Fire Research Report

Implementation of Urban Fire Spread Model as NZFS Tools

Victoria University of Wellington
GNS Science

March 2008

A dynamic urban fire spread model developed previously by GNS Science and Victoria, University of Wellington has been extended to take into account the effects of earthquake damage on building flammability and to allow the user to alter wind strength and direction during a scenario. An alternative variant of the model was developed to speed up the modelling process to allow for multiple analyses in a shorter time-frame.

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Implementation of Urban Fire Spread Model as NZFS Tools

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ABSTRACT

A dynamic urban fire spread model developed previously by GNS Science and Victoria, University of Wellington has been extended to take into account the effects of earthquake damage on building flammability and to allow the user to alter wind strength and direction during a scenario. An alternative variant of the model was developed to speed up the modelling process to allow for multiple analyses in a shorter time-frame.

The existing model was demonstrated to the New Zealand Fire Service for a recent fire that occurred in Rongotai. In addition NZFS nominated a number of other locations in Wellington and the model was tested at these locations. Multiple scenarios were run for each ignition location using different wind conditions and modes of fire spread to demonstrate the effect of altering these parameters and to enable the results of the model to be compared with the known effects of such changes.

The simulation run for Rongotai Road showed the modelled fire spreading as it did during the actual event and gave a good indication of the probable losses in the actual and other wind conditions if the New Zealand Fire service had not prevented further fire spread.

The model can be developed to provide information on likely paths and modes of fire spread which would help in fighting a large scale urban fire. This information must be used with caution as effects such as wind gusts and local wind shifts can not be fully predicted. In many instances it is possible to predict with some confidence whether a fire will or will not cross an open space, but there will always be an area of uncertainty where it may or may not occur. The model should be seen as an aid to decision making, rather than sued to make decisions.

KEYWORDS

Post Earthquake Fires, GIS, Earthquakes, Fires, Fire Spread, Urban Areas

1.0 INTRODUCTION

In 2002 GNS Science and Victoria University completed a report funded by the NZFS contestable fund that reported on the results of models developed to assess the spread of fire in urban areas [1,2].

The first model developed and described in detail was a static model which used GIS buffer analysis to create envelopes around buildings based on a critical separation distance nominated by the user to create burn zones. The results were used to estimate the losses likely in Wellington city for uncontrolled building fires.

The second model developed and described was a dynamic model that converted building polygons to regular sized cells and used a cellular automaton technique to propagate fire-spread on a cell by cell basis. This second model was used to simulate fires in Napier city following the 1931 earthquake when more than 400 buildings were destroyed by fires that spread uncontrolled through 11 city blocks for almost 24 hours. The results of the modelling fitted well with observations from the 1931 fires in terms of direction of fire spread and timing of events [3].

The dynamic fire spread model produces results that appear to be useful in predicting fire spread rate and extent but has several shortcomings. The tool requires expensive software (ArcGIS at $35,000) and hardware, and run times are very long. Extensive training in GIS is required before non-GIS staff can format the data required for the tool to run, and a moderate level of knowledge is required to use the tool. The code is considered suitable for research use but is not easily deployed for use in the field.

2.0 METHODOLOGY

This project involved the addition of new features to the dynamic model and development of existing features and the user interface in collaboration with the New Zealand Fire Service. This was carried out as follows:-

i) A new fuel layer was added to the model. This layer simulates Wellington City following a Wellington Fault earthquake. Buildings likely to be damaged during the earthquake to such an extent that their flammability would be altered were reclassified.
ii) The existing code was demonstrated by running multiple fire scenarios to a person experienced in fire spread between buildings. Gordon Baker of the NZFS was nominated by the Chief of the Wellington Fire District, Jon Graham, for this role.
iii) The effect of changing the various fire spread parameters was demonstrated during this phase.
iv) Adjustments to the fire spread parameters and other minor changes necessary to the code were made.
v) Any changes necessary to increase the usability and accuracy of the modelling have

been recorded.

vi) Potential model development has been considered throughout the project

vii) Alternatives for rewriting the tool using a new language to move the tool from its reliance on expensive software have been investigated.

3.0 THE DYNAMIC FIRE-SPREAD MODEL

The dynamic fire-spread model uses a “cellular automaton” technique to model the spread of fire over time. A GIS is used to divide a map of the area of interest into a set of equal-sized square cells, and then each cell is allocated the properties of whatever fills it. For example, a cell mostly occupied by a building is deemed to be fuel and takes on the properties of the building, i.e. the cladding material, roof type, height, proportion of windows, and so on. A cell that lies mostly over items like roadway, grassland, and paved areas, is deemed to be empty, and thus a hindrance to the spread of fire. Spread of fire from one cell to another (represented as a change of cell state) depends on the initial state of the cell (burning or not), cell attributes (fuel or not), and a set of rules. More information on the model is available in previous research reports [1,2].

The rules are complex and take into account such things as the size of the burning fire-front, the temperature of the fire, the decrease in heat flux with increasing distance (i.e. increasing size of gap), and the flammability of cladding materials. The dynamic model allows fire to spread to flammable structures by 5 modes:-

i) ***contact*** , where a burning cell will ignite a combustible cell in direct contact with it

ii) ***spontaneous ignition***, where cells are heated by intense radiation across a gap to a sufficient level to cause spontaneous ignition of combustible materials (Fig. 1)

iii) ***piloted ignition***, that is by sparks falling on combustible surfaces preheated by radiation across a gap (Fig. 1)

iv) ***branding***, where larger pieces of burning material are blown across a gap by the wind.

v) ***via non-fire rated roofs and other openings,*** where structures with non-flammable claddings can be ignited by piloted ignition following collapse of an adjacent non-fire rated roof or by piloted ignition through openings such as broken windows (Fig. 2).

Figure 1. Fire spread by radiation.   Spontaneous ignition (mode ii) requires higher levels of radiation than piloted ignition (mode iii), however piloted ignition also requires sparks.

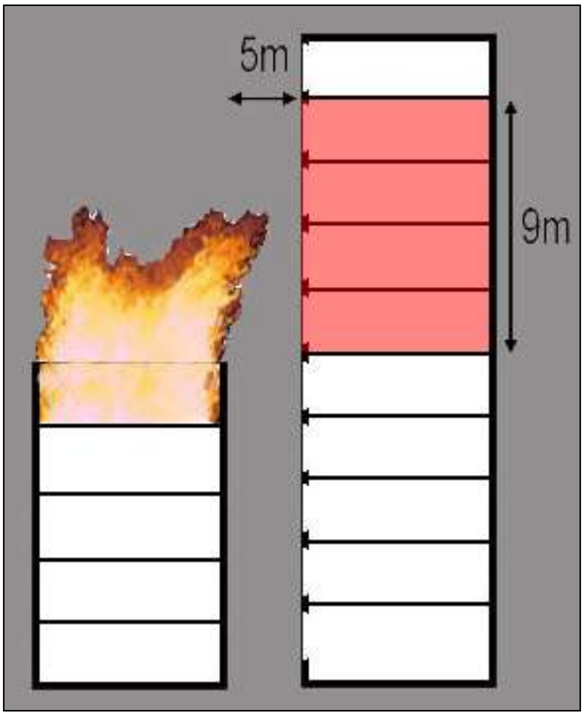

Figure 2. Fire spread via a non-fire rated roof. The 5 m horizontal separation and 9 m vertical are the limits from the New Zealand Building Code Acceptable Solutions

The model includes factors for wind direction and strength but does not yet account for other biasing factors such as ground slope and active suppression.

The dynamic model allows the user to assign probabilities for spread mechanisms where fire-spread is not guaranteed to be successful (for example, burning brands may be blown onto a building but fail to ignite it because they fall on a non-combustible roof).

Probabilities for the various methods of fire spread are given in Table 1 which summarises the previous studies [1,3]. The probability associated with spread through openings (windows) is dependent on the state of the windows in the target building. Post-earthquake probabilities are higher than pre-earthquake probabilities reflecting the likelihood of broken windows after an earthquake. The probability is also dependent on the distance between the two buildings.

Mode of fire spread	Type	Probability	
		Pre-earthquake	Post-earthquake
Contact	Fixed	100%	100%
Spontaneous	Fixed	100%	100%
Piloted	Variable	10%	10%
Brand	Variable	0%	0%
Roof collapse	Variable	30%	30%
Openings			
0-3 m separation	Variable	4%	5%
3-6 m separation	Variable	10%	41%
6-18 m separation	Variable	1%	30%

Table 1. Probabilities associated with various modes of fire-spread. Fixed type probabilities are not able to be changed by the user. Variable type probability values can be altered. The value given is the default value. Branding is difficult to predict and generally only happens in wind speeds of over 30 km/hr, however it was reported during the fires after the Kobe earthquake with a wind speed of about 20 km/hr[5].

To run the model, at least one initial cell (the fire source) is “ignited”, and then all surrounding cells are interrogated, one at a time, to determine whether or not the conditions are such that any of them will be ignited from the burning cell or cells. The interrogation process is repeated hundreds or thousands of times until the spreading fire finally reaches a barrier that it cannot cross. The mechanics of the process is that the entire set of cells is scanned repeatedly, on a cell by cell basis. During the scanning process cells are “activated” one at a time and, whilst activated, a cell’s state is changed according to its current state and properties, the states of surrounding cells, and the fire-spread rules.

Because of the repetitive nature of the scanning process there is a built-in time step which makes it straightforward to model time-variant states such as the build-up and decline of a fire. In the development of the dynamic fire-spread model in Wellington we originally assigned a time of 2.5 minutes to the interval between scans. Consequently the transition through the various stages of a fire was also multiples of 2.5 minutes. The time for a fire in a single cell to progress from ignition to full intensity burning was set at 7.5 minutes (3 scans), the time of burning at full intensity was 40 minutes (16 scans), and the burn-down time was 12.5 minutes (5 scans).

One of the objectives of the Napier study [3] was to verify these time settings and it appeared that the initial assessment of 2.5 minute steps made for the Wellington suburban environment did not transfer to the Napier CDB environment very well. The time-step interval had to be increased to 10 minutes per step for the model to reproduce known spread rates.

The commercial buildings in the central business district of Napier were predominantly of heavier construction, such as brick masonry or concrete with non-combustible claddings and were relatively small and highly compartmentalised compared to modern commercial buildings. Fire spread through these older types of buildings would therefore be much slower than for light timber frame building with combustible claddings or modern commercial buildings with lighter construction and larger internal spaces.

It is considered that the time-steps of 2.5 minutes per model step are reasonable for domestic buildings in Wellington. This time is consistent with the time taken for a post-flashover fire to penetrate a hollow core door. Three time steps or 7.5 minutes is used to model the growth phase of the fire from ignition of the cell to flashover. It is also consistent with anecdotes from fire service personnel of fires going completely through a light timber house in the order of 20 minutes.

3.1 Changes Implemented to the Dynamic Fire-spread Model

The existing dynamic fire-spread model was demonstrated to the NZFS representative, Gordon Baker, and following discussions several enhancements were made.

The model was expanded beyond the CBD to include all of Wellington city using building polygons provided by Wellington City Council for the 2002/03 studies [1]. The model now contains over 76 000 polygons representing the buildings in Wellington city with attributes such as wall cladding, roof cladding, floor area, footprint area, and an estimate of value and residents by day and night.

The model was adjusted so that the user could interrupt a running fire-spread scenario and effectively step back in time to adjust the wind speed and direction. This modification was introduced for two reasons. Firstly it allows a user to look at the effect of changing these parameters part way through a scenario and allows useful sensitivity testing of the model. However, the main reason for implementing the change was to test the feasibility of the model being used during an actual fire where changes of wind speed and direction could be expected to occur.

A variant of the model was developed with the aim of quickly determining the extent of uncontrolled fire spread. Normally the model would allow fire to spread through a building on a cell by cell basis, thus if a building was 10 cells wide, the fire would take 10 steps to spread from an exterior wall through the building to the opposite side. This variant of the model ignites the whole building as soon as one cell in the building is ignited thereby allowing the fire to spread to adjacent buildings more quickly. The only flaw with this faster variant of the model is that fire spread is no longer time dependent since a fire can spread through two buildings of different dimensions in one step. Consequently the path a fire might take through a block of houses can vary given the same conditions when running the two variants. Also the faster variant can not be used if a wind change is to be modelled as the time to implement the wind direction change can not be determined. However it does allow the consequence of a fire to be determined much more quickly than the full model and was used for some of the scenarios described below.

The final modification implemented was to provide the user with the option to run the fire over Wellington city before or after a Wellington Fault earthquake. To implement this option ground shaking was modelled for a Wellington Fault earthquake and a modified building dataset created. Claddings in this modified building dataset were altered to reflect likely changes in flammability resulting in cladding damage following the expected levels of Modified Mercalli (MM) Intensity ground shaking as below:

- brick veneer buildings and un-reinforced masonry buildings experiencing M10 shaking were recoded to be as flammable as wooden buildings
- 60% of buildings experiencing MM10 shaking were coded as having broken windows
- 20% of brick veneer buildings and 20% of un-reinforced masonry buildings experiencing MM9 shaking were recoded to be as flammable as wooden buildings
- 20% of buildings experiencing MM9 shaking were coded as having broken windows
- the remaining buildings were unchanged.

Appendix 1 gives descriptions of effects of various levels of ground shaking from MM7 to MM12.

3.2 Scenarios run with the Enhanced Dynamic Fire-spread Model

Scenario fires were run using the model and assessed by Gordon Baker with the view of determining if the model could be of use as a fire fighting tool.

Animations (mpegs) were created of each scenario and are included with this report. The animations show the buildings as a series of regular 3 m cells (white or green) and the intervening space as black. White cells are buildings with flammable claddings (e.g. wood). Green cells are buildings with non-flammable claddings (e.g. brick, concrete). The fire is represented by a colour change in the burning cell from yellow through orange to red and back finishing as grey. The colour changes represent the various stages of fire growth and decay. A single cell takes 3 time steps to progress from ignition (yellow) to full intensity burning (red), remains at that intensity for a further 16 time steps, and then decays to nothing (grey) over a further 5 time steps. The Rongotai Rd fire site was chosen to model a real fire event. The Fifeshire Ave and Riddiford St sites were chosen because they were familiar to NZFS personnel and represented building types and configurations commonly found in Wellington City.

3.2.1 Rongotai Road, Wellington

Five scenarios were run for a fire starting in an address on Rongotai Road (Fig. 3). It was chosen to compare the model with an actual fire that occurred in a house in this vicinity and spread to an adjacent house before the arrival of the fire service. Conditions were calm at the time of the fire. The building footprints indicate that all buildings in the block in which the fire started are separated by less than 6 m from adjacent buildings and that many, including the house where the fire started, are separated by less than 3 m. The scenarios were run focusing on the northwest end of the block.

Figure 3. Rongotai Road, a typical moderate density older neighbourhood.

RR_Scenario_1 was run with no wind, with only contact and spontaneous ignition enabled, and with the buildings in the pre-earthquake condition. The model suggests that without fire service intervention the fire would have spread both east and west down Rongotai Road, destroying 24 buildings on the south side of the block within the area of interest before self extinguishing. The model used for this scenario was the fast variant of the model.

RR_Scenario_2 was run with no wind, with contact, spontaneous and piloted ignition enabled, and with the buildings in the pre-earthquake condition. The model suggests that without fire service intervention the fire would have spread both east and west down Rongotai Road, passing through buildings on one property to those on the northern side of the block, and then east and west from there until more than 44 buildings within the area of interest were on fire. The model used for this scenario was the fast variant of the model. The same scenario was run with the slow variant of the model with slightly differing fire spread paths (see RR_Scenario_5).

RR_Scenario_3 was run with a fresh breeze (29-39 km/hr) from the south, with contact, spontaneous and piloted ignition enabled, and with the buildings in the pre-earthquake condition. The same number of buildings were burned as in RR_Scenario_2 (although this is not seen in the animation as the model was terminated earlier than for RR_Scenario_2), but the southerly wind allowed sparks to ignite buildings on the northern side of the block via two paths rather than just the one path seen in Scenario 2.

RR_Scenario_4 was run with a near gale (40-59 km/hr) from the southeast, with contact ignition, spontaneous ignition, piloted ignition and branding enabled, and with the buildings in the pre-earthquake condition. The fire spread through the southern side of the block as in the previous scenarios but also jumps to directly to buildings on the northern side of the block at two locations as a result of branding and to isolated buildings not ignited in other scenarios. The fire also jumps to the block to the northwest. This scenario is not considered very realistic as the probability of brands igniting structures on which they fall in the model was set at a level that likely exceeds realistic probabilities. It does, however, demonstrate the effect of branding on fire spread speed and path.

RR_Scenario_5 was run with no wind, with contact, spontaneous and piloted ignition enabled, and with the buildings in the pre-earthquake condition. These are the same parameters as for RR_Scenario_2 but using the full (slower) variant of the model. The same buildings are destroyed by fire but the fire path is different to that seen in RR_Scenario_2. The fire takes longer to burn around to the northern side of the block and houses there are ignited by sparks from those on the southern side before the fire can reach them from adjacent buildings. This is to be expected as this variant of the model slows down spread through buildings (but not via piloted ignition) compared with the faster running version.

3.2.2 Fifeshire Avenue

Figure 4. Fifeshire Ave, a moderate to high density commercial neighbourhood.

FA_Scenario_1 was run with no wind, with contact and spontaneous ignition enabled, and with the buildings in the pre-earthquake condition. The model suggests the fire would be contained within the source building.

FA_Scenario_2 was run with no wind, with contact, spontaneous and piloted ignition enabled, and with the buildings in the pre-earthquake condition. Again the model suggests the fire would be contained within the source building. No animation was made of this scenario.

FA_Scenario_3 was run with no wind, with contact and spontaneous ignition, with piloted ignition enabled and set at 100% probability, and with the buildings in the pre-earthquake condition. The fire spread to engulf a further 5 buildings, the first by piloted ignition, then a further three by direct contact or spontaneous ignition, and the fifth building by piloted ignition. This model shows the effect of varying one of the probability controlled modes of fire spread and shows how sensitive the model can be to this parameter.

FA_Scenario_4 was run with no wind, with contact, spontaneous and piloted ignition enabled, and with the buildings in the post-earthquake condition. The model suggests the fire would be contained within the source building and no animation was made of this scenario.

FA_Scenario_5 was run with no wind, with contact, spontaneous and piloted ignition enabled, roof burn-through enabled, and with the buildings in the pre-earthquake condition. The fire spread via the roof and openings to adjacent buildings with non-flammable claddings. In the building database the source building is described as having concrete walls and an iron roof. Adjacent buildings have the same cladding but are up to a floor higher. From there the fire passes through the same flammable structures burned in FA_Scenario_3 but also several adjacent buildings with non-flammable claddings. In total 21 buildings are burned.

FA_Scenario_6 was run with no wind, with contact, spontaneous and piloted ignition enabled, roof burn-through enabled, and with the buildings in the post-earthquake condition with some claddings damaged and glass broken. Comparison of the first frames of FA_Scenario_5 and 6 shows that only one building (to the east of the source building) has had the flammability of its cladding altered (shown as green in FA_Scenario_5 and white in FA_Scenario_6) as a result of the earthquake. The fire spread from the source via the roof and openings to adjacent buildings igniting more of the buildings than in the previous scenario. The flammability of the cladding on these buildings was not altered by the earthquake, and the fire spread to the two buildings to the east not ignited in FA_Scenario_5 via the openings because under earthquake conditions the probability assigned to spread via openings is greater. From there the fire passes through the same flammable structures burned in FA_Scenario_5 but also the building with the altered cladding state. In total 27 buildings are burned.

3.2.3 Riddiford Street

RS_Scenario_1 was run with no wind, with contact and spontaneous ignition enabled, and with the buildings in the pre-earthquake condition. The model suggests the fire would be spread by direct contact through six adjacent buildings but be prevented from spreading further by buildings with non-flammable cladding.

Figure 5. Riddiford Street, a high density mixed commercial and residential neighbourhood. Scenarios 6, 7, and 8 burned beyond the area of the image.

RS_Scenario_2 was run with no wind, with contact, spontaneous and piloted ignition enabled, and with the buildings in the pre-earthquake condition. The model suggests the fire would spread by direct contact through six adjacent buildings. As the result was the same as for RS_Scenario_1, no animation was made.

RS_Scenario_3 was run with no wind, with contact and spontaneous ignition enabled, and with the buildings in the post-earthquake condition. Comparison of the first frames of RS_Scenario_1 and 3 shows that several buildings have the flammability of their cladding altered (shown as green in RS_Scenario_1 and white in RS_Scenario_3) as a result of the earthquake. The model suggests several of the buildings with non-flammable claddings in the same block as the source building would be sufficiently damaged to allow the fire to spread by direct contact. As a consequence the model suggests the fire would destroy nine buildings but be prevented from spreading further by undamaged non-flammable buildings.

RS_Scenario_4 was run with no wind, with contact, spontaneous and piloted ignition enabled, and with the buildings in the post-earthquake condition. The model suggests the fire would be spread by direct contact through nine adjacent buildings. As the result was the same as for RS_Scenario_3, no animation was made.

RS_Scenario_5 was run with no wind, with contact, spontaneous and piloted ignition enabled, roof burn-through enabled, and with the buildings in the pre-earthquake condition. The fire spread via the roof and openings to adjacent buildings destroying the whole block (25 buildings).

RS_Scenario_6 was run with the same conditions as RS_Scenario_5 but with piloted ignition probability set at 100% and produced the same results suggesting street widths are sufficient to contain a fire in calm conditions under pre- and post-earthquake conditions. No animation was made of this scenario.

RS_Scenario_7 was run with a moderate breeze (20-29 km/hr) from the south, with contact, spontaneous and piloted ignition enabled, roof burn-through enabled, and with the buildings in the post-earthquake condition with some claddings damaged and glass broken. The fire spread via the roof and openings to adjacent buildings destroying the whole block (25 buildings) as in the previous scenario. However, sparks blown by the wind ignited buildings in the block to the north and the fire spread through that block destroying another 57 buildings. Driven by the wind, the fire continued to jump from block to block until it had engulfed four blocks and the scenario was terminated. In total some 140 buildings are burned.

RS_Scenario_8 was run with a moderate breeze (20-29 km/hr) from the south but with a wind change part way through the run, with contact, spontaneous, and piloted ignition enabled, roof burn-through enabled, and with the buildings in the post-earthquake condition with some claddings damaged and glass broken. This scenario started with a moderate southerly wind but at step 26 the model was stopped, the wind was changed to a gale force (62-74 km/hr) northerly and the model restarted at step 22. This allowed the fire to jump across the street to the next block to the south (something that did not happen in RR_Scenario_7) and from there jump several more streets in that direction. It also jumped to a block to the east of the source of the fire not ignited in RR_Scenario_7. The fire destroyed the 140 buildings burned by RR_Scenario_7 plus an additional 27 buildings in the block to the east and 197 buildings in the southern blocks.

4.0 OBSERVATIONS

The results of the various scenarios are shown in Table 2. It was not possible to test all possible combinations of fire spread modes but sufficient were tested to make some general observations.

In all scenarios contact and spontaneous ignition was enabled. Enabling piloted ignition increase losses in two of three locations. Branding was enabled at only one location but also increased losses. Enabling fire spread through roofs and other openings further increased losses in the two locations tested.

The inclusion of earthquake damage from a Wellington Fault event did not always increase fire losses and when fire losses increased it was by less than 30%.

Wind was included at two locations doubling the losses in a moderately densely populated neighbourhood for two different wind strengths but more than quadrupling losses in a densely populated neighbourhood even at low wind speeds. With a wind change to gale force and a direction change part way through the scenario losses more than doubled again. The scenarios run indicate that in moderate to densely populated parts of Wellington, building separation is not sufficient to prevent fire spread within a block but under calm conditions a fire is unlikely to jump a street. The introduction of a wind, however, can alter this situation and dramatically increase losses.

Area	Scenario Name	Fire Spread Modes Enabled					Wind	Earthquake Building Damage	Number of Buildings Destroyed
		C	S	P	B	R			
Rongotai	RR_Scenario_1	✓	✓					No	24
	RR_Scenario_2	✓	✓	✓				No	44
	RR_Scenario_3	✓	✓	✓			29-39 km/hr from south	No	44
	RR_Scenario_4	✓	✓	✓	10		40-59 km/hr from southeast	No	51
	RR_Scenario_5	✓	✓	✓				No	44
Fifeshire	FA_Scenario_1	✓	✓					No	1
	FA_Scenario_2 *	✓	✓	✓				No	1
	FA_Scenario_3	✓	✓	100				No	6
	FA_Scenario_4 *	✓	✓	✓				Yes	1
	FA_Scenario_5	✓	✓	✓		✓		No	21
	FA_Scenario_6	✓	✓	✓		✓		Yes	27
Riddiford	RS_Scenario_1	✓	✓					No	7
	RS_Scenario_2 *	✓	✓	✓				No	7
	RS_Scenario_3	✓	✓					Yes	9
	RS_Scenario_4 *	✓	✓	✓				Yes	9
	RS_Scenario_5	✓	✓	✓		✓		No	25
	RS_Scenario_6 *	✓	✓	100		✓		Yes	25
	RS_Scenario_7	✓	✓	✓		✓	20-29 km/hr from south	Yes	140
	RS_Scenario_8	✓	✓	✓		✓	20-29 km/hr from south 62-74 km/hr from north	Yes	364

Table 2. Summary of settings used and results of the scenarios created. Scenarios that produced the same result as a previous one were not made into animations and are denoted with an asterisk after the name. Fire Spread Mode C is ‘Contact ignition’, S is ‘Spontaneous Ignition’, P is ‘Piloted ignition’, B is ‘Brand Ignition’ and R is ‘Roof Collapse’ and ‘Openings’. A ✓ in the mode column indicates the default probability was used. Where a probability was altered from the default the probability in entered in the column. Fire spread modes and default probability values are given in Table 1.

4.1 Model realism

The model has been constructed with the best building data available but details of individual buildings have not been verified. As a result the model will contain errors that will affect fire spread patterns and timing and could negatively impact on its usefulness.

The models run for Rongotai Road, Fifeshire Avenue and Riddiford Street were demonstrated to officers of the New Zealand Fire Service. Feedback indicated that the models appeared realistic.

4.2 Potential uses of model

The model could be used to generate scenarios for desktop training exercises.

If it were rewritten to improve ease of use and speed it could be used to assess the potential consequences of not being able to respond to a fire. This could be important when restrictions are placed on man-power and machinery such as could be expected following an earthquake and it becomes necessary to choose which fires to fight with the limited resources available.

The information from the model must be used with caution and by individuals who understand the potential for variation. Its most applicable use in the short term may be for resource allocation as a similar model is used by the Tokyo Fire Department[7]. When multiple fires occur the model could be used to quickly determine whether individual fires will burn out quickly, affecting few buildings and are a low priority and where pre-existing fire-breaks such as wide roads and parks may prevent fire spread, with little or no fire-fighting intervention.

4.3 Model shortcomings

4.3.1 Model Complexity

The dynamic fire-spread model is complex with six modes of fire spread modelled. The model allows the user to assign probabilities for spread mechanisms where fire-spread is not guaranteed to be successful (piloted, brand, roof burn through, and opening penetration). Default values for each probability are offered to the user (see Table 1) but may be changed to any value. The model stores a pre-computed randomly assigned value (in the range 1 to 99) for each cell in the model for each mode of fire spread, and only those cells that have values less than the probability value selected by the user are able to be ignited by that form of ignition. As a consequence the model imitates a real fire, since not all sparks landing on preheated surfaces result in ignition.

The use of probability, however, introduces complexity to the model. The random assignment of values means that it is unlikely that a model will replicate an actual fire that spreads by one of these modes. In the modelling of the Napier fires [3], the modelled fire jumped westward across Hastings Street in the vicinity of the W.R Henderson pharmacy, whereas the historical evidence suggested that the crossing point should have been further to the south. In subsequent runs, the piloted ignition probabilities assigned to the buildings across Hastings Street from the W R Henderson pharmacy were altered in order to prevent this from occurring. And the converse situation will also occur, where the modelled fire does not jump a gap where a real fire would.

There is no solution to this problem since it can not be known with certainty whether a mode of spread will actually allow a real fire to spread, and even if it were possible to know this, no way to code it into the model. One solution would be to run a model with the probability of a particular mode of spread being set to 100% to see which gaps could be breached by that mode of spread. Two scenarios were run with piloted ignition probability set to 100% to investigate which gaps could have been breached but were prevented by the default probability. At Fifeshire Avenue the fire spread to a further five buildings that were in close proximity but at Riddiford Street building separation was greater and the fire did not spread further.

When cells are in direct contact and are flammable the assumption that fire will definitely spread is justified as the probability of a fire not spreading in this situation is very low and if fire were not to spread by direct contact, then spread by other modes would almost certainly occur anyway. The distance at which spontaneous ignition occurs is mostly affected by the assumption of the radiator temperature, but if spontaneous ignition did not occur in reality then piloted ignition is still very likely. Piloted ignition is most dependent on wind speed and direction. Wind speed is not constant and nor is direction. Furthermore local effects due to buildings and topography will always occur, including sudden wind shifts and gusts. It is not unknown in Wellington for the wind in a small area to be blowing in the opposite direction from the general direction of the wind. This can be seen in wind records from measuring stations that are relatively close together having obvious differences in wind speed and direction. In work done at Kyoto University in modelling The Sakata City Fire of 1976, using the wind record from two weather stations in the area produced different results [6].

4.3.2 Desirable variables

There are some variables that are desirable to include in the model, in order to increase it's realism, however these have not yet been incorporated.

4.3.2.1 Slope

Slope has a significant effect on the rate of fire spread in rural fires, with rates of spread up a 30 degree slope being 6 times faster than on the flat [8]. In the current urban model slope is not included.

The effect of slope in urban fire spread depends on how much it offsets adjacent buildings. On steep slopes, where the base of one house is above the roof of the next, fire is more likely to spread by spontaneous ignition to adjacent houses that are above the source. The majority of the heat radiated towards houses that are below the fire pass over the roof which would provide some protection. Fire spread by spark is also more likely for houses above since this mode of spread requires pre-heating of the surface that is ignited by a spark. Fire spread by branding is probably more likely for houses below the fire since the brand material would not need to be lifted very high to fall into plastic guttering. On low slopes where the buildings are less than a 1 m difference in elevation little effect is expected.

Building height is included in the current model and elevation could also be included. Visibility analysis would also need to be included and this process, which is used for the roof burn-through mode of spread and the openings mode of spread, takes time to run and could be expected to further slow the model.

4.3.2.2 Vegetation

The effect of vegetation in fire spread was discussed by a previous study [2] and was tested using the static fire spread model in Karori where trees and shrubs fill much of the space between houses and line many of the roads and much of the waste land surrounding the suburb is filled with small trees and shrubs along with stands of highly flammable gorse.

Capture of vegetation data from satellite imagery is possible but imagery with sufficient resolution is expensive. For that study, vegetation was captured from aerial photography for several blocks. The study assumed that all vegetation was flammable, and concluded that losses estimated for models run without including vegetation might be 50% of estimates made with vegetation included.

Including vegetation in the full dynamic model would not be simple. The current model assumes a time step of 2.5 minutes for a fire to pass through a 3 m cell of fuel. This was developed with buildings in mind. If the fire could pass through vegetation at a quicker rate then the model would need to be recalibrated for shorter time steps and changes made to the code to slow the passage through building fuel. Fires in rural areas have seen the fire front taking less than a few seconds to pass through a 3 m cell of dry grass [9] and 30 seconds to pass through a 3 m cell of gorse [10]. Other vegetation types will have different rates of fire propagation and each new rate will introduce more complexity and further slow the model down.

Vegetation could be easily included in the faster variant of the model since the time related to the each model step is irrelevant.

4.3.2.3 Other inputs

In the work to date it has been assumed that fire fighting would be non-existent or ineffective. This is considered likely to be the case after a major earthquake in Wellington but for the tool to be of use in other situations, or if resources are enhanced modelling the effect of fire suppression may be a desirable feature in the model.

If fire spread through vegetation is to be considered, then the recent weather is of great significance as the flammability of vegetation is highly dependant on how dry it is. A simple input for this variable may be the Fire Weather Index (FWI) used for helping to estimate the risk of wild fires.

Point sources of water, such as streams, salt water sumps or swimming pools can be identified and located in the model giving the Fire Service additional useful information on potential water supplies. The model with this information could also be used to determine appropriate locations for any future emergency fire-fighting water supplies. A similar model has been used to plan emergency water storage in Kobe[11].

4.3.3 Model Efficiency

The model runs in ArcInfo grid requiring any potential user to purchase expensive proprietary GIs software (ArcGIS at $35,000) and hardware. This software is not the most efficient method to run the simulations and recent experience suggest rewriting the model to run in another language could cut run times from many hours to several minutes. Rewriting the code should be possible for about $50 000.

Extensive training in GIS is required before non-GIS staff can format the data required for the tool to run, and a moderate level of knowledge required to use the tool. The code is considered suitable for research use but is not easily deployed for use in the field.

5.0 CONCLUSIONS

This model has the potential to be developed into a useful tool for fire-fighting in a post-earthquake fire situation rapidly providing information for resource allocation and evacuation.

The model needs to be operated and interpreted by individuals who understand its limitations and the potential variation between the model output and actual fire spread and the possible causes of this variation.

The model has the potential to quickly demonstrate the effects of changing conditions, in particular wind speed and direction but should be rewritten to be free of proprietary GIS software which places significant financial costs on potential users as well as dramatically slowing performance.

The model, when used to model a real fire (Rongotai Rd) demonstrated the effect that New Zealand Fire Service intervention had in reducing the property losses.

The model can also be used in forward planning for the New Zealand Fire Service, town planning and as a tool to assess the affects of potential building code changes in respect of fire spread.

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APPENDIX 1 MODIFIED MERCALLI SEISMIC INTENSITY SCALE FOR NEW ZEALAND - 2002

MM7 Zone

People
General alarm.
Difficulty experienced in standing.
Noticed by motorcar drivers who may stop.

Fittings
Large bells ring.
Furniture moves on smooth floors, may move on carpeted floors.
Substantial damage to fragile contents of buildings.

Structures
Unreinforced stone and brick walls cracked.
Buildings Type I cracked, some with minor masonry falls.
A few instances of damage to Buildings Type II.
Unbraced parapets, unbraced brick gables, and architectural ornaments fall.
Roofing tiles, especially ridge tiles may be dislodged.
Many unreinforced domestic chimneys damaged, often falling from roof line.
Water tanks Type I burst.
A few instances of damage to brick veneers and plaster or cement-based linings.
Unrestrained water cylinders (Water Tanks Type II) may move and leak.
Some Windows Type II cracked.
Suspended ceilings damaged.

Environment
Very small ($\leq 10^3 m^3$) disrupted soil slides and falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings are common.
Fine cracking on some slopes and ridge crests.
A few small to moderate landslides (10^3-10^5 m^3), mainly rock falls on steeper slopes (> 30˚) such as gorges, coastal cliffs, road cuts and excavations.
Small discontinuous areas of minor shallow sliding and mobilisation of scree slopes in places.
A few instances of non-damaging liquefaction (small water and sand ejections) in alluvium.

MM8 Zone

People
Alarm may approach panic.
Steering of motorcars greatly affected.

Structures
Buildings Type I heavily damaged, some collapse.
Buildings Type II damaged, some with partial collapse.
Buildings Type III damaged in some cases.
A few instances of damage to Structures Type IV.
Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down
Some pre-1965 infill masonry panels damaged.
A few post-1980 brick veneers damaged.
Decayed timber piles of houses damaged.
Houses not secured to foundations may move.
Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Environment
Cracks appear on steep slopes and in wet ground.
Significant landsliding likely in susceptible areas.
Small to moderate slides (10^3-10^5 m^3) widespread; mainly rock and disrupted soil falls on steeper slopes (steep banks, terrace edges, gorges, cliffs, cuts etc).
Significant areas of shallow regolith landsliding, and some reactivation of scree slopes.
A few large (10^5-10^6 m^3) landslides from coastal cliffs, and possibly large to very large ($\geq 10^6 m^3$) rock slides and avalanches from steep mountain slopes.
Larger landslides in narrow valleys may form small temporary landslide-dammed lakes.
Roads damaged and blocked by small to moderate failures of cuts and slumping of road-edge fills.

Evidence of soil liquefaction common, with small sand boils and water ejections in alluvium, and localised lateral spreading (fissuring, sand and water ejections) and settlements along banks of rivers, lakes and canals etc.

MM9 Zone

Structures
Many Buildings Type I destroyed.
Buildings Type II heavily damaged, some collapse.
Buildings Type III damaged, some with partial collapse.
Structures Type IV damaged in some cases, some with flexible frames seriously damaged.
Damage or permanent damage to some Structures Type V.
Houses not secured to foundations shifted off.
Brick veneers fall and expose frames.

Environment
Cracking on flat and sloping ground conspicuous.
Landsliding widespread and damaging in susceptible terrain, particularly on slopes steeper than 20˚.
Extensive areas of shallow regolith failures and many rock falls and disrupted rock and soil slides on moderate to steep slopes (20˚-35˚ or greater), cliffs, escarpments, gorges and man-made cuts.
Many small to large (10^3-10^6 m^3) failures of regolith and bedrock, and some very large landslides ($10^6 m^3$ or greater) on steep susceptible slopes.
Very large failures on coastal cliffs and low-angle bedding planes in Tertiary rocks. Large rock/debris

avalanches on steep mountain slopes in well-jointed greywacke and granitic rocks. Landslide-dammed lakes formed by large landslides in narrow valleys

Damage to road and rail infrastructure widespread with moderate to large failures of road cuts and slumping of road-edge fills. Small to large cut slope failures and rock falls in open mines and quarries

Liquefaction effects widespread with numerous sand boils and water ejections on alluvial plains, and extensive, potentially damaging lateral spreading (fissuring and sand ejections) along banks of rivers, lakes, canals etc. Spreading and settlement of river stopbanks likely.

MM10 Zone

Structures

Most Buildings Type I destroyed.
Many Buildings Type II destroyed.
Many Buildings Type III heavily damaged, some collapse.
Structures Type IV damaged, some with partial collapse.
Structures Type V moderately damaged, but few partial collapses.
A few instances of damage to Structures Type VI.
Some well-built timber buildings moderately damaged (excluding damage from falling chimneys)

Environment

Landsliding very widespread in susceptible terrain.

Similar effects to MM9, but more intensive and severe, with very large rock masses displaced on steep mountain slopes and coastal cliffs. Landslide-dammed lakes formed. Many moderate to large failures of road and rail cuts and slumping of road-edge fills and embankments may cause great damage and closure of roads and railway lines.

Liquefaction effects (as for MM9) widespread and severe. Lateral spreading and slumping may cause rents over large areas, causing extensive damage, particularly along river banks, and affecting bridges, wharves, port facilities, and road and rail embankments on swampy, alluvial or estuarine areas.

MM11 Zone

Structures

Most Buildings Type II destroyed.
Many Buildings Type III destroyed.
Structures Type IV heavily damaged, some collapse.
Structures Type V damaged, some with partial collapse.
Structures Type VI suffer minor damage, a few moderately damaged.

MM12 Zone

Structures

Most Buildings Type III destroyed.
Many Structures Type IV destroyed.

Many Buildings Type V heavily damaged, some with partial collapse.
Structures Type VI moderately damaged.

Categories of Construction

Buildings Type I:

Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete, or composite materials (e.g. some walls timber, some brick) not well tied together. Masonry buildings otherwise conforming to Buildings Types I-III, but also having heavy unreinforced masonry towers. (Buildings constructed entirely of timber must be of extremely low quality to be Type I).

Buildings Type II:

Buildings of ordinary workmanship, with mortar of average quality. No extreme weaknesses, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces. Such buildings not having heavy unreinforced masonry towers.

Buildings Type III:

Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed to resist earthquake forces.

Structures Type IV:

Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken (mid-1930's to c. 1970 for concrete and to c.1980 other materials).

Structures Type V:

Buildings and bridges designed and built to normal use standards, i.e. no special damage limiting measures taken, other than code requirements, dating from since c. 1970 for concrete and c.1980 other materials.

Structures Type VI:

Structures, dating from c. 1980, with well-defined foundation behaviour, which have been specially designed for minimal damage, e.g. seismically isolated emergency facilities, some structures with dangerous or high contents, or new generation low-damage structures.

Windows Type I:

Large display windows, especially shop windows.

Windows Type II:

Ordinary sash or casement windows.

Water Tanks Type I:

External, stand mounted, corrugated iron water tanks

Water Tanks Type II:

Domestic hot-water cylinders unrestrained except by supply and delivery pipes.

H (Historical):
Important for historical events. Current application only to older houses, etc.

General Comment:

"Some" or "a few" indicates that the threshold of a particular effect has just been reached at that intensity.

"Fragile contents of buildings". Fragile contents include weak, brittle, unstable, unrestrained objects in any kind of building.

"Well-built timber buildings" have: wall openings not too large; robust piles or reinforced concrete strip foundations; superstructure tied to foundations.

Buildings Type III-V at MM10 and greater intensities are more likely to exhibit the damage levels indicated for low-rise buildings on firm or stiff ground and for gs on soft ground. By inference lesser damage to low-rise buildings on soft ground and high-rise buildings on firm or stiff ground may indicate the same intensity. These effects are due to attenuation of short period vibrations and amplification of longer period vibrations in soft soils.