into the vulnerability of certain communities and better inform the preparatory or response actions required.

Assessing evacuation performance is key to emergency planning and real-time emergency response. This includes estimating how conditions evolve, how resources are allocated, and quantifying community evacuation given the procedures and routes available.[10] Political stakeholders need evidence regarding resource reallocation, especially given the challenges posed by multiple hazards. Catastrophic wildfires have enormous economic impact on the region affected (for example, Fort McMurray; AB, Canada) and potentially pose existential threats to affected communities (for example, Paradise; CA, US). These two cases are outlined in Appendix B.

Wildfires may have an impact on community infrastructure (power, communication, etc.) and local resources involved in the emergency response. This could result in the resources from surrounding regions being required to help combat an incident. Communities can quickly become more isolated. The immediate fire damage and smoke effluent produced can have short-term health implications on those involved in the incident and affect those in more remote areas over the longer term (for example, adversely affecting those with asthma in surrounding areas). The event can therefore affect the capacity to respond, the capacity to recover and the viability of a community going forward.

Regulatory opportunities

Lessons might be learned from other approaches of regulatory planning and design in adjacent domains, especially regarding fire safety. For instance, in the built environment, two parallel regulatory approaches have been employed to address fire safety design issues: prescriptive and performance-based approaches. [11]

Prescriptive approaches embed the knowledge and expertise gathered into a set of regulations that must be followed within the scope of the regulatory framework. This approach requires that each element of a system covered by the code has a minimum acceptable standard. For example, prescriptive building safety codes may require a specific number and design of egress routes. Given that the regulations are applied, a building design is deemed to be

8 https://www.nfpa.org/Public-Education/Fire-causes-and-risks/Wildfire/Firewise-USA/Firewise-USA-Resources/Firewise-USA-sites

9 https://www.nfpa.org/Public-Education/Fire-causes-and-risks/Wildfire/Codes-and-standards

10 It may also be key for regulatory oversight should a performance-based approach be adopted.

11 It should be noted that irrespective of the approach adopted, historically fire regulations do not adequately capture the interaction between core elements or the implications of design decisions between different organisations, that is the unintended consequences of design decisions on other domains or other elements within an organisational hierarchy, such as the impact of safety on security, security on operations.

sufficiently safe for its intended occupancy and use. Such a prescriptive approach functions effectively if (a) there is sufficient expertise and understanding embedded in the regulations, (b) the conditions faced are known and understood, (c) the evidence and expertise on which the regulations are based are still applicable, (d) the building design falls within the regulatory scope (in other words, it does not have novel design properties that are not addressed).

The *performance-based* approach requires an expert practitioner to assess the evacuation performance achieved and compare it with projected fire conditions for a representative set of scenarios. That is, the code does not prescribe specific design requirements (although it might indicate best practice), but rather provides goals, for example, with regard to fire safety, that should be met by a system. This then determines whether the design in place allows for the affected population to reach safety in time given the fire conditions faced. Both aspects are quantified, compared, and a performance assessment made. This approach (a) allows for the effectiveness of different design solutions and emergency procedures to be compared for given scenarios, (b) allows for a variety of community designs to be addressed given that they do not have to be previously accounted for within the scope of a prescriptive framework, (c) provides an opportunity to, diagnose, where issues arise and suggest remedial actions. However, it requires more resources, expertise, and means to quantify performance. Developing frameworks to enable and oversee this performance-based approach are similarly expensive and pose significant challenges. These require a body of expertise, sufficient fundamental data to support modelling applications, independent experts to support the peer-review process and so on.

Given the challenges posed by wildfire evacuation (in terms of changing conditions, evolving scenarios and multiple interacting components), *future regulatory efforts may benefit from a performance-based approach*. This is no panacea and requires robust engineering tools that capture core evacuation and fire dynamics, sufficient guidance on the use of these tools and oversight of this use. However, given the complexity of wildfire evacuation (demonstrated in the following sections), performance assessment may be a viable means of identifying challenges, suggesting remedial actions, and of determining the vulnerability of a community to the conditions that might arise given the assumed challenges and remedial responses in place.

In the coming sections, we outline the wildfire evacuation system, demonstrate its complexity, and provide an example application of a wildfire evacuation model. This will enable us to explore this complexity and show that such performance-based approaches are possible, albeit that the evacuation models employed to assess performance are still relatively immature.

What is the system being considered?

We will examine the wildfire evacuation system from the human perspective, although it is acknowledged that this is only one approach and that focusing on other perspectives would produce equivalently complex systems. We also focus here on the period of the incident itself. The complexity described here extends to time periods before and after the incident (for example, return/recovery activities), but is beyond the limited space available here.

The outcome of a community evacuation from a wildfire is sensitive to:

- the incident – the severity and spread of the fire conditions
- the measures in place to address the incident (for example, prior planning, intervention activities and emergency resources)[12]
- the population affected directly or indirectly, their capabilities and their response (for example, the decision-making of the resident population)
- those already using resources that might be used during the incident (for example, background traffic)
- the way this response plays out on the traffic system available (for example, the road network).

Figure 3 is a simplified depiction of the elements present during a wildfire evacuation and the possible interactions between them: [13]

- **A fire may develop.** The location, severity and spread of this fire will be sensitive to the fuel present (for example, vegetation and prior attempts to manage this vegetation), the topography (for example the slope of the land and the terrain), and the weather (for example, the temperature, length of dry season, existence of storm activities, etc.).
- **Planning and intervention efforts.** These affect the public activities before the incident, the emergency procedures and resources to intervene during the incident (for example, notification, the response required, managing traffic flow). The intervention subsequently performed will be sensitive to the situational awareness of emergency decision-makers, the resources available for this

12 Along with the regulatory constraints mentioned in the previous section.

13 Each of which might reasonably be considered a complex or chaotic system.

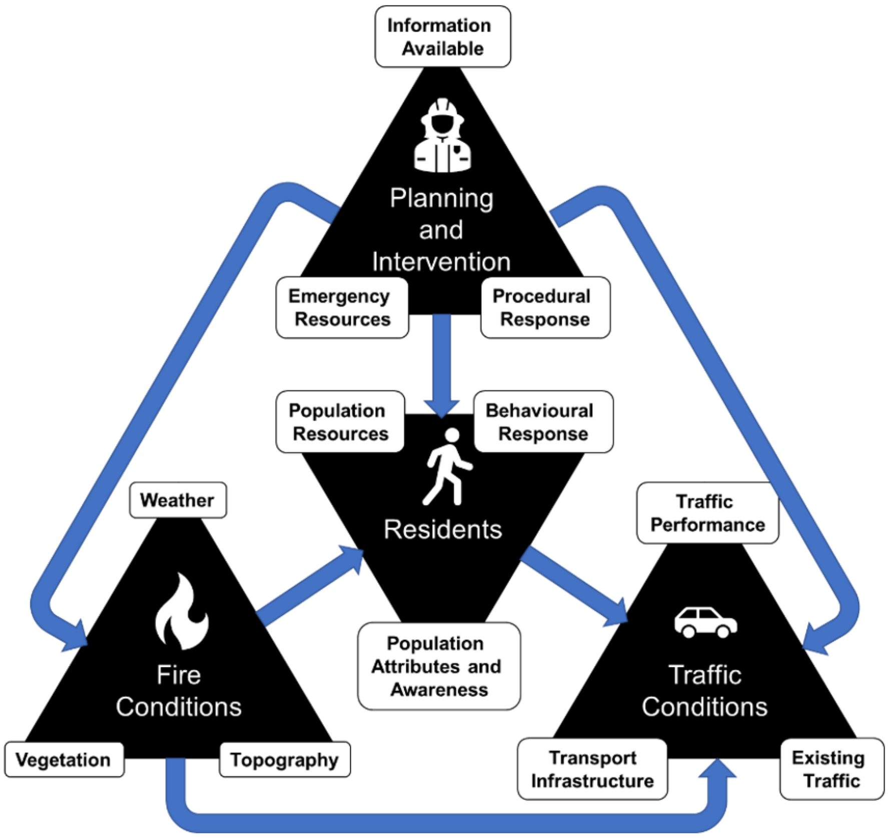

Figure 3: Simplified version of factors that affect wildfire evacuation.

intervention, and the planning in place.

- **The members of the public** (for example, community residents – citizens) **subjected to the incident** and those sharing resources involved in the evacuation. The success of the public's response will depend on the community size and characteristics (for example, the proportion who have movement impairments); the community understanding of the existence, location, and severity of the wildfire incident; and the resources available to the community (for example, access to a vehicle, somewhere to go). This will influence the decision-making process and the eventual evacuation actions taken. This will be constrained by the available infrastructure (for example, how many routes lead to safety), along with the social grouping within which a resident finds themselves. Initially, this response might involve citizen movement – for example, walking to a local place of safety or moving to a vehicle. As such, one of the outcomes of the citizen movement might be an input into the traffic system and the local conditions produced within it.
- The **traffic conditions** produced during the evacuation are initially influenced by the demand produced by the arriving evacuees into the system and the traffic already there (for example, background traffic formed from routine traffic from the surrounding areas that is not part of the evacuation, or evacuating vehicles already present in the traffic system). The conditions will be shaped by the configuration and capacity of the traffic infrastructure in place (for example, the road network design, road condition, road width), efforts to manage the movement of the traffic and the demand placed on the route capacity available.

These elements interact as shown in **Figure 3** to produce conditions over the timeline of the incident. At the scenario level, the event can be viewed as unfolding across several distinct stages (see **Figure 4**). It is apparent that the coupling between the incident, the evacuating citizenry, and attempts to manage and mitigate the incident are embedded within this timeline.

In reality, such a timeline is a composite of many individual decision and actions, crudely categorised into recognisable classes.

Several decision-making models are available to describe evacuee response [23–25]. One commonly used example is the Protective Action Decision Model [26]. This asserts that the response process begins when the public are first exposed to physical and social cues.[14] After the public interact with this information in several ways (receive it, pay attention to it, and interpret it), they determine the information's credibility as an indicator of an actual threat and determine the action required (for example, evacuation or staying in place). Depending on the success of their action, a resident may need to reappraise – looking for more information to update their situational picture and inform a new decision. Kuligowski established several variables that might influence resident decision-making [27]. A summary of her analysis is shown in **Table 1**.

14 This model was developed to account for decisions in response to disasters in general, rather than wildfires.

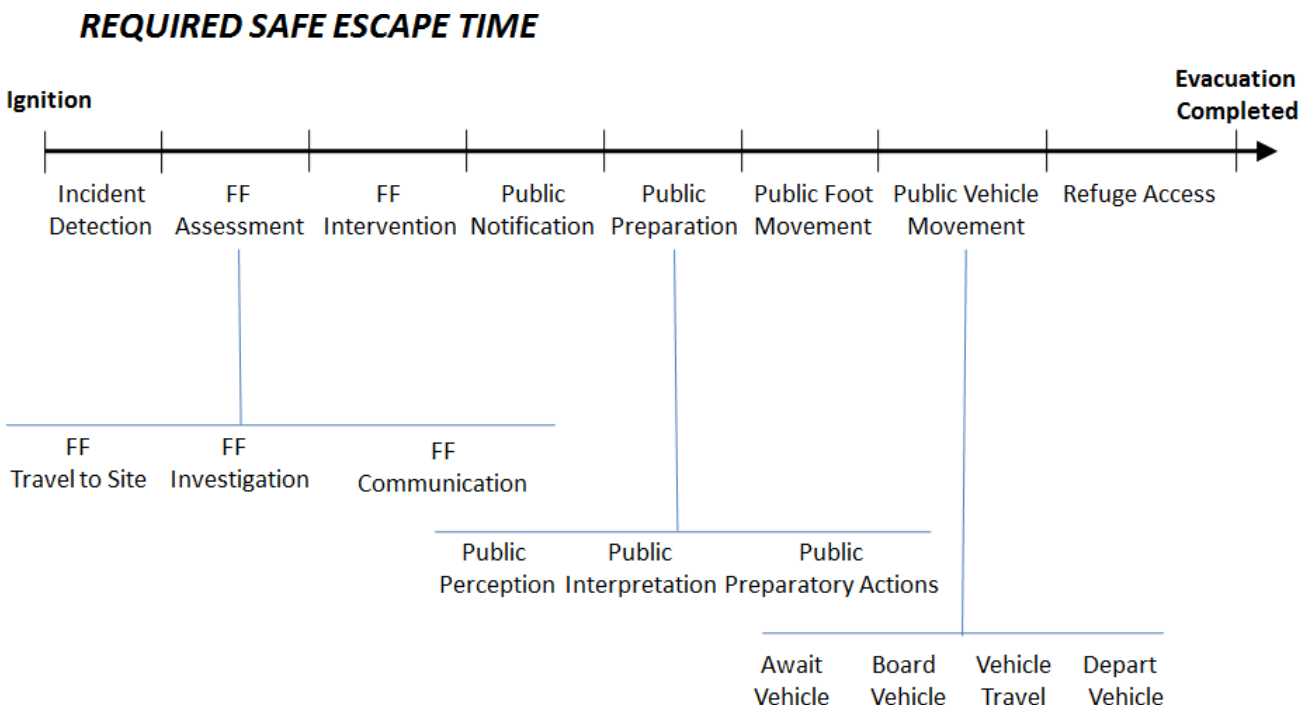

Figure 4: Community Evacuation Timeline. FF=Firefighter(s). [7,17,22]

Factor	Impact	
	Perception of Risk	Evacuation Decision
↑ Education Level	+	
↑ Length of residence	–	
↑ Previous experience with wildfire evacuations	+/–	+/–
↑ Previous awareness of fire risk	+	+
↑ Income	+	+/–
↑ Physical fire cues	+	+
↑ Receiving warnings from a trusted source	+	+
↑ Receiving warnings in-person		+
↑ Receiving official or voluntary evacuation notices		+/–
↑ Gender (female)		+
↑ Risk perception		+/–
↑ Having an evacuation plan		+
↑ Having taken home preparation actions		–
↑ Age (older)		–
↑ Having children		+
↑ Having pets/livestock		–

Table 1: Factors identified by Kuligowski (from available research) that might affect evacuation performance [27]. + indicates a positive impact, – a negative impact, and +/– an inconsistent or variable impact. Gaps indicate insufficient information available to make a judgement.[15]

15 Other factors certainly exist – either not sufficiently represented in research literature that is or in literature not widely available, for example having source of income from/on the land under threat.

It is apparent that many factors affect the decision-making process of a member of the public. In terms of a wildfire evacuation this response might be characterised in the following manner:

- whether they decide to evacuate or stay
- when they initiate movement
- the mode of transport selected
- the route chosen
- the non-evacuation or preparatory actions/journeys required before a deliberate movement to a place of safety
- the speed at which they can traverse this route
- the target chosen
- the resources available to complete the action and reach the chosen target.

An attempt at characterising or quantifying evacuation performance should account for these elements, even if only implicitly.

The actions taken by the community and emergency responders during the wildfire will produce conditions that evolve during the incident itself. The initial fire may develop and spawn new fires remote from the original source through the transport of firebrands (see **Figure 5**). Similarly, multiple communities may be affected by a single fire and be subject to different information and guidance, and may fall within different jurisdictions. Therefore, both the fire conditions and the evacuation process will vary over space and time. A simple example of these evolving conditions is shown in **Figure 5**.

Understanding the development of the fire alone is not a sufficient predictor of the impact of the incident on nearby populated areas [28]. *A community is not equally vulnerable to different wildfires and different communities are not equally vulnerable to the same wildfire*. A simple example is presented.

In **Figure 6** (top row), the blue site has a built-up, well-resourced population with some midrise structures and offices. The green site (see **Figure 6** (bottom row)) is more rural – with fewer resources. Otherwise, the community footprint is the same shape and size in both rows. The three versions of the blue and green sites (comparing horizontally) have the same population, with different road connections – for example, number, location, and size of roads. The same population (comparing within the blue or within the green conditions) may have a different evacuation potential given the different road networks available – even when exposed to the same fire. This affects the overall capacity and the flexibility of the evacuation plan, for instance, the impact of a loss of a route when there are two roads, might be different from when there are five.[16] If we now compare vertically – across different site populations for the same road

16 This assumes that the number of vehicles tests the overall capacity of the road network at some point.

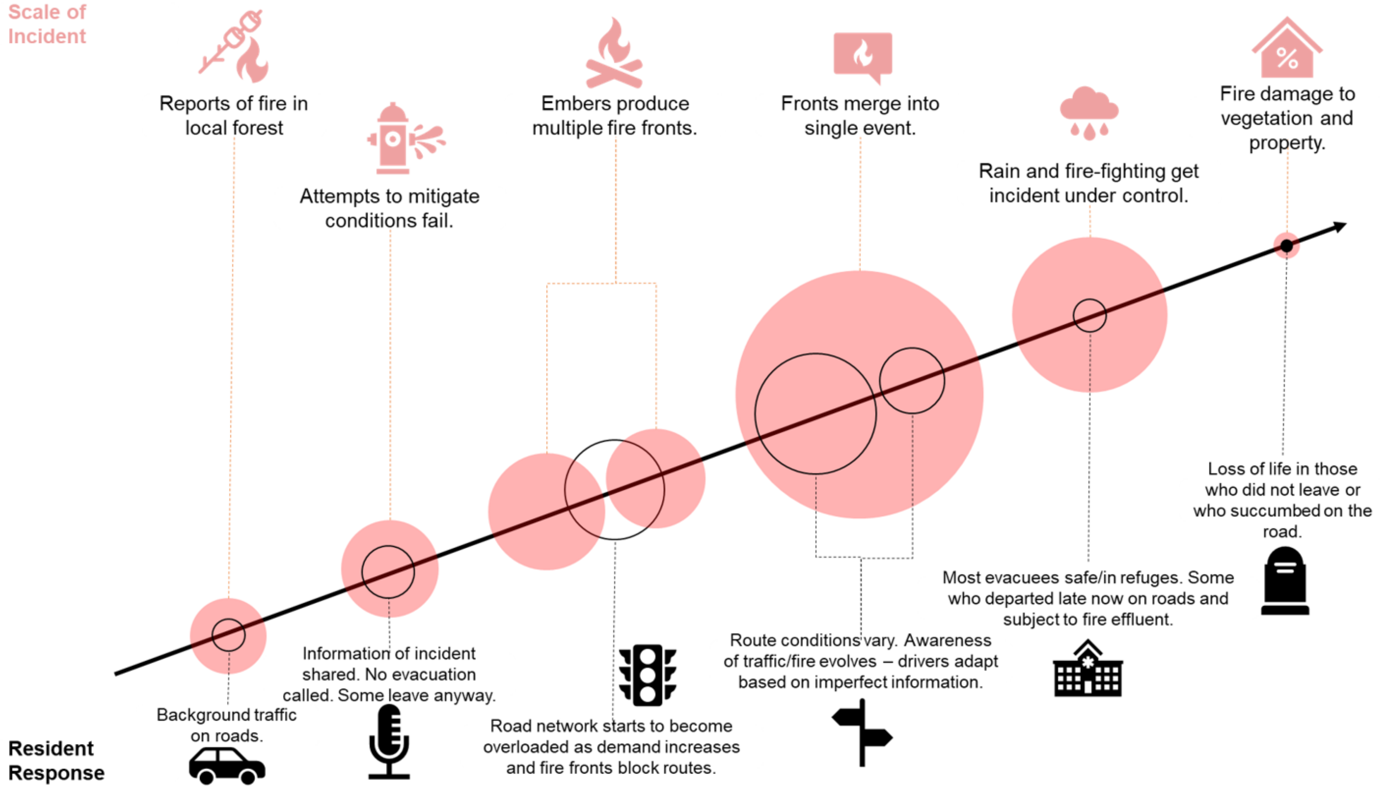

Figure 5: Timeline of evolving conditions.

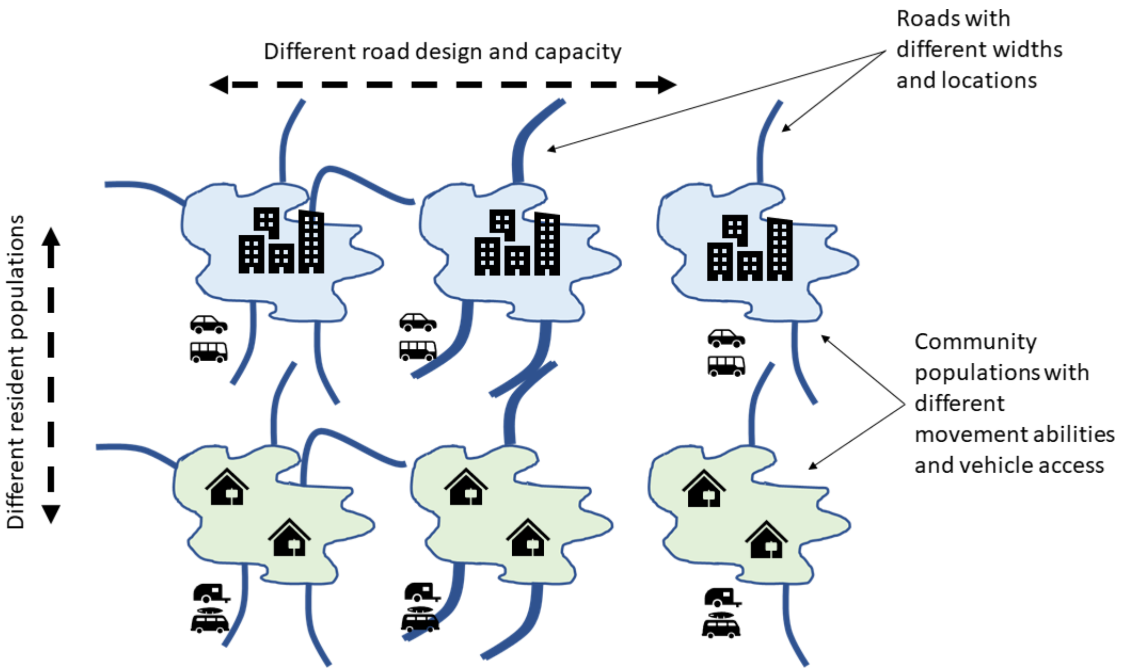

Figure 6: Scenario-specific community vulnerability.

network design – the evacuees will exploit the same road network differently, given their capabilities, awareness, and resources, including decision-making, access to vehicles. Quantifying evacuation performance helps determine the extent of these differences and their impact on the outcome. *Quantifying these facts helps inform our design, planning, and response decisions.*

A wildfire evacuation is therefore formed from interacting parts. The area and population affected evolves over time. The human response to this incident will vary given where they are and what they are doing, the information available, their roles/objectives, the resources available, and the options open to them, in other words, it is not reasonable to assume a uniform response.

Why is the subject characterised as 'complex' rather than 'complicated'?

WUI incidents and subsequent evacuations present a unique challenge to planners and responders. The nature of the WUI incident is varied in how it starts[17] and the factors that influence it and how it evolves; complex; dynamic – both temporally and spatially; can involve multiple jurisdictions; and has the potential to last for long periods of time (for example, the Fort McMurray incident lasted over two months). As noted by Cohn et al: *"Wildfires have attributes such as scale, timing, duration, and multiplicity of causes that set them apart from other disaster events and that make the inferential leap from the disaster literature a little tricky."* [29]

This poses a problem for understanding the dynamics involved and developing insights sufficiently robust for use in community planning, land use planning, and emergency response.

Decisions made during community planning and management[18] are all heavily reliant on evidence – the scope, refinement, accuracy, and credibility of the information on which a response is based. The success of the affected community's response to WUI fires depends on their ability to:

- prepare for the hazards
- adapt their response to the evolving conditions of the incident
- and recover from disruptions in the immediate aftermath of the incident and in the longer term.

To successfully respond to a wildfire incident, those involved must have an understanding of contemporary and near future events that affect their attempts at reaching safety or remaining safe [30], that is, a reasonable situational awareness on which to base decisions. Situational awareness is the information available on the scenario faced allowing a picture to be formed on which decisions might be based – evidence of what is happening and where [31]. Efficient information sharing is crucial to ensure this picture is contemporary and accurate.

Two aspects of wildfire scenarios undermine the evidence that might be used to inform planning. *Firstly, wildfires are evolving given*

17 From lightning strikes to barbecues.

18 Including property upkeep, emergency planning, public education, responder training, and during the evacuation itself.

the environmental and societal drivers identified earlier. They are occurring in new locations, producing more extreme conditions, and subjecting new populations to these conditions. Given this, insights gained from examining historical events might be less applicable and less instructive. *Secondly, the complexity of wildfire events (see below) makes the use of analytical tools extremely challenging*. It is not easy to derive analytically how the myriad factors from diverse subject domains interact to produce aggregate conditions at the various levels of agency – both during the incident and relating to the overall outcome.

Given the challenges posed to the traditional evidential supports (of analytical derivations and empirical correlations), wildfire evacuation modelling might fill at least some of the gaps present to explore the way the many elements interact and their consequences. Any model applied will inevitably be a gross approximation; however, coupled with subject matter expertise it might at least demonstrate the impact of certain factors, the way in which factors interact, and the sensitivity of the outcome to this interaction. This demonstration might suggest the collection of more fundamental data or more refined analysis.

The complexity of wildfire evacuation is produced by the factors present that come from multiple domains and their interaction at various levels of granularity. Agents who are active during an incident will have different responses open to them. They will influence (and be exposed to) different sets of external conditions and actors, and have different resources and objectives. A simple example will help build this complex narrative.

Individuals affected by a wildfire may become aware of a wildfire through different means (for example, official communications, direct exposure to fire cues, informal conversation with neighbours, unreliable sources on social media) [32]. Before this awareness they will have been likely involved in routine activities (see the bottom layer of Figure 7). These individuals will process this information and either individually or collectively determine when and how to respond. Assuming that they are in a household, the residents may discuss the situation, prepare and decide upon a response – whether they choose to evacuate and when they choose so to do.

If they are part of a social group, then this response will likely involve assessing the capabilities of those with them (for example, preparatory requirements, movement abilities).

They might eventually walk to their vehicle or a shared vehicle or use public transport. Depending on their location, they may interact with other residents inside their building (for example, in a multioccupancy structure) with resultant congestion/interactions emerging in a staircase, or interact when moving to shared parking areas (see the second and third 'rungs' of **Figure 7**). This admittedly seems like a trivial example here – not affecting overall performance. However, if you transpose this to the evacuation of a 50-storey office block or a hospital then these interactions and resultant delays can become extremely serious indeed.

As such, emergent conditions might arise from the pedestrian evacuation (for example, queuing on stairs, boarding a public vehicle). On the streetscape outside of their building they may encounter other pedestrians moving to a local place of safety or their vehicles (see rung four of **Figure 7**).

If they are not at home (for example, they are at work), then before evacuating they may need to return home – potentially moving away from safety on foot or by vehicle given that their home has to be evacuated. This has implications for traffic congestions and road management and more directly on the delays incurred before their movement to a place of safety. These non-evacuation journeys might be included within preparatory delays or in the movement activities. This might depend on whether the actions are conducted after their initial movement is towards a place of safety and does not involve them returning home, but simply stopping off en route.

Assuming that evacuation to a remote location is necessary, pedestrians will likely board a vehicle and then move off joining the traffic system (see rung four of **Figure 7**). If this is public transport (or an emergency vehicle) then the capacity of the vehicle might limit the individual's/group's ability to board and move off – there might not be room for them on board – forcing them to wait for the next available berth.

The vehicle will eventually be the basic 'unit' of evacuation – hosting several individuals – that then is the level of agency. The arrival of this vehicle into the traffic system (for example, leaving a residential property and travelling along a road into the road network) is effectively the connection between the pedestrian evacuation and the traffic evacuation. As such the resident's initial decision-making, preparation, and movement to the vehicle might generate local emergent conditions of interest; these in turn provide input into the higher-level traffic evacuation. As such, a wildfire evacuation might reasonably be depicted as a system of multi-layered complexity.

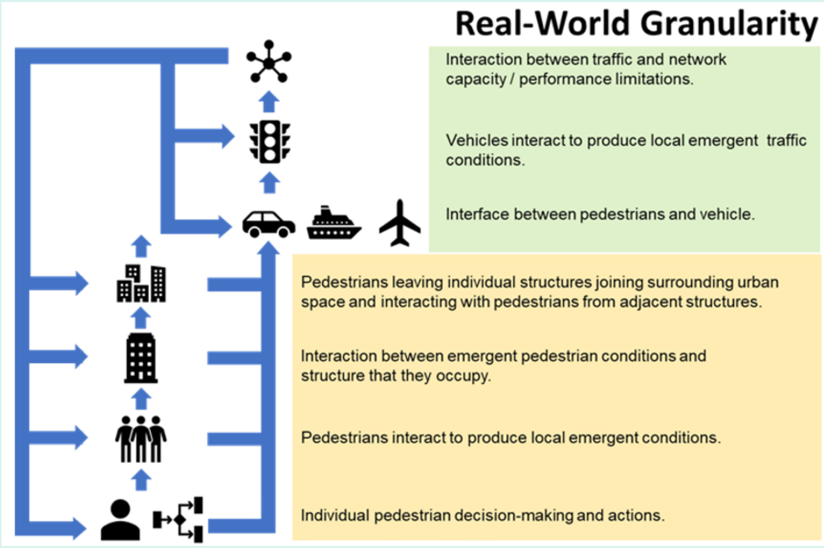

Figure 7: Connection between pedestrian and vehicle evacuation systems.

This narrative represents a slightly informal take on the factors at play and how they interact – in a reasonably intuitive manner. However, this does not definitively ensure complexity over complication. To do so, we adopt the structure developed by the University of York (*The York Framework*) [33].

The York Framework identifies several characteristics that are required to indicate complexity. These are now paraphrased and applied to wildfire evacuation to demonstrate the necessary parallels:

- Agency operates at multiple levels within the wildfire evacuation 'system': including individual, residence, street, community, local, regional, national, and international. These may all affect the conditions produced during an incident and the eventual outcome – both local and general. In some situations, several of these levels will be active at the same time, given their different capabilities, objectives, and opportunities. The mode of this agency changes according to the conditions faced and the resources available, for example, pedestrian, car, bus, aircraft. This complicates the evacuation dynamics produced – increasing the variables present, but also increasing the 'levers' available to influence the evacuation outcome (see **Figure 8**).
- At a certain scale, wildfire response requires *numerous government, non-profit, NGOs, and private organisations to collaborate* to successfully tackle the fire and evacuate threatened members of the public. Individual agencies are unlikely to be able to respond to the disaster single-handedly. In addition, local and individual actors will also be responding – organisations along vertical and horizontal axes (scale and jurisdiction). The multiplicity of different actors complicates attempts to choreograph and manage the evacuation. The best that might be expected is the distribution of evacuees across the network capacity, within time windows, and broadly towards suggested objectives. This still leaves scope for variation in the response, where actors use their agency according to resources and objectives (**Figure 8**).
- Various elements of the system are formally structured, for instance, local government. However, the interaction between entities at the same level or between levels may well be ad hoc depending on the disruption caused by the wildfire itself (disrupting the stability of these structures). There is no international organisation (for example, equivalent to ICAO for the global aviation industry) producing guidelines for wildfire response and management that are universally adopted (or that address agreed scope of factors – especially relating to community response). Different organisations are involved in responding to different aspects of wildfires in different countries (for example, in the UK, the military and the Salvation Army responded to the Saddleworth Moor fires in addition to firefighters) [34].
- Although not an agent, the *fire itself* is highly dynamic, sensitive to local conditions (including vegetation, topography, weather) and affects the actions and interactions of human organisations responding to the incident. As such, the incident is an evolving, exacerbating factor that adds to the complexity of the system. It is not simply a static, precisely documented boundary condition as it affects the manner in which agents interact during the incident (for example, visibility, routes available, threat posed to property), as well as their capacity to act on their objectives.
- The conditions produced (as experienced by the evacuating population) will be the result of interactions between physical, environmental, organisational, and individual actors. The status of these will not always be completely known – obscuring details that might affect the outcomes produced and

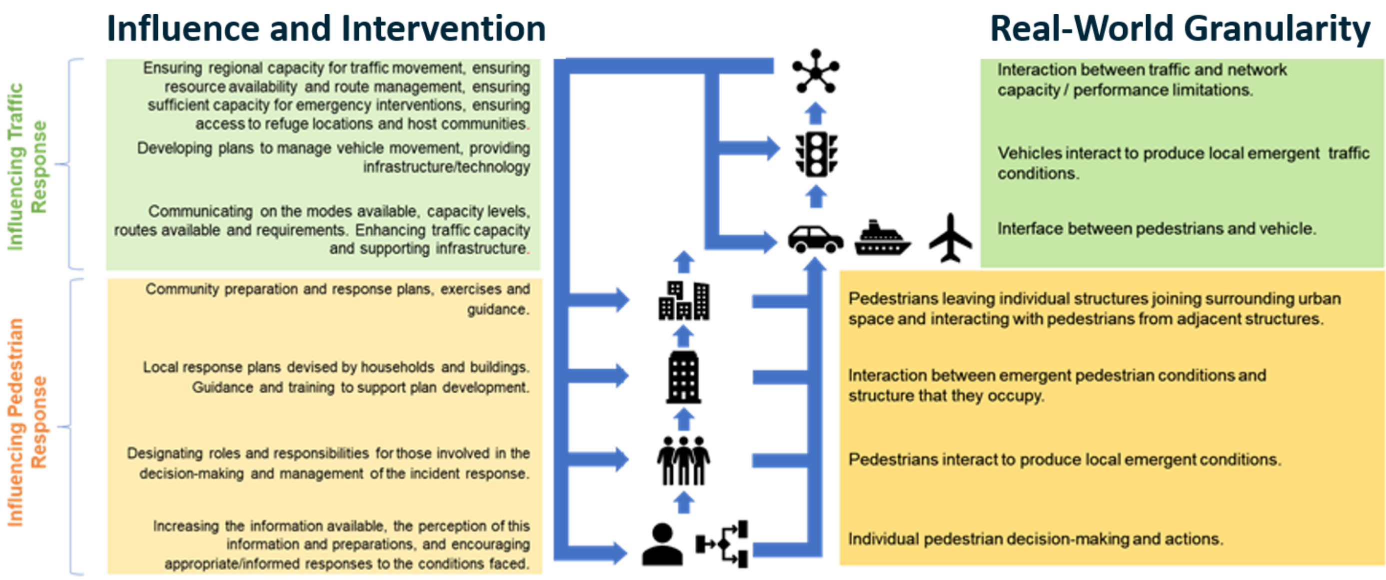

Figure 8: Example opportunities for intervention at the various levels of agency.

bounding the rationality of any decision-making process.

- The outcomes produced by these interactions will be experienced at different scales – the individual, group, community, organisational, regional, national, and international. As such the outcomes will affect actors in different ways (depending on their roles, responsibilities, and objectives) and also be perceived differently.
- The nature of wildfire events is changing given factors beyond the incident (for example, wider environmental conditions). This means that it is difficult to draw specific insights from historical incidents (even those that are similar or proximate) given that one or more of the underlying conditions might have changed – affecting the outcomes produced.
- It is extremely challenging to derive findings analytically that might inform decision-making relating to a specific wildfire evacuation given the crowd of interacting factors, the dynamism of the conditions and the ambiguity of the situation.
- Unlike traditional building fires [35], wildfires can quickly produce multiple incident locations that evolve independently or merge producing events of a different scale. These events will affect local concerns (for example, the community infrastructure and population directly exposed) and remote concerns (for example, smoke affecting air travel, remote communities, longer term health concerns[19]).[20]
- The progression of a wildfire event is significantly affected by wider concerns beyond the site of the incident itself, for example, climate change, land use policies, seasonal variations in weather. Perhaps more subtly, it is affected by the desires and actions of residential communities, for example, more people want to live in the wildland–urban interface, meaning that the number vulnerable to wildfire events is increasing and that many of the newly vulnerable might not have experience in the nature of these events.
- Local interactions between actors can have enormous consequences disproportionate to their size and intent. For instance, two evacuating vehicles might be involved in an accident during the evacuation blocking a route out of town that produces enormous congestion elsewhere leading to thousands of other evacuees being delayed and exposed to encroaching smoke conditions. A story from a local news outlet (accurate or otherwise) might encourage people to evacuate earlier or later than required and use the same route out of town, leading to that route being overloaded. This in turn might produce congestion on that route, delaying arrival at a safe location and increasing the chances of traffic accidents (as above).
- Wildfire events involve factors from entirely different domains, including human, environmental, and physical. The interactions between these factors are very much bidirectional: for instance, the fire affects a community, responders attempt to douse the fire. These interactions generate new conditions that affect how actors within each domain 'act' and the information

19 https://www.independent.co.uk/climate-change/news/brazil-amazon-wildfire-pollution-health-b1916379.html

20 Building fire regulations assume a single fire incident.

available that can influence the decision-making of those actors with agency, for example, how a resident responds when a fire service deploys resources or when a local authority calls for a community to evacuate. This highly coupled system has such interactions across space and over time.

- A wildfire event evolves over time, going from not existing, to initial ignition, to development, spread, decay, being controlled, and being extinguished. These 'stages' pose different opportunities for intervention and pose different threats. (It should be noted that the wildfire incident is only a small window within the timeline of a space or community – and as such reflects a catastrophic shift in the scenario.) These threats require local actors (individuals, responders, and authorities) to adjust their responses. This leads to both a physical and behavioural timeline marked by transition where communities might be required to remain, evacuate, or return given the incident or where the incident is not a factor; where it is considered worthy of investigation or mitigation; where it is considered a threat to community, and when it is eventually no longer a threat.
- The community affected by the incident will ideally be informed of the conditions faced and the required response. Local authorities and emergency services will support this effort and attempt to shape it. However, evacuees will have agency within this effort – for example, organising when they respond, the routes used, where they are going – up to the point when mandatory procedures are enforced (although even here 'enforcement' cannot oversee all aspects of individual response). Evacuee agency may be coordinated to promote efficient use of the resources available. If not, actors (for example, households evacuating via their vehicles) might self-organise and use the resources available (for example, the road network) more organically.
- Actors adapt to the conditions faced, assuming sufficient resources, information, and time. For instance, the loss of a road will lead evacuating vehicles to redirect. In some instances, the loss of a road network requires responder support to provide other modes of transport (for example, a helicopter). As such the evacuation 'system' copes with the changing conditions faced in an attempt (albeit not always from a unified perspective) for the evacuating actors involved to reach a place of safety.
- Information might be incomplete, outdated, ambiguous, and unevenly distributed. Responses at all levels may therefore be based on an inaccurate and delayed picture of the actual conditions faced. Therefore, across the range of actors involved, responses to the wildfire conditions may be delayed or inappropriate – certainly suboptimal. Decision-makers in a command centre may deploy resources based on assumed wind and fire progression, residents may base their response on historical fire incidents (and their previous success in dealing with the conditions).
- A wildfire may have both local and broader implications – both in time and space. An incident may have longer term implications for a community – affecting trade, tourism, property values, mental health, education, and public services and so on. These are outcomes beyond the immediate physical damage done by the incident to life and property. Similarly, the incident might affect those further away from the incident, for example, the health of those with respiratory conditions in nearby locations, relocated communities might overload services in host locations, insurance rates might rise for whole regions, emergency responder practices might evolve for future events.

Given that the characteristics identified in *The York Framework* could be transposed onto the wildfire evacuation system, we then mapped the core factors present in a wildfire evacuation onto *The York Framework* schematic. This breaks a complex system down into:

- *exacerbating factors* (external elements that complicate the management of a wildfire)
- *causes of system complexity* (internal elements that contribute to the complexity of the outcomes)
- *consequences of this complexity* (emergent conditions that result from incident complexity)
- *design-time controls* (attempts to mitigate the conditions faced before the incident occurring)
- *operation-time controls* (attempts to mitigate the conditions faced during the incident)
- and then *the system failures* that might occur (unwanted outcomes as a consequence of the incident).

This framework identifies the core aspects of safety scenarios to be identified and related in a systematic way. **Figure 9** shows core aspects of a wildfire evacuation overlaid onto this framework. This could have been approached in several ways; however, it is apparent that the elements identified can reasonably be mapped onto the *The York Framework* structure – both in terms of its key components and the three levels at which exacerbating factors might affect the outcome (governance, management, and task/technical factors, shown in green shades in **Figure 9**).

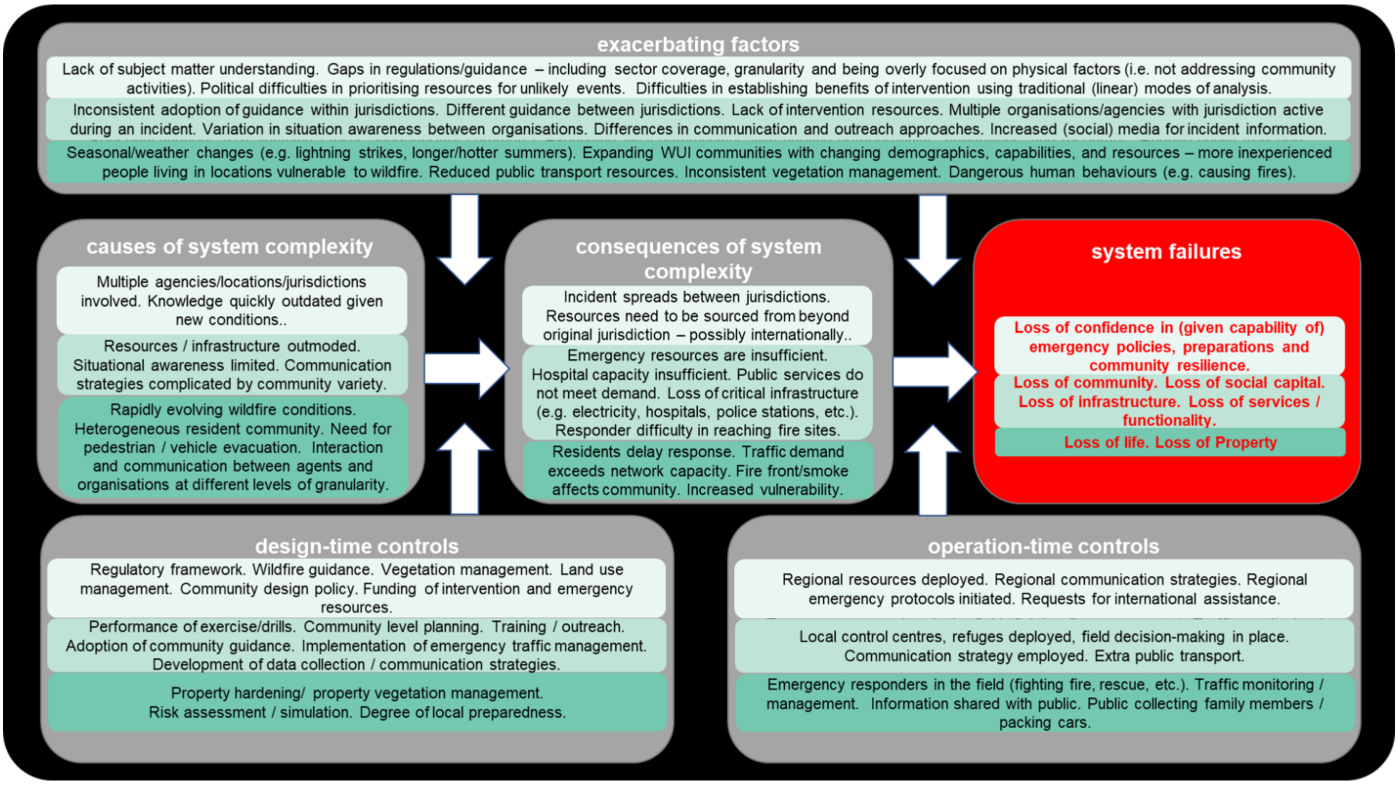

Figure 9: Overlay of wildfire evacuation factors onto *The York Framework*.

Wildfire evacuation appears to satisfy most if not all the requirements outlined in *The York Framework*. This has implications for how such events might unfold, their sensitivity to initial and evolving factors, and the capacity of stakeholders to understand how they might evolve, how they might intervene (and the levels of this intervention) or how effective planned interventions might be.

Who are the key stakeholders related to this case study?

Wildfire events that affect human populations typically occur on property owned by multiple individuals and organisations. At a minimum, wildfires occur on wildland owned by one group that affects properties or infrastructure owned by others [36]. As an incident increases in size, so do the number of individuals, groups, and organisations affected. The scale of a wildfire can mean that it extends beyond the original source location (indeed, beyond one fire) – beyond a structure, a community, a region, and even beyond a nation. This contrasts with typical structure fires, where horizontal spread to other structures is not commonplace.

It is possible that a wildfire affects different regulatory jurisdictions. Depending on the scale, it may spread between local government jurisdictions affecting regional considerations. This might require the coordination of multiple local authorities. It may eventually attract national (requiring coordination between multiple regional authorities) or even international intervention – depending on whether international aid is needed or whether the fire crosses national boundaries. Given the nature of fire effluent, the fire front itself may be completely within a particular jurisdiction; however, smoke might be transported hundreds of kilometres into neighbouring regions or nations. *The negative impact of a wildfire is not limited to the fire front.* Where the incident spreads beyond a particular jurisdiction, so the intricacy of the response increases along with the importance of a coordinated response – with responsibilities, resources, and information requiring coordination between organisations with potentially different priorities, practices, languages, and cultures. As such, *wildfires are not just bigger (building) fires – and the associated response cannot simply be extrapolated from building fires*. The scale of the event produces much more complex organisational challenges given that actors operate at different points in the decision-making hierarchy, with responsibility for different jurisdictions (from individual to national) and associated objectives. The interest and intervention of such stakeholders vary greatly across the timeline of an incident.

A range of different stakeholders can be identified – who have a role and an interest in the outcome of wildfire events. These include:

- members of the public
- property owners
- community managers/leaders
- construction
- safety managers
- urban/land planners
- practitioners (for example, consultants, engineers)
- designers
- insurers
- investigators
- advocacy groups
- emergency responders/ emergency planners
- local/regional/national government
- non-government organisations
- developers/construction industry
- land/forestry managers
- designers/safety practitioners
- business owners/industry
- providers of critical infrastructure (for example, hospital managers, utility providers)
- regulation/guidance developers
- academics/subject matter experts.

Perhaps the most varied stakeholders are members of the public, whose experience, connections, and resources vary with their relationship with the community in question. They are subject to the emergency conditions in place and have agency over their own and their social group's response. Each public group is affected differently and has different responses open to them to mitigate the threat to them ranging in risk, cost, and impact. As such, they are stakeholders who are impacted by the wildfire in different ways and whose influence may range from direct to peripheral.

The influence of these stakeholders varies according to their role when they are active and the scale at which they operate. Within each stakeholder type there is a hierarchy that determines their attributes, influence, and exposure to the outcome of the incident – from government (for example, local/regional/national), emergency responders, social groups and safety managers (for example, with potential responsibilities for the population of a floor of a building, an entire building, a chain of buildings, a community).

The degree of their interest will vary along the timeline of an incident [37–40]. Many of these stakeholders are associated with a community long before a wildfire incident occurs (for example, residents, designers, insurers, property owners), while others are focused on a narrower range of time periods (for example, investigators, tourists, emergency responders). Focusing on the narrow period associated with the incident itself, we can see several activities directly involved with the occurrence, development, and outcome of a wildfire, and subsequent evacuation for a small set of stakeholders (see **Figure 10**).

The severity and scale of an incident (and the geographical jurisdictions affected) will determine the government resources deployed during an incident. Equivalent organisational hierarchies within private

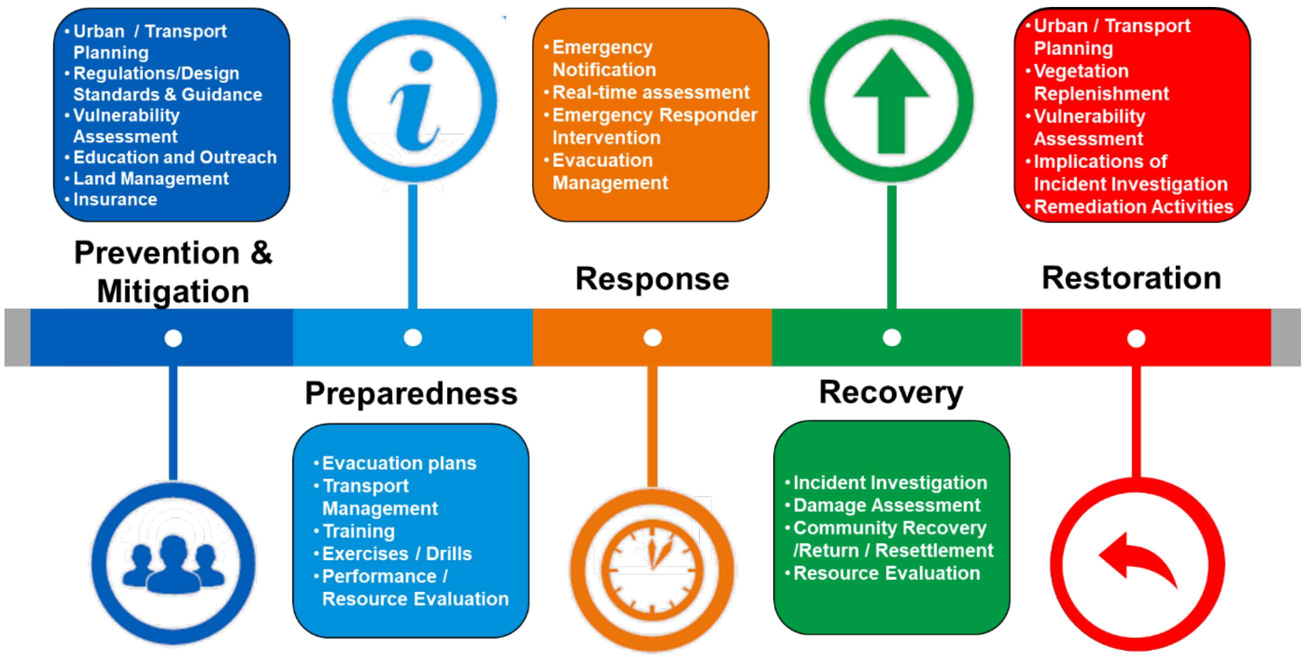

Figure 10: Stakeholder activities along the incident timeline.

organisations will determine the nature of their response. It may well be that organisations deploy at different levels given their degree of agency and their interest/responsibility regarding the incident. This may lead to interactions between and within organisations at different levels to meet a range of organisational objectives. Coordination efforts are not simply based on aligning individuals at equivalent levels in different organisations. Of critical importance is for multiple organisations to establish and have a common picture of the incident – a shared situational awareness. This includes a shared understanding of the decisions being taken and the resources deployed, to avoid duplication and enhance efficiencies.

Previous comments regarding the challenges of extrapolating from historical events to current threats are not intended to diminish the importance of learning lessons from the past. This activity is critical. Post-incident, lessons might lead to developments in the regulations and guidance available that shape practice and response in future incidents. Such challenges can also have significant stakeholder impact beyond the incident (see **Figure 11**).

Local fatalities, injuries, and property loss will be of primary concern. Other local people might have been displaced – being forced to evacuate, likely by car, to a refuge or shelter somewhere further afield. Depending on the severity and longevity of the wildfire, this displacement may be considerable, to the extent that their return is questioned entirely. Beyond this group, the fire effluent itself might affect the health of those remote from the incident, for example, affecting air quality and exacerbating respiratory conditions. It is likely that many fatalities that are caused by exposure to the fire effluent but not at the incident site are not accurately recorded [36]. The communities hosting refugees from the fire will likely be disrupted (financially and socially) – at a minimum shouldering the burden of sudden new arrivals. Finally, there is the rest of society who funds the government response/emergency intervention to the incident. This cost may be amplified through damage to the economy, loss of businesses, reduction in transport, and a general change or loss of social capital.

Wildfires affect stakeholders at multiple levels and over different timeframes. Some of these effects are tangible and clearly associated with the fire (for example, loss of property), some are remote (for example, hosting refugees), while others are more indirect and ambiguous (for example, damage to the economy, change of public opinion). It is possible that the impact of wildfire incidents on stakeholders is overly simplified and underestimated given the many influences apparent and the subtlety of some factors.

This implies that the impact of the wildfire on the well-being of different populations is underestimated given assumptions relating to temporal/spatial remoteness, but also given the complexity of the incident (and the various organisational responses) and its impact on different communities.

Approach

Previously we established that wildfire evacuation was complex. This, coupled with the evolving conditions undermining direct insights from historical events, implies that other means of quantifying evacuation performance are necessary. A range of (computational) models are available to model traffic movement [41]. These range from sophisticated simulation tools to flow-based approaches. Similar tools exist for modelling the two other important layers comprising a WUI fire evacuation: fire development and pedestrian movement [7].

It is fully acknowledged that any model (be it an exercise or a computational tool) is a simplification of reality. Many of the real-world factors are omitted, and simplified versions included. Such a simplified model is used here as a proxy for wildfire evacuation – to explore the conditions produced and the sensitivities of the outcome to the underlying conditions. The simulated complexity should then only be seen as a portion of the real-world conditions that emerge given the many factors absent from the simulated environment.[21] In this vein, we focus here on human response to the fire rather than the fire conditions themselves, although the impact of the fire on route availability is examined. This is to reduce the number of modelling assumptions and again contain the factors modelled to assess a reduced

21 It should be noted that thoughtful simplification in computational models has benefits, since it not only reduces the computational power required to run scenarios, it also can simplify outputs so that broad trends become more easily apparent to an end user.

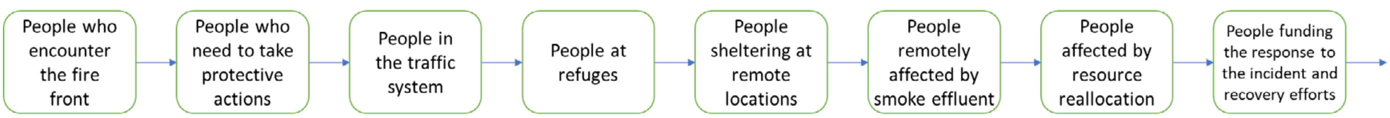

Figure 11: The reach of a wildfire incident and the impact on different communities. Effects of the incident ripple well beyond the incident site.

level of complexity – precluding accusations of 'complexity inflation'.

Here, we use a macroscopic model that includes pedestrian response, traffic movement, and wildfire conditions. The relatively simple WUI-NITY model is employed here [16]. It only captures a subset of the factors that we previously identified as affecting evacuation performance (see **Figure 12** and compare the example cases in Appendix B with model capabilities outlined in Appendix C). It is acknowledged that this macroscopic model excludes explicit representation of organisation/responder intervention (and interaction), the interaction between individuals and vehicles, the development of the environmental conditions including the fire (although the model can represent this explicitly), and the impact of the weather on it. Instead, these factors are either implicitly represented (for example, through the loss of route capacity) or represented at a lower level of refinement (for example, flow attained rather than flow generated). This represents a deliberately simplified 'model' of reality – to demonstrate that even under these simplified conditions, this partial system is complex. However, as we will see, using only a subset of the modelling 'levers' available within this tool it is still able to demonstrate the complexity of the process and the (in)sensitivity of the outcomes to modifying underlying factors: in other words, to provide actionable insights. This model was developed by the authors of this work and is freely available.

Any evacuation model requires empirical data for configuration and validation. A community evacuation exercise was observed in 2019 and data collected on various aspects of the community response [16]. Although the intention of the prearranged drill was to enhance the community's evacuation performance, our data collection efforts were intended to:

- provide insights into the underlying evacuation dynamics
- generate a data-set suitable for evacuation modelling (using the WUI-NITY model), to quantify evacuation performance.

The initial intention was to configure the wildfire evacuation model to reproduce the drill conditions and test whether the model estimates were reasonable and then examine the implications should an evacuation of the entire community be required, assuming that the population performs as they did during this drill, given different planning, design, or scenario factors. Here, we examine how changes in the initial conditions impact the results produced and provide insights into emerging conditions and underlying dynamics.

In addition, a second set of scenarios has been examined based on more general assumptions (that the full population evacuates in accordance with general wildfire evacuation expectation rather than the drill conditions) to test whether the sensitivities identified are specific to the assumptions made in line with the drill data.

The method employed is shown in **Figure 13**. We gathered data from the drill and configured the initial conditions within the model (primarily regarding population size, initial delays, route use, and target location). The model was then employed to explore the original drill conditions and see the sensitivity of these results to changes in the initial delays (derived from

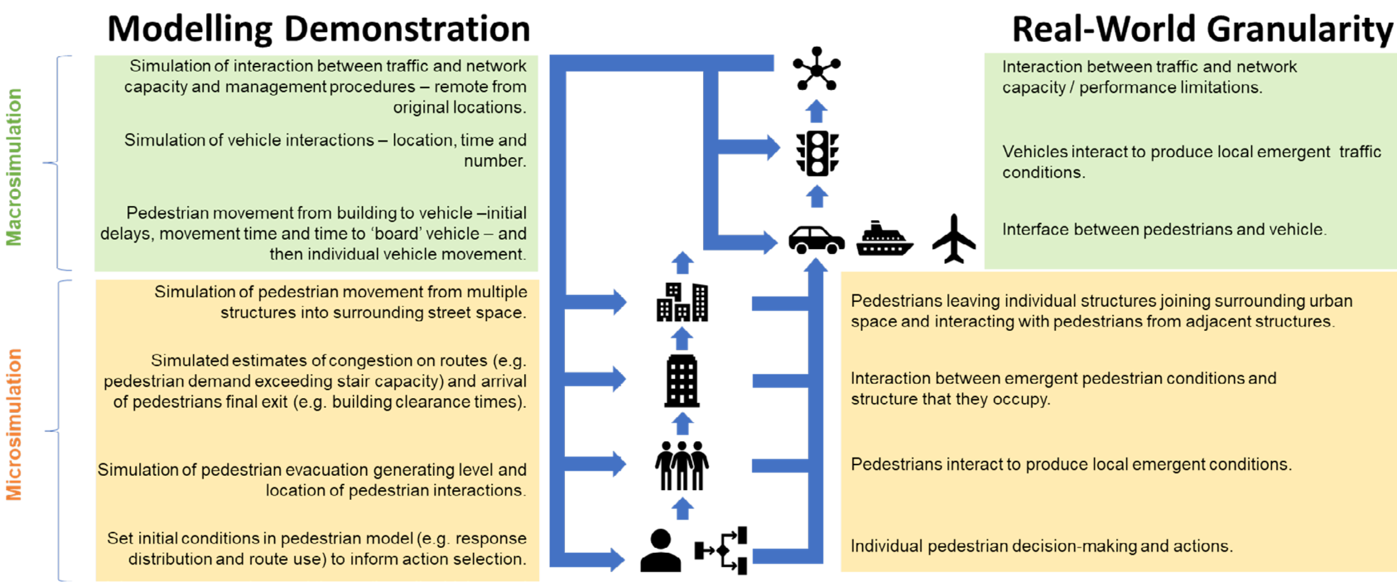

Figure 12: Relationship with real-world granularity.

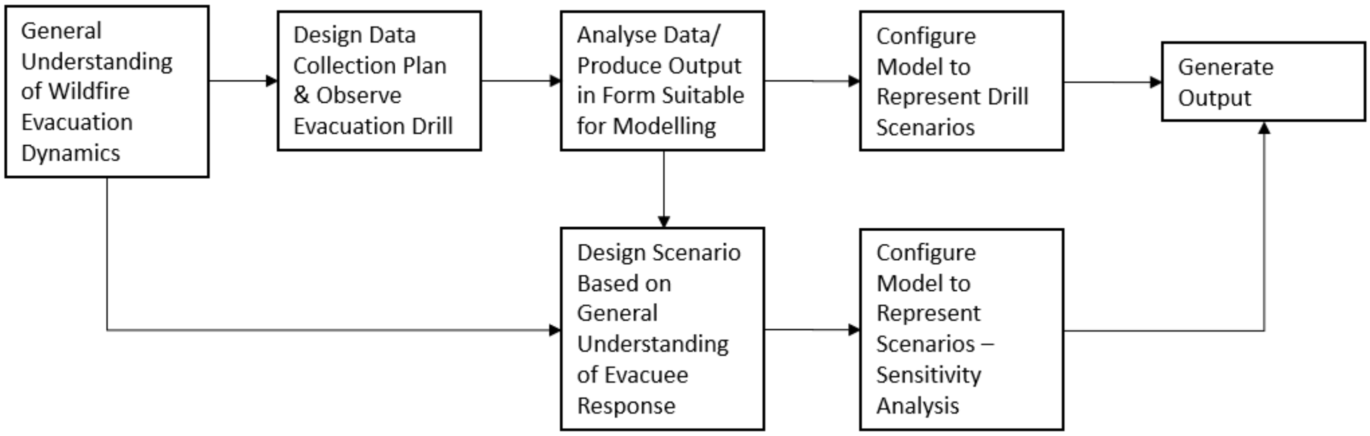

Figure 13: Modelling process employed.

general literature) and route use (based on proximity of residential communities). Other scenarios were also examined exploring the sensitivity of the modelled results to increasing the population, extending the initial delays, and losing an egress route. Numerous other factors could also have been examined (for example, type of population, new road configuration, wildfire development), however, to simplify the discussion only a limited number of variables are examined.

Normally, evacuation models might be applied to a broader array of scenarios and the insights generated would be examined in more detail. Here, the type of insights generated is of more interest than the specifics, along with the model's capacity to reflect the interaction between represented factors (over time) – as a proxy for the complexity of real-world wildfire evacuation.

The Drill

On the 27 July 2019, Roxborough Park community in Colorado (US) arranged a community evacuation drill to reinforce emergency preparedness of the community in case of wildfire. Such an event is not commonplace either in the US or internationally.[22] Roxborough Park is a WUI community that is surrounded by Roxborough State Park on three sides [16]. Roxborough includes approximately 900 homes and covers approximately 8.98 km^2. Roxborough Park has been exposed to two recent wildfire events: the 1996 Buffalo Creek Fire and the 2002 Hayman Fire. Roxborough Park has a wildfire protection plan that includes the use of evacuation strategies.

Currently the community has three primary egress routes (see **Figure 14**), with an extra route across a golf course (not used during the drill). These three routes were accessed via gates located close to the community housing. This is mentioned here as observations were made at these locations. It should be noted that the drill involved vehicle evacuation and no fire conditions were present. Therefore, a significant source of incident complexity (the fire itself) was not part of the drill – making the intricacies of the results produced here more compelling.

The residents had prior knowledge of the drill.[23] A total of 133 households registered to participate – impressive given that the event took place on a Saturday morning. It is speculated that another 5–10 households joined the drill during the event without registration. Before the drill, registered participants received information on the evacuation routes available. On the day of the drill, an alert was given at 9.00am to the participants via text, email and/or phone call. After receiving the alert and occasionally engaging in preparatory actions, participants accessed their vehicles and selected one of the evacuation routes available. It is expected that the preparatory delays incurred are optimistic given the prior notice afforded the participants.

Surveys were conducted to determine where people started, the routes they used, estimates of key activities (for example, the time they left their property or arrived at the assembly point). This was to support the modelling efforts. Along with the observations

22 It should be noted that any results presented here beyond the original drill do not reflect the current preparedness or vulnerability of Roxborough and are presented here purely to demonstrate the complexity of wildfire evacuation -and the use of a model as a proxy for the complexity.

23 This is another reason why the second stage of modelling was performed – to account for a different response given that it was known to be an exercise.

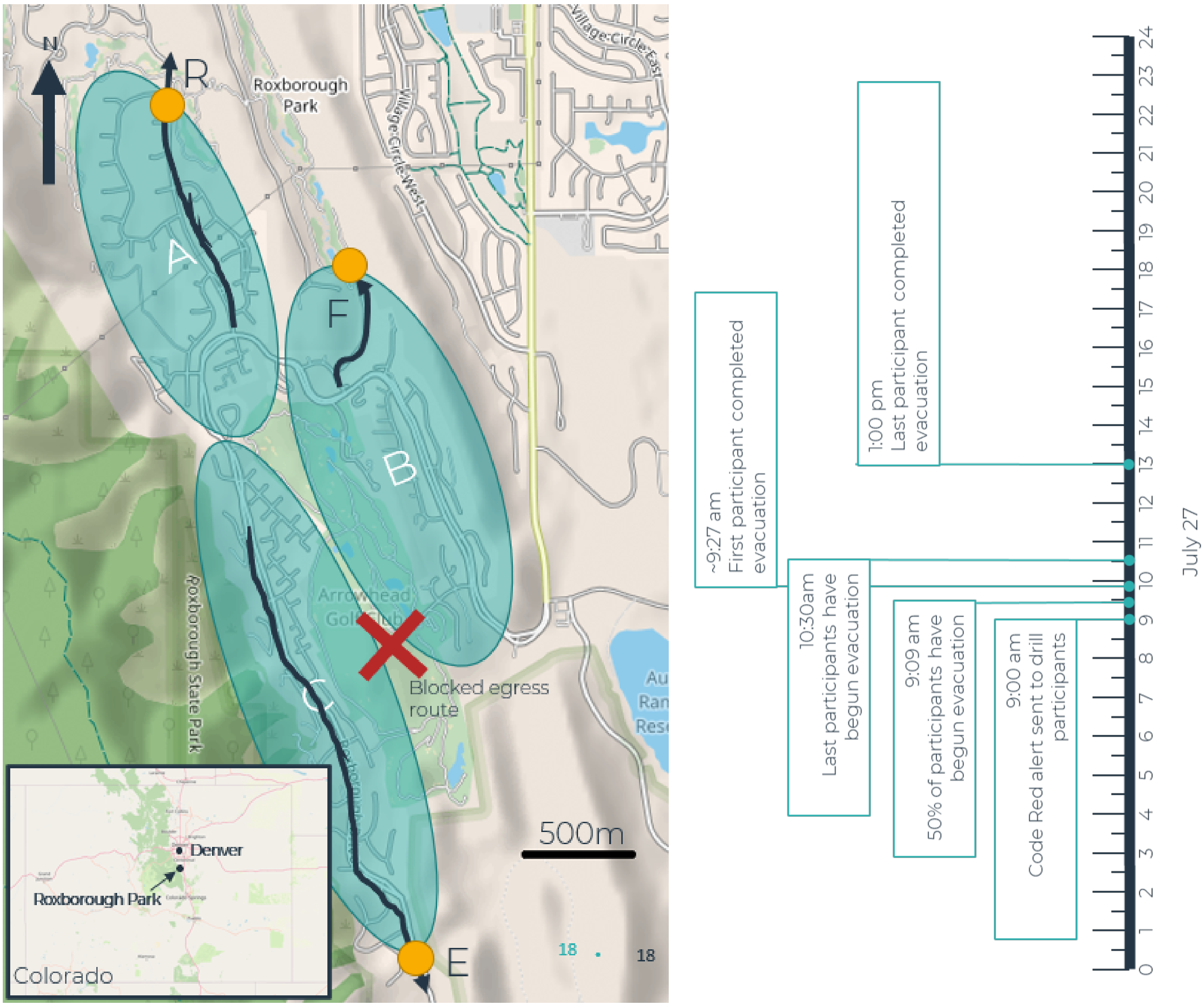

Figure 14: Area involved in the evacuation and incident timeline. Shaded areas (A-C) show residential locations. Arrows show active egress routes (labelled R, E and F), orange circles show approximate location of gates and inset shows location of Roxborough in relation to Denver. Map source: OpenStreetMap

made at the three gates and the assembly point, the data collected established several important performance elements: initial delays, route use, derived route loading, and arrival times. Observers compiled 107 data points for vehicles at the three gates and 53 arrival times were recorded at the assembly point. Once the evacuation drill was completed, the participants then met with the drill organisers at the assembly point to hand in their completed surveys and participate in a drill debrief. The observations made during the drill were used to configure the tool in the first set of scenarios and to provide a benchmark against which model performance could be compared (the overall evacuation time, see **Figure 15**).

From the surveys and the observed arrival times at the three gates,[24] initial delays were estimated at an average of 35 minutes, ranging between 6 and 105 minutes. The survey indicated that the population split unevenly between the three available routes (24% used Route F, 45% used Route R, and 31% used Route E). The use of the routes was sensitive to the starting location of the residents. Arrival times at the assembly point were generated from survey response estimates and observation. Both the survey and observation estimates of arrival times extended to over 135 minutes.

Initially, the drill scenario was represented within the evacuation model. The road network in and around the community was depicted in a Geographic Information System (GIS) environment (within the WUI-NITY model, see Appendix C)

24 Which given their proximity to the starting locations were used as conservative estimates of the time for people to leave their properties.

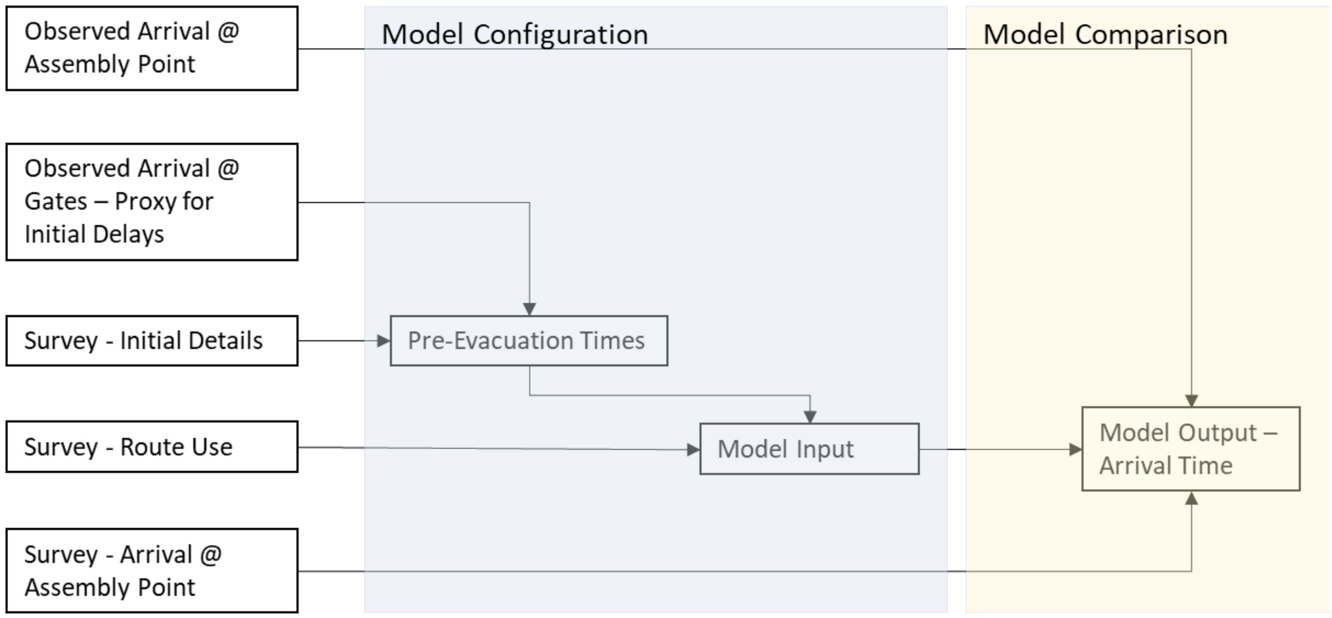

Figure 15: Roxborough drill data application.

and the population distributed to broadly reflect the local residential community. Delays were assigned to these residents reflecting the data collected from the drill along with the split between the routes available.

Results

Three questions were posed in this first phase of modelling:

- Can the conditions in the original drill be approximated?
- What would have happened during the drill if a route had been lost?
- What would have happened if the full community evacuated in a manner comparable to that seen during the drill (that is, assuming similar initial delays and route use)?

The model was configured using the survey and observations, specifically to approximate the distribution of initial responses and the routes to be used.

Figure 16(a) shows the comparison between the simulated and reported evacuation performance for the drill conditions. It charts the percentage of residents having arrived at the assembly point over time. It shows that the original observations/simulated curves are closely aligned and that the simulated evacuation time is within 10% of the original overall evacuation time. This allowed sufficient confidence to investigate other scenarios – at least to demonstrate the sensitivity of the results to changing scenario conditions. **Figure 16 (b)** shows the results produced when:

- Scenario 1.1: the drill conditions were simulated with an assumed population of 484 people
- Scenario 1.2: the drill conditions were simulated with the fire assumed to block a route with an assumed population of 484 people
- Scenario 1.3: the entire community evacuating with an assumed population of 3,030 people, with all routes available.

It is apparent that the three scenarios produced broadly similar overall evacuation times – approximately 7,000s or 116 minutes. This may not appear intuitive given the different initial scenario conditions. Superficially, someone assessing these overall evacuation times might assume that the scenario outcomes (or more precisely the conditions experienced by the evacuating population within these scenarios) are similar. This is not the case.

On closer inspection the road network had sufficient spare capacity to cope with the increased population size or the loss of a route (and associated road capacity), so that extra demand did not unduly extend the *overall* evacuation time. However, similarity in the overall performance masks key differences in the conditions that emerged during the simulation through the arrival patterns of the residents into the road network. These differences are suggested in the shape of the evacuation curves shown in Figure 16(b). This can be further examined by digging into the underlying conditions that generated these evacuation curves (see **Figure 17**). This represents the number of people still evacuating and the speeds achieved during the evacuation.

Figure 17(a) shows the number of residents evacuating over time –

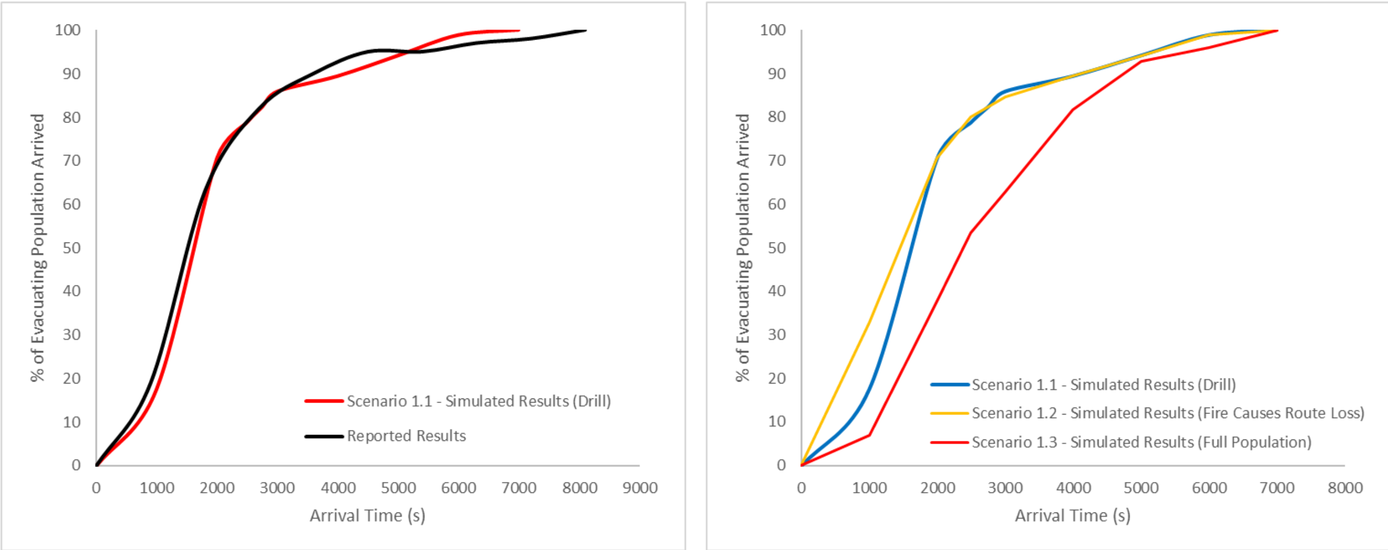

Figure 16: (a) Reported and simulated results reflecting the drill; (b) simulated results of Scenarios 1.1 (drill conditions), Scenario 1.2 (drill conditions with loss of route) and Scenario 1.3 (drills conditions with entire community evacuating). The population size has been normalised to allow direct comparison of the curves.

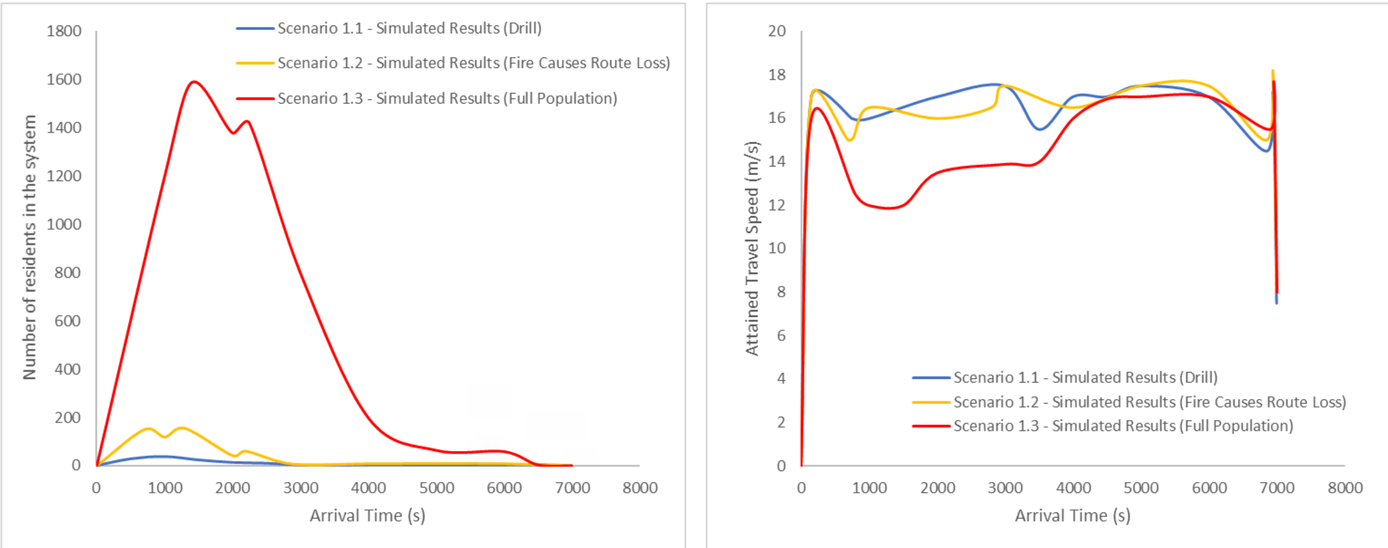

Figure 17: (a) Number of residents still in the evacuation over time for Scenarios 1.1(drill conditions), Scenario 1.2 (drill conditions with loss of route) and Scenario 1.3 (drills conditions with entire community evacuating); (b) vehicle travel speeds reported over time.

the number of evacuees still in the evacuation system having not yet reached a point of safety. This is an indication of the *vulnerability* of a community to the given scenario at any point in time. Effectively, the residents still in the traffic system have not yet arrived at a place of safety, and therefore would still be vulnerable to a wildfire in a real incident should the conditions change and affect one of the evacuation routes being used.[25] It is apparent that the loss of a route (in Scenario 1.2) initially delays the evacuation of some residents, with 60-80 more residents still evacuating between 500-1500s in comparison to the drill conditions where all routes were available (Scenario 1.1). If the remaining routes were compromised, then these would represent extra vulnerabilities to the worsening conditions. More dramatically, the full community evacuation (in Scenario 1.3) produced a sustained and considerable increase in the resident population still evacuating in comparison to the other

25 As noted in the case studies, it is not a given that someone reaching refuge is safe from the incident, but for the sake of comparison this simplification is assumed in this example.

scenarios with a peak difference of over 1,000 residents between 500–1500s. This is a result of the much greater initial demand placed on the road network caused by the larger number of vehicles on the road at the same time, that then abated as the evacuation unfolded.

The underlying reason for these developments can be seen in **Figure 17(b).** Here the average travel speeds achieved over time during Scenarios 1.1–1.3 are reported. It should be noted that the populations simulated in these scenarios had the same initial speed distributions – and so differences in the achieved speeds were due to the conditions faced. The loss of a route in Scenario 1.2 initially produced more fluctuations in the travel speeds (in comparison to the drill conditions in Scenario 1.1) with speeds dipping below those evident in the drill conditions between 1,250 and 3,000s. This suggests that congestion built up on the remaining routes during these times before demand subsided. The reduction in travel speeds during the evacuation of the full community in Scenario 1.3 was much more significant, with a drop from 16 m/s to 12–14 m/s for a period of 2,500s. This implies sustained congestion affected the passage of the evacuating residents for almost half of the evacuation.[26] This would have had implications on the exposure of individual evacuees if the scenario had involved an actual fire – even if the overall outcome (for example, evacuation time) was similar.

The experiences of a hypothetical resident might help demonstrate these consequences. In the drill conditions, the resident started to evacuate after a period of time (for example, 45 minutes). They moved to their vehicle and then headed into the traffic system. The roads were busy, but they were able to maintain a reasonable speed (for example, 16 m/s), before arriving at the assembly point in 60 minutes. If the same resident had behaved in the same way during the full population evacuation, they would have encountered many people on the road and would have only been able to maintain a travel speed of 13 m/s. They would have spent more time in the traffic system before gaining access to the assembly point at a comparable time. This might have had serious consequences had the wildfire conditions affected the route ahead of them, for example, blocked the route after 50 minutes while they were still moving slowly in traffic. These conditions and this vulnerability is formed from the interaction between the evacuating residents, the road network, and the wildfire conditions.

A second set of scenarios has been examined to explore the outcomes should the population respond according to our general understanding of previous incidents, rather than according to the responses observed in the drill. Here, the baseline scenario (Scenario 2.1) assumes that the full population (3,030 residents) responds over a narrower time window (with 95% of the population starting to evacuate in 60 minutes, and 5% choosing not to evacuate – to stay in place) and that no information on route use is available, with residents assumed to use their nearest route available. In the second scenario (Scenario 2.2) the population size is increased by 50% (over 4,500 residents) with other conditions equivalent to Scenario 2.1. In the third scenario (Scenario 2.3) the initial delay period is extended, such that 95% of the population starts to evacuate by 90 minutes (with 5% choosing not to evacuate – to stay in place) with all other conditions comparable to Scenario 2.1. The last scenario (Scenario 2.4) examines the impact of losing Route F with all other conditions equivalent to Scenario 2.1.

The 'baseline' scenario (Scenario 2.1) produces an evacuation time of **77 minutes** (4,600 s) (see **Figure 18**). This acts as a benchmark against which the other results in this set of scenarios can be compared. Figure 18 focuses on the number of *vehicles* still in the system (as opposed to residents) – to demonstrate another type of insight that might be provided. This type of insight may be of interest to traffic managers trying to better mitigate congestion, whereas the number of residents still in the system may be of more interest to community managers attempting to understand the vulnerability of community members.[27]

When the population size is increased in Scenario 2.2, the overall evacuation time increases to 80 minutes (4,800 s). A relatively modest overall increase given the substantial increase in population size.[28] Again, this indicates that road capacity has not yet been fully exhausted such that it constrains flow. Scenario 2.3 produces an overall evacuation time of just over *106 minutes* (6,400 s). The extended evacuation time is apparent in **Figure 18**. This insight might have implications, for instance, encouraging the

26 Of course, this is only a model – only indicative. However, it at least captures some of the complexity highlighted previously and warrants further examination. It is a clue to something potentially significant.

27 It is also more sensitive to demographic factors such as the number of residents assumed to be in each vehicle.

28 Perhaps more importantly, the impact of the population size is not linear. Its impact is in conjunction with other scenario attributes such as initial delays and road network capacity affecting the influence of the increased demand.

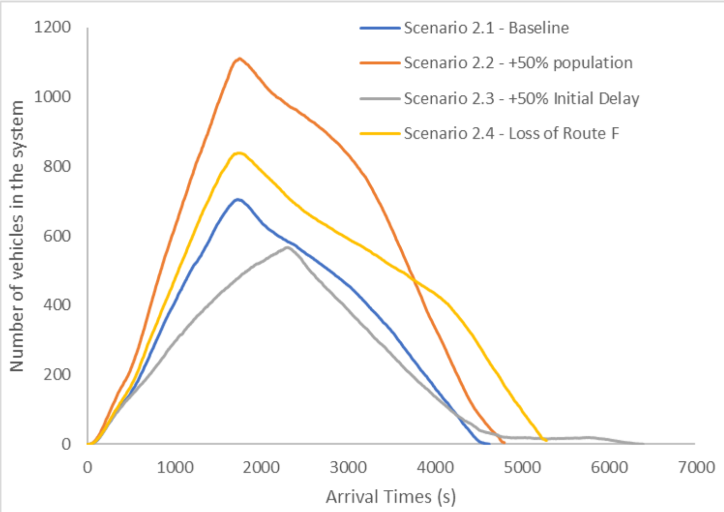

Figure 18: Number of vehicles still in the system during Scenarios 2.1 (Baseline), Scenario 2.2 (+50% Population Size), Scenario 2.3 (+50% Initial Delay), and Scenario 2.4 (Loss of Route F).

emergency management to focus on notification strategies given the impact of delayed response on the outcome. In Scenario 2.4, a route is assumed lost. This generates an evacuation time of just over *88 minutes* (approximately 5,300 s). Scenarios 2.2–2.4 might be considered for assessing the effectiveness of evacuation strategies (affecting response times), community planning (route options) or the sensitivity of the results to the impact of the fire itself (or its robustness should a route be out for construction, or be needed for firefighter access or other reasons) (see **Figure 19**).

As before, the model user can dig down further into the results to explore the conditions evident during the evacuation process, as indicated by the attainable travel speeds. The increased population size in Scenario 2.2 reduces the travel speeds in comparison to Scenario 2.1. This is because there are simply more people on the road in a similar period. The attained travel speeds increase in Scenario 2.3 when vehicles enter the system over a longer period – indicating fewer (or less protracted) interactions. The population can travel more quickly given their delayed and more distributed evacuation commencement. Finally, the loss of a route in Scenario 2.4 has an initially modest impact on the travel speeds attained, which gets much more significant as vehicles start to overload the remaining two routes available (for example, after 4,000s).

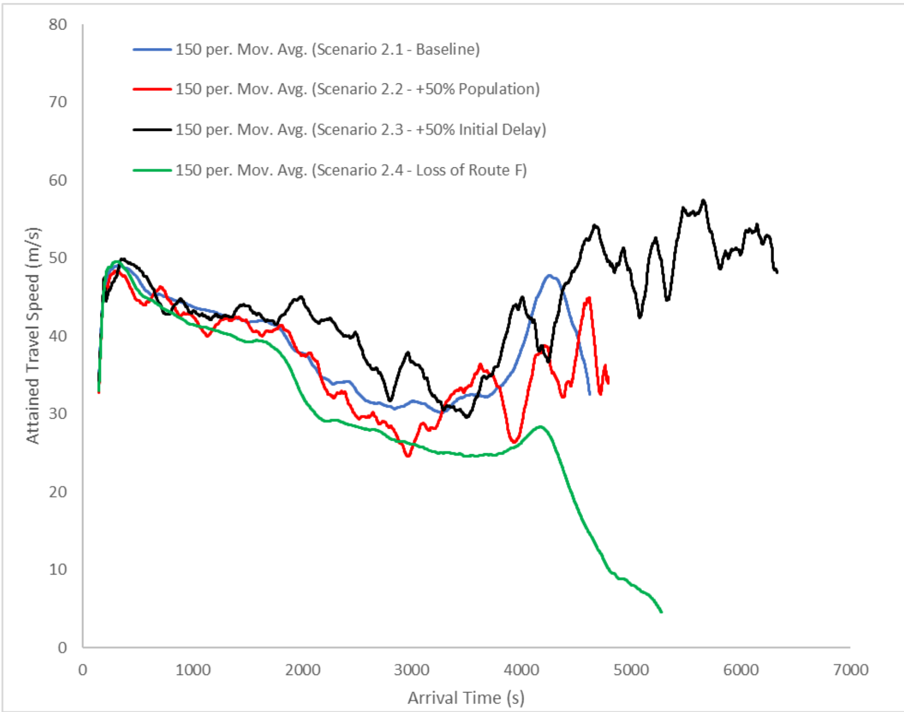

Figure 19: Attained travel speeds during Scenarios 2.1–2.4. The curves represent moving averages to simplify the trends. Scenarios 2.1 (Baseline), Scenario 2.2 (+50% Population Size), Scenario 2.3 (+50% Initial Delay), and Scenario 2.4 (Loss of Route F).

The reader should also be aware of the limitations of the approach presented here. Both the chosen modelling approach and the empirical data are far from perfect. There is an inherent uncertainty in both: for instance, in both cases the variability of the data collected and produced is unknown. However, as mentioned, in this context the results of these scenarios are of less significance than:

- the demonstration of interacting factors present during (admittedly simulated) wildfire evacuations
- the capacity of even a relatively simple model to capture the impact of different factors on the overall outcome
- the insights provided, enabling the user to explore the relationship between the underlying dynamics, the arrival levels during the evacuation and the overall evacuation times.

These findings further indicate the complexity that might be present during the evacuation of the relatively simple network shown here and that modelling approaches might be used to provide valuable insights that might otherwise be difficult to gain by using other means.

Implications

This brief modelling exercise has demonstrated several things:

- The model representation of the original drill conditions provided some confidence in its capacity to capture basic elements of evacuation performance and explore the complexity of the system. Of course, this representation is partial and limited in nature.
- The model was able to represent several scenarios by varying key factors, for example, population size, route availability, initial delays, amongst others. These are factors that (for various reasons) are expected to be influential in an actual response. The model was able to at least capture a subset of the underlying dynamics by implicitly/simply capturing some of the factors expected to influence performance. These scenarios reflected conditions beyond those in the original drill.
- Results were produced reflecting conditions that evolved during the scenario (reflecting the experiences of the evacuees or the emergent conditions produced on the road network), and at the end of the evacuation – at target locations (for example, the arrival at locations of safety).
- The impact of changes to the initial conditions did not automatically or linearly translate to changes in the emergent conditions or to the final outcomes. The outcomes were sensitive to the extent, nature, and interaction of underlying factors over time of the evacuee demand placed on the network (influenced by the population size and the time that evacuation commenced) and the capacity of the network at various locations.
- The examination of these types of scenario would allow the model practitioner to identify critical routes, route capacities, threshold population levels, and allowable initial delays – in essence, the core elements of an emergency evacuation plan and considerations in community design.
- Even with this extremely simple road network and community design, without the modelling of the evacuation conditions it would have been challenging to analytically derive these findings. The complexity was apparent even through the application of a deliberately simplified model of the real-world conditions. This complexity would have been much more evident if more of the underlying factors had been represented or the underlying scenario was larger in scale.

The focus here has not been on the model or modelling itself. Instead, this model has been used as a crude proxy for the wildfire evacuation system – to explore its sensitivity to changes in the initial conditions, the evacuee response, and the relationship between the underlying dynamics and the aggregate outcomes produced. It is contended that this has been achieved.

Future Steps

This work has examined the assertion that *wildfire evacuation is a complex system*. This was demonstrated by reviewing the factors involved in the system and their impact on the conditions that emerge, and then mapping these insights on to *The York Framework*. This complexity is unsurprising given the range of factors that affect the outcome of wildfire evacuations, the range of stakeholders active in these events, and the interactions between them over the timeline of an event. The capacity of the responding population to take on information and act on it, given a changing landscape, makes this system able to develop iteratively and informally.

Wildfire evacuations are becoming more difficult to analyse directly given the extent and speed with which wildfire scenarios (and associated conditions) are evolving. As such they are reducing the options open to researchers and practitioners to establish community vulnerability (the capacity for the community to cope with the wildfire conditions faced). For instance, directly deriving lessons from historical incidents is becoming more challenging as underlying historical and future scenario conditions diverge. Establishing this vulnerability is essential for planning and allocating resources – whether calculated before or during the incident. The outcome of such an incident is sensitive to the highly coupled nature of the factors present: fire, weather, topography, population demographics, physical infrastructure, and emergency procedures and organisational resources. Addressing any one of these factors alone may be of benefit but might produce situations still vulnerable to issues posed by inadequacies in one of the other elements. Analysing any one of these factors alone will give partial insights and be liable to miss key dynamics.

The simple modelling approach described here demonstrated (a) that wildfire scenarios are amenable to modelling given sufficient information and (b) that changes to the scenarios can be charted as affecting the evacuation dynamics and outcomes. This is encouraging for future modelling efforts but, more importantly for this work, also demonstrates the impact that interventions might have over the scenario conditions faced – *interventions may have variable impact, but that the nature* *of this impact might be captured.* The modelling 'levers' demonstrated here are only a subset of those available. However, even these might be configured to represent the impact of changes on the outcome of an incident, for example, various design, regulatory, guidance, or management efforts. For instance, informing the target population, managing the use of routes, providing new refuges, etc. As such, *numerous interventions and plans can be tested* ***before*** *they go into practice. The recognition that wildfire evacuation systems are enormously challenging and complex, does not imply that they are beyond interrogation/simulation and beyond successful and evidence-based intervention. Indeed, the case might be made that because wildfire evacuations are so complex that they require interrogation and innovative analysis all the more*.

Regulatory structures are appearing that are designed to cope with the new pressures on community design from wildfire incidents [42]. The variability and evolution of wildfire evacuation scenarios may make them less amenable to a formal prescriptive regulatory approach that requires a prior estimate of the wildfire events that might be faced – the attributes that constitute them and the potential community responses to them. This is particularly difficult given how wildfires might evolve during a single incident – in size, shape, severity, and location – and how that might affect a range of different communities over prolonged timelines.

A more flexible and representative approach might require community vulnerability to be determined and addressed from the bottom up – generating situations to be addressed by recombining scenario constituent parts such as underlying community attributes, expected fire conditions, intervention measures, infrastructure – and then examining the performance for each scenario. Rather than determining the scenarios of concern before analysis and then prescribing required practice based on those assumptions. The former approach might be better suited to exploring the many scenarios that might develop that vary geographically and temporally. Going forward, this requires a modelling capability to quantify performance. We have only touched on the required modelling capability here. However, research and practice are moving quickly to fill gaps in these capabilities.

Although these multijurisdictional events will require a coordinated regulatory system, with interventions deployed at various levels of granularity – ranging from behavioural nudges [43], to local communication, outreach/education, guidance, best practice measures, and to more traditional regulatory structures [17]. In addition to different levels, these interventions may occur at different times along the incident timeline. These approaches will be targeted to actors at different levels of their respective organisational/social hierarchies (and of course residents), who have different reaches within the evacuation system. The wildfire event itself will have implications for these actors – who will have different responsibilities, access to different information and access to varied resources. It would be challenging to guide the various interventions described (for example, in the form of regional or national guidance) without first assessing directly the potential scenarios that might be faced and (ideally) quantifying outcomes.[29]

Historically, prescriptive approaches evolved over decades, derived from the lessons learned from previous research, best practice, and real-world incidents – so-called 'tombstone technologies', in other words, things went wrong, problems were identified, pros/cons debated, potential interventions examined, preferences established, and then generalised to equivalent designs. This approach might well be reasonable where situations are simple or stable, or where the technological measures, social factors, environmental conditions, and the nature of the threat evolve at a known pace.[30] Unfortunately, technology (for example, the intervention of social media), environment (for example, climate change and its impact on the dry season), and social factors (for example, demographic changes and societal preference for living in the interface regions) are changing quickly and in an interdependent manner. The basis for performance-based approaches is that there are too many interacting factors and too many novel outcomes for a predetermined set of rules to be established such that they have representative scope and ensure an acceptable level of safety. Instead, performance-based approaches define goals that should be met to attain an acceptable level of safety. Exploration and numerical assessment are then required to provide evidence of the safety levels in place.

As mentioned, regulatory approaches are appearing and will fall between two extremes. An entirely top-down 'statist' prescriptive approach to regulation does not require performance to be tested before community designs and emergency plans are implemented. This approach misses an opportunity for comparison and also obscures the many opportunities available to engage stakeholders – at their various levels of agency and influence – often required during the modelling process.

An entirely bottom-up 'libertarian' version of a performance-based approach to regulation is more

29 Even within a prescriptive framework there might be benefits in modelling scenarios of interest to reassure guidance developers of the impact of any suggested changes.

30 Or at least slower than the cycle of the prescriptive regulations in place.

likely to capture the complex dynamics at play and would require assessment of the outcomes produced. Without constraints, this might not ensure consistent practice (in terms of the scenarios examined, the methods used, and the tools employed), or ensure a coordinated response that effectively choreographs resources and knits together the planned interventions. Simply identifying the factors to be examined by practitioners without some overarching guidance gleaned from historical situations might produce variable practice and inconsistent approaches. Although having the capacity to capture the system complexity, the potential variability in this approach does not ensure the scope or refinement of the insights provided.

Inevitably, an overarching structure is required that recognises the complexity of these challenging situations, but which assumes that performance will be assessed within this framework – requiring the underlying factors (and their interactions) are identified and examined. Practitioners might be constrained within such a framework but be required to quantify the performance of different designs and procedures, taking into the account various aspects of the wildfire event. Tools would be needed to reflect the scenarios attributes (for example, fire, population, topography), that combine to generate the conditions during the evacuation. The framework would provide a baseline, while the practitioner would try to capture key scenario conditions by operating within this regulatory structure.

Future practice will have access to more evidence (including enhanced sensor technologies, mobile technologies, UAVs,[31] with more weight given to capturing information on evacuee decision-making and response) – on the conditions present, the population, and the evolving evacuation conditions. Our capacity to process and interpret this is already evolving through traditional means and through AI approaches (for example, machine learning) that can also inform community planning (for example, through generative design).[32] As such, we may soon have access to richer data on which to develop and build models that are sufficient to capture more of the complexities of wildfire evacuations. As discussed, the more representative these are, the more confidence we will have in their projections made and the better informed our designs, plans, and interventions will be in facing up to wildfire evacuations. *These estimates might eventually be integrated into a regulatory system that is flexible enough to account for the scenarios faced and exploit the modelling capabilities available – to recognise the underlying complexity of the system and represent (and exploit) the resilience that such systems afford.*

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Affiliations

Prof Steve Gwynne, Research Lead, Movement Strategies (a GHD company); Industrial Professor of Evacuation and Pedestrian Dynamics, Department of Fire Safety Engineering, Lund University, Sweden.

Dr Georgia Bateman, Senior Consultant, Movement Strategies (a GHD company).

Dr Erica Kuligowski, Vice-Chancellor's Senior Research Fellow, School of Engineering, Royal Melbourne Institute of Technology, Australia.

Dr Max Kinateder, Assistant Research Officer, Fire Safety Unit, National Research Council, Canada.

Afroza Mallick, Research Student, Department of Fire Safety Engineering, Lund University, Sweden.

Hannah Nevill, Research Student, Department of Mechanical Engineering, Imperial College London, UK.

Dr Enrico Ronchi, Associate Professor, Department of Fire Safety Engineering and Department of Transport and Roads, Lund University, Sweden.

Prof Guillermo Rein, Professor of Fire Science, Department of Mechanical Engineering, Imperial College London, UK.

Amanda Kimball, Executive Director, Fire Protection Research Foundation, National Fire Protection Association, US.

Appendix A: Example Incidents

Location	Date	Area Involved	Injuries	Fatalities	Number Evacuated	Description
Kabylia, Algeria	9–15/8/21	29,884 ha	Unknown	90	Unknown	Suspected arson, very arid area
Table Mountain, South Africa	18/4/21	400 ha	5	0	~50,000	Suspected arson, heavy smoke initially prevented aerial firefighting deployment
Arakapas, Cyprus	3-5/7/21	5,000 ha	Unknown	4	10 villages	Heatwave fanned by strong winds, possible arson
Dzüko Valley	29/12/2011/1/21	81 ha	0	0	Unknown	Uninhabited area, strong winds, steep terrain
Simlipal, India	3–4/21	Unknown	0	0	Unknown	Dense forest hindered firefighting efforts
Siberia, Russia	6/21	572,000 ha	0	0	2 villages	Toxic smoke affected air quality
Turkey	28/7–12/8/21	170,000 ha	800+	9	10,000+	Most injuries because of smoke inhalation
Locations across Greece	3/8/21–present	125,000 ha	20+	2	1,000+	Suspected arson
Locations across Italy	7–8/21	15–20,000 ha	Unknown	5	150+	Suspected arson, strong winds
Patagonia, Argentina	7–11/3/21	2,000 ha	Unknown	7+	200+	Possibly caused by electrical fault, strong winds
Jerusalem, Israel	15–19/8/21	2,000 ha	0	0	~2,000	Strong winds
Saint-Tropez, France	16–23/8/21	6,000 ha	20+	2	2,700+	Strong winds, poor visibility

Table 2: 2021 Wildfire events reported in mainstream media that did not occur in North America or Australia.

Appendix B: Wildfire case studies

The dynamics of a wildfire evacuation vary – depending on the scenario. Two case studies have been selected to demonstrate several aspects of wildfire evacuation and related community safety (with the attributes of complexity identified previously):

- the evolving incident conditions (weather, fire development, remote fire locations, fire weather)
- the response of the affected population (for example, pedestrian movement, traffic movement), reflecting the diversity and vulnerability of the affected population and effectiveness of their decision-making (affected by information available).
- attempts at managing the outcome and the conditions faced (notifying people, fighting the fire, managing traffic, deciding to evacuate the community), given the organisations, and groups present, emergency procedures employed at the local and regional levels, deployment of emergency resources.
- outcomes / consequences (including loss of life, loss of property, loss of routes, traffic conditions, local/national impact).

The text is colour-coded to highlight where these factors are mentioned in the cited material. This is simply to demonstrate that the factors were at play, rather than assigning weight to the significance of their impact on the outcome.[33] However, a fairly superficial review of these cases or similar will establish the importance of these factors on the outcomes produced [44]. Several of these factors are examined in the modelling outlined in the body of the report – connecting the simple modelling approach adopted and the reality of the conditions faced in wildfire emergencies.

Fort McMurray, Alberta, 2016 [44,45]

At 4.00pm on 1 May 2016 a 0.02 km^2 wildfire was spotted in the Wood Buffalo area deep in a forest – 15–20 km southwest of Fort McMurray (Alberta, Canada). Wood Buffalo has a population of more than 125,000 people including rural and urban communities. Of these, approximately 35% are temporary residents and 10% are First Nation communities, so have different levels of familiarity with the local area and different relationships with local authorities (see **Figure 20**).

Strong winds (> 70 km/hr) and high temperatures (daily temperatures > 30°C and humidity < 12%) promoted the development of the fire. The immediate emergency response included water bombers being deployed, followed by warnings issued to nearby campgrounds of the possibility of an upcoming evacuation. Within six hours of the fire initially being spotted an evacuation centre was opened on MacDonald Island and a local state of emergency declared. However, the next day warning levels were reduced given that wind conditions improved and appeared to be blowing the fire away from the city.

On 3 May conditions changed again and the fire entered Fort McMurray leading to tens of thousands of people evacuating in short order to refuge centres in various locations. Some of these evacuation centres were affected by changing fire conditions requiring them to eventually be evacuated themselves. During this (re)evacuation, two people were killed in a car accident (so, not directly by the fire itself). By the end of the day, over 60,000 residents had evacuated, including all 105 patients at the Northern Lights Regional Health Centre. Highways were quickly overloaded with traffic. To cope with this, convoys were formed.

By 4.00pm on 4 May structures had been destroyed with 100 km^2 of wildland involved. A provincial state of emergency was declared with 80,000 people instructed to leave. By the 5 May, there were 49 separate fires burning and 4,000 people had to be airlifted from work camps north of Fort McMurray. Firestorm conditions were reported and spot fires ignited new fires over 1 km from the original source. On 6 May, 8,000 workers were evacuated from 19 oil sites as the fire spread north.

Most people who fled the region did not have short-term contingency plans in place other than getting away from the immediate danger. Local industry and residents, communities, post-secondary institutions, and parks offered to host evacuees. Reception centres were quickly put up across Alberta in numerous locations.

On May 6, the Alberta premier announced emergency evacuation funds. The deployment and use of firefighting resources peaked on 3 June with approximately 2,197 firefighters actively engaged. The government informed Albertans of the evolving situation with news conferences, information bulletins, social media, websites, call centres, emails, telephone town halls, etc. Across the incident, more than 88,000 people were evacuated. This primarily involved private vehicles, although public buses, and aircraft were also involved. Smoke generated by the fire affected the evacuee capacity to drive along the routes still available. The incident lasted during May, June and July of 2016 affecting nearly 6,000 km^2 of land. Over 2,400 structures were destroyed in

33 The colour scheme was selected to enhance visual accessibility: https://color.adobe.com/create/color-accessibility

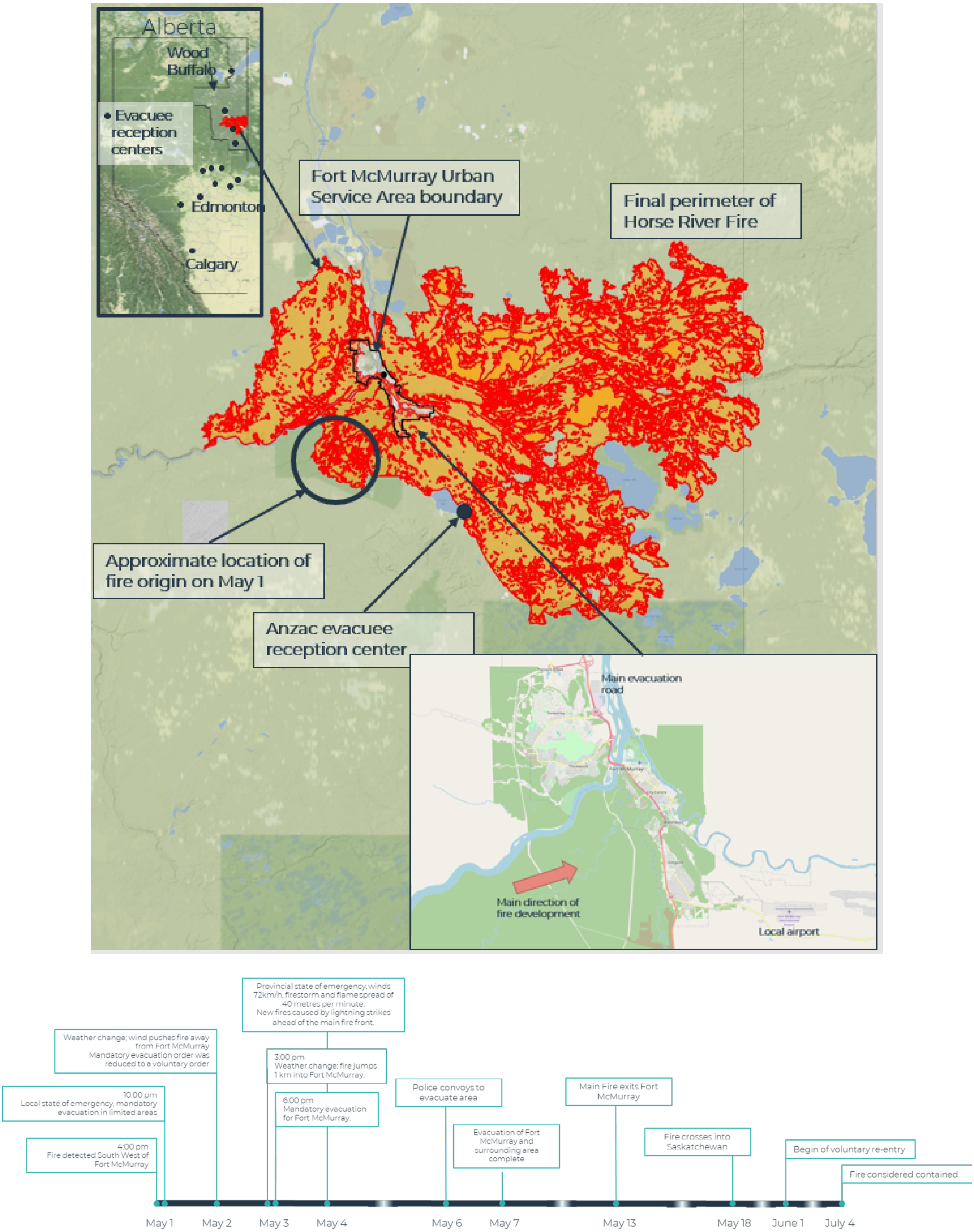

Figure 20: Area affected by the Fort McMurray incident and the timeline of events [7,46,47].
Map source: OpenStreetMap

the fire and gas/electricity/water supplies disrupted, and the local airport closed.

Management and evacuee decision-making were conducted continuously throughout the response. These occurred at various organisational levels (given the nature of the scale and severity of this event). There are numerous examples where these decisions (and their outcomes) might have benefited from more timely, more accurate, and more complete information. For instance:

- downgrading of evacuation status
- use of evacuation routes
- allocation of evacuees to refuge camps
- traffic management
- refinery evacuation
- community evacuation
- re-entry management.

Camp Fire, California, US, 2018 [48–64]

The Camp Fire (8–25/11/18) was a fast-moving wildfire that severely impacted Butte County and the town of Paradise in California (US). It started in the early morning of Thursday, 8 November 2018 near Pulga in Butte County, California, US. An evacuation order was issued 50 mins after the fire was first noted (at 7.20am). The fire took 85 minutes to affect Paradise (8.45am). At 9.42am, evacuation routes from Paradise were reported as blocked. *Severe congestion along main roads and other streets hampered the movement of traffic*. In addition, several evacuation routes were overcome by fire – reducing the road capacity away from the fire. Some evacuees escaped on foot, while others were trapped in their vehicles. The affected community included the elderly, those with movement impairments and low-income communities – all of whom struggled during the evacuation process from Paradise and surrounding towns. Vehicles ran out of petrol and abandoned cars blocked the travel lanes. Fallen trees also blocked routes. Contraflow and shoulder usage were established but severe bottlenecks persisted. Local shelters in Butte County filled up quickly. Tent shelters were established. However, poor weather and insanitary conditions led to an outbreak of norovirus. Hotels were fully booked and increasingly poor weather (including substantial rain and sometimes subfreezing temperature) made shelter challenging.

The area had preparations in place (for example, communication strategies, and evacuation preparations), given a history of wildfire activities in the local area. Paradise officials had previously planned/practiced evacuation, with a phased evacuation plan in place. Paradise experienced significant setbacks as the speed and magnitude of the Camp Fire overwhelmed response capabilities. However, the incident conditions blocked two of the four routes out of town. Many residents were stuck given the blocked and overloaded routes, taking refuge in the temporary refuges provided. The evacuation primarily involved residents using private vehicles, with some instances of pedestrian evacuation along fire-impacted routes, and the use of buses for nursing homes and schools. The incident produced extremely poor visibility levels that greatly affected the evacuation and led to car accidents. It also produced health problems in the impacted area and affected air quality as far away as San Francisco (~240 km away).

Fire fighters set up multiple temporary refuges areas to protect the evacuating public. It burned over 600 km^2 fuelled by dry vegetation, high winds (Santa Ana winds of 65–80 km/hr), and low humidity (down to 11% humidity). The terrain in the affected area included hills, forests foothills, and canyons – requiring by narrow and winding road routes. The fire affected the communities of Concow, Magalia, and Paradise in Northern California. It followed a period when the area had experienced 200 days without significant rainfall [48,50]. The potential for wildfire was identified and communicated throughout the area [48,50]. The fire was caused by an electricity transmission line igniting vegetation near the town of Pulga. It spread rapidly, and soon after the start of the fire, the town of Paradise (with population of 26,000) was evacuated. The incident involved a multiagency/multijurisdictional response including Cal Fire, Butte County Sheriff Department, Paradise Police Department, US Forest Service, California Department of Transportation, California Department of Corrections and Rehabilitation, California Highway Patrol, California Office of Emergency Services, National Weather Service, California Conservation Corps, Butte County, and the City of Chico. Over 1,000 personnel were involved in the emergency response, employing over 70 fire engines (see **Figure 21**).

Only about 30% of Paradise residents were registered for emergency alerts. Damaged phone lines and power outages reduced communication, and lack of resources (personnel and infrastructure) hampered the dispatch centre. Delays of up to 30 minutes for evacuation orders were observed. Some residential neighbourhoods could not be reached given the rapid spread of the fire. The elderly and disabled populations in the area required help, especially those without vehicles. While plans recognised this need, insufficient extra resources were provided. *Officials did not use the Integrated Public Alert and Warning System (IPAWS) to reach residents. There were concerns that the message would be shared too widely further overloading the road network* [48,50].

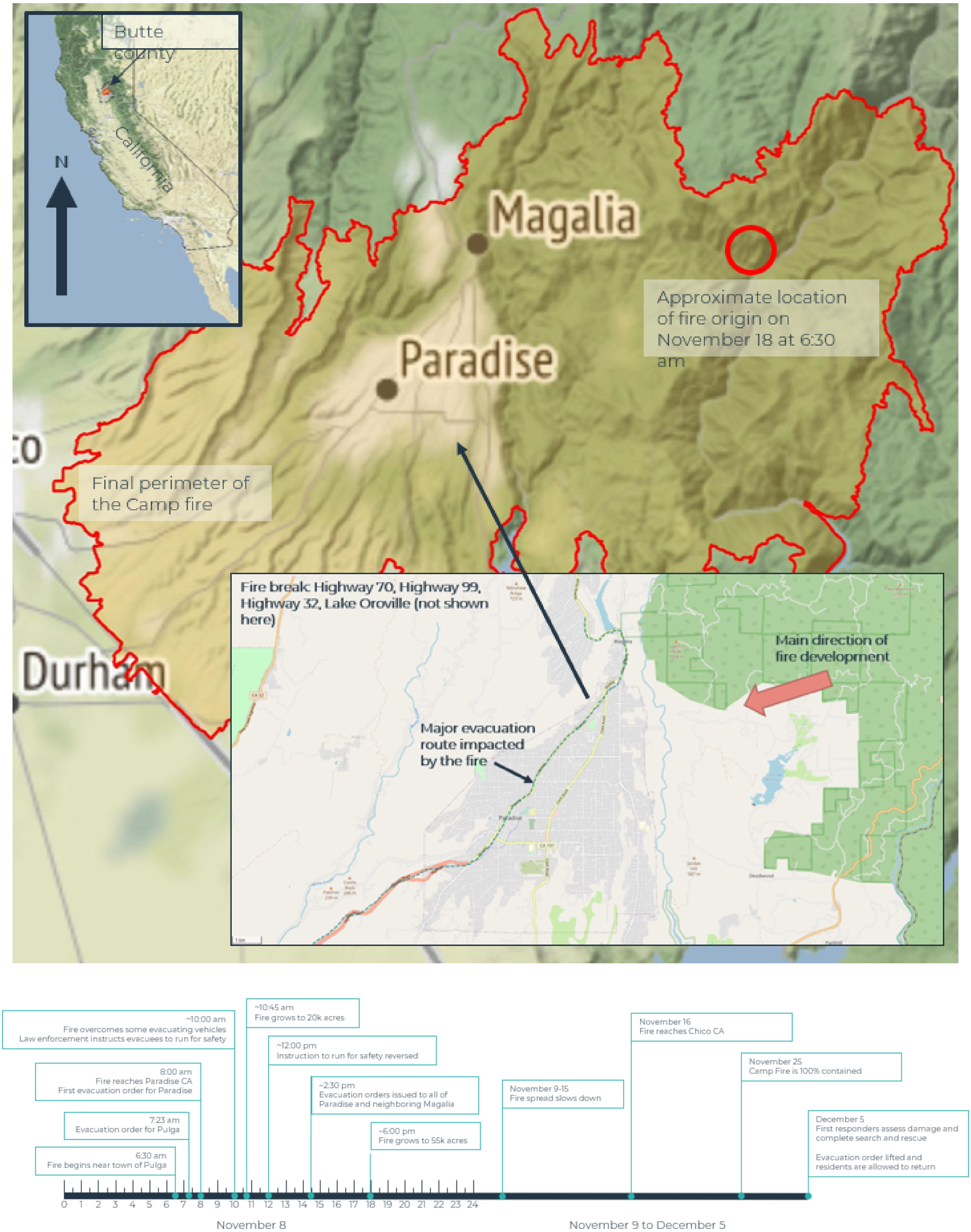

Figure 21: Area affected by the Camp Fire incident and the timeline of events [7,65]. Map source: OpenStreetMap

Approximately 52,000 people were ordered to evacuate from the Camp Fire. 85 people died, making it at the time the deadliest wildfire in Californian history. The fire caused approximately US$16.5 billion in damages with 13,972 residences, 528 businesses, 4,293 minor structures destroyed. Impacts of the wildfire were far-reaching as the entire town of Paradise was devastated by the wildfire. Smoke from the fire travelled as far as San Francisco, approximately 240 km away. In the longer term, the fire led to a housing crisis, public health challenges, and major environmental damage the wider Butte County area. The recovery process is anticipated to last multiple years.

Appendix C: WUI-NITY model

WUI-NITY is based on the coupling of three different modelling layers to produce an assessment of the evacuation response in context with the emergency conditions. The wildfire spread layer is simulated based on the FARSITE (Fire Area Simulator) model, which models fire behaviours for surface, crown, spotting, and fuel moisture [16,66]. For the pedestrian layer, a simple pedestrian response and movement model has been developed. This primarily represents the delays exhibited by subpopulations before responding (for example, moving to their vehicles). As such the primary role of the pedestrian response is the decision to evacuate, the route to be used and the time that this process takes as an input into the traffic system. WUI-NITY includes a default population distribution based on the Gridded Population of the World v42 to model this layer [22]. The third layer in the platform is based on the Lighthill–Whitnam–Richards traffic evacuation model (LWR model), which requires less computational time and is easy to implement [16,67]. In addition, ‘trigger buffer’ perimeters are created using a submodel named PERIL (Population Evacuation trigger algorithm) [68]. This perimeter can be any geographical feature surrounding an area of interest. When a fire intersects this perimeter, it is assumed to trigger the need for an evacuation for the population residing in that area [69]. However, this feature is not tested in this work. In this study, the wildfire spread layer is not taken into consideration explicitly. Only the pedestrian and traffic models are considered for the simulation.

The population count for a certain area for the simulation is redistributed based on the road network provided by Open Street Map (OSM). The model then generates households over the area following the redistributed population. The default setting of WUI-NITY allocates one to five members and one car to evacuate for each household. However, access to maximum two cars based on the size of the household is permitted. Default walking speed when moving towards the car ranges between 0.7 and 1 m/s [70]. The platform calculates the maximum capacity of the roads based on the information from OSM. The present version of WUI-NITY does not model evacuation on foot and only considers private vehicles as a means of escape [22].

This enables the user to assess evolving conditions and assess community vulnerability.

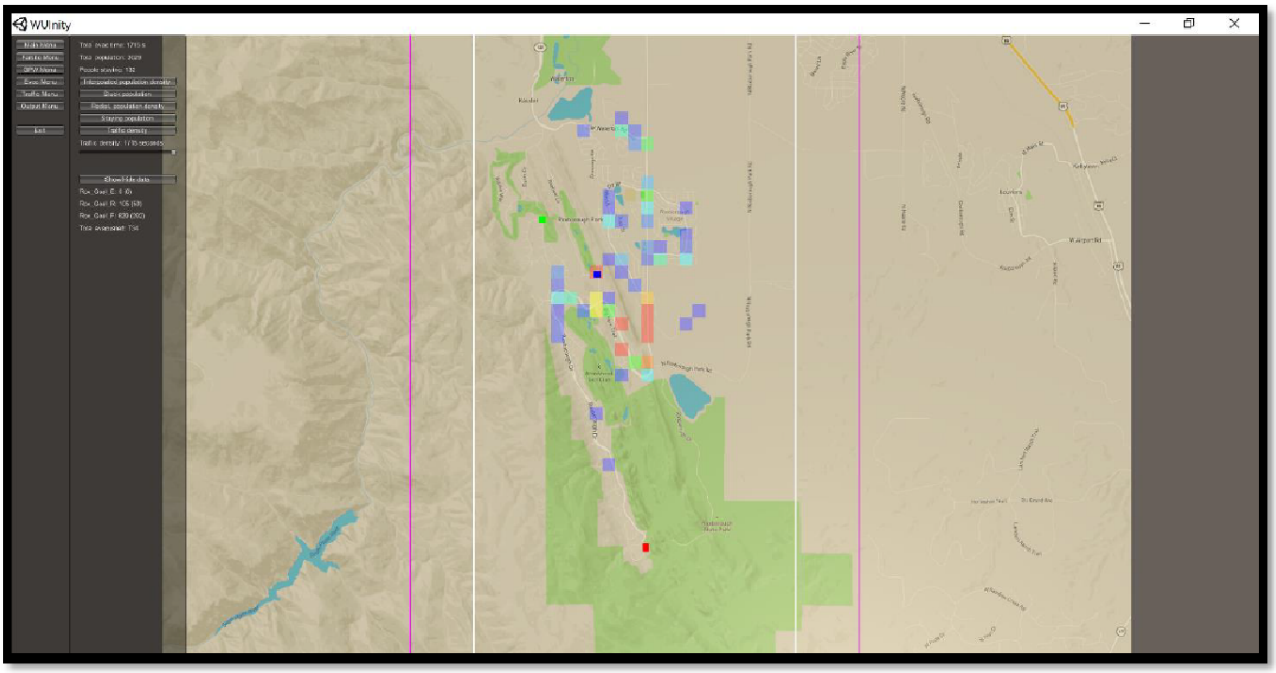

Figure 22: Example output from the WUI-NITY model when applied to Roxborough evacuation. Coloured pixels indicate vehicle density along egress routes. [16]