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EARTHQUAKE SCENARIO, MELBOURNE

Mw 5.5, 6.0 & 7.0

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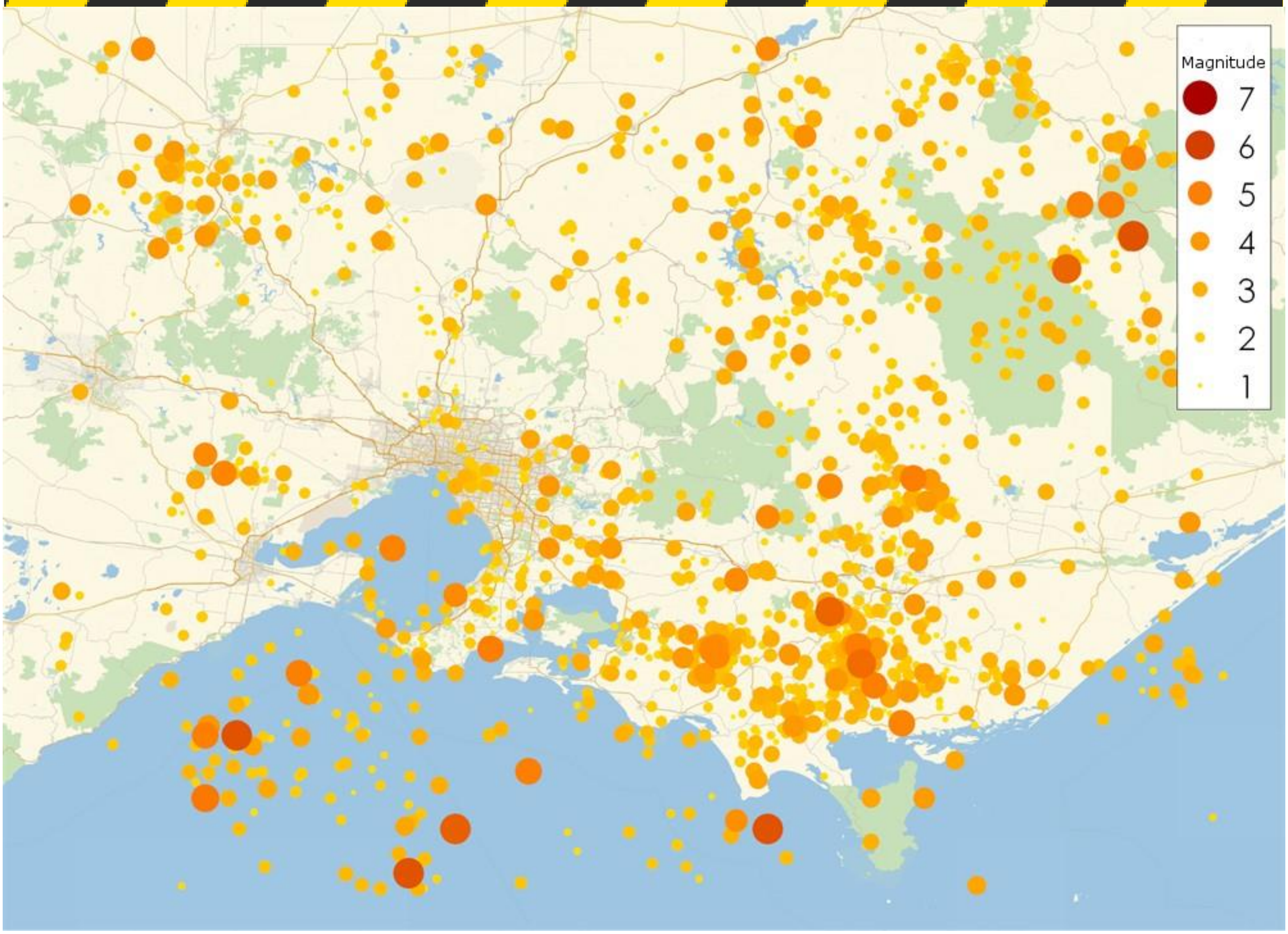
Bushfire and Natural Hazards CRC



Version	Release history	Date
1.0	Initial release of document	05/01/2017

Australian Government
Department of Industry, Innovation and Science

Business Cooperative Research Centres Programme

Publisher:
Bushfire and Natural Hazards CRC

January 2017

Citation: Koschatzky V, O'Brien J, Somerville P (2017) Earthquake Scenario, Melbourne, Bushfire and Natural Hazards CRC

Cover: Historical earthquake epicentres in southern Victoria.

TABLE OF CONTENTS

Summary

Despite its low seismic activity, Australia is more vulnerable to earthquakes than one would expect due to the concentration of population and the large stock of buildings which are structurally unable to withstand even moderate seismic shaking. This was demonstrated by the 1989 M5.6 Newcastle earthquake, one of the costliest natural disasters in Australia, despite its low magnitude. One question elicited by these circumstances is: what would happen if one of Australia's main cities were hit by an earthquake similar to the Newcastle earthquake? An example of a near miss is the 1954 M5.6 Adelaide earthquake, whose epicentre, far from developed areas at the time, would lie in densely developed areas were it to occur today. Providing realistic estimates for natural disaster scenarios is essential for emergency managers. A systematic approach to developing such scenarios can reveal blind spots and vulnerabilities in planning. Following the Adelaide Scenario delivered in 2015 we now look into a series of realistic disaster earthquake scenarios for the city of Melbourne.

1 Earthquake Hazard

1.1 Tectonic setting

Australia is a tectonically stable continental region, SCR, (Johnston, A.C., 1994) surrounded by plate boundaries extending from New Zealand through the islands of the Western Pacific to New Guinea and Indonesia. Australia is more seismically active than other SCRs, and the western half of Australia has experienced numerous surface faulting earthquakes in the past century. There is also clear evidence of surface faulting earthquakes in Victoria.

1.2 Active faults

Earthquakes occur when the two opposite sides of an active fault slip past each other. Three kinds of active faults are illustrated in the top panel of Figure 1. Most of the faults in Victoria are reverse faults (left side), in which one side (the hanging wall side) moves up and over the other side (the foot wall side). Reverse faulting earthquakes result in horizontal shortening of the crust. Normal faulting earthquakes, shown in the centre panel, result in horizontal extension of the crust, and are uncommon in Australia because Australia is generally subject to high compressive stress. Strike-slip earthquakes, shown in the right panel, result in horizontal movement of one side of the fault past the other side.

In Australia, faults usually occupy the depth range of zero to 15 or 20 km, and their lengths are typically tens of km to over one hundred km. The earthquake begins at a point on the fault called the hypocentre, with slip spreading rapidly across the fault surface at a speed of about 2.5 to 3 km/sec. The amount of slip on the fault generally increases with the magnitude of the earthquake. A magnitude 6 reverse faulting earthquake typically ruptures a fault having a length of about 10 km and a width of about 10 km with an average slip of about 30 cm. A magnitude 7 reverse faulting earthquake typically ruptures a fault having a length of about 50 km and a width of about 20 km with an average slip of about 1.5 m.

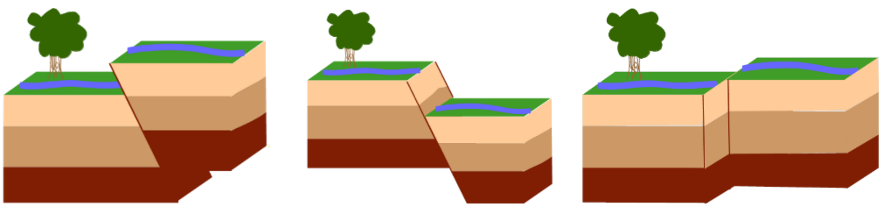


Figure 1: Three types of faults: Reverse, Normal, and Strike-Slip

Following Clark and McPherson (2011) and Sandiford (2003), we consider potentially active faults as those that have undergone displacement under the current stress regime in Australia, and hence may have the potential for displacement in the future. The age of the current stress regime in Australia is estimated to lie in the range of 5 to 10 million years (Sandiford, 2003). In Australia, geological maps typically show numerous faults but do not indicate whether they are active in the current stress regime; most of them are probably not. For example, if these faults were previously active under a different stress orientation, it is possible that they are now unfavourably oriented to undergo slip under the current stress orientation. However, if they are favourably oriented, then consideration should be given to the possibility that they have been reactivated under the current stress regime. Clark and McPherson (2011) and Clark et al. (2012) analysed a catalogue of over 322 neotectonic features, 47 of which are associated with named fault scarps. The faults in the region surrounding Melbourne are shown in Figure 2. The data were derived from analysis of DEMs, aerial photos, satellite imagery, geological maps and consultation with State survey geologists and a range of other earth scientists including Dickinson et al. (2002), Figure 3. Verifying the features as active faults is an ongoing process. The catalogue varies in completeness because sampling is biased by the available data bases, the extent of unconsolidated sedimentary cover, and the relative rates of landscape and tectonic processes.

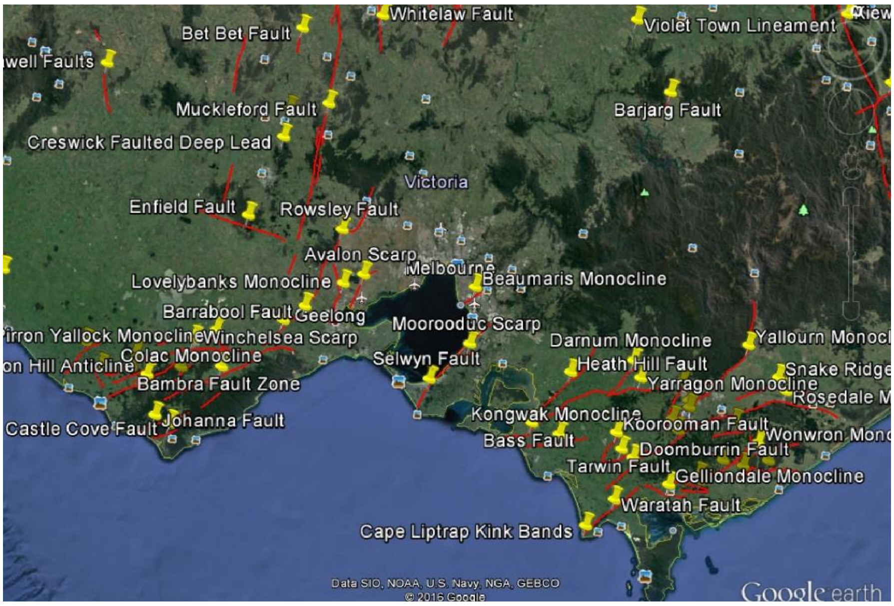


Figure 2: Neotectonic features in southern Victoria. Source: Clark and McPherson (2011)

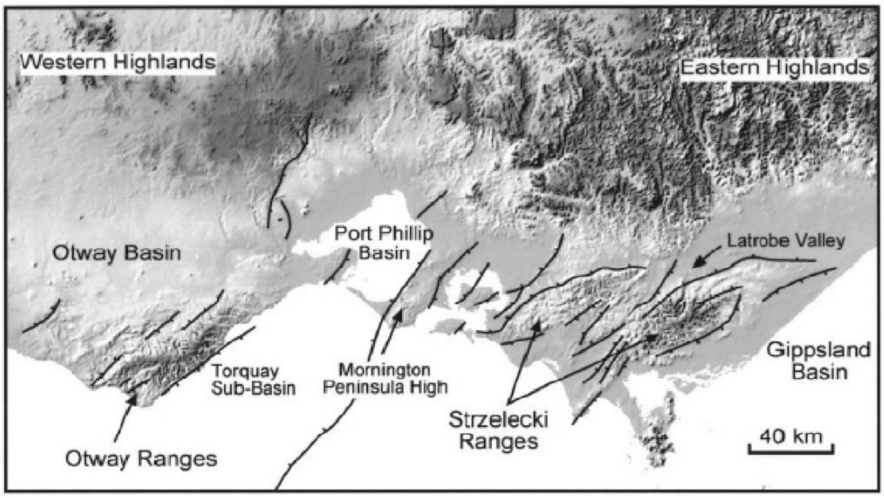


Figure 3: Active faults in southern Victoria. Source: Dickinson et al. (2002)

1.3 Historical seismicity

The historical seismicity on the Melbourne Region is shown in Figure 4 and has been described by McCue (2015). Melbourne has experienced fewer earthquakes than the surrounding regions, especially to the east, where relatively frequent earthquakes are associated with active faulting that is uplifting the Strzelecki Ranges (Figure 3). There are no historical reports of significant earthquake damage in Melbourne.

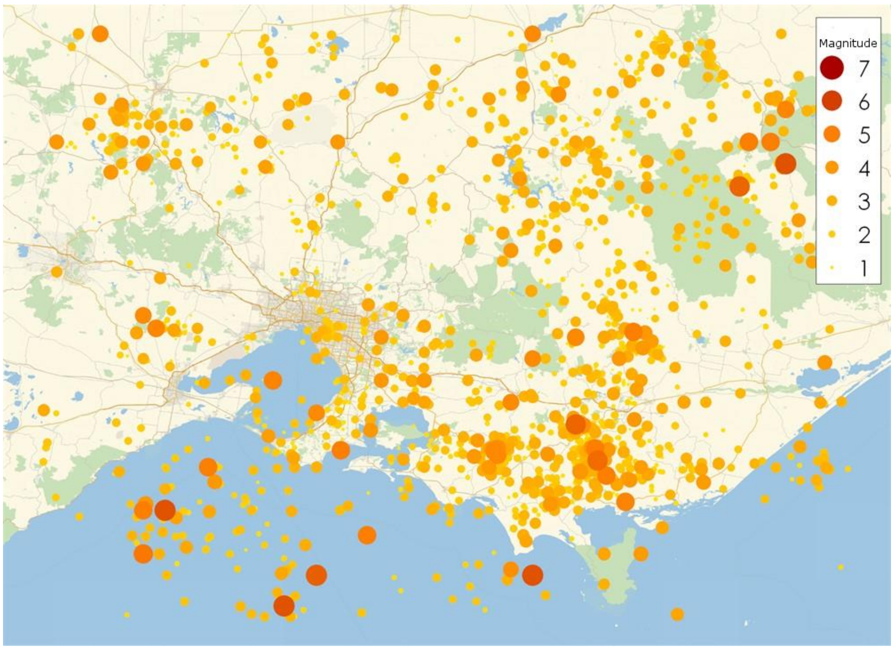


Figure 4: Historical earthquake epicentres in southern Victoria.

The largest earthquake that has been felt in Melbourne is the 10 April 1922 Ocean Grove earthquake, (McCue, 2015). The MMI intensity of the earthquake is shown in Figure 5. McCue (2015) reviewed widely varying reports on the location and magnitude of the earthquake, with locations varying from north of King Island to Flinders Island in Tasmania to east of Lorne, Victoria, and magnitudes varying from 4.8 to 5.7. He concluded that the earthquake occurred east of Lorne with a magnitude of 5.7. Ground shaking was felt at Burnie on the northwest coast of Tasmania, it was felt strongly on King Island, and was felt as far west as Warrnambool and north to Ivanhoe in Victoria. It was felt throughout Melbourne; a chimney reportedly collapsed in Glen Iris and several places reported that crockery had vibrated off shelves and broken in Pakenham, Portarlington, Cranbourne and East Malvern. The MMI Intensity in Melbourne shown in Figure 5 is 3.5, corresponding approximately to light perceived shaking and no potential damage (Figure 6).

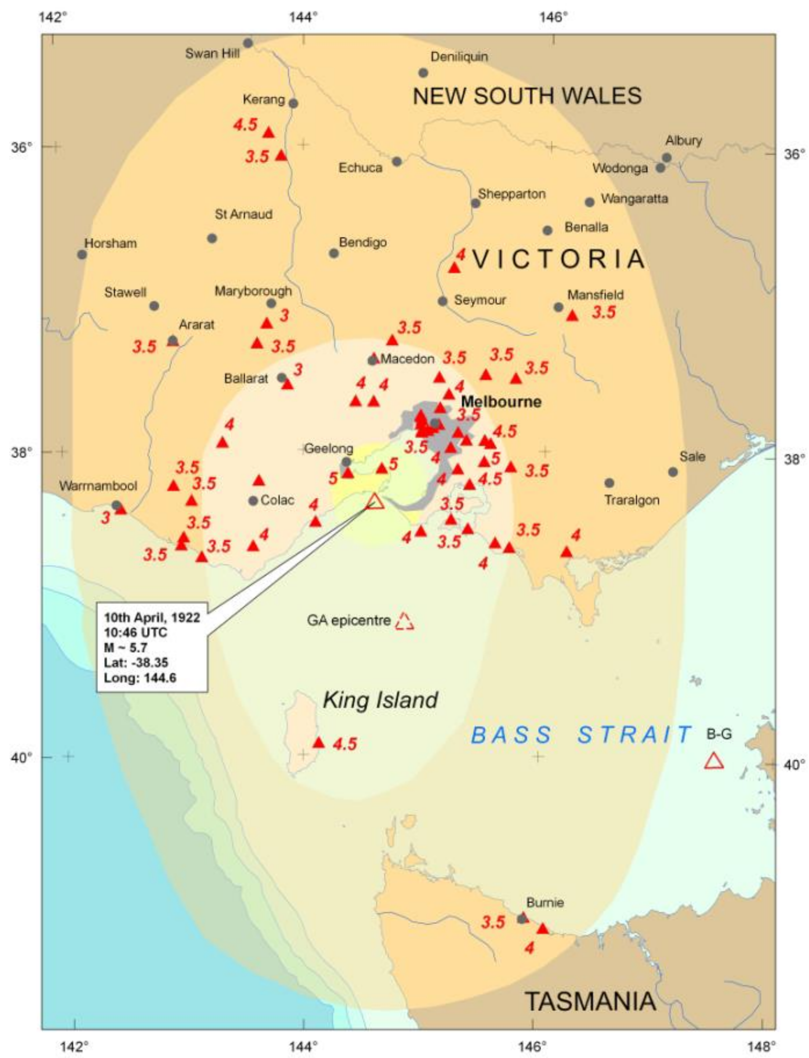


Figure 5: MMI Intensity map of the 1922 M 5.7 Ocean Grove earthquake. Source: (McCue, 2015)

The most recent earthquake to affect Melbourne is the magnitude 5.4 earthquake that occurred near Thorpdale about 10km south of Moe on 19 June 2012. This earthquake was followed by a normal aftershock sequence in which the frequency of aftershocks decreases with time. The largest aftershock had a magnitude of 4.5, consistent with the observation that the largest aftershock typically has a magnitude that is about one unit lower than the mainshock. It seems most likely that the Moe earthquake occurred either on the Morwell fault or the Yarram fault.

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL. (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 6: Relationship between Intensity and ground motion level expressed as peak ground acceleration (%g) and peak ground velocity (cm/sec)

The intensity distribution of the Moe earthquake, with contours elongated to the north (Figure 7), seems most compatible with the occurrence of the earthquake on the Morwell fault, because rupture beginning at depth and rupturing updip to the north would focus energy in that direction. The Yarram fault dips up to the south. Some minor building damage was reported in the Latrobe Valley close to the epicentre, and in the eastern suburbs of Melbourne. The ground shaking intensity experienced in Melbourne was MMI IV, corresponding to moderate perceived shaking and very light potential damage (Figure 6).

2 Scenario selection

Under request from the end users we consider three events of magnitudes 5.5, 6 and 7 with the epicentre between 7.5 and 9 km underneath the Melbourne CBD, Figure 8. These are events significantly larger than the ones historically recorded within the city and do not lie on any of the known faults considered as active. Nevertheless, it is still possible for such events to occur, although with quite remote probabilities.

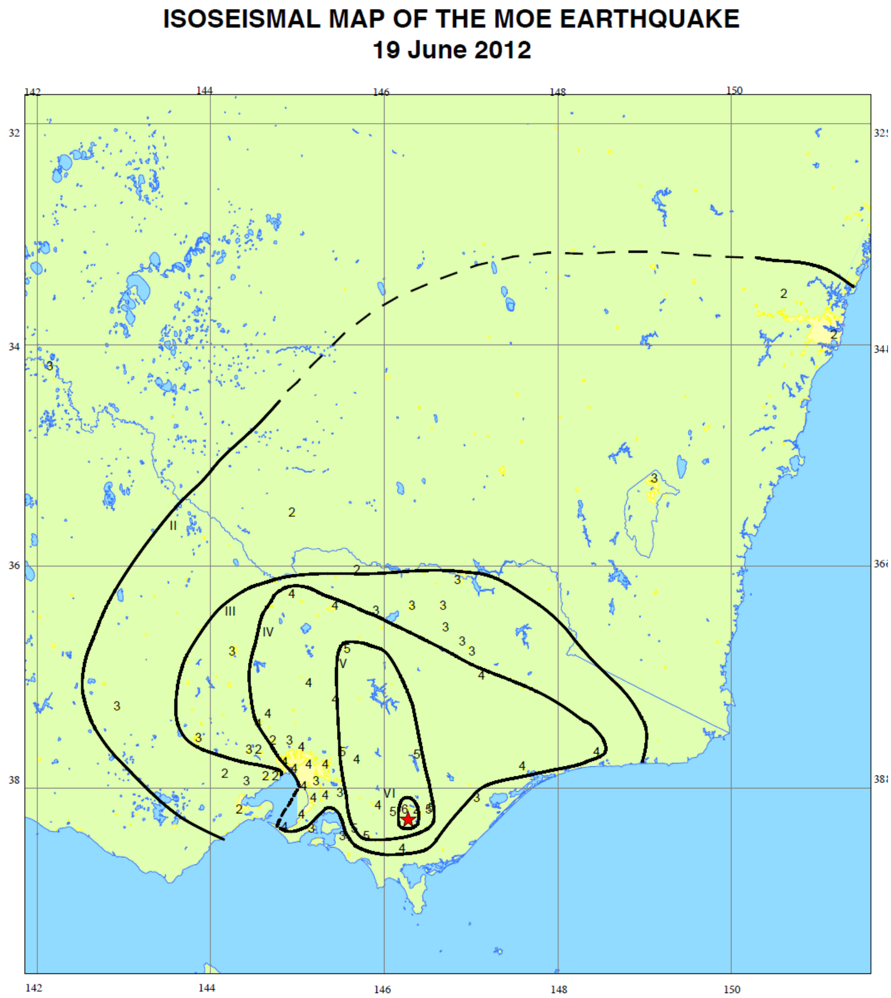


Figure 7: MMI Intensity map of the 2012 M 5.4 Moe earthquake. Source: Geoscience Australia

Figure 8: Surface projection of the three considered event fault ruptures. Green: Mw 5.5, Orange: Mw 6 and Purple: Mw 7.

3 Methodology

Loss modelling is the exercise by which statistical models are developed to quantify damage (material, financial and casualties) based on the physical parameters of a disaster event. To perform this exercise it is necessary first to estimate the probabilities of the physical parameters that may lead to damage. For earthquakes this is: the probability of an event occurring at a given location, soil conditions, and probable ground motion levels. To calculate damage, it is necessary to use a set of statistical models that tell us how much damage is expected for a given level of ground shaking.

We estimate the probable ground motion level for the chosen events, magnitude 5.5, 6 and 7 earthquakes with epicentres shown in Figure 8, using the ground motion prediction equations developed by Somerville et al. (2009) and the soil condition maps from McPherson and Hall (2006).

The calculation of losses is performed with the methodology developed by the US Federal Emergency Management Agency (FEMA) through its model HAZUS (FEMA, 2004). This model is derived from expert opinion and past-event experience. The HAZUS methodology provides functional relationships between physical earthquake parameters and probability distribution of building or infrastructure response to shaking. Physical earthquake parameters can be peak ground acceleration (PGA), velocity (PGV), displacement (PGD) or the full response spectrum.

The HAZUS methodology describes four damage states and provides the probabilities for a particular building or facility to be in any one of these. HAZUS also provides the financial cost relative to the total value associated with each damage state; this allows us to calculate loss estimates for this scenario.

The HAZUS methodology also provides estimates of the number of casualties. These estimates take into consideration the probability that a structure will collapse, the spatial distribution of people at different times of the day, and the likelihood of a person being indoors or outdoors at the time of the earthquake.

The methodology provided by HAZUS entails a high degree of uncertainty since many factors determining the outcome of an earthquake cannot be modelled without specific information about the circumstances. For example, the time of day plays an important role in determining human casualties. The first Christchurch earthquake on September 4th 2010 hit at 4:25 am. In spite of the many collapsed buildings in the CBD, no fatalities resulted. The aftershock on February 22nd, on the other hand, occurred during business hours (12:51 pm on a Tuesday) and killed 168 people. The fact that the aftershock's ground motions greatly exceeded building code levels while the mainshock's ground motions were generally at or below building code levels in Christchurch was another cause of the larger number of casualties in the February event. The same can be said of the 2007 Gisborne earthquake, which hit at 8:55 pm resulting in no direct casualties, despite many parapets falling in footpaths across the town (see section 2 of AEE (2008)).

To estimate the damage (material, financial and casualties) caused by the earthquake we combine the following exposure and hazard datasets:

- Population distribution data, from an analysis of the 2011 Census and statistics provided by the Department of Higher Education.

- Inventory (building stock distribution) data, from the National Exposure Information System (NEXIS) database and the Geocoded National Address File (G-NAF) database.

- Damage state probabilities, calculated using Risk Frontiers' earthquake loss model QuakeAUS. This model implements the HAZUS methodology for the damage states estimate on top of a seismic source model (Hall et al., 2007), and ground motion prediction equations (Somerville et al., 2009), developed specifically for Australia.

4 Exposure

In this section we summarise the data sources and the methodology followed to model the exposed buildings, population and essential facilities.

4.1 Buildings

Exposure data consisting on the number of addresses exposed are taken from the Geocoded National Address File (G-NAF) database, developed by PSMA (PSMA, 2015). G-NAF combines over 13 million addresses all over Australia from 10 authoritative sources: each of the governments of Australia, the Australian Electoral Commission and Australia Post.

Each address in G-NAF has a unique identifier and geographic coordinates.

Data on building types and age distributions across Australia are taken from the National Exposure Information System (NEXIS) database, developed by Geoscience Australia (Geoscience Australia, 2015). NEXIS maintains information about residential, commercial and industrial buildings. In the version used for this scenario, the data is aggregated at a SA1 level - the smallest Australian Census block with detailed demographic data.

4.2 Population

We estimate the population distribution at two different times of a mid-week day:

- 2.00 AM (Night time scenario)
- 2.00 PM (Day time scenario)

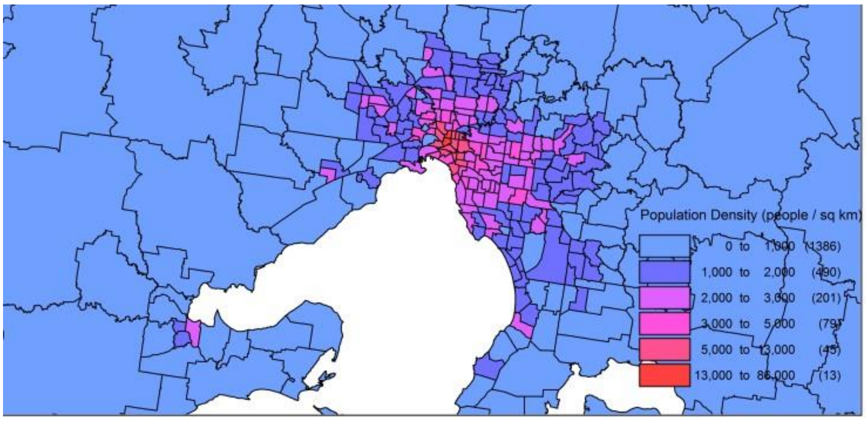
These scenarios are expected to generate the highest casualties for the population at home and the population at work/school, respectively. Table 1 provides the relationships used to determine the population distribution. There are two multipliers associated with each entry in the table. The first multiplier apportions the population of a given occupancy into indoors and outdoors. The second multiplier indicates the fraction of the total population that is present in an occupancy at a particular time. For example at 2AM, 99% (0.99) of the population will be in a residential occupancy and 99.9% (0.999) of those people will be indoors. Figure 9 shows the estimated population density during the day and at night time.

Table 1: Population Distribution at different times of the day.

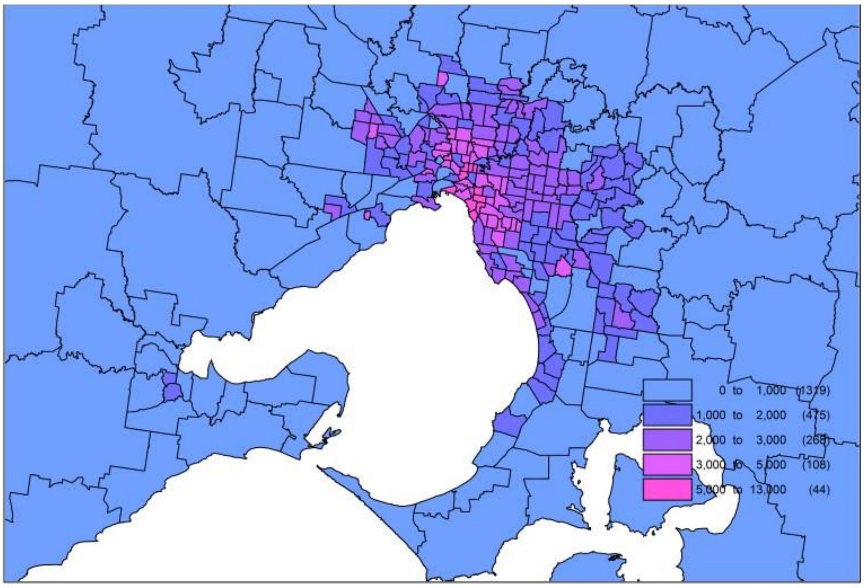
Occupancy	2.00 AM	2.00 PM	Notes
		INDOOR	
Residential	(0.999)0.99(NRes)	(0.7)0.74(DRes)	Residents at Home
Commercial & Industrial	(0.999)0.02(Wor)	(0.8)1.0(Wor) +(0.8)0.2(DRes)	Workers Residents Attending Business
Educational		(0.8)1.0(L15) +(0.8)0.06(DRes)	Pre-Schoolers and Grade Students Higher Education Students
		OUTDOOR	
Residential	(0.001)0.99(NRes)	(0.3)0.74(DRes)	Residents at Home
Commercial & Industrial	(0.001)0.02(Wor)	(0.2)1.0(Wor) +(0.2)0.2(DRes)	Workers Residents Attending Business
Educational		(0.2)1.0(L15) +(0.2)0.06(DRes)	Pre-Schoolers and Grade Students Higher Education Students

Where:

NRes: All Residents
DRes: Not Working
L15: All Residents Less Than 15 **Wor:** Working



(a) Day Time.



(b) Night Time

Figure 9: Population Density in greater Melbourne area

4.3 Essential facilities and infrastructure

We gathered data about the location of critical buildings and infrastructure from two databases:

- RoadNet, developed by Map Data Services.
- Features of Interest, developed by the Public Sector Mapping Agency (PSMA).

5 Hazard modeling

We model the events (Figure 8) as rupturing fault planes. The epicentres lie between 7.5 and 9 km underneath the Melbourne CBD. The faults are dipping at 45 degrees to the ESE. Fault dimensions are consistent with Leonard (2010) and Somerville et al. (2009).

5.1 Ground shaking

Spectral acceleration is used to model ground shaking, and describes the response (e.g. amplitude, maximum velocity) of a simple harmonic oscillator (mass-spring system) subject to seismic ground motion. This definition is important because buildings can be modeled as simple harmonic oscillators to a first approximation. As a general rule, the resonance frequency of a building depends on its height and rigidity; according to an engineering rule-of-thumb, by a factor of 10 of the motion period (i.e. a 10 storey building will respond to 1s spectral acceleration, 5 storey to 0.5s and so on).

The ground motion levels for the chosen events are calculated using the ground motion prediction equations developed by Somerville et al. (2009) and the soil condition maps from McPherson and Hall (2006). We calculate the full demand spectrum for each location.

Figure 10 shows the median peak ground spectral acceleration at all the affected locations for the three scenarios. Generally speaking, damage is expected to occur when the peak ground acceleration exceeds 0.1g, shown by blue shading in figure 10.

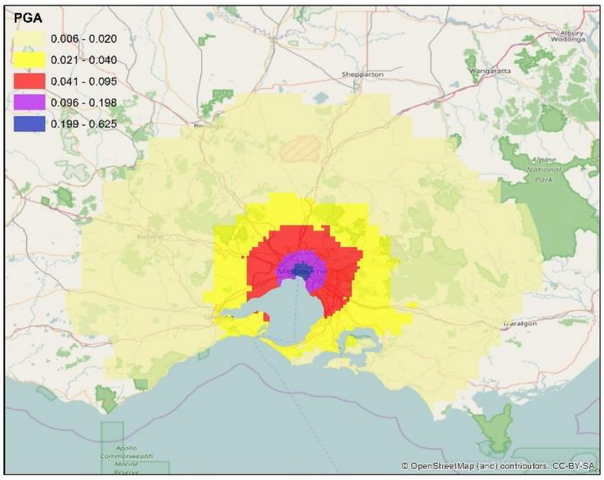
We performed a Monte Carlo simulation of the ground shaking for each of the scenarios which results in a probability distribution of losses and casualties. These results are shown in figures 12, 13 and 14. Monte Carlo simulation refers to the process of randomly selecting combinations of random variables to account for the random nature of these parameter values.

5.2 Ground displacement and liquefaction

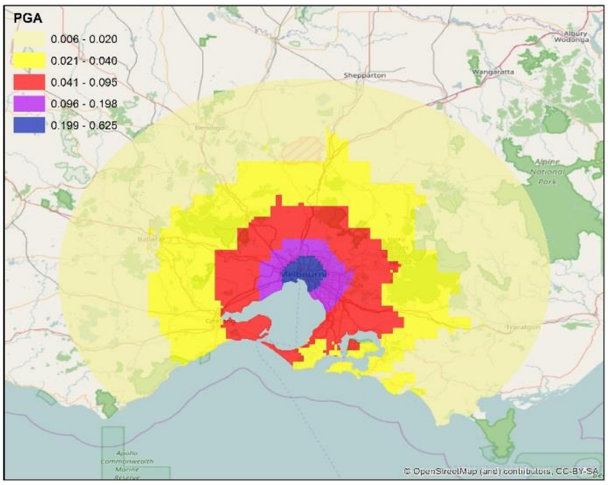
In this section we discuss permanent ground displacement due to liquefaction. Liquefaction is a soil behavior phenomenon in which saturated soil loses a substantial amount of strength due to high excess pore-water pressure generated by, and accumulated during strong earthquake ground shaking. The likelihood of experiencing liquefaction at a specific location is primarily influenced by soil type, ground shaking intensity and duration, and depth of groundwater.

Liquefaction damage was one of the main causes of destruction in the Christchurch 2010 event, affecting transportation and water networks. In general it has greater probability of occurrence along river banks and, when it occurs, it tends to damage bridges as river banks start sliding towards each other. We have produced a liquefaction potential map for Melbourne by using a geostatistical model that uses distance to water bodies, elevation, soil type and ground shaking to parameterize the probability that a site will liquefy, (Knudsen et al., 2009). For these scenarios, liquefaction would likely occur around the banks of the Yarra River and of the creeks and rivers around the CBD, and could potentially destroy a number of bridges.

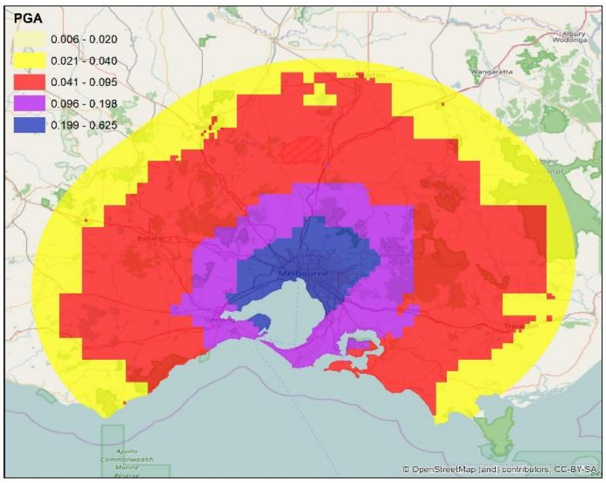
Combined with shaking, liquefaction damage may render parts of Melbourne inaccessible for large extents of time and cause long term infrastructure damage – see the historical notes on water supply damage in Christchurch in the Adelaide Earthquake Scenario Technical Note. Figure 11 shows an overlay of the Melbourne road network and the liquefaction potential map for each of the 3 scenarios.



(a) Mw 5.5

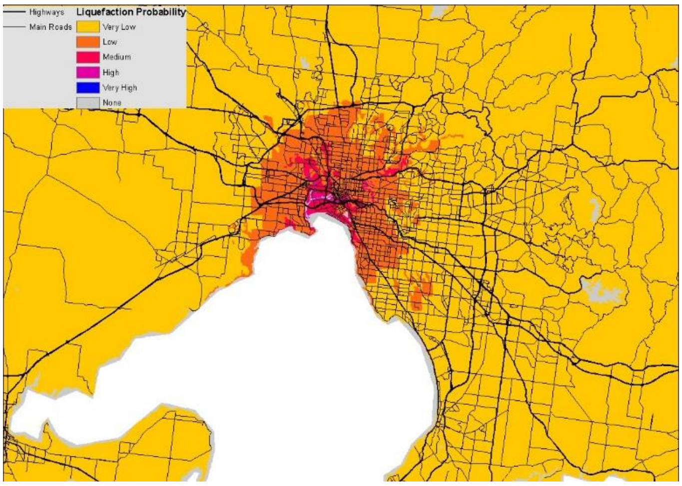


(b) Mw 6

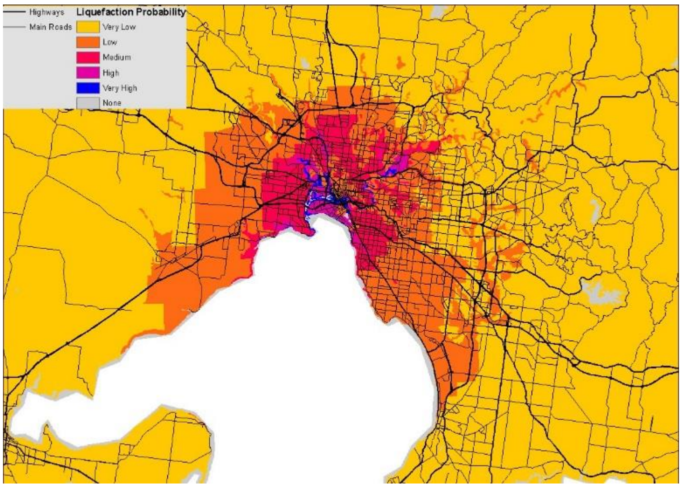


(c) Mw 7

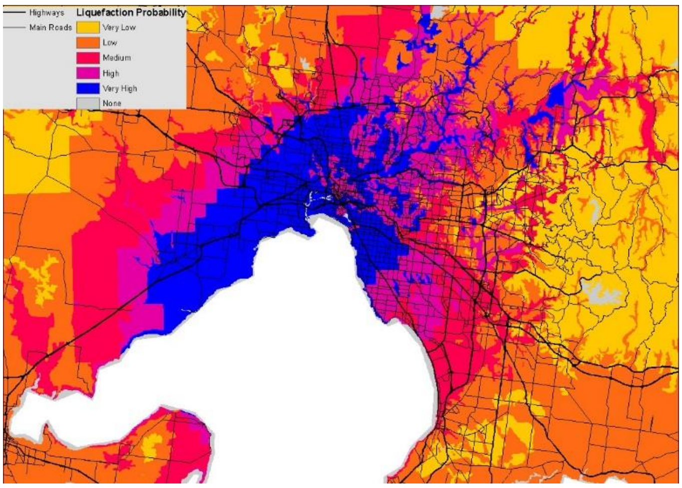
Figure 10: Median Peak Ground Acceleration (PGA) for the three scenarios. Mw = magnitude. The epicentres are located at the centres of the blue zones



(a) Mw 5.5



(b) Mw 6



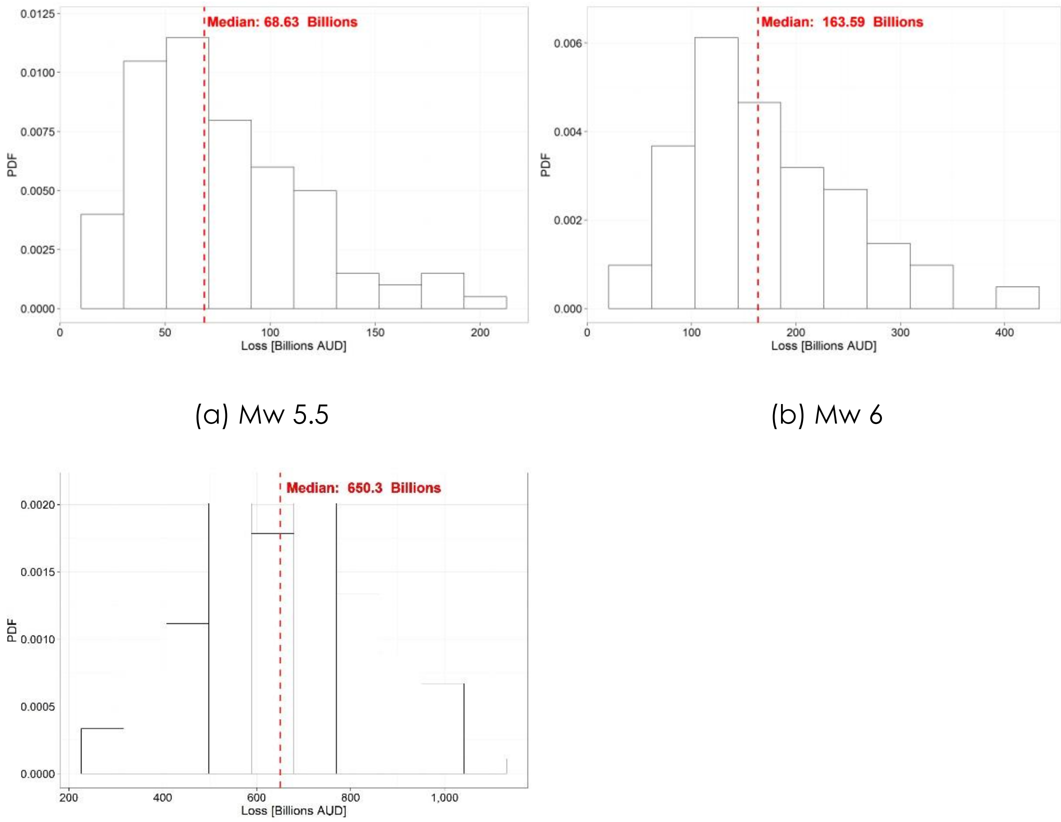
(c) Mw 7

Figure 11: Liquefaction potential map for Melbourne. Hot colours represent areas with higher probability of liquefaction. Mw = magnitude

6 Impact modeling

For each of the three selected scenarios, Figure 8, we performed a Monte Carlo simulation of the hazard which generates a probability distribution of losses and casualties. Figure 12 shows the probability distributions of losses to buildings for the three scenarios, the median value is highlighted in Red. Figures 13 and 14 show the distributions of casualties (severe injuries and deaths) at day-time and night-time for the three scenarios.

In the remainder of the report we focus on the outcomes of the median events. Figure 15 show a breakdown of losses to buildings for the three events while Figure 16 and 17 shows the breakdown of casualties by injury level at day- and night-time for the three events.



(a) Mw 5.5

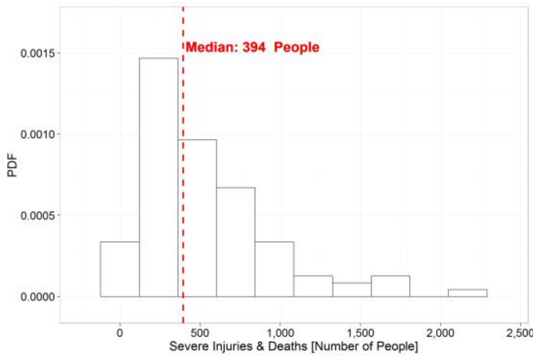
(b) Mw 6

(c) Mw 7

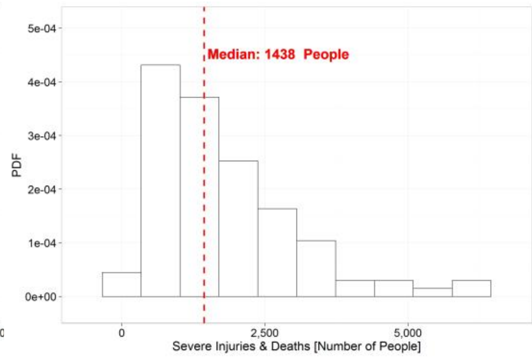
Figure 12: Probability distribution of losses to buildings.

6.1 Building damage

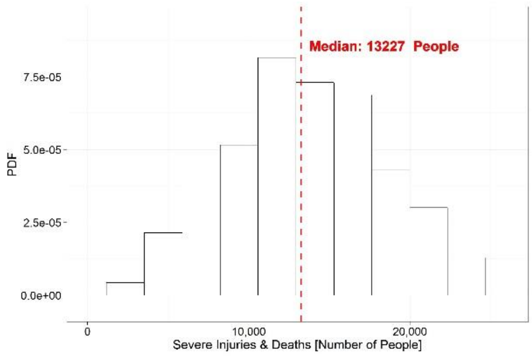
The demand spectrum described in section 5.1 is applied, via the capacity spectrum method described in HAZUS, FEMA (2004), to each building category present in the location according to NEXIS. This allows the evaluation of the structural response of every particular building to each particular demand spectrum. We then use the vulnerability curves provided by HAZUS which best match the NEXIS building categories to estimate the probable damage to the buildings. Figures 15 show the extent of the damage to buildings. Table 2 summarise the number of Buildings Destroyed (Count of Replacement Values) by event for the whole area.



(a) Mw 5.5



(b) Mw 6



(c) Mw 7

Figure 13: Probability distribution of Casualties, Day-Time.

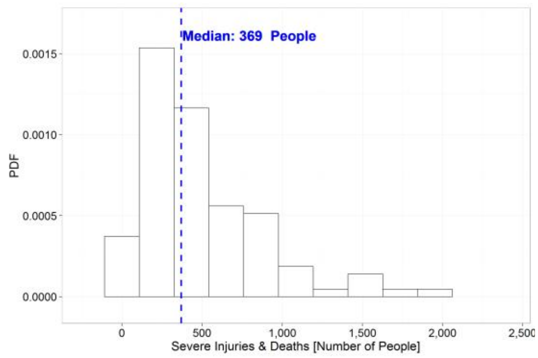
Table 2: Number of Equivalent Addresses Destroyed.

Event	Number of Addresses
1	63,452
2	126,955
3	609,138

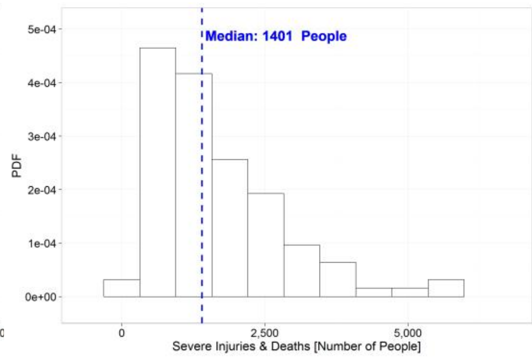
6.2 Casualties

We apply the ground shaking calculated by the Risk Frontiers earthquake model for the chosen scenario to the local building inventory. The damage states probabilities for the building stock are used in conjunction with the estimated population distribution to calculate casualties. The output from the HAZUS model is given on a four level injury severity scale:

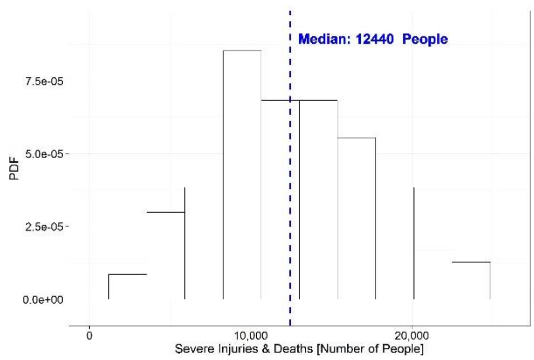
- **Severity 1:** Injuries requiring basic medical aid that could be administered by paraprofessionals. Injuries that could be self-treated are not considered.
- **Severity 2:** Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life threatening status.
- **Severity 3:** Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously.
- **Severity 4:** Instantaneously killed or mortally injured.



(a) Mw 5.5



(b) Mw 6



(c) Mw 7

Figure 14: Probability distribution of Casualties, Night-Time.

Figures 16 and 17 shows the median spatial distribution of severe injuries and deaths (sum of severity 3 and 4) to be expected from the modeled events.

Table 3: Median total casualties by severity level and time of the day (Number of People).

	Event 1		Event 2		Event 3	
Severity	Day	Night	Day	Night	Day	Night
1	4,039	4,037	12,581	12,875	101,947	103,937
2	1,252	1,285	3,741	3,860	31,576	31,412
3	104	93	412	381	4,631	4,190
4	197	181	779	744	8,690	8,159

6.3 Essential facilities

Essential facilities comprise hospitals, fire and police stations, emergency operation centres and schools – all are essential to provide support in the event of an earthquake (schools provide evacuation centres). Such buildings are designed to withstand higher levels of shaking than ordinary buildings.

It is expected that hospitals should continue to operate even in the event of failures in the power and water networks. Using the appropriate HAZUS methodology, we have estimated a loss of capacity in the epicentral area (where the earthquake begins) of up to 22%, and up to 14% in the area encompassing the Melbourne CBD, which includes the Royal Melbourne Hospital. Figure 18 maps the loss of capacity overlain with hospitals, police, fire and SES stations, and ambulance centres and Figure 19 shows the same data focussing on central Melbourne. It is estimated that in event 3 the 90 hospitals nearest to the fault will experience a damage of 20% and 23 of those will experience damage on the order of greater than 50%. The hospitals near central Melbourne experiencing greater than 20% damage are shown in Figure 20 and those that are labelled sustain greater than 50% damage.

Some hospitals may have to interrupt their functioning for safety reasons; others may sustain extensive or even complete damage.

Schools are expected to experience similar rates of damage as hospitals, but these facilities are likely to lack the capacity to generate their own power; thus we expect that only those far from the epicentre will be usable as temporary shelter. In Table 4 we show the number of facilities expected to experience sufficient damage to hinder their operations (i.e. > 10%).

Table 4: Number of essential facilities expected to experience damage in excess of 10%. Note that these represent addresses classified as these types of facilities and may not represent actual facilities e.g. land owned by the Metropolitan Fire Brigade classified as Fire Stations)

Facility	Event 1	Event 2	Event 3
Hospitals	0	2	110
Schools	4	24	941
Fire Stations	1	2	119
Police Stations	0	4	79
SES Stations	0	3	31
Ambulance Stations	0	2	74

6.4 Infrastructure

The following summarises impacts to infrastructure as modelled using the HAZUS methodology. Damage was estimated using ground motion parameters shown in Figure 10, where areas referred to as "near the epicentre" correspond approximately to the purple coloured regions in Figure 10. This area includes approximately 1.17 million (Event 1), 1.9 million (Event 2), 2.63 million (Event 3) addresses and more than 77 (Event 1), 105 (Event 2), 132 (Event 3) hospitals. This methodology does not take into account increased costs due to shortage of labour and/or materials (demand surge) and should be seen as an estimate of the amount of work without considering the inter-relationships between downtimes from different infrastructures.

- **Transport:** Roads may be blocked as a consequence of debris from fallen buildings. Roads may also be shut where there is the potential for surrounding building to fail during aftershocks, even if no debris has yet fallen. As a result, and as observed in Christchurch, areas of the CBD may be cordoned off for a minimum of 7 days following the event. This is described further in the Adelaide Earthquake Scenario Technical Note (Koschatzky et al., 2015).

  - *Bridges and tunnels:* In the absence of liquefaction, bridges may be closed for a day to a week for inspection and repairs of moderate damage. Near the epicentre, a small number of bridges could experience extensive to complete damage and take a minimum of 150 days to be completely restored. Liquefaction may cause damage to bridges at locations indicated with hot colors in Figure 11. For event 2 18% of bridges and 12% of tunnels and for event 3 87% of bridges and 42% of tunnels will be subject to moderate damage and closed for between a day and a week.

  - *Trams and trains:* At this ground shaking level (in the absence of liquefaction) there is a significant proportion of railway lines slightly damaged. However, some rail and light rail bridges close to the epicentre may be extensively damaged and take a minimum of 110 days to be repaired. A greater proportion (60% in event 1, 85% in event 2 and 100% in event 3) of railway and tram lines close to the epicentre will experience minor damage, which corresponds to a downtime of 2 to 7 days but may be longer depending on ground rupture patterns. The fuel and maintenance facilities for this infrastructure located in the proximity of the epicentre will mostly suffer minor to moderate damage, which may add 2 to 7 days to the downtime. The fuel and maintenance facilities in the neighborhood of the epicentre will also have a 15% chance (event 1), 29% (event 2) and 66% (event 3) to suffer extensive damage, with associated downtimes of up to 4 months.

– *Airports:* Melbourne airport is situated around 10 km from the epicentre zone of this scenario for event 1 and within the affected zone for events 2 and 3 and is situated on soft soil which is prone to liquefaction (a very low risk for event 1 and event 2 and a low risk for event 3). Airports are usually well built and are expected to perform reasonably well. However, as observed in Christchurch, airports are expected to be closed for a short period of time for damage assessment.

- **Electricity:** The HAZUS methodology provides downtime estimates for several types of electrical components and facilities. The complete failure of large power components, such as transformers or substations, may occur in the proximity of the epicentre with a probability of around 12% (event 1), 40% (event 2) and 92% (event 3), and downtime of approximately two months. According to the HAZUS model, almost all addresses close to the epicentre will experience at least minor power failures with downtimes of up to 3 days (if no nearby substation is completely damaged).

Some power stations, close enough to the epicentre to sustain some slight or moderate damage will take a month or longer to fully recover. Utilising previous analysis for VicSES, a representative timetable for recovery of functionality of an electric powerplant is outlined in 5. Since many of the power plants that supply Melbourne are located in the Latrobe Valley, the downtimes described in Table 5 would apply not only to Melbourne earthquake scenarios but also to Latrobe Valley earthquake scenarios. However, the impacts on other infrastructure in Melbourne from Latrobe Valley scenario earthquakes may be negligible or much smaller than those from Melbourne earthquake scenarios. The Latrobe Valley has significantly higher seismic hazard than Melbourne.

The scenario described above is consistent with historical experience in Christchurch (2010) and Newcastle (1989) (Koschatzky et al., 2015).

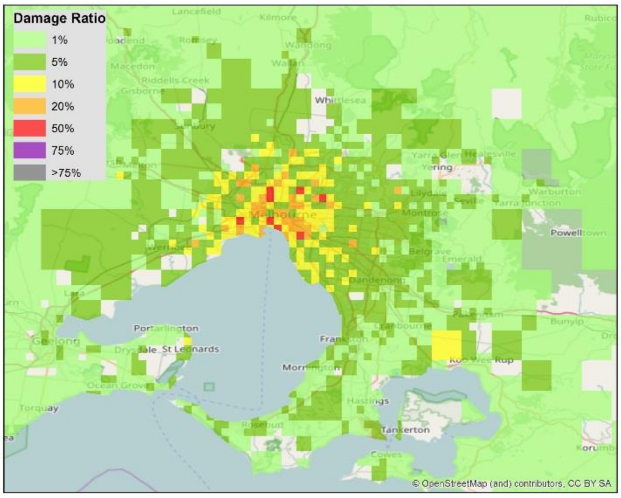
Table 5: Recovery of functionality of an electric power plant following scenario earthquakes

Event	After 1 day,%	After 2 days,%	After 10 days,%	After 100 days,%
Mw 5.5	60	90	99	100
Mw 6.0	50	85	98	100
Mw 7.0	20	50	90	100

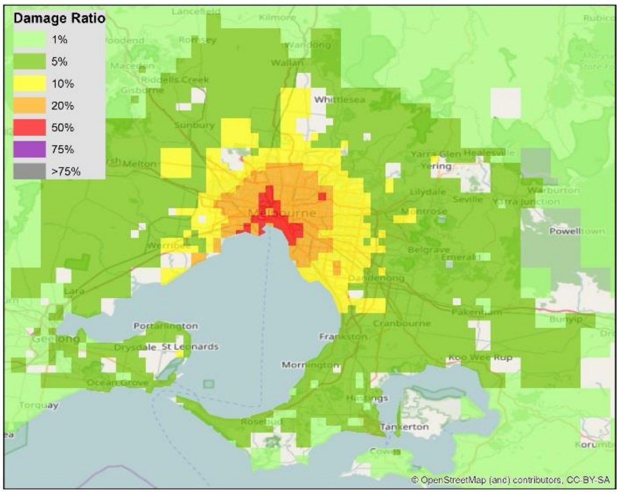
- **Water supply:** Major water facilities such as pumping stations and reservoirs may experience extensive damage with a probability of 7% (event 1), 16% (event 2) and 46% (event 3), which implies a downtime of 40 days (FEMA, 2004). Minor damage may occur across the network, with a downtime of 3 days (if no major system was completely damaged). In case of liquefaction, breakage of pipes is likely to be widespread in the hot coloured regions in Figure 11, and concerns over contamination may render the water not suitable to drinking. This is supported by the experience in Christchurch (Koschatzky et al., 2015).

- **Waste water:** Extensive damage is modelled to occur in 10% (event 1), 26% (event 2) and 70% (event 3) of waste water systems near the epicentre even without the occurrence of liquefaction; addresses within this zone may be without sewage services for up to 150 days. This is supported by the experience in Christchurch (Koschatzky et al., 2015).

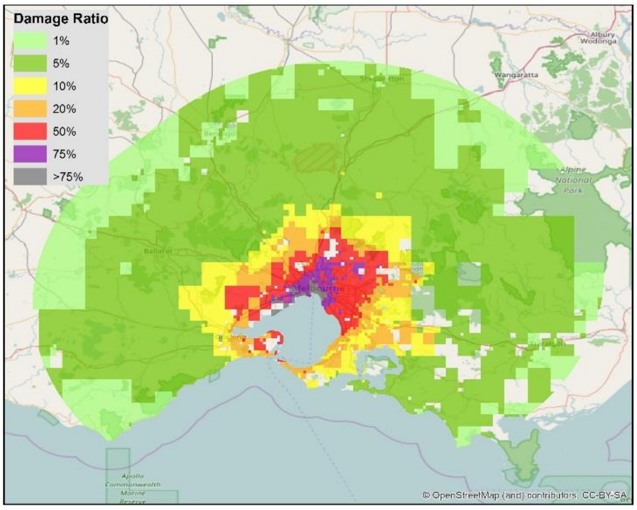
- **Communications:** We have estimated that most of the area near the epicentre will experience moderate to extensive damage with downtimes ranging from less than 3 to 30 days. About 16% (event 1), 39% (event 2) and 69% (event 3) of the major facilities (central offices and broadcast stations) located in the area near the epicentre will experience extensive damage with associated downtimes of up to a month. 20% of operations will be completely destroyed with restoration taking beyond 90 days. Refer to Koschatzky et al. (2015) for Christchurch's experience.



(a) Mw 5.5

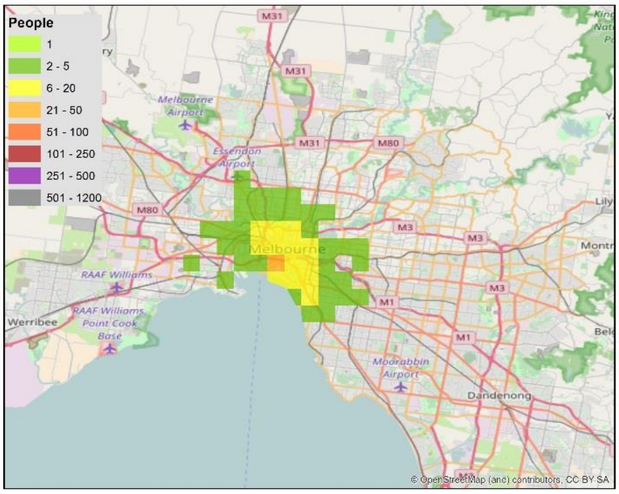


(b) Mw 6

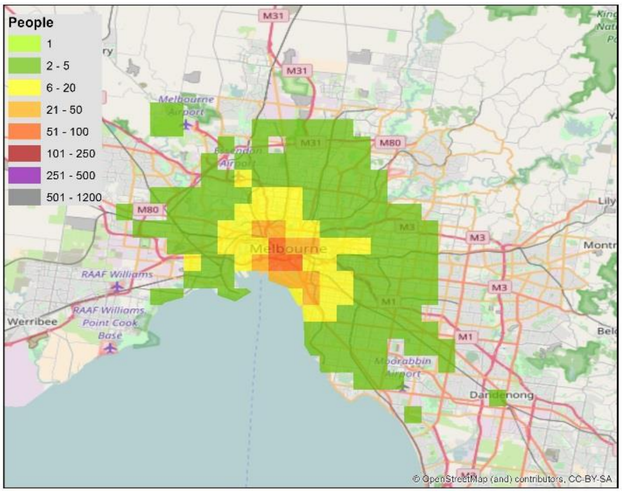


(c) Mw 7

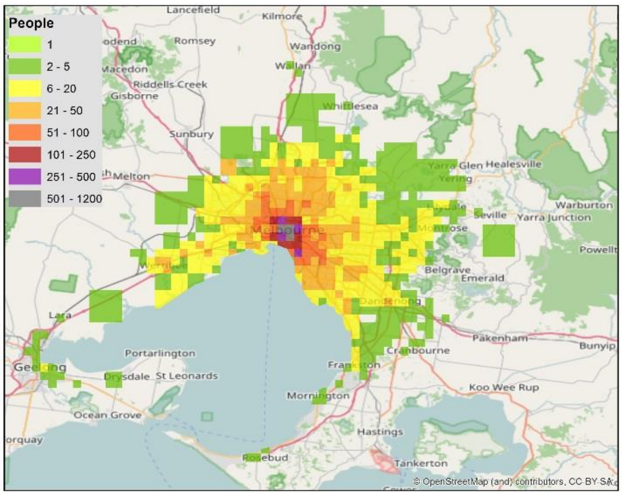
Figure 15: Building Damage: Percentage of Replacement Value of the local building stock. Mw = magnitude



(a) Mw 5.5

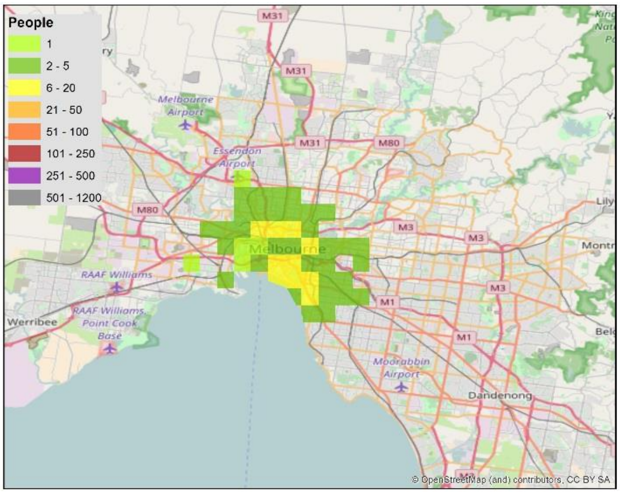


(b) Mw 6

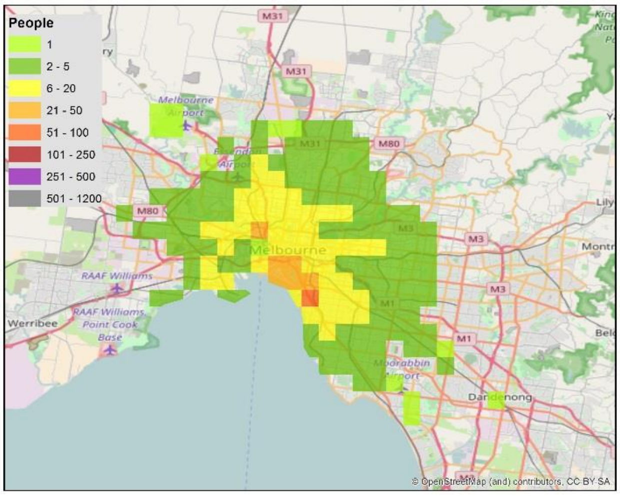


(c) Mw 7

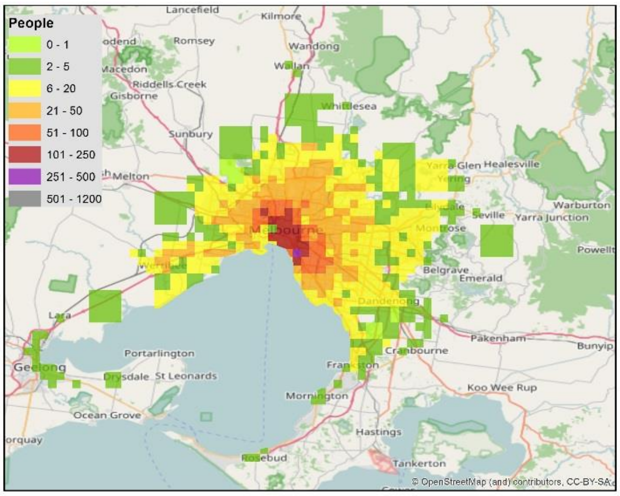
Figure 16: Severe Injuries and Deaths, Day-Time. Mw = magnitude



(a) Mw 5.5

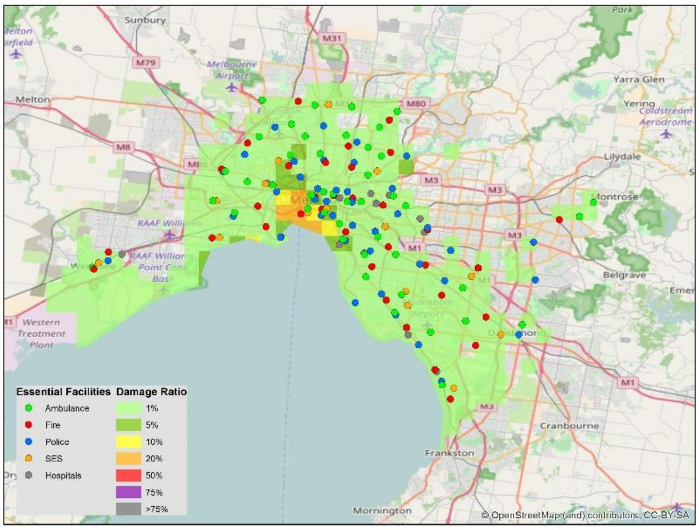


(b) Mw 6

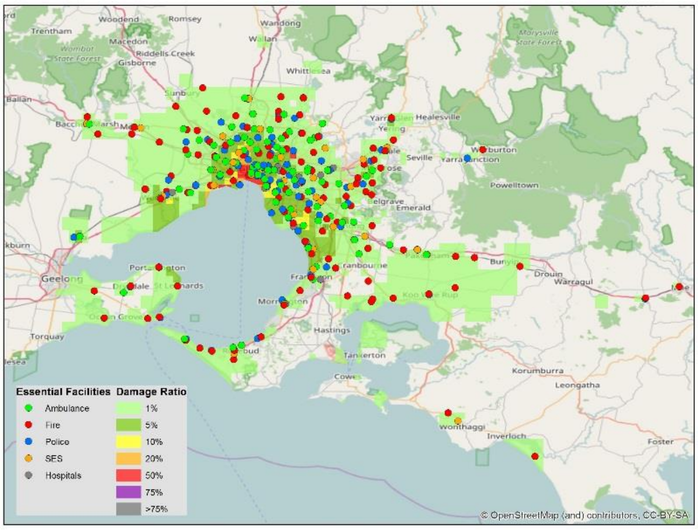


(c) Mw 7

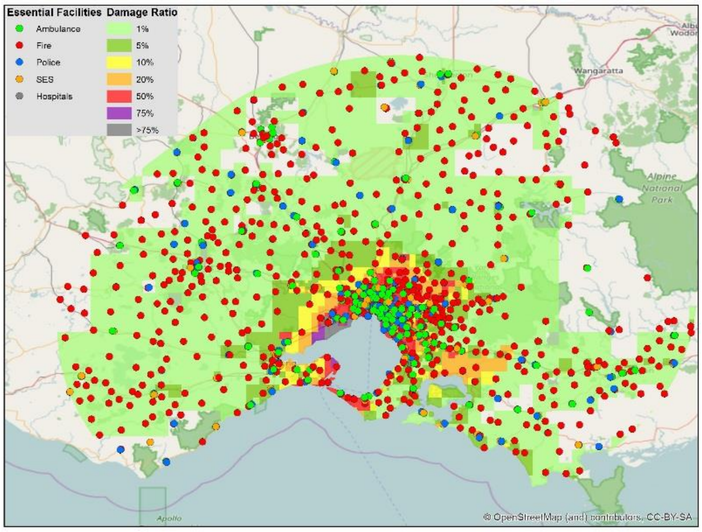
Figure 17: Severe Injuries and Deaths, Night-Time. Mw = magnitude



(a) Mw 5.5

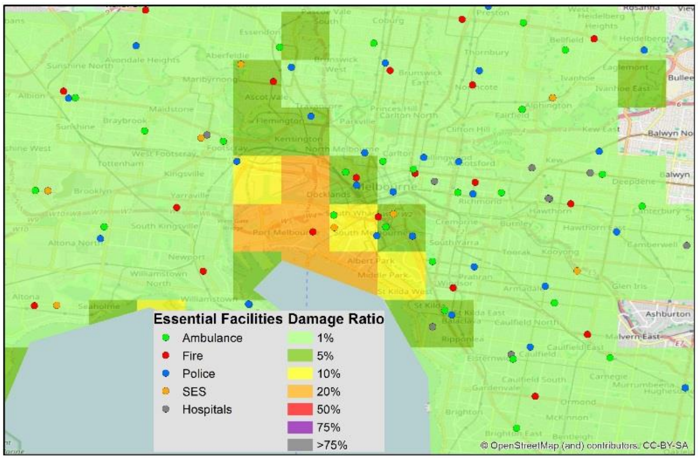


(b) Mw 6

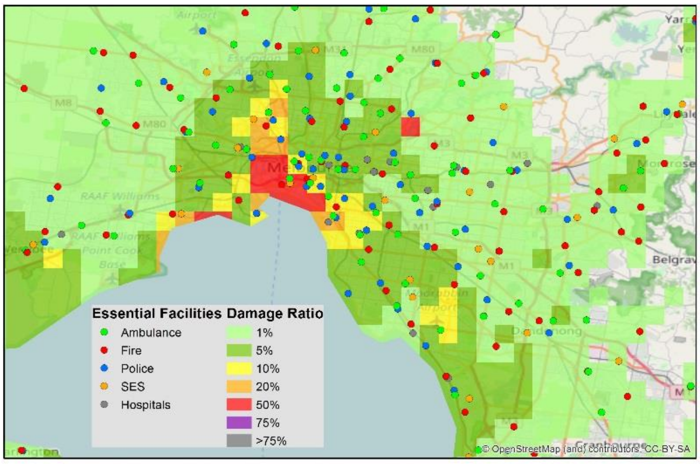


(c) Mw 7

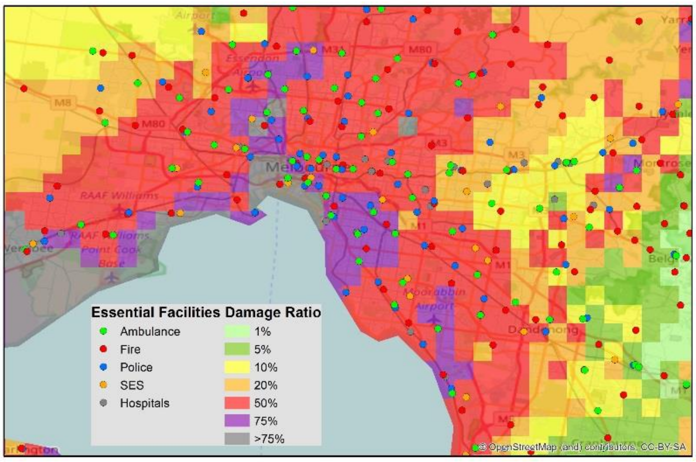
Figure 18: Damage Ratio to essential facilities. Mw = magnitude



(a) Mw 5.5

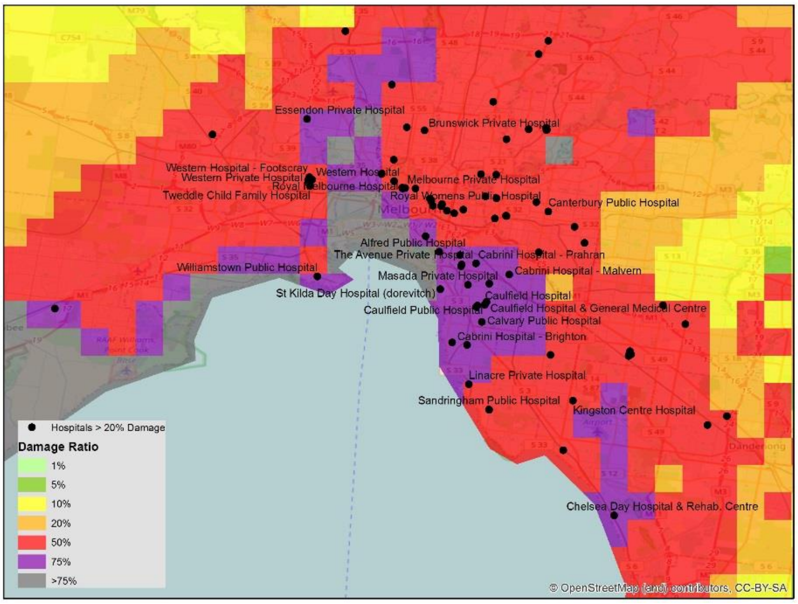


(b) Mw 6



(c) Mw 7

Figure 19: Damage Ratio to essential facilities around central Melbourne. Mw = magnitude



(a) Mw 5.5

Figure 20: Hospitals sustaining more than 20% Damage around central Melbourne. Mw = magnitude

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