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MODELLING FIRE FOLLOWING EARTHQUAKE FOR WELLINGTON CITY, NEW ZEALAND

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Abstract

Fires are a common secondary hazard following earthquakes and, on rare occasions, can develop into major events with severe consequences. Wellington City has many characteristics that make it susceptible to fire following earthquake (FFE), including the potential for conflagrations and significant losses (e.g. property, infrastructure and casualties). Wellington is in a zone of high seismic hazard, with the highest contributing earthquake source being the Wellington Fault, producing a typical earthquake magnitude of M_W 7.5 and having an approximate 10% chance of rupturing within 100 years[1].

Previous FFE modelling for Wellington City used a simple ignition model to estimate number of ignitions and a fire spread model that could account for wind speed but not wind direction[2]. Following an extensive literature review of globally available ignition and fire spread models for FFE, we selected the ignition model developed by Elhami Khorasani et al.[3] from US event data as the most appropriate for application to Wellington City. We have developed a fire spread model that accounts for wind speed and direction, by buffering individual buildings using GIS to reflect how far fire can spread given the ignition locations, building combustibility and weather conditions.

Stochastic modelling utilizing both the spread and ignition models and varying input parameters can produce loss and impact results across many potential scenarios. One hundred simulation runs of a Wellington Fault M_W 7.5 earthquake scenario were performed for this study, which provide an indication of the distribution of loss and impacts for FFE in Wellington City. The average number of ignitions per scenario was 34. The modelling can account for uncertainties and variations within the input parameters including seismic source, ground motion, wind speed and wind direction.

The stochastic modelling results show a lognormal distribution of losses. The median scenario loss is $1.49 billion New Zealand Dollars (ranging between $0.55 billion and $17.65 billion at 95% confidence); however, nearly 20% of scenarios had estimated losses exceeding $4 billion. A median loss for a single burn zone (the extent of fire spread following an ignition) of $24 million (ranging between $0.5 million and $670 million at 95% confidence) indicates the potential benefit of suppressing a single ignition.

Examination of the relationship between wind speed and loss shows a strong correlation. For wind speeds over 25 km/h, an increase of 10 km/h in wind speed is associated with ~$4 billion of increased loss. This indicates that by considering the weather conditions following an earthquake event, a rapid assessment of the threat from FFE could be undertaken.

The FFE modelling is informed by frequent feedback from key stakeholders in Wellington City including emergency management, the fire service and infrastructure managers. The modelling forms the scientific evidence base for current risk reduction initiatives, including community messaging and proposals for asset investment.

Keywords: risk; ignition; spread; modelling; probabilistic

1. Introduction

Fires are a common secondary hazard following earthquakes and can result in extensive damage if they spread over a large area (known as a conflagration). New Zealand's capital city, Wellington, has many characteristics that make it susceptible to FFE, including the potential for conflagrations and significant losses (e.g. property, infrastructure and casualties). Wellington is in a zone of high seismic hazard, with the highest contributing earthquake source being the Wellington Fault, producing a typical earthquake magnitude of M_W 7.5 and having an approximate 10% chance of rupturing within 100 years[1]. For a Wellington Fault rupture scenario, earthquake damage may cause widespread ignitions, particularly from physical damage to reticulated gas pipes and electrical networks. Secondary perils, including liquefaction and landslides, may also cause damage. Factors that exacerbate the risk of fire spread following an earthquake in Wellington include: a high proportion of wooden structures, closely spaced buildings, steep slopes, high wind zones, and vegetation as a potential fuel source. Widespread damage to water supply and transport networks are likely to make firefighting difficult, and fire service resources are likely to be very stretched[4].

Although conflagrations following earthquakes are rare, there have been a number of events with significant impacts in the last century or so. Some of the most notable events are listed in Table 1; these events have been the main focus of studies into ignitions and fire spread, and the data collected has been used to inform FFE modelling. The recent literature on FFE modelling has benefited from further analysis of these events, especially following the 2011 Tōhoku, Japan earthquake and tsunami that caused a large number of ignitions. Advancements in spatial modelling techniques have also contributed to improved FFE models.

As part of the 'It's Our Fault' research programme, we are updating fire following earthquake (FFE) modelling for Wellington City, building on earlier work undertaken over a decade ago. Cousins et al.[2] developed ignition and spread models based on the data and technology available at the time. The ignition model estimated the number but not location of ignitions. The spread model used for loss estimates accounted for wind speed, but not direction. To update and improve the previous modelling, we are refining the ignition and spread models used to provide risk and loss estimates. This paper details the progress made to date, and the direction of our ongoing work.

Table 1 – Summary of significant FFE events. Adapted from Khorasani and Garlock[3]; Scawthorn et al.[5].

Event	**No. of Ignitions**	**Earthquake Magnitude (M_W)**	**Impact**
Tōhoku, Japan (2011)	293	9.0–9.1	Fires due to both earthquake and tsunami.
Kobe, Japan (1995)	108	6.9	5000+ buildings destroyed due to fire, 550 fatalities.
Northridge, USA (1994)	110	6.7	Majority of fires confined to building of origin.
Napier, NZ (1931)	>10	7.8	Central business district destroyed, 116,000 m^2 of burnt area.
Tokyo, Japan (1923)	277	7.9	447,000 houses destroyed, 38.3 km^2 of burnt area, 140,000 fatalities.
San Francisco, USA (1906)	52	7.8–8.3	28,000 buildings destroyed, 12.2 km^2 of burnt area, 3000 fatalities.

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1.1 Objectives

The modelling presented in this paper is intended to provide a scientific evidence base for evaluating the risk and impacts of FFE in Wellington City. FFE is of particular interest to several organisations, including but not limited to: Fire and Emergency New Zealand (FENZ), Wellington Region Emergency Management Office (WREMO), Wellington Lifelines Group (WeLG), Wellington Water, the Earthquake Commission (EQC) and central and local government. These organisations each play a role in the management of FFE risk. Importantly, FFE may affect anyone living or working within Wellington Region and therefore a wider public understanding of the risk may be beneficial for risk reduction activities.

To serve the needs of these groups, the key objectives of the modelling are to:

[1] Identify areas of relatively high FFE risk.

[2] Generate impact and loss estimates for multiple scenarios.

[3] Develop communication materials for decision-makers and the general public, including maps.

The objectives and modelling are refined based on feedback from key stakeholders via frequent meetings and workshops. The work presented here represents the progress to date, and all results should be considered preliminary. The models are being further developed at the time of writing.

1.2 Wellington City Study Area

The study area for FFE modelling is the urban area of Wellington City, shown in Fig. 1. The purple boundary shows the extent of the focused maps used in this paper, which is chosen to visualise Wellington central city suburbs in sufficient detail. Generally, there is higher risk and greater impacts identified in the modelling for the areas included in the focused maps, relative to areas not shown.

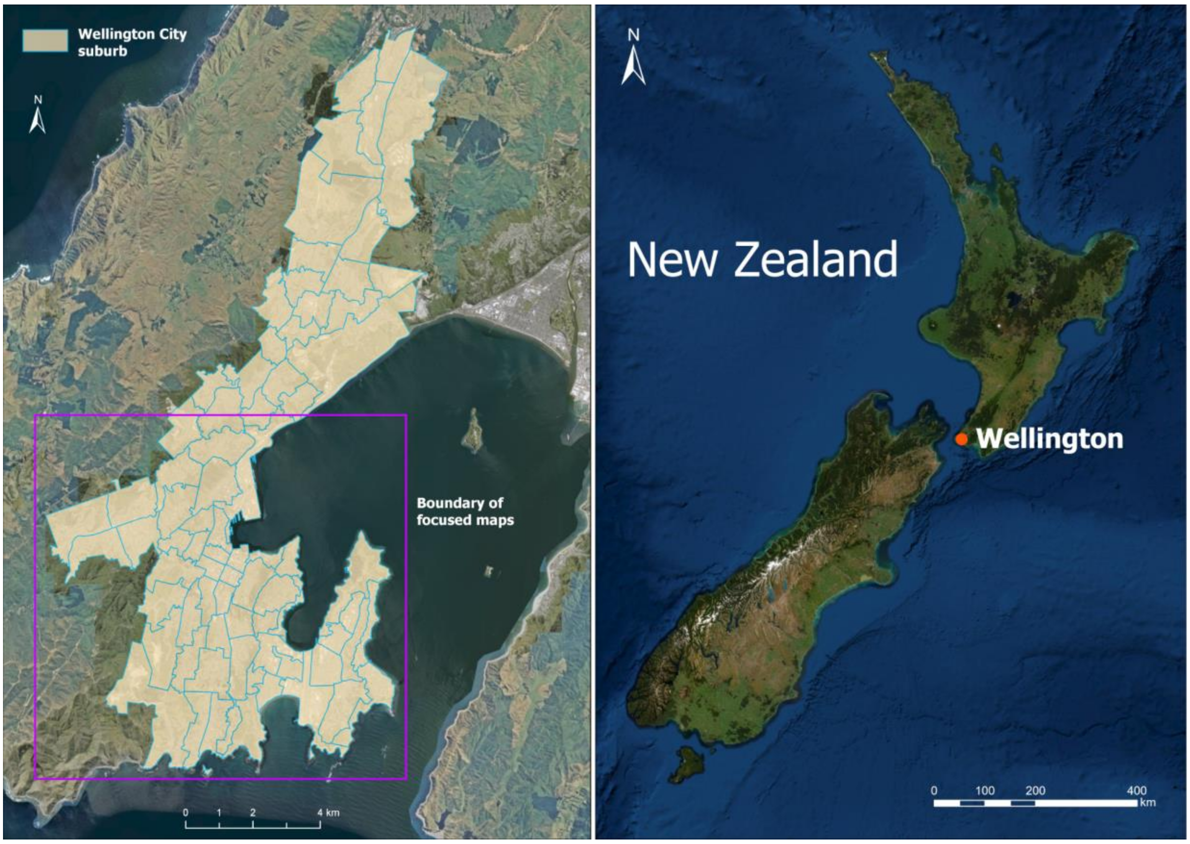

Fig. 1 – Wellington City study area, showing the boundary of focused maps provided in this paper.

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2. Existing Models

The first stage of revisiting FFE modelling for Wellington was a literature review of globally available models for estimating ignition and fire spread, detailed in Scheele et al.[6]. Subsequently, we examined the models for suitability of application to the context of Wellington City.

2.1 Ignition models

Ignition models estimate the number of ignitions after an earthquake and are an essential input for fire spread modelling. Ignitions following earthquakes are most commonly caused by damage to electrical or gas supply systems, including mains breaks and overturning of appliances. For example, in the 1994 Northridge, USA earthquake, there were over 250 failures in the gas network[7]. Of the 110 ignitions, 54 were related to gas failures. The vast majority of ignitions occurred in wood-frame residential structures that are highly susceptible to fire. Analysis of post-earthquake fires in Japan from 1995–2017 found that 70% of all ignitions started within a day of the main earthquake[8].

Ignition models attempt to capture the factors that lead to ignition, often using representative input variables. Most ignition models are developed using empirical data from historical earthquakes in either the US or Japan. Older models (approximately pre-2009) typically output the number of ignitions relative to building floor area and a measure of earthquake intensity (e.g. MMI or PGA). More recent models generally output the probability of ignition for a geographic analysis unit (e.g. for city blocks or individual buildings), and the model equations often use more than one variable to estimate probability of ignition (e.g. PGA, population density, building combustibility, etc.). An advantage of this approach is that the number and distribution of ignitions can be varied across a study area, depending on the characteristics of the location and the earthquake event.

For application to Wellington City, we examined available ignition models that were able to output the probability of ignition. Our preference was for models developed using US event data, due to the similarities in building and infrastructure characteristics (e.g. the presence of reticulated gas networks); however, all potentially suitable models were considered. The ignition models that potentially fit the criteria include Davidson[9], Nishino et al.[10], Yildiz and Karaman[11], Himoto et al.[12], Anderson et al.[13] and Elhami Khorasani et al.[3], summarised in Scheele et al.[7]. When considered in detail, most published ignition models were not appropriate for our purposes as they are often developed for a specific context and purpose.

The most appropriate ignition model was recently published by Elhami Khorasani et al.[3]. Empirical data from seven US earthquake events (1983–2014) where ignition occurred were used to develop the model. The variables in the equation for predicting probability of ignition are peak ground acceleration (PGA), total building square footage (SF) and population density (PD). Probability of ignition can be estimated for both an area (e.g. suburb) or individual buildings. Different estimates are derived based on the construction type of buildings, categorised as wood, mobile homes or non-combustible.

2.2 Spread models

Post-earthquake fire spread models estimate the area burnt, considering the characteristics of the built environment and the ignition locations. Recent FFE models are mostly simulations, many of which utilise GIS- and physics-based fire spread equations. Models may incorporate various factors, for example, building attributes (combustibility, building separation, height), weather (wind speed and direction, rain), vegetation, slope, fire suppression, and so on. Empirical data underpins models to various degrees, with most observations from events in Japan and the United States.

Spread models from the literature were assessed for suitability of application to Wellington City, including those developed by Himoto and Tanaka[14], Nishino et al.[10] and Urban Fire Simulator[15, 16]. The main criteria for evaluation were models that: used physics-based fire spread rules (due to applicability to all

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contexts), included factors of interest (such as fire suppression) and had the potential to improve on previous FFE modelling for Wellington City.

Consistent across all existing published models is that validation is difficult (due to very few historical FFE events for which data is available), and application to other contexts is problematic. The existing models developed specifically for Wellington[2] are still the most appropriate, as they have been created with consideration for the specific characteristics of Wellington City and local stakeholder needs. However, based on the limitations of the existing models, a new spread model was developed building on the previous work[2].

3. New Spread Model

The new spread model developed for Wellington City is conceptually based on the static burn zone model by Cousins et al.[2]. Buffers around buildings are used to account for the maximum distance that fire will spread to another building, based on the critical separation distance (wind speed) as shown in Table 2. The critical separation distances were derived from loss and wind speed data as reported from historical US earthquakes[5], and signify the maximum distance a fire can spread given the wind conditions. The most important difference in the new spread modelling is the inclusion of wind direction, which alters how buffers around buildings are applied. Unlike the static burn zone model, in which burn zones are pre-calculated depending on the critical separation distance (effectively dividing the built environment into blocks), the new spread model is calculated on the fly.

Table 2 – Wind speed and critical separation distance (the maximum range a fire can spread given the wind conditions), derived from historical US earthquake data (adapted from Cousins et al.[2]; data originally from Scawthorn[5]).

Wind Speed (km/h)	Critical Separation Distance (m)
0–4.9	12
5–9.9	13
10–14.9	13
15–19.9	14
20–24.9	16
25–29.9	18
30–34.9	23
35–39.9	28
40–44.9	33
45–49.9	42
50+	45

To determine whether a building is combustible or not, the RiskScape[1] building point attributes are matched to the building footprints layer by joining the attributes of the closest point. The 'construction type' attribute from the RiskScape building database is used to determine whether a building is combustible or not.

[1] RiskScape is an impact and loss modelling tool jointly developed by GNS Science and the National Institute of Water and Atmospheric Research. The building database covers all of New Zealand, represented as points. Buildings have many attributes, including replacement cost, construction type, floor area, use category, occupancy, etc.

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All wooden buildings are combustible, and all other types are assumed to be non-combustible. Fire is assumed not to spread to non-combustible buildings but, if an ignition starts in one, the building is assumed to burn but fire will not spread from there.

To estimate fire spread, first the ignition model (developed by Elhami Khorasani et al.[3]) is used to distribute ignitions across buildings within the study area, randomised for each simulation run. From wind rose data, wind speed and direction are randomly selected based on the probability of each wind speed and direction occurring. Ignited combustible buildings are then buffered by the critical separation distance for calm conditions (12 m). Depending on the wind conditions, the buffer is then moved in the direction of the wind until the critical separation distance for that wind speed is reached. Any building that falls within the buffers and is combustible will catch fire, and the buffering process on newly ignited buildings will begin until the critical separation distance is reached. This process continues until no further buildings are ignited i.e. the fire has spread as far as it can, given the conditions. The resulting burn zones can vary in size considerably, as shown in the mapped scenario run in Fig. 2.

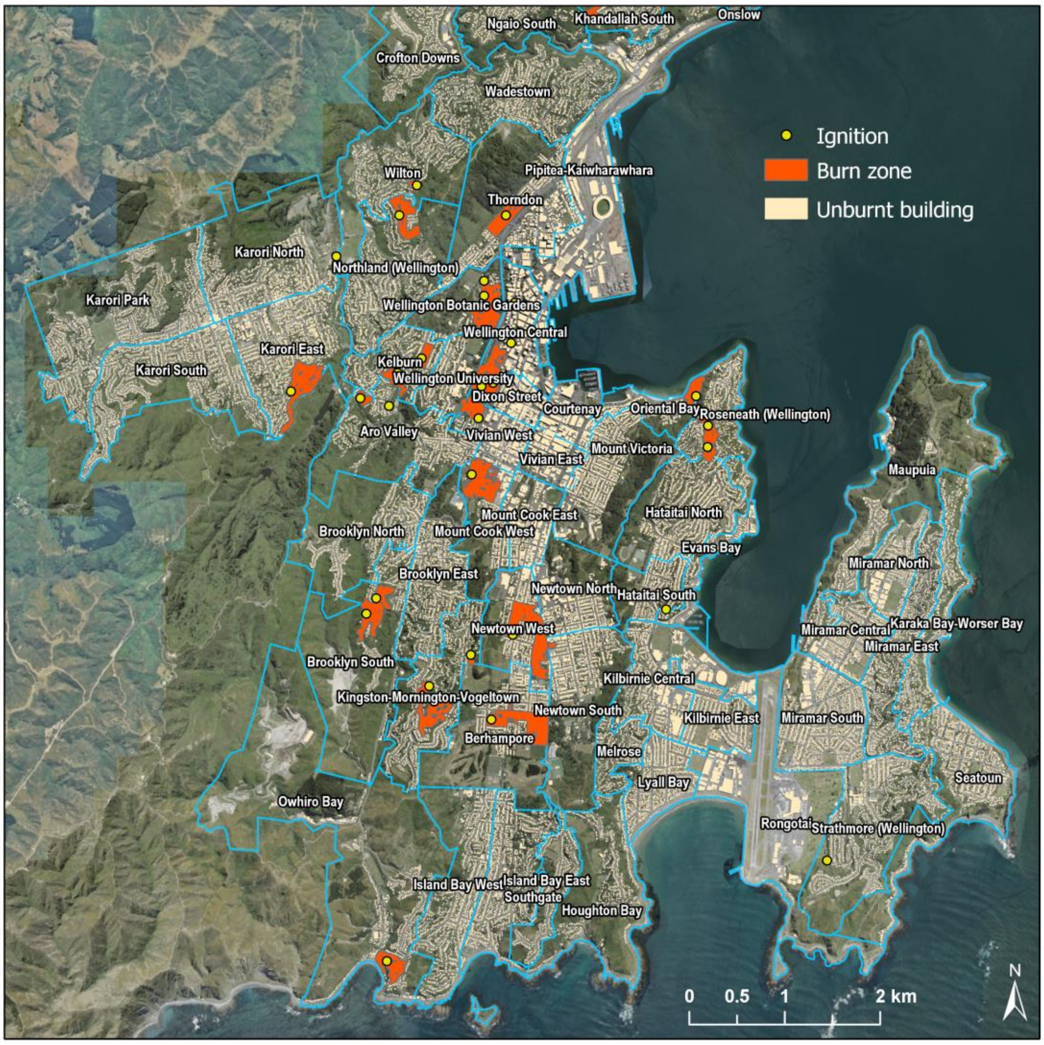

Fig. 2 – Example of ignition locations and fire spread for one scenario (run number 20 out of 100). This scenario involved 40 ignitions, a NW wind at 22.5 km/h (16 m critical separation distance) and approximately $1.95b of loss with 2900 buildings burnt. Not all ignitions and burn zones are shown (some are further north out of frame). Every simulation run of the model will produce different ignition distributions and burn zone extents.

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By using moving buffers of 12 m separation distance, the assumption that fire can spread in all directions due to physical processes (such as radiation) is maintained, as well as incorporating the effect of wind speed and direction. This is a significant improvement over the Cousins et al. static model[2], which assumes fire can spread evenly in all directions based on the wind speed (critical separation distance) and cannot account for wind direction. In the static model, burn zones can become unreasonably large for higher wind speeds.

To generate loss and impact information, the final burn zone buffers are dissolved (joined together), and all building points that are within the burn zones are used to calculate loss (building replacement value and contents value) and other impacts (e.g. population affected). Note that loss estimates are the maximum possible fire loss as the existing shaking loss is not calculated first, however the shaking loss will be estimated in future work.

By varying the ignition distribution, wind speed and direction, or other input parameters, both the ignition and spread models can be used for stochastic modelling. For example, a Monte Carlo modelling process involving randomness in each simulation run can be used to account for uncertainty and produce a distribution of loss and impact estimates that provide insights into the range of possible scenarios.

4. Scenario Modelling Results

This section describes the results of running 100 simulations of the ignition and spread models, for a Wellington Fault magnitude 7.5 earthquake event (Fig. 3). Each simulation has a different distribution of ignitions, and wind speed and direction are randomly sampled from Kelburn wind rose data. Importantly, all results presented here should be considered preliminary, as further testing and adjustments to the models are necessary to ensure reliability in the results. A larger number of simulations is required (e.g. 1000 or more) for stability of results, given the variability of input factors (such as wind speed and direction, and earthquake scenarios in the future). However, the following results provide an indication of the magnitude and distribution of events.

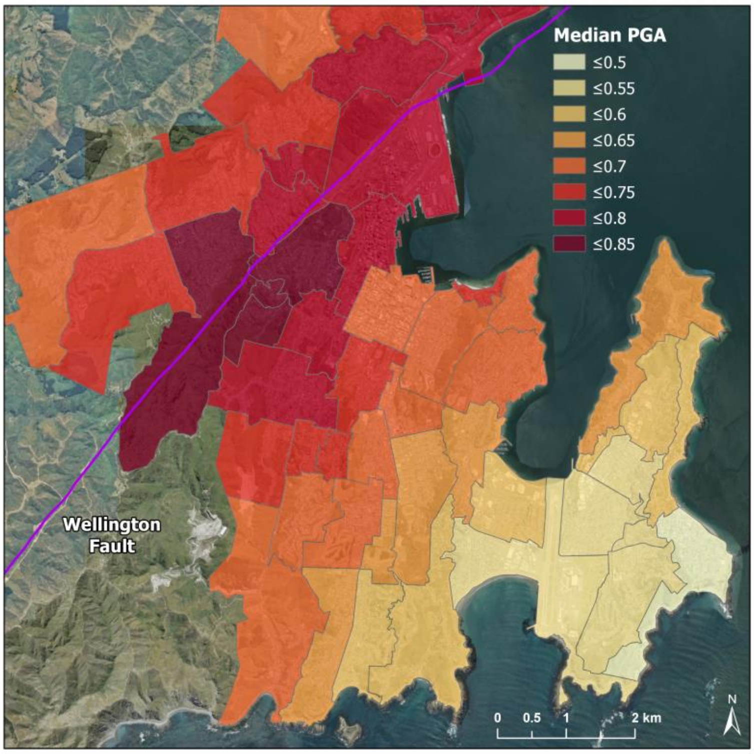

Fig. 3 – The median PGA per Area Unit (suburb) for a Wellington Fault magnitude 7.5 earthquake.

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Summary statistics for the 100 simulated runs are shown in Table 3. The mean number of ignitions is 34, which is slightly lower than the 39 ignitions expected if no randomness was included in the simulations (based strictly on the probabilities of ignition). Loss estimates vary widely and follow a lognormal distribution. All losses are reported in New Zealand Dollars ($1NZD = $0.65USD at time of writing). The median loss is $1.49 billion; however, nearly 20% of scenarios had estimated losses exceeding $4 billion. The number of buildings burnt and the population affected in burn zones follow a related lognormal distribution to losses. The frequency of loss per meshblock (the smallest aggregation unit for the NZ Census) is shown in Fig. 4, calculated as the number of buildings burned in a meshblock (summed for all scenarios) divided by the number of buildings in a meshblock (to normalise for meshblock size). The distribution of loss frequency drops with distance from the Wellington Fault due to reduced PGAs.

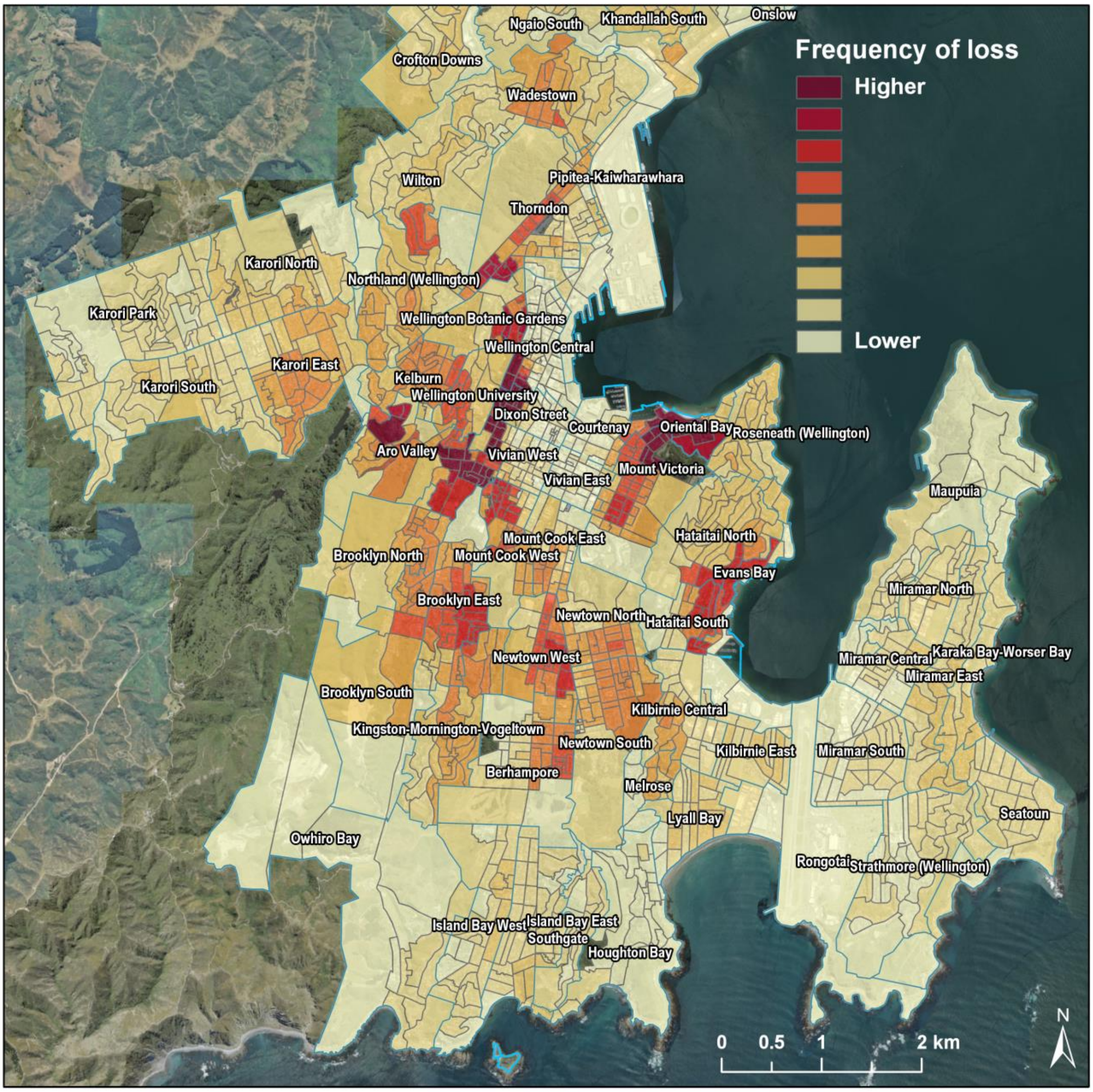

Fig. 4 – Map showing the frequency of loss per meshblock, calculated as the number of buildings burned in a meshblock (summed for all scenarios) divided by the number of buildings in a meshblock (to normalise for meshblock size).

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Table 3 – Summary statistics of 100 simulated runs of ignition and fire spread.

Variable	Min	Median	Mean	Max
Ignitions	19	33	34	55
Loss	$0.38b	$1.49b	$2.64b	$17.65b
Buildings in burn zones	750	2,610	4,860	33,480
Population in burn zones	1,600	7,000	12,400	82,700

Variables in the simulation runs can be examined to identify potential relationships. The relationship between wind speed and loss is examined in Fig. 5. Losses are similar for all wind speeds up until about 20 km/h, reflecting the very modest increases in critical separation distances (Table 2). For wind speeds over about 25 km/h, there is an increase in loss of about $4 billion for every 10 km/h wind speed increase. Overall, the relationship between wind speed and loss can be considered strong.

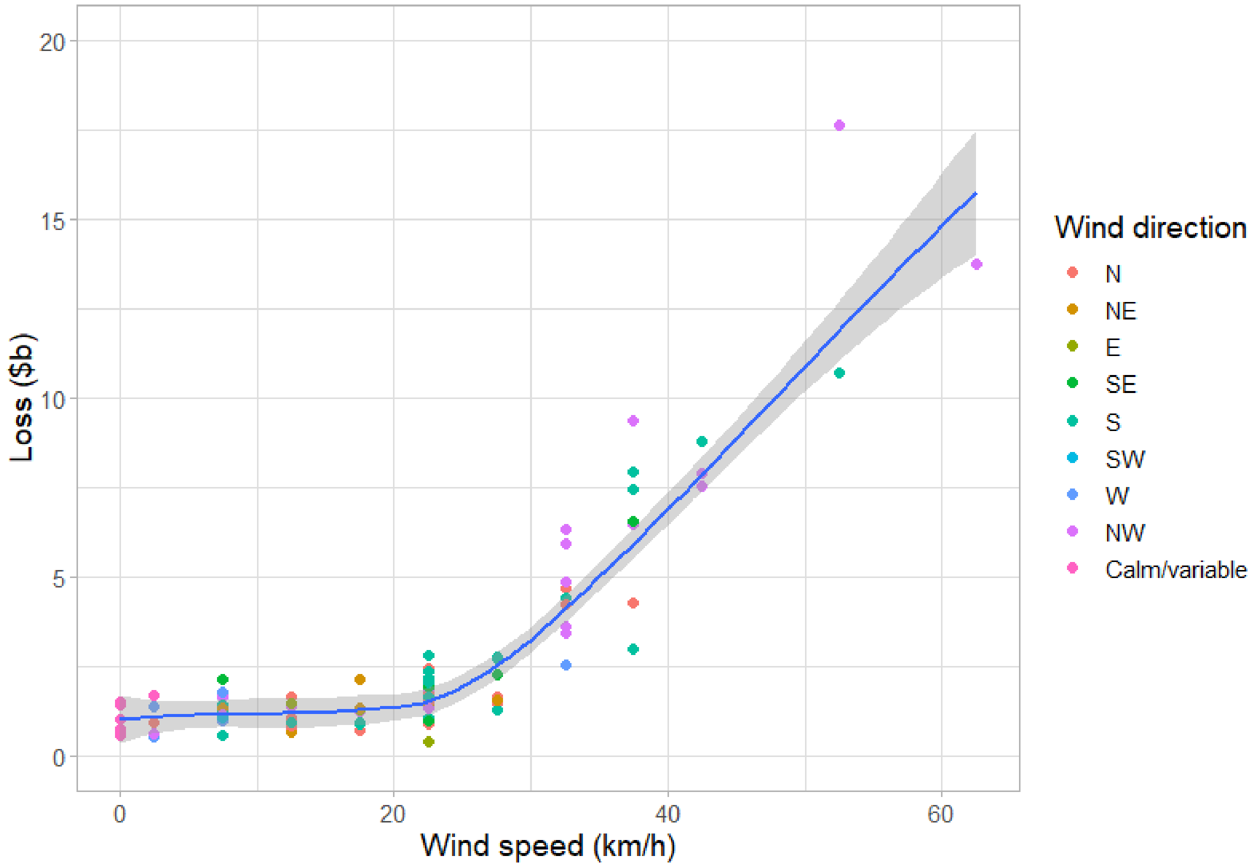

Fig. 5 – Relationship between wind speed (km/h) and loss (billions of dollars) for 100 simulation runs. For wind speeds over about 25 km/h, there is an increase in loss of about $4b for every 10 km/h wind speed increase.

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5. Uncertainties and Limitations

Modelling of FFE is complex and there are many sources of uncertainty. The main uncertainties and limitations are described here, which are important to note while interpreting the modelling process and results.

As with all modelling, the quality of the data that enters the models has a significant influence on the results. While we have used the best data that is currently available, some datasets have known problems that hinder the accuracy of results. Specifically, the mismatched locations between many of the RiskScape building points (containing attribute information) and the building footprints (used in creating burn zones) means that matching attributes to the footprints is not accurate if done using automated processes. For this reason, it was necessary to assess impact and loss within burn zones using the building points directly. Occasionally, clusters of building points are located outside of burn zones, even if they should be associated with footprints within the burn zones. This has implications for the accuracy of impact and loss results, and significant effort is required to properly match the building attributes and footprints (beyond the scope of this project).

The ignition model used[3] applies only for potential ignitions in buildings. Ignitions and potential fire spread from other locations is not considered in the modelling. For example, broken gas pipelines are a potential ignition source that is not accounted for.

For practical reasons, it is necessary to simplify the modelling of physical processes that lead to ignition and fire spread. The fire spread model and critical separation distances were developed with respect to physical rules, but do not explicitly consider all modes of fire spread independently. Depending on the scenario, specific processes (e.g. branding) may have significant effects that are not fully accounted for in the modelling. Two notable factors for fire spread are slope and vegetation, which are not currently incorporated in the spread model.

At this stage, fire suppression is not included in the modelling; therefore, the results are worst-case. Fires could be suppressed by the fire service or residents, and some buildings may have functioning suppression systems. Fire suppression will be included future modelling.

For any given simulation run, the distribution of ignitions and fire spread will be different from a real event. While examination of individual simulation runs (e.g. Fig. 2) can be useful for understanding possible outcomes of FFE events, the results are better interpreted once aggregated or analysed considering many simulation runs. Currently, the number of simulation runs presented in this paper (100) is insufficient to reliably capture the range of potential scenarios, and the results should be treated as indicative of the potential outputs only. A limitation of the spread modelling is the computational resource required (100 simulation runs took 1.8 days to process on a desktop computer with an Intel Xeon processor and 32GB of RAM), meaning there is a practical limit to how many simulation runs can be performed. Future work will aim to optimise the model to improve performance and reduce run times.

The modelling presented in this paper is based on one ground motion map, which is the median PGA for a Wellington Fault magnitude 7.5 earthquake. Variations in PGA for both the Wellington Fault scenario and other potential fault sources can be included in future modelling. Additionally, pre-existing loss from earthquake shaking is not currently accounted for but can be in the future (as it was in Cousins et al. 2012[17]).

Applying models to Wellington City that are developed using empirical data from international historical events assumes that the characteristics of the events and the local context are similar. Although fire spread characteristics are the same, building construction and sources of ignition differ between locations. The difference is difficult to quantify without extensive research.

Finally, validation is a problem for all FFE modelling due to relatively few events having occurred in recent decades. Without any recent FFE events in New Zealand, any future validation will have to compare against historical events from overseas.

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6. Conclusions

Building on previous FFE modelling work for Wellington City[3, 17, 18] and a literature review of globally available models[6], we are updating FFE modelling to provide a scientific evidence base for decision-makers. The application of a new ignition model and development of an improved fire spread model provide a new suite of tools for understanding FFE risk in Wellington City.

The ignition model developed by Elhami Khorasani et al.[3] has been applied, providing the ability to randomise the number and distribution of ignitions per building. This is an improvement on previous ignition modelling that only estimated the total number of ignitions within the study area as a function of MMI and total building floor area, which were then randomly distributed across the study area. There is a similar mean total number of ignitions between models, which is expected due to both being developed from similar empirical datasets.

The fire spread model now includes both wind speed and direction, which is a significant improvement on the previous static model[2]. Stochastic modelling utilising both the fire spread and ignition models and varying input parameters are able to produce loss and impact results across many potential scenarios. 100 simulations runs were performed for this study, which provide a preliminary indication of the distribution of loss and impacts for FFE in Wellington City.

The stochastic modelling results show a lognormal distribution of losses, with a median loss for a scenario of $1.49 billion. A median loss for burn zones of $24 million indicates the potential savings of suppressing an ignition. Wind speed is shown to have a greater effect on the loss than the number of ignitions per scenario. By considering the weather conditions following an earthquake event, a rapid assessment of the threat from FFE could be undertaken.

Recommendations for future work:

- Running the ignition and spread models for a larger number of simulations (e.g. 1000) to produce more stable results. This would take approximately 18 days at the current speed of processing (using the same equipment). Optimisation techniques should be explored.
- Running the model considering variations in PGA for the Wellington Fault scenario. Other fault sources can also be included.
- The inclusion of suppression for ignition and/or fire spread. Suppression of ignitions could be randomised, for example, to quantify the effect of residents putting out small fires on their own. As noted by Thomas et al.[18], preventing or suppressing ignitions is the most cost-effective mitigation measure.
- The loss and impact due to earthquake shaking can be compared with FFE, as in Cousins et al.[17].
- Validating the spread model against historical events should be undertaken using future simulations for Wellington City.
- Development of an accurate building database for Wellington City with attributes attached to building footprints. This work is beyond the scope of the FFE modelling project under ‘It’s Our Fault’ but would be helpful for many projects that utilise building attribute data.

7. Acknowledgements

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