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A SOUTHEAST QUEENSLAND TROPICAL CYCLONE SCENARIO

Wind damage and impacts

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Cover: Cyclone wind damage during Tropical Cyclone Marcia in Queensland, February 2015.

Photo by Matthew S Mason.

TABLE OF CONTENTS

ABSTRACT

Tropical cyclones are devastating events for the communities they affect. Realistic disaster scenario analysis is a simulation technique that can be used by disaster management agencies to understand the potential impacts of these storms and help them better prepare for their inevitable occurrence. This report describes research undertaken to develop such a scenario and detail its impacts.

The primary aim of this project was to assess the potential impacts of a category 4 storm impacting the populous region of southeast Queensland. A perturbed version of the track taken by Severe Tropical Cyclone Dinah in 1967 was chosen for simulation and the key findings of this work are as follows:

- The simulated scenario track remained off shore throughout its life, but makes its closest passage to the mainland near Harvey Bay. While not making official landfall it does pass over the holiday destinations of Fraser and North Stradbroke Island causing widespread damage to buildings in those areas.
- Maximum simulated wind speeds over land were approximately 60 m/s, which is greater than the 500 year design wind speed for the region (wind region B).
- The worst affected region was Harvey Bay and its surrounds (including Fraser Island).
- Approximately 50,000 buildings were simulated to experience moderate structural damage, which may lead to occupants needing to seek emergency shelter. A further 8,000 are expected to suffer major structural damage and in many instances will need to be completely rebuilt. 70-90% of this damage is to older homes built prior to any stringent wind resistant design requirements.
- As a result of the extensive damage to residential buildings 50,000 occupants are expected to seek alternate accommodation following the storm. In the worst impacted areas along the northern beaches of Harvey Bay, 60-70% of residents will need to do this. Such numbers cannot be able to be accommodated locally.
- Losses will run into the tens of billions. For the wind-induced structural building damage simulated here, approximately $12 Billion in loss is expected.
- Impacts are highly sensitive to simulated storm parameters such as track and intensity, so the highest quality event information is needed if realistic impact results are to be generated.

Future work will further develop both the wind hazard and vulnerability models used in the current simulation and will seek to include new model components that simulate tropical cyclone induced rainfall, coastal inundation and their impacts.

INTRODUCTION

Tropical cyclones impact much of the Australian coastline. On average 5 make landfall each year with 2 of these impacting Queensland. Tropical cyclones bring strong winds, heavy rains, and coastal and riverine flooding, all of which can have significant impacts on communities and businesses in the landfall region and beyond. Historically Queensland has experienced many damaging storms, with Severe Tropical Cyclones Larry (2006), Yasi (2011) and Marcia (2015) being some of the more recent events to cause widespread damage to the state. It is essential, therefore, that the potential impact of such events are understood so that appropriate preparation can take place.

One way of estimating potential cyclone impacts is through the development of hypothetical scenarios where simulation techniques are used to numerically generate realistic events with the range of resulting damages modelled. These types of simulations are often termed ‘disaster scenarios’ and can be tailored to generate results of interest to particular end users. Disaster scenarios are widely used throughout the financial (e.g. insurers and reinsurers) and emergency management sectors to plan for future events so they have the capacity and experience to deal with such events when they arise.

This report details the first in a series of tropical cyclone ‘realistic disaster scenarios’ to be delivered as part of the Bushfire and Natural Hazards CRC project, “*Using realistic disaster scenario analysis to understand natural hazard impacts and emergency management requirements*”. It describes a category 4 storm that passes by south east Queensland and details the resulting impacts to buildings and their occupants. To this point only wind related impacts have been modelled, with inundation related hazard and impacts to be included in subsequent scenario simulations. Once these advanced modelling capabilities become available, this scenario will be revisited and additional impacts will be assessed.

This report is structured as follows. The following section describes in detail the meteorological conditions that define the scenario event, and includes a description of the nature and impacts of Severe Tropical Cyclone Dinah (1967) upon which this scenario is based. This is followed by a section detailing the underlying model methodology implemented, including a description of the wind field and vulnerability models as well as the exposure information utilised. Scenario results are then presented with a focus on the event’s damage to buildings and resulting structural losses and population displacements. This section also briefly describes a small set of sensitivity tests undertaken to assess the impact of varying some storm parameters within the scenario. The report is concluded with a summary of results and an outline for future research.

SCENARIO EVENT DEFINITION

The tropical cyclone scenario chosen for simulation is a perturbation of the track and intensity of Severe Tropical Cyclone Dinah, which occurred in 1967 (Figure 1). Wind and waves generated by this event impacted southeast Queensland and northern New South Wales, but fortunately the storm remained off-shore so the extent of damage was limited. Dinah reached a minimum central pressure of 945 hPa as it tracked to within around 70 km of the Queensland coastline before moving southeast away from the coast between Gladstone and Bundaberg. Despite the storm moving away from the coast it still came to within 150 km of the Sunshine Coast and 200 km of Brisbane while a Category 4 storm. Damaging storm surges were reported from Yeppoon down to the Gold Coast, with wind damage to buildings and crops reported from the Rockhampton down to Grafton (Munich Re 2007, Callaghan 2011). Many of the near-shore islands, including the tourist destinations of Herron, Lady Elliot and Fraser Islands experienced strong winds, high swells and associated damages (Harper 2001, Callaghan 2011).

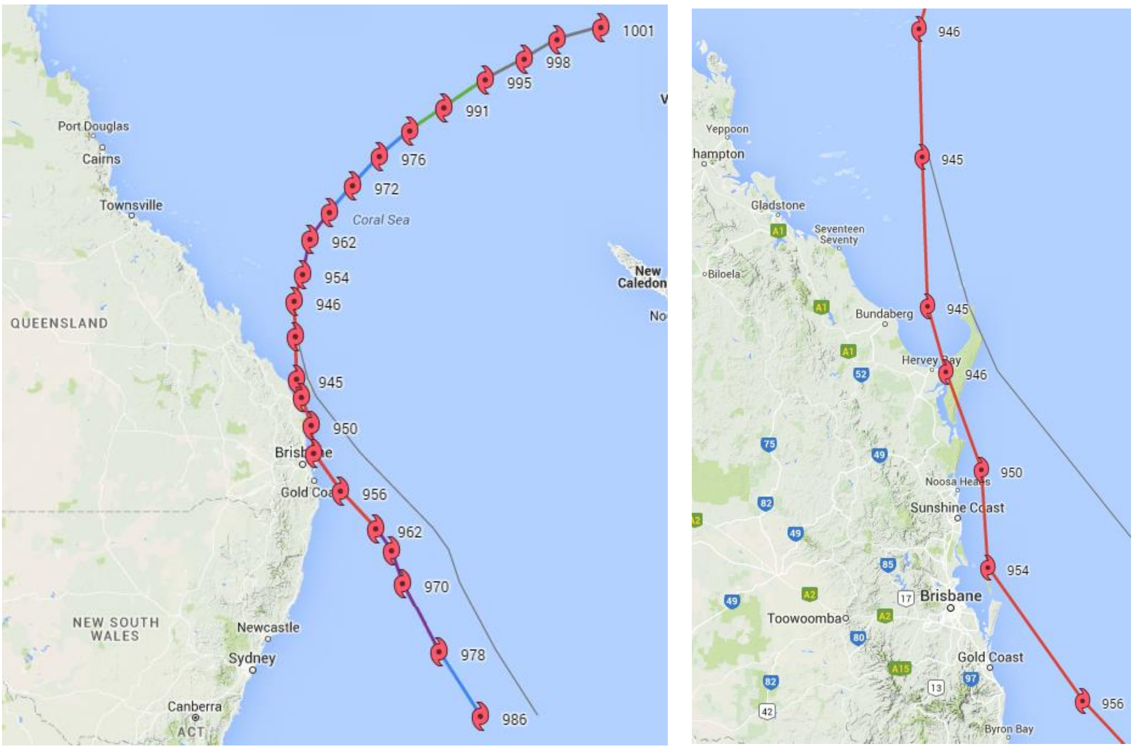

FIGURE 1 INITIAL TROPICAL CYCLONE DINAH TRACK AND INTENSITY (THIN GREY LINE, PRESSURES GIVEN IN HPA) AND MODIFIED TRACK (COLOURED LINE) TO BE SIMULATED FOR THIS SCENARIO. COLOURING OF TRACK LINE INDICATES TC CATEGORY AND IS UNCHANGED FROM THE ORIGINAL TC DINAH RECORD (GREEN, BLUE, PURPLE AND RED REPRESENT AUSTRALIAN BOM CATEGORY 1, 2, 3, 4 RESPECTIVELY). RIGHT IMAGE IS AN INSET OF THE FULL TRACK IMAGE (LEFT) IN THE REGION OF NEAREST COAST PASSAGE.

The scenario is not an exact replication of TC Dinah, but instead assumes that instead of recurving southeast in the Gladstone-Bundaberg region, it tracks south and crosses Fraser Island. After this point the storm remains offshore but within 40 km of land before recurving in a similar manner to Dinah as it passes Brisbane (Figure 1, Table 1). The nearest coast passage is near Harvey Bay, where the storm gets to 10 km from the mainland. The storm intensity time history remains as it was for the actual event, and maintains Category 4 status (central pressure < 955 hPa) down to Brisbane/Gold Coast. While it is not common for cyclones in the region to attain such low central pressures, they are above the estimated Maximum Potential Intensity (MPI) of 940 hPa discussed in Harper (2001). Given the storm remains offshore, as in the original event, maintenance of the same pressure time history is considered realistic.

TABLE 1. TROPICAL CYCLONE DINAH AND CURRENT SCENARIO TRACK AND INTENSITY INFORMATION.

TC Dinah				**Scenario**				
Date	**Time**	**Latitude**	**Longitude**	**Latitude**	**Longitude**	**Cp [hPa]**	**RMW [km]**	**Cat.**
22-Jan	23:00	-12.7	163.8	-12.7	163.8	1001	18	TS
23-Jan	11:00	-13.1	162.2	-13.1	162.2	999	18	TS
23-Jan	23:00	-13.8	161	-13.8	161	998	18	TS
24-Jan	11:00	-14.5	159.6	-14.5	159.6	995	18	1
24-Jan	23:00	-15.5	158.1	-15.5	158.1	991	18	1
25-Jan	11:00	-16.3	156.9	-16.3	156.9	984	18	2
25-Jan	23:00	-17.2	155.8	-17.2	155.8	976	18	2
26-Jan	11:00	-18.2	154.8	-18.2	154.8	972	18	2
26-Jan	23:00	-19.1	154	-19.1	154	968	18	3
27-Jan	11:00	-20	153.3	-20	153.3	962	18	3
27-Jan	23:00	-21.2	153	-21.2	153	954	18	4
28-Jan	11:00	-22.1	152.7	-22.1	152.7	946	18	4
28-Jan	23:00	-23.3	152.8	-23.3	152.7352	945	18	4
29-Jan	7:00	-24.7	153.2	-24.7	152.792	945	18	4
29-Jan	11:00	-25.3	153.5	-25.3	152.9704	946	18	4
29-Jan	17:00	-26.2	154.3	-26.2	153.338	950	18	4
29-Jan	23:00	-27.1	155.1	-27.1	153.4056	954	18	4
30-Jan	06:00	-	-	-28.3	154.3678	956	18	4
30-Jan	11:00	-29.5	157.7	-29.5	155.6408	962	18	3
30-Jan	14:00	-30.2	158.3	-30.2	156.24	964	18	3
30-Jan	23:00	-31.2	158.7	-31.2	156.64	970	18	3
31-Jan	11:00	-33.3	160	-33.3	157.94	978	18	2
31-Jan	23:00	-35.2	161.5	-35.2	159.44	986	18	1

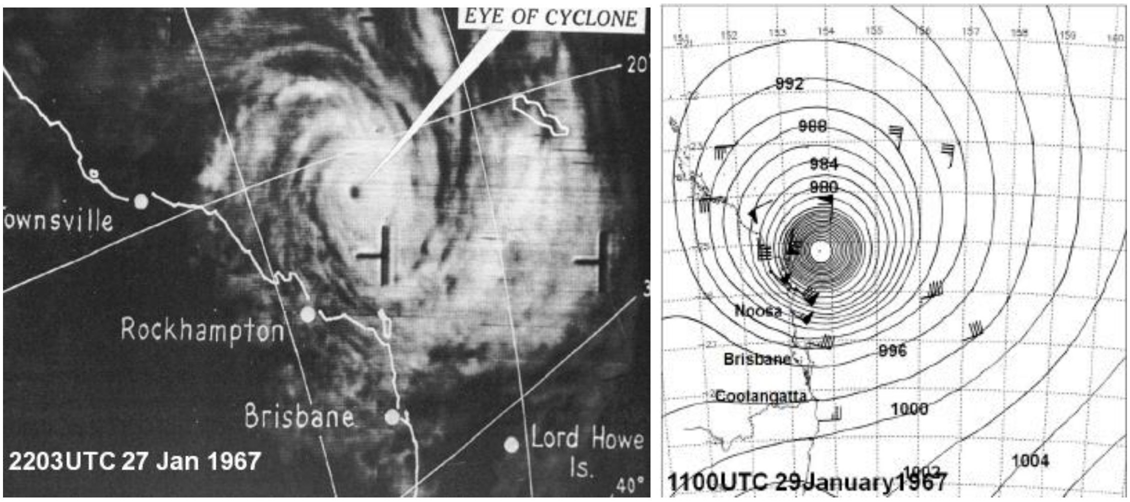

FIGURE 2 EXAMPLES OF (LEFT) RADAR IMAGERY AND (RIGHT) MEAN SEA LEVEL PRESSURE PLOTS AVAILABLE FOR TC DINAH (CALLAGHAN 2011).

TABLE 2. RMW AND B PARAMETER VALUES USED IN SENSITIVITY TESTS.

Sensitivity test	RMW [km]	B parameter
S1	12	1.4
S2	25	1.0
S3	18	1.2
S4	18	1.2

Little information detailing the physical characteristics of Dinah, such as its size (i.e. radius of maximum winds, RMW) eye wall diameter, or an appropriate Holland B parameter, could be sourced. While it is not imperative that the exact nature of Dinah is repeated for this scenario, use of a similar sized storm is desirable. As such, a combination of RMW = 18 km and a constant Holland B parameter of 1.2 were selected. As discussed further later in this document, this combination generates a maximum over-ocean gust wind speed (V3) of 70 m/s, roughly equating to the maximum winds during Dinah—based on available satellite imagery, mean seal level pressure charts (e.g. Figure 2) and generic pressure-RMW relationships (Hardy, McConochie et al. 2003). These parameters are used to generate results presented in the results section for the baseline scenario.

While scenario modelling is most often used for long term capacity planning, it can also be of use prior to or immediately following a storm to assess immediate damage and requirement. This use is more complicated than the purely hypothetical situation because there is a need to accurately incorporate event information into the model. Unfortunately however, storm parameters such as those discussed in the previous paragraph are never known with any certainty prior to an event, or even immediately following it, so significant uncertainty will always exist in any damage forecast. For instance, currently in the Atlantic basin hurricane forecasts have an approximate 24 and 48 hour mean track errors of 60 – 70 km and 130 km, respectively[1]. Storm intensity forecasts are similarly uncertain, with their 24 and 48 hour errors being of the order of 5 m/s and 8 m/s. While similar numbers could not be sourced for the Australian region, the relative magnitude of these errors will be similar. The combination of these potential errors coupled with uncertainties around storm size and dynamics (e.g. eye wall replacements) mean that it is exceeding difficult to generate single, deterministic values for expected damage when operating in a forecast sense. As such Probabilistic 'spreads' of potential damage are of most use and should be explored.

To investigate the potential uncertainties that may arise if attempting to issue damage forecasts, four exploratory sensitivity analyses have been undertaken. In the first two, the RMW and Holland B parameter are varied to investigate the potential influence of changes in storm size and intensity (in maximum velocity terms). For the remaining two the storm track is shifted by 50% of the mean forecast location error east and west of the simulated scenario track to assess the influence of storm location on the impacts. Here we focus on a potential 24 hour forecast made prior to the storm's closest passage to land and implement an increasing error based on predicted forward motion. Table 2 indicates the storm variables used in sensitivity tests 1 and 2 and Figure 3 shows the storm tracks used for S3 and S4. Track displacement from the original scenario is

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[1] http://www.nhc.noaa.gov/verification/verify5.shtml

approximately 30 km at Harvey Bay and 50 km as the storm passes Brisbane. The westerly track (S3) is shown in Figure 3 to make landfall near Bundaberg and as such the central pressure is decayed as per a simple time over land decay function (Kaplan and DeMaria 1995, Vickery 2005). We note that these sensitivity tests are not a full probabilistic analysis of variable influence on impacts, but instead highlight the variability in damage forecasts that may reasonably be produced given known uncertainties in storm parameters. The estimated number of displaced persons is the variable compared between scenarios.

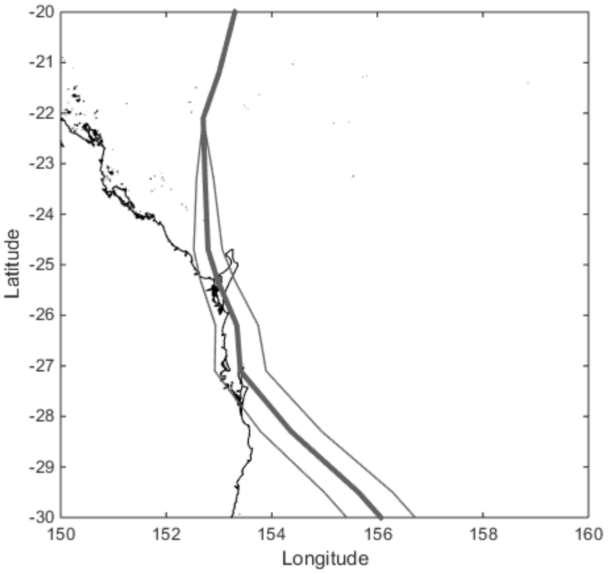


FIGURE 3. ALTERNATE STORM TRACKS USED FOR SENSITIVITY ANALYSES S3 AND S4 SHOWN AS THIN LINES WITH THE ORIGINAL SCENARIO TRACK, SHOWN AS A BOLD LINE.

MODEL METHODOLOGY

As with all catastrophe risk models the scenario model is made up of three primary components; hazard, exposure and vulnerability (Grossi, Kunreuther et al. 2005). The hazard module generates the requisite information required to describe the hazard under consideration, which in this case is the maximum cyclone induced wind gusts. The exposure module provides information on what assets, e.g. buildings, infrastructure or people, are exposed to the simulated hazard and any of the underlying information about those assets that may be pertinent for describing the subsequent hazard impacts. This could include the type and value of buildings that make up a given area, the population in that area, or the network of infrastructure that population is reliant on for recovery. The vulnerability module takes both hazard and exposure information and generates a metric that describes the impact of a simulated event on the exposed assets or population. Mason and Parackal (2015) describe a wide range of vulnerability models of relevance to tropical cyclone impact modelling, in particular those that can be used for modelling impacts in Australia. Each of the model components implemented in the scenario analysis are described in further detail throughout this section.

WIND FIELD MODELLING

The scenario wind field is generated through time using the analytical linear boundary layer model developed by Kepert (2001) coupled with a gradient level vortex model (Holland 1980). This coupled model can generate a full three dimensional wind field in consideration of storm parameters such as size and intensity as well as asymmetries introduced due to the translational speed of the storm. Underlying surface roughness is considered through a drag coefficient term with the additional feedback of a diffusivity term that transmits this information throughout the boundary layer. Through a series of cross-validation experiments, Khare et al. (2009) showed the validity of this model against reconstructed tropical cyclone wind fields.

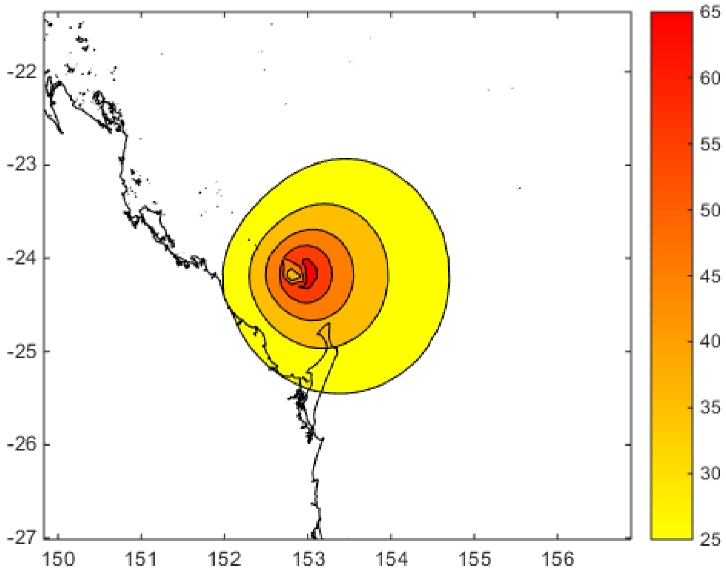


FIGURE 4. EXAMPLE OF ASYMMETRIC WIND FIELD GENERATED BY SCENARIO WIND FIELD MODEL. WIND SPEEDS ARE IN M/S AND ARE 3 SECOND GUSTS AT 10 M HEIGHT.

For the scenario simulation only a two dimensional wind field is required given the formulation of vulnerability curves utilised is based on surface wind speeds. As such, the surface-relative wind speed and direction was calculated at an elevation of 10 m for all model grid points. Instantaneous wind fields were calculated at one hour time steps and the maximum wind gust at each grid point over the entire storm duration was stored for use with the vulnerability models. An example of the instantaneous wind field generated by the model is shown in Figure 4, where the asymmetric nature of the storm winds are evident as seen by the local maxima in the front left quadrant of the wind field (Note the storm is moving southward).

The complex role that terrain and topography play on defining the surface wind field within a tropical cyclone has been simplified for this scenario. For grid points over water the surface roughness is assumed to have a value of z_0 = 0.002 m and for those over land a roughness length of z_0 = 0.02 m. Strictly speaking the surface roughness over water is dependent on wind speed up to a mean 10 m value of approximately 20 - 30 m/s, remaining approximately constant beyond this (Vickery, Wadhera et al. 2009). The use of a single value is considered justified in this instance because damage is primarily driven by strong winds and the chosen roughness value is representative of this regime.

For winds over land, the surface roughness can vary by several orders of magnitude based on the level of development of the underlying land. This translates to a possible variability in surface wind speeds of the order of 15 - 20% for the range of typical rural and suburban terrains. Topography, i.e. hills, can also play an important role in defining surface wind speeds. Winds tend to speed up as they move over a slope and decelerate as they move down them. These effects are localised, however, and only influence those buildings sited on or near the topographic feature. Despite the potentially significant modification of local wind speeds due to both terrain and topography, use of a single value of roughness, and the assumption of flat topography, is considered reasonable for the following reasons. Firstly exposure data was only available on a regional basis. This means that the ensuing analysis must be conducted on a regional level and thus a wind speed representative of that experienced over the entire region must be generated. Use of localised modification factors would not therefore be appropriate in this situation. Secondly, many vulnerability models are developed with reference to a uniformly defined wind speed value, typically over open flat terrain. This means that even if local modifications were used to generate a wind speed estimate, a conversion back to a flat open terrain would be required for it to be implemented in the vulnerability model. Lastly, modern buildings are designed and constructed considering the modifying effects of terrain and topography on their local wind environment (Standards Australia 2011). This means buildings sited on a hill are notionally designed to resist stronger winds than those on flat ground. As such, the level of damage expected for these two buildings could be reasoned to be more closely aligned with its regional wind speed rather than the local wind speed at a site. These points considered, the use of a wind speed representative of that experienced over flat open terrain is believed to be a justified simplification.

The Kepert (2001) boundary layer model also requires specification of a radius to maximum winds (RMW), a Holland B (peakedness) parameter and a diffusivity coefficient. Both the RMW and B values are storm parameters that can vary over the lifecycle of a storm. However, for simplicity they are assumed to remain constant in the current simulations, as defined previously. An empirical relationship has been developed to relate diffusivity to surface roughness and is implemented. Storm translation speed also influences the surface wind field, and is included in the model through an asymmetric term in the analytical formulation. Translational speed is simply drawn from storm track information.

EXPOSURE INFORMATION

In many models, as in this one, availability of exposure information often drives model complexity. That is, where only course resolution or aggregated information is available about exposed assets, little is gained by generating complex and/or granular hazard information. To this end, the resolution of the hazard and vulnerability models were driven by the exposure data available through the National Exposure Information System (NEXIS) database, which was used for sourcing all building and demographic information utilised in this scenario (e.g. Dunford, Power et al. 2014, Power and Dunford 2014).

The NEXIS database has been designed and development by Geoscience Australia with the aim of providing a nationally consistent source of exposure information for use in natural disaster risk assessments. The database utilises publically available information, statistics and survey data to generate statistical estimates of exposure over a range of regional scales. As such it does not provide precise information on the number or nature of all assets/populations it documents, but provides a statistical estimate that can be used for regional risk assessments, such as undertaken here. The NEXIS database is continually undergoing revision and refinement and updated information will be incorporated into future scenario simulations as it becomes available.

For the current simulation NEXIS data aggregated to the Statistical Area Level 2 has been used. This aggregation represents medium-sized general purpose areas that are designed to represent communities that interact socially and economically (ABS 2012). While finer NEXIS aggregations are available (e.g. SA1, Mesh Block), SA2 was used here because it more appropriately represented the scale on which emergency management decisions were made. Finer resolution implementation will be explored in future research.

The specific NEXIS data fields utilised, and a brief description of these fields are as follows. Further information on these fields can be found in Geoscience Australia (2012).

- Population estimates: This is the estimated number of people residing in an area based on the 2011 Census.
- Number of buildings (residential, commercial, industrial): The number of buildings present in a SA are divided into three main categories, residential, commercial and industrial. Several sub-classes of residential building are provided but in this case all are aggregated into two sub-categories based on age; pre 1980 and post 1981. Similarly, commercial and industrial building counts are also sub-divided into these epochs.

- Structural value of building stock: The estimated total value of residential, commercial and industrial buildings in a given area, excluding contents.

Figure 5 shows a map of southeast Queensland with SA Level 2 regions shown and colouring based on exposed population density. The greatest densities are seen, as expected, in the greater Brisbane region, with the smaller populations of the Sunshine Coast and Hervey Bay also highlighted.

VULNERABILITY MODELS (WIND ONLY)

A preliminary assessment of publically available vulnerability models that relate tropical cyclone hazards (wind, wind driven rain and storm tide) to building and infrastructure damage is presented in Mason and Parackal (2015). They highlight the relatively sparse availability of detailed (Australian) models and recommend that for this scenario (wind damage only) a modified version of the suite of building damage functions (curves) developed by Geoscience Australia (GA) be implemented as the basis for estimating building damage and subsequent population displacement. Justification for this recommendation is provided in that document and the reader is directed there for further clarification. At the time of writing exposure information relating to power networks had not yet been successfully sourced, so the proposed vulnerability assessment for these assets will be undertaken as future research.

Building damage

The GA suite of vulnerability curves are presented in Figure 6 in their original form. These are notionally for new buildings constructed using current practice. Each curve represents the expected mean performance of a building type designed for a particular design wind speed. As noted in Mason and Parackal (2015), these are primarily heuristic curves and thus do not consider progressive failure in a systematic manner. Plot also on Figure 6 are the so-called pre-1981 and post-1981 Walker curves for Queensland housing (Walker 1995, Walker 2011). These curves are widely used throughout the insurance industry and are based on observations of cyclone damage to housing in North Queensland since Cyclone Tracy.

Figure 7 presents the aggregated and modified version of the curves used for this scenario. Different curves are used for buildings in cyclonic (C) and non-cyclonic (N) wind regions, and for residential or commercial/industrial buildings. Additionally, different curves are used to differentiate between the expected impact on buildings constructed prior to (pre 1981) and following (post 1981) the introduction of stringent wind resistant design practice in Queensland, as introduced by Walker (1995). At this point all implemented curves should be considered as preliminary and subject to change throughout the life of this project. In particular, when new curves become available through the concurrent Bushfire and Natural Hazards CRC project, "*Improving the resilience of existing housing to severe wind events*", these will be implemented as appropriate.

Four curves are used for buildings in non-cyclonic wind regions, primarily representative of Region B (Standards Australia 2011), though in the current implementation they are also applied to buildings in Region A. This simplification will likely under estimate the impact in Region A, but in practice the scenario wind speeds are low in these areas and they do not contribute considerably to the reported impacts. Two curves are used for residential building damage (pre and post 1981 vintage) and the remaining two are for commercial/industrial buildings. The latter building types, in theory, should behave similarly with respect of structural damage, given they are designed to the same base standard (AS/NZS1170.2), but conceptually it was reasoned that residential buildings would sustain marginally larger damage to non-structural components than the more 'engineered' commercial facilities. As with the Walker curves, the pre 1981 curves generate greater damage than the post 1981 curve for a given wind speed.

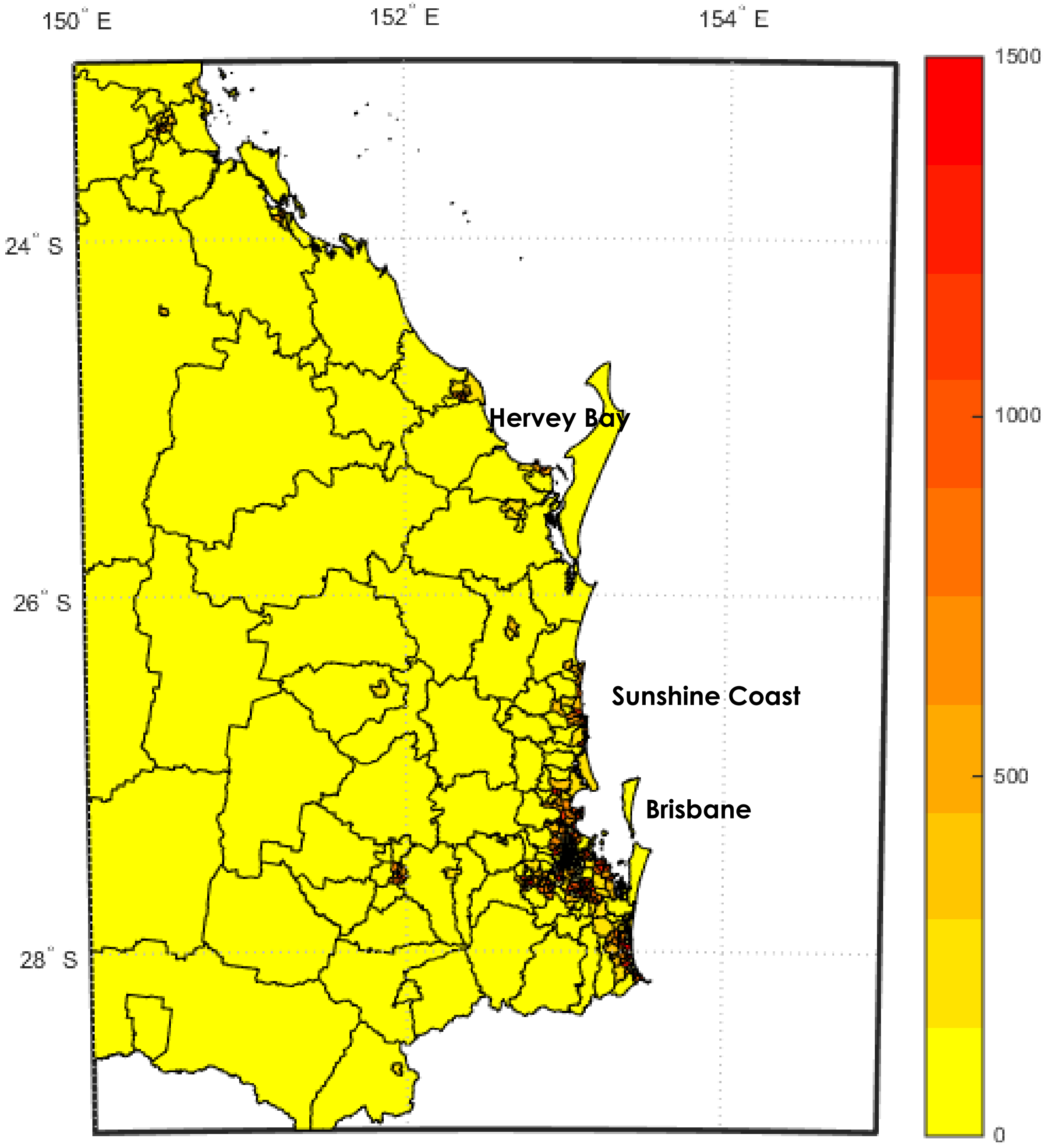


FIGURE 5. SA LEVEL 2 BOUNDARIES (QUEENSLAND ONLY) WITH COLOURS REPRESENTING RESIDENTIAL POPULATION DENSITY IN PEOPLE PER SQUARE KILOMETRE.

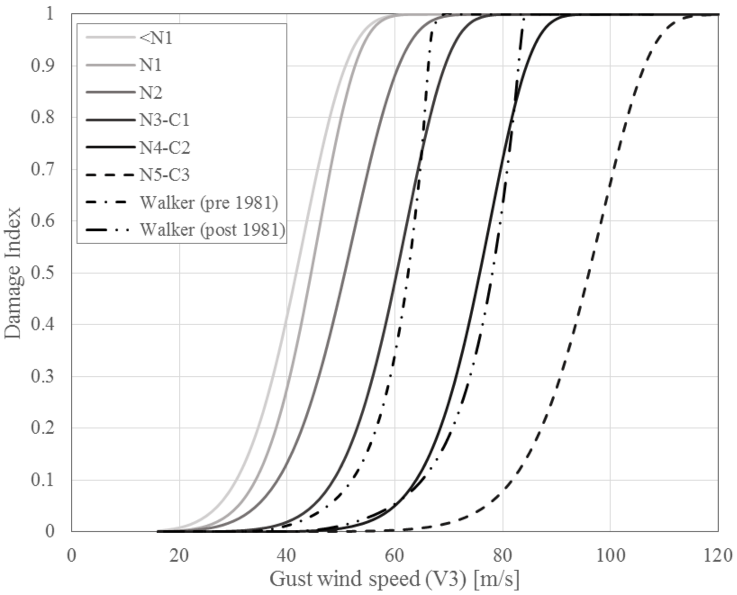


FIGURE 6. GA AND WALKER BUILDING VULNERABILITY CURVES RELATING DAMAGE INDEX (REPAIR COST/BUILDING VALUE) AND MAXIMUM 3 SECOND GUST WIND SPEED (V3). 'N' AND 'C' CODES ARE BASED ON NOMENCLATURE USED IN THE AUSTRALIAN WIND LOADING STANDARD FOR HOUSING, AS4055 (STANDARDS AUSTRALIA 2012) FOR NON-CYCLONIC (N) AND CYCLONIC (C) WIND REGIONS. REFER TO THAT STANDARD FOR FURTHER INFORMATION ON THOSE CLASSIFICATIONS.

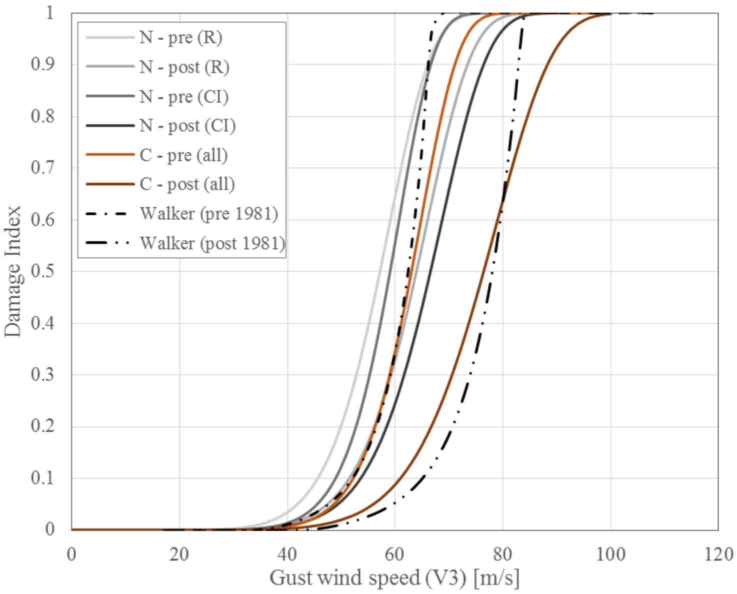


FIGURE 7. VULNERABILITY CURVES IMPLEMENTED IN THE CURRENT SCENARIO ANALYSIS. WALKER CURVES ARE SHOWN FOR REFERENCE. AGAIN N DENOTES NON-CYCLONIC WIND REGIONS (REGIONS A AND B IN AS/NZS1170.2) WITH C INDICATING CYCLONIC (REGION C). R INDICATES CURVES USED FOR RESIDENTIAL CONSTRUCTION AND CI FOR COMMERCIAL AND INDUSTRIAL BUILDINGS.

Two curves, pre 1981 and post 1981, are used to estimate mean damage in cyclonic wind regions (Region C). These curves are a blend between the form of the GA curves and the magnitude of the Walker curves, as seen in Figure 7. In fact the form of all equations follows that of the GA curves (Wehner, Ginger et al. 2010), which allow a single equation to be used to represent the mean damage over the entire damage spectrum. Walker (2011) suggests that this approach may not accurately replicate damage, particularly at low damage ratios, but simplicity was favoured for this scenario given little validation data currently exists in open literature to justify a more complex model, and as highlighted earlier, improved models are currently under development by researchers within the CRC, which will be implemented in later iterations of this scenario.

While it is imperative that the mean level of damage to a region is understood, it is also of interest to know the spread (uncertainty) of damage that may occur within a modelled region. That is, the spread of building damage index values that could be expected if it were possible to carry out the analysis on an individual building level. This, of course, will just be a statistical representation and will not actually be representative of damage levels to particular buildings. Additionally, it is of interest to know the uncertainty in the mean damage index itself, as all regions exposed to the same wind speed will not necessarily experience the same mean damage level. This occurs because not all factors that contribute to building damage are explicitly modelled and some level of epistemic uncertainty will remain. Knowledge of the combined effect of these uncertainties is particularly important for disaster management as it allows more accurate estimates of displaced population and number of damaged buildings to be made.

Within this simulation uncertainty models for both the mean damage index and sub-regional variability are implemented. For the uncertainty in regional mean damage index a random value from within the range of +/- 5% of the calculated mean value determined using the functions shown in Figure 7 is used. This sample size is not based on any particular data set but is consistent with the author's experience dealing with regionally averaged loss/damage data. Further research is however required to ensure the validity of such a simplified approach.

For sub-regional uncertainty quantification a sample of random values equal to the number of buildings within that region are drawn from a Beta distribution about the mean damage index value (including the regional uncertainty just discussed). Use of this type of distribution allows for a broad band of sub-regional damage indices to be simulated while still retaining the mean index as originally calculated. In practice even in regions where the mean damage index is low a wide spectrum of damage is observed on a building to building level (e.g. Henderson, Ginger et al. 2006, Ginger, Henderson et al. 2010, Boughton, Henderson et al. 2011), including many complete structural failures. The Beta distribution allows such a range to be simulated. As with the regional uncertainty quantification, research is still required to validate the sub-regional model, but for the current scenario a fixed a value of 1.5 is used with the model β parameter estimated using a(1-MDI)/MDI, where MDI is the mean damage index. New research by Smith and Henderson (2015) provides a set of insurance claims data that may be used to validate the current uncertainty quantification approach and will be explored as such a source in future research.

To exemplify the range of possible damage indices that could be simulated for a set of 1000 statistical buildings, Figure 8 shows the mean damage index curve and individual realisations of damage due to random wind speeds between 30 m/s and 80 m/s. The broad spectrum of possible loss values for any given wind speed is clearly seen, mimicking, at least qualitatively, the spread of damage indices observed in insurance loss data analyses (Sparks and Bhinderwala 1994, Walker 2011, Smith and Henderson 2015)

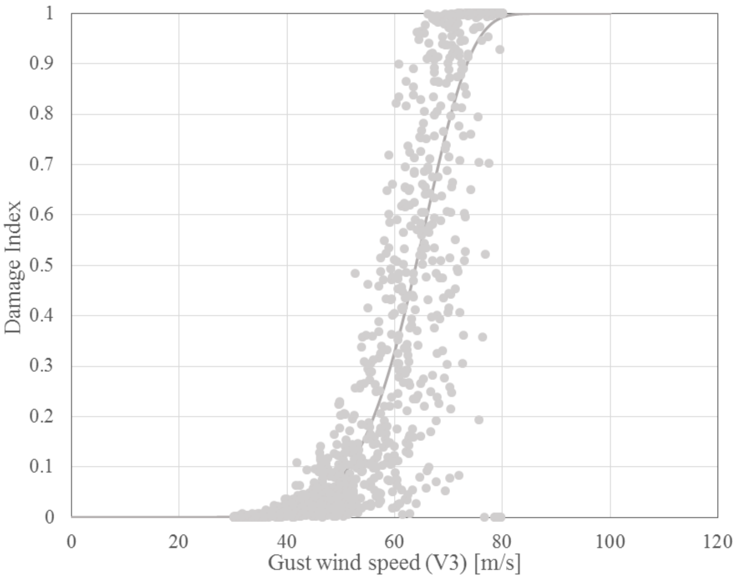


FIGURE 8. MEAN AND VARIABILITY IN DAMAGE INDEX VALUES FOR STATISTICAL BUILDINGS (POST 1981, RESIDENTIAL) IN WIND REGION B.

Using damage data generated by the vulnerability model it is possible to estimate the number of buildings within a predefined set of damage states for a given region. The use of damage states is common in seismic risk assessment and this type of aggregated damage assessment is similarly useful when assessing wind risk because it allows buildings with different physical damage but similar resulting impacts or repair/rebuild requirements to be grouped. Following Smith and Henderson (2015) we define three possible states a building may be in following an event; Damage States (DS) 1, 2 and 3. These states correspond to Minor, Moderate and Severe damage, with broader definitions of the types of damage expected given in the following points (Smith and Henderson 2015).

- Damage State 1 (Damage Index < 0.1): Minor damage to the roof, façade or non-structural elements. This could be due to direct wind loading, tree fall or water ingress. For this analysis this state also includes buildings with negligible damage (i.e. DI ~ 0).
- Damage State 2 (0.1 ≤ Damage Index < 0.5): Moderate damage to the roofing, wall cladding or other façade elements. Some level of damage to the main resistance structure could be expected.
- Damage State 3 (Damage State ≥ 0.5): Major/total failure of roof and subsequent ingress of water and/or failure of the main force resisting structural system. Not all buildings in this state will require complete replacement, but this will be the case for some.

For each region the number of buildings in each state is counted and the requisite requirements can be evaluated based on these numbers. It should be noted that damage state counts are based on estimated statistical damage levels at each building and not on the mean damage index for the region. As such, even if the mean damage index is less than, say, 0.1, DS2 and DS3 counts can be greater than zero.

Population displacement

The direct impact of tropical cyclone winds on the community is felt through damage to the built environment, as discussed. The result of such damage is a loss of residential housing for the period of repair or reconstruction which leads to a population that must be housed elsewhere. Many of these people will stay with friends or family, move (temporarily or permanently) out of the community, or seek hotel, rental or government subsidised accommodation. It is therefore of interest to estimate the potential number of displaced persons so the requirements for alternate accommodation can be planned for. Note that here we define displacement as the need for housing following an event, not the number of people requiring shelter during the event, which may be higher in areas prone to storm tide inundation or where the average resistance of the building stock is low. This form of displacement will be addressed when the model is extended to include inundation hazard and impacts.

The method utilised here for estimating displacement follows the HAZUS methodology (FEMA 2009) and is explicitly linked to residential building damage. Equation 1 describes the current approach, where P_R is the number of displaced persons per region, S_R is the regional population, f_s is the probability density function of simulated loss ratios, and w_s is an un-inhabitability function that approximates the proportion of buildings with a given damage index that will be uninhabitable. w_s is a linear function that increases from 0 at DI = 0.1 to 1 at DI = 0.5 suggesting that all buildings with DI < 0.1 will be habitable and all DI > 0.5 will be uninhabitable. Those in between, i.e. damage state 2, will have an increasing level of uninhabitability as DI increases.

$$P_R = S_R \int_0^1 f_s(DI) \cdot w_s(DI) dDI \qquad (1)$$

The present approach is a simplified version of the full HAZUS methodology within which additional variables are included for displacement due to loss of power and single- and multi-family dwellings are treated separately. Given vulnerability models implemented here treat all residential buildings of a given age homogeneously, this type of disaggregation is not currently done. Future implementations will address these issues and the full displacement model discussed in FEMA (2009) will be employed.

Loss estimation

As already discussed, the damage index represents a ratio between the cost of repairing a building following a cyclone and the total value of that structure. For the current simulation this value is the value of the structure only and does not include the value of contents. Given this definition, the estimation of losses is relatively straightforward and the damage index at a statistical building is simply multiplied by the value of that building. Building values (again, these are statistical values and do not represent any particular building within a region) are drawn from a lognormal distribution of possible values with a total sum equal to the regional structural values provided in NEXIS for each building type. For simplicity (and possibly naively) it is assumed that building values and estimated damage indices are independent and are randomly matched. Regional losses are then estimated by aggregating loss at each statistical building, and total event losses are estimated by summing all regional losses.

SCENARIO RESULTS

SIMULATED WIND FIELD

Progressive maximum wind speeds and overall storm maximum wind speeds have been simulated for the event at an SA2 resolution over land. As outlined in the Methodology section, these wind speeds assume flat open terrain (z_0 = 0.02 m) and are a 3 second average gust. Additionally, maximum wind speeds have been calculated on a uniform grid over the entire storm track so an overall picture of the storm's wind field can be assessed. For grid points over the ocean a surface roughness of z_0 = 0.002 m is assumed.

Figure 9 show the maximum gust wind speed footprint for the scenario. The maximum event wind speed was simulated to be approximately 70 m/s (250 km/h), and occurred over the ocean north of Fraser Island. The strongest band of winds occurs on the eastern side of the storm so stays predominantly offshore, except for the short period where the storm passes over Fraser Island. Gust wind speeds greater than 60 m/s (215 km/h) are maintained as the storm passes past southeast Queensland and moves out to sea. These strong winds, while not impacting land, will generate large swells and potentially high storm tides throughout the region. These tides and their resulting impacts will be simulated during future research.

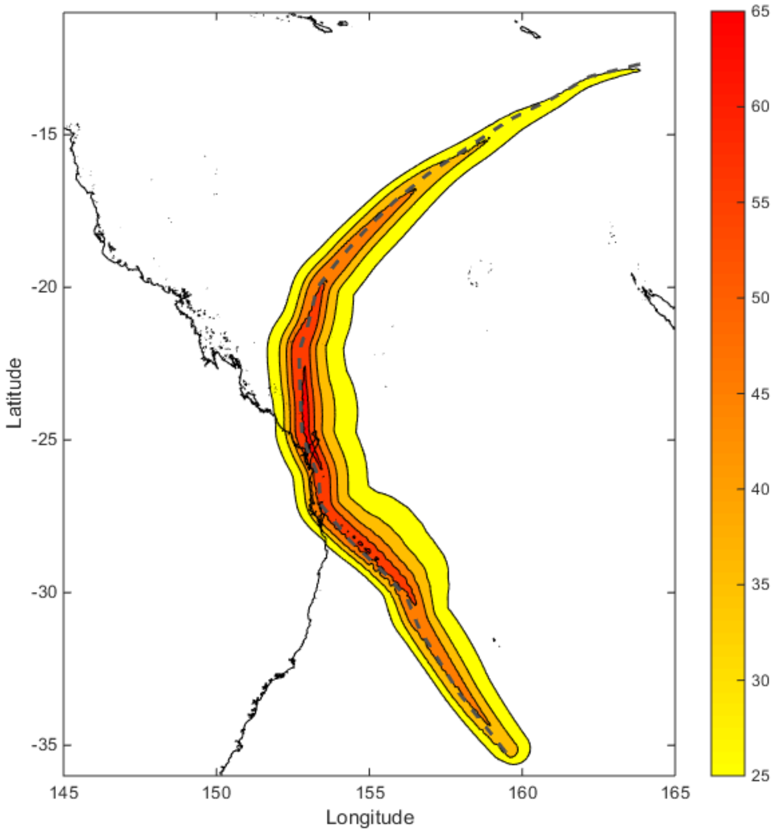
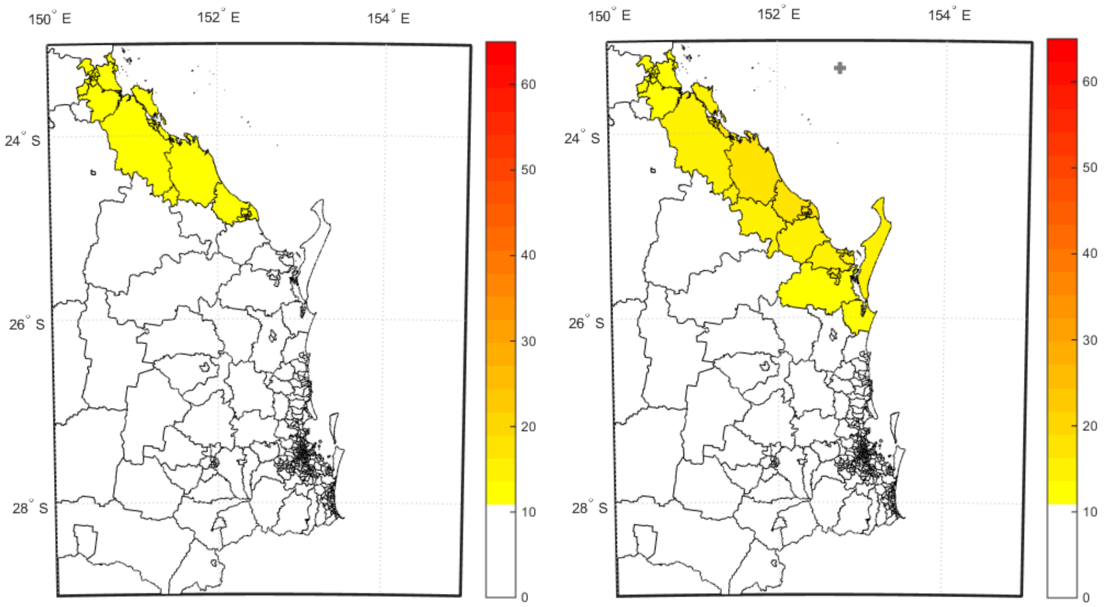


FIGURE 9. MAXIMUM WIND SPEED FOOTPRINT FOR SCENARIO. WIND SPEEDS ARE 3 SECOND AVERAGED GUSTS AT 10 M OVER EITHER OPEN TERRAIN (LAND) OR REPRESENTATIVE OCEAN ROUGHNESS. GREY DOTTED LINE INDICATES THE CYCLONE TRACK.

Figure 10 shows the progressive maximum wind speed experienced by each statistical area as the storm tracked past southeast Queensland. At time t = -24 hrs only minor winds are felt on the mainland along the coast north of Harvey Bay. 12 hours prior to closest passage winds are being felt further south into the Harvey Bay and Fraser Island areas. By the time the storm makes its closest passage to land, approximately 10 km east of Harvey Bay and across Fraser Island, the maximum overland wind gusts of approximately 58 m/s (210 km/h) are being felt in that region. Damaging gusts of around 120 km/h are at the same time being experienced on the Sunshine Coast, with winds sustained at or above this level for several hours. Storm maximum winds of approximately 45-50 m/s (160-180 km/h) are experienced in the Sunshine Coast area, which, while not being beyond the regional design wind speeds (Standards Australia 2011), are high enough to cause widespread damage. By t = 6 hrs, winds are beginning to pick up in the Brisbane area, with maximum winds experienced in this area by around t = 12 hrs. Maximum gusts of approximately 40 m/s (150 km/h) are felt in the northern and eastern suburbs of Brisbane, which again will not lead to significant numbers of total building failures, but will lead to widespread minor to moderate damage.

For the scenario, the maximum overland gust wind speeds were recorded on Fraser Island (60 m/s), with Harvey Bay (58 m/s) feeling the strongest winds on the mainland. In total, 128 SA2 regions experience wind gusts greater than 125 km/h (35 m/s), or what would be classified as category 2 cyclonic winds on the Bureau of Meteorology's cyclone category scale[2]. Further, 26 experience gusts greater than 165 km/h (46 m/s) signifying category 3. The maximum gust simulated for the top 50 regions, based on displaced population (see Population Displacement section), are reported in Table A1 (Appendix A).



(a)

(b)

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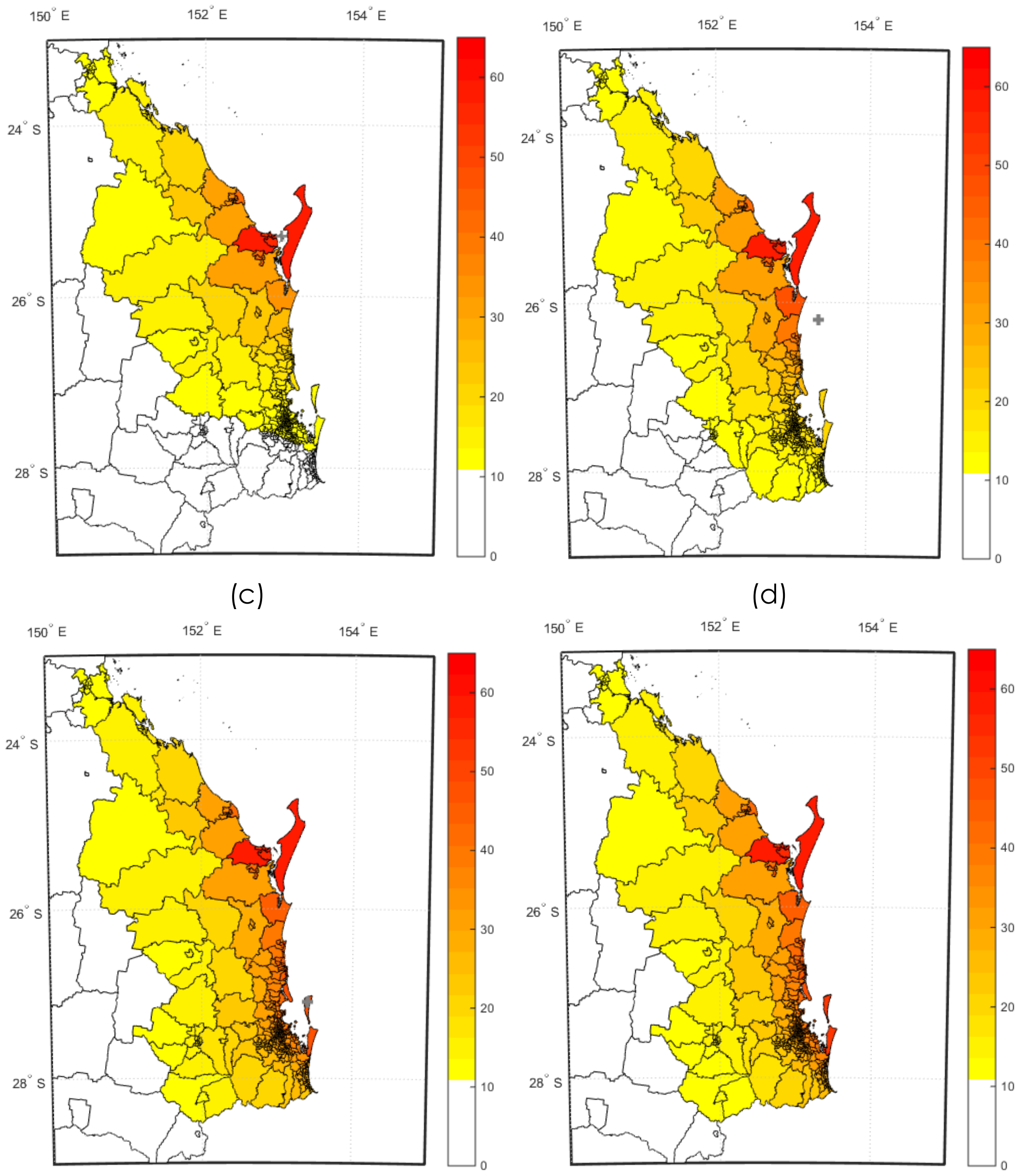
[2] http://www.bom.gov.au/cyclone/about/intensity.shtml



(c)

(d)

(e)

(f)

FIGURE 10. MAXIMUM 3 SECOND GUST RECORDED AT CENTRE OF SA2 REGIONS (QUEENSLAND REGIONS ONLY SHOWN) FOR (A) T = -24 HR, (B) T = -12 HR, (C) T = 0 HR, (D) T = 6 HR, (E) T = 12 HR AND (F) OVERALL STORM MAXIMA. WIND SPEEDS ARE IN M/S AND ARE AT 10 M HEIGHT IN OPEN FLAT TERRAIN. TIME (T) IS MEASURED FROM THE TIME WHEN THE STORM MAKES ITS CLOSEST PASSAGE WITH LAND. THE LOCATION OF THE CENTRE OF THE CYCLONE IS INDICATED BY THE CROSS MARKER.

Considering simulated gusts are estimated 3 second averages and that the Australian Wind Loading Standard, AS/NZS1170.2 (Standards Australia 2011) deals with 0.2 second gusts, the scenario simulates winds beyond the current design level for Importance Level 2 structures (e.g. housing) in these areas. (Note, you can roughly convert from 3 second to 0.2 second gusts speeds by multiplying by 1.1; the 500 year return period gust used for Importance Level (IL) 2 structures on flat open terrain in Region B is 57 m/s, 60 m/s for IL3 buildings, e.g. commercial structures). One would therefore expect relatively extensive damage to older housing stock and moderate damage to newer buildings in several areas along the coast.

BUILDING DAMAGE

Building damage has been estimated for all Queensland SA2 regions. For emergency management planning, damage to residential buildings is of most importance and is thus discussed in more detail than commercial and industrial buildings in this section. Aggregated numbers of damaged commercial and industrial buildings are however presented in Appendix A and discussed in more detail when detailing loss estimates.

Figure 11 shows the mean damage index for residential buildings due to the scenario event. Results are shown for both pre- and post-1981 buildings. As highlighted earlier, the damage index scale ranges from 0 indicating no damage to 1 indicating repair/replacement costs equating to the value of the structure. Figure 11 shows the same data as Figure 12, but for the smaller areas around Harvey Bay, the Sunshine Coast and Brisbane, with the colour scales adjusted for each. MDI values for the 20 SA2 regions experiencing the highest mean damage are also shown in Table 3.

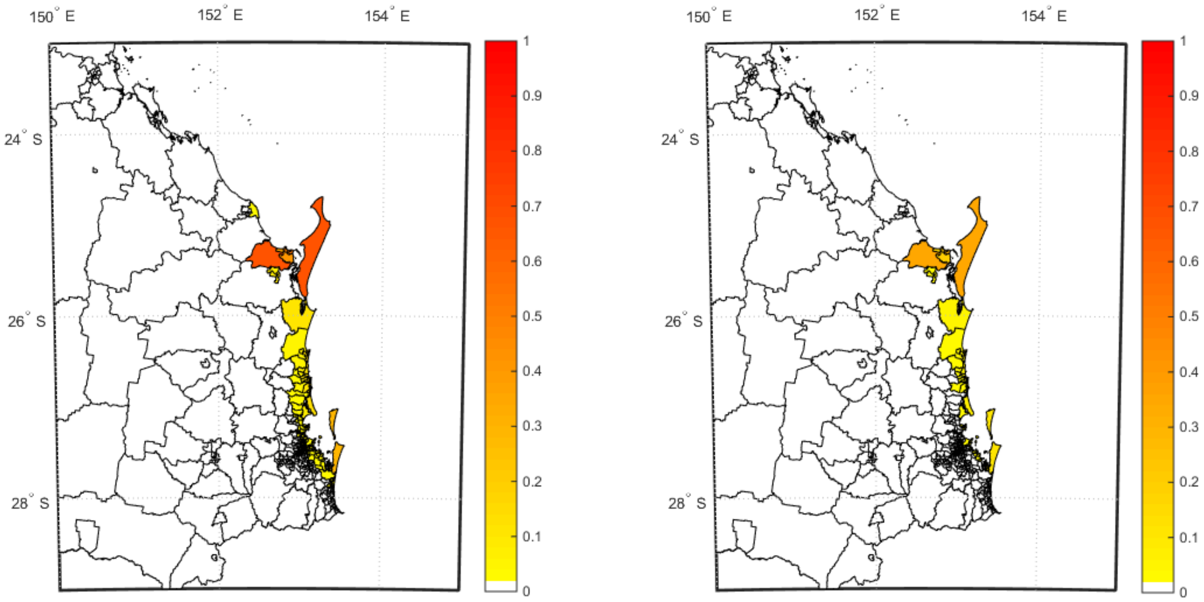


FIGURE 11. MEAN DAMAGE INDEX (MDI) FOR RESIDENTIAL BUILDINGS IN ALL SA2 REGIONS IMPACTED BY THE SCENARIO EVENT. LEFT IMAGE INDICATES DAMAGE TO PRE-1981 HOUSING, WITH THE RIGHT POST-1981. WHITE REGIONS INDICATE A MDI < 0.02.

The largest MDI values are simulated for Fraser Island and the SAs in and around Harvey Bay. MDI values of greater than 0.4 are shown in several regions indicating wide spread damage to these areas and thus a great call for emergency intervention and also post event reconstruction. With mean values of this magnitude it should be expected that a large number of properties will have DI values greater than 0.5 - 0.6, when considering the spread of damage within a region. While a structural damage index of 1 by definition represents complete destruction, in reality values at or above around 0.6 would necessitate a complete rebuild. As such, many of the residential properties in these regions would be unfit for occupation for an extended period of time and may need to be completely rebuilt.

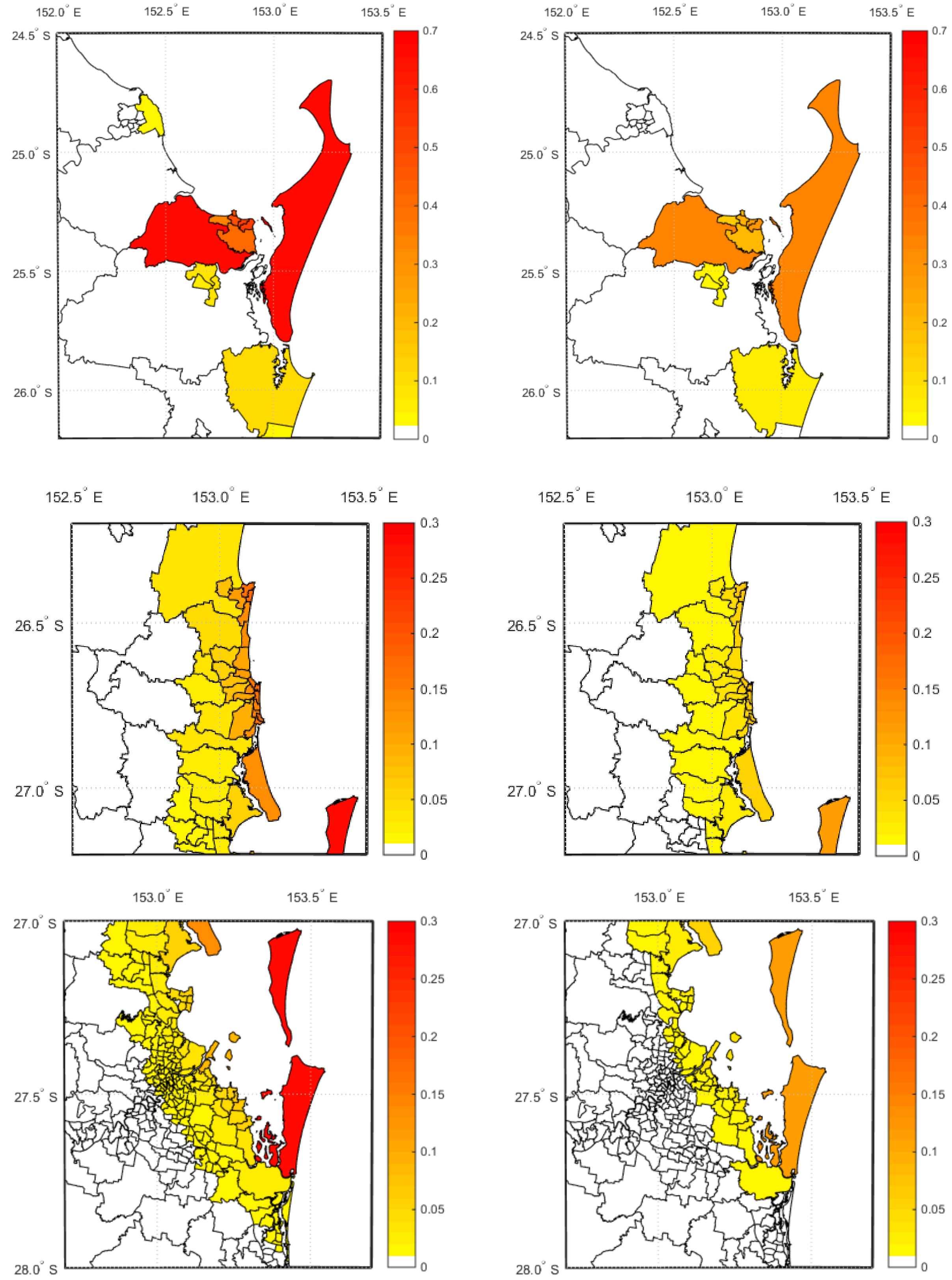


FIGURE 12. AS FOR FIGURE 11, BUT FOR THE ZOOMED IN REGIONS OF HARVEY BAY, SUNSHINE COAST AND BRISBANE (TOP TO BOTTOM ROW). IN THE UPPER IMAGE WHITE REGIONS REPRESENT MDI < 0.025, WHILE IN THE LOWER TWO WHITE INDICATE MDI < 0.01.

Outside the Harvey Bay/Fraser region, the largest MDI value is found in the Redland Islands area. This region encompasses many of the islands off the coast of Brisbane, including Moreton and North Stradbroke Island. The presence of large MDIs so far south is not unexpected given that the storm travels directly over the northern part of Morten Island (Figure 10e). However, physically it is not realistic that all these islands will experience such strong wind speeds, but given an entire statistical area is assigned a single wind speed based on the location of its centroid it is unavoidable with current model resolution. Future scenarios will move towards a much finer simulation resolution so such limitations (which could be said for many of the statistical areas) can be minimised.

TABLE 3. MEAN DAMAGE INDEX (MDI) VALUES FOR 20 SA2 REGIONS WITH LARGEST VALUES (BASED ON RESIDENTIAL DAMAGE). NOTE THAT INDUSTRIAL DAMAGE INDEX VALUES ARE THE SAME AS COMMERCIAL EXCEPT FOR SOME MINOR VARIABILITY DUE TO UNCERTAINTY MODELLING.

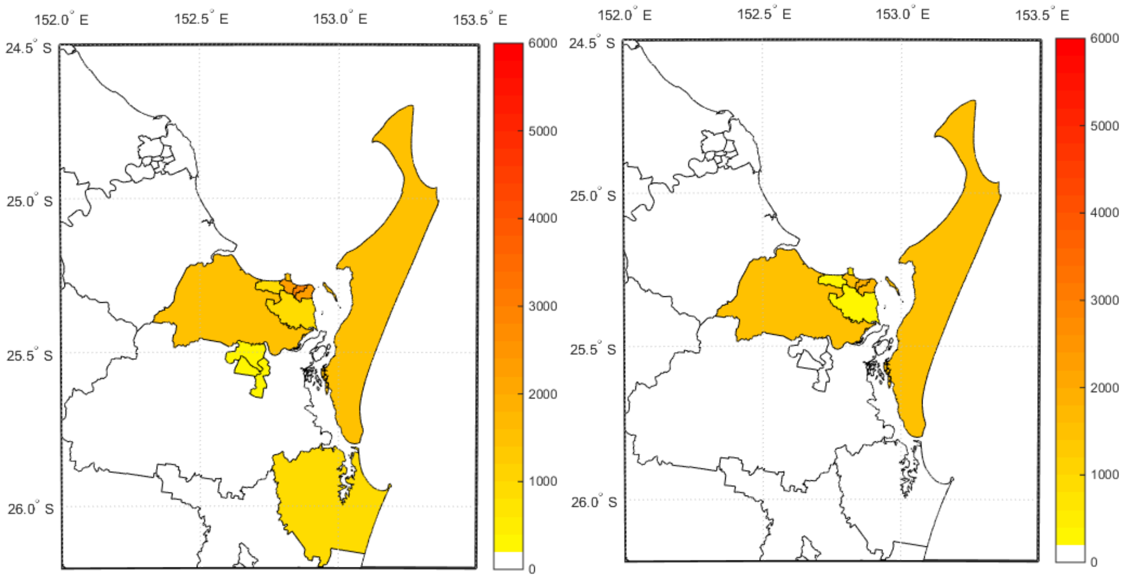
Rank	SA2 Name	MDI (Res, pre)	MDI (Res, post)	MDI (Com, pre)	MDI (Com, post)
1	Burrum - Fraser	0.68	0.35	0.56	0.26
2	Urangan - Wondunna	0.54	0.28	0.45	0.21
3	Torquay - Scarness - Kawungan	0.53	0.26	0.43	0.19
4	Pialba - Eli Waters	0.48	0.21	0.36	0.15
5	Point Vernon	0.45	0.20	0.36	0.16
6	Booral - River Heads	0.41	0.19	0.33	0.13
7	Craignish - Dundowran Beach	0.35	0.14	0.22	0.10
8	Redland Islands	0.29	0.11	0.19	0.08
9	Noosa Heads	0.17	0.07	0.09	0.04
10	Moffat Beach - Battery Hill	0.17	0.06	0.10	0.05
11	Buddina - Minyama	0.17	0.07	0.10	0.05
12	Sunshine Beach	0.17	0.07	0.10	0.05
13	Caloundra - Kings Beach	0.17	0.06	0.09	0.04
14	Parrearra - Warana	0.16	0.06	0.09	0.04
15	Aroona - Currimundi	0.15	0.05	0.08	0.04
16	Mooloolaba - Alexandra Headland	0.15	0.06	0.08	0.04
17	Wurtulla - Birtinya	0.14	0.06	0.08	0.04
18	Peregian	0.14	0.05	0.07	0.03
19	Mountain Creek	0.13	0.05	0.07	0.04
20	Bribie Island	0.13	0.05	0.08	0.04

Moderate MDI values of greater than 0.15 are also evident in the Sunshine Coast region, with the tourist destinations of Mooloolaba, Caloundra and Noosa Heads each experiencing damage of this order. Depending on timing, these areas may be highly populated with seasonal tourists who must be considered by planning agencies. Fortunately, damage levels to commercial buildings, such as hotels, is expected to be less than to general residential building which may mean extensive evacuations are not required (note that this may not be the case if they are located in storm tide zones). This said, survey work following recent tropical cyclones by the author and colleagues, has shown that strata-type multi-residential or holiday apartment buildings are being damaged beyond the level expected by many engineers and therefore are unlikely to be well represented by the implemented vulnerability models.

Damage to pre-1981 buildings is noticeably higher than to newer structures, and is shown to spread over a larger geographical area. This fact complicates issues when considering pre-event warnings and evacuations as it necessitates differing levels of action by occupants of housing of different age. Considering this fact it is important that home owners have some appreciation of the strength of their homes so appropriate action can be taken if required. Fortunately, with time the number of pre-1981 housing is decreasing due demolition/rebuild or the implementation of significant structural retrofits that bring these homes up to (or approaching) current standards.

While MDI distributions shows damage relativities between regions of uniform building density, the actual level of impact is perhaps more clearly depicted by the number of buildings within a *damage state*, or DI range. As outlined in 0 three damage states (DS) are defined here, DS1 (minor), DS2 (moderate) and DS3 (major). Moderate and major damage states are of most importance to the scenario as buildings within these states present those that will require some level of repair/reconstruction requiring the occupants to seek alternate accommodation. While damage will be sustained by some buildings classified as DS1, repairs are not expected to render the building uninhabitable. By presenting damage in this way we attempt to generate absolute impact metrics that may be of more use for emergency/reconstruction/resilience planning than damage index values.

Figure 13 presents maps of the aggregate number of buildings per statistical area classified as DS2 (left) and DS3 (right) following the scenario event. The reader is referred to Appendix A for further details of counts within specific areas.



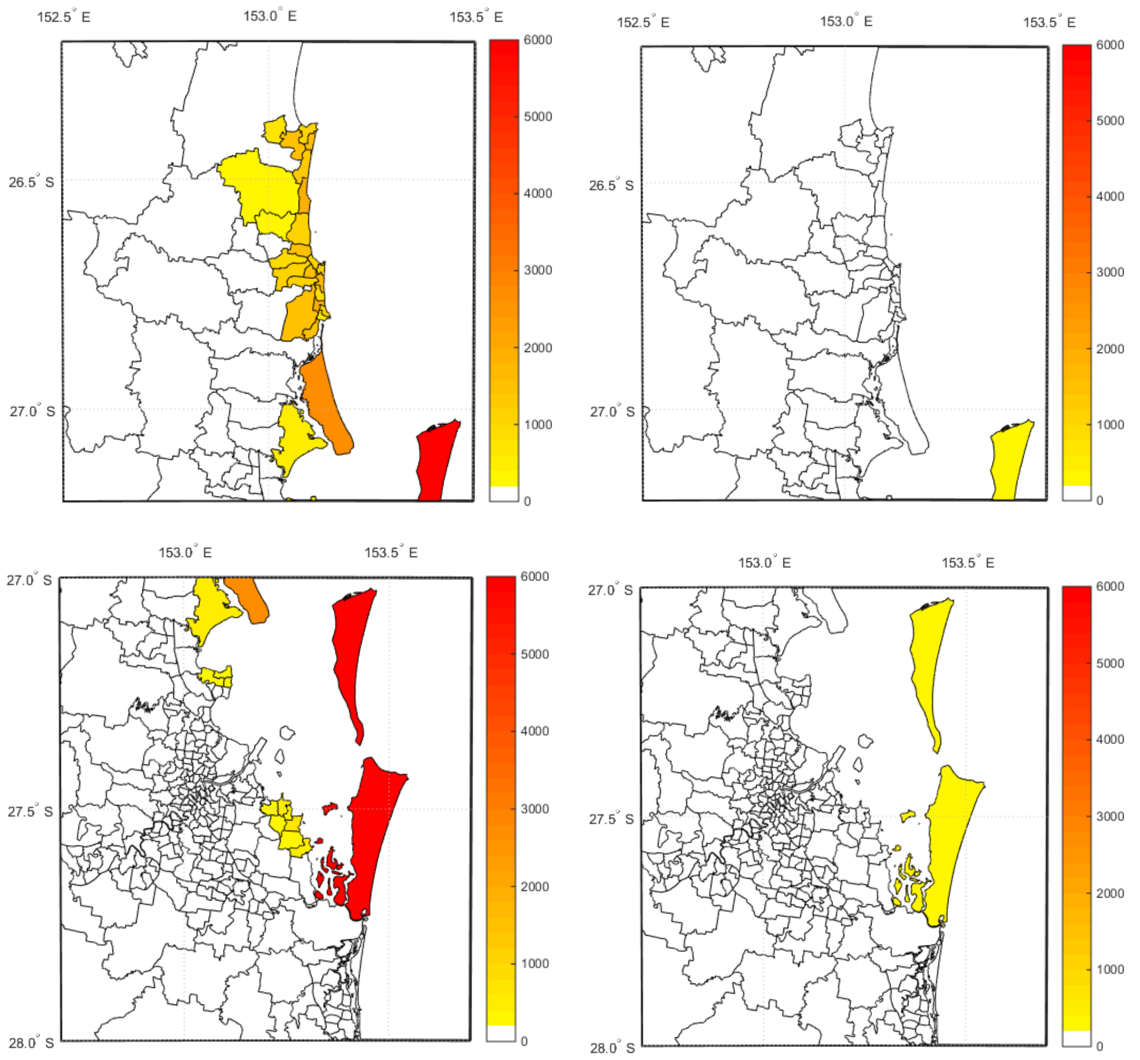


FIGURE 13. DS2 (LEFT COLUMN) AND DS3 (RIGHT COLUMN) RESIDENTIAL BUILDING COUNTS FOR WIDER HARVEY BAY (TOP), SUNSHINE COAST (MIDDLE) AND BRISBANE (LOWER) REGIONS. WHITE REGIONS IN ALL IMAGES REPRESENT < 200 BUILDINGS.

Unlike for the damage index results, the statistical area with the largest number of buildings within either DS2 or DS3 is towards the south of the impacted area, the Redland Islands near Brisbane. In this area there are almost 6000 residential buildings that are expected to achieve one of these two states. This potentially presents a unique problem for planners in that the islands are remote from the mainland and prior to the storm passage a decision would need to be made about whether to evacuate residents to Brisbane (or elsewhere), or shelter on the Islands with the possibility that supplies and communication channels may not be readily available following the storm. For a category 4 storm, as simulated here, given the intensity of winds would exceed the level that even new buildings are designed to safely withstand, evacuation may be appropriate, particularly for the more sparsely populated islands. This said, only a few percent of these buildings are expected to be within DS3, so it may be the case that enough suitable accommodation exists on the islands to shelter in place.

Looking more specifically at only the major damage state (DS3), it is evident that the vast majority of structures attaining this level of damage are in the Harvey Bay-Fraser Island regions. Several thousand buildings are expected to have damage states greater than 0.5 in and around Harvey Bay with around 1500 on

Fraser Island and into the Burrum area (on the mainland) suffering the same fate. Damage throughout this region is therefore extensive. When combining both DS2 and DS3 counts it is found that upwards of 80% of residential buildings in these areas sustain damage to these levels. This fact means that local alternate accommodation is unlikely to be found for many of the people whose homes have been destroyed. The situation on Fraser Island would be particularly bleak and it is expected that if residents were not evacuated prior to the storm they would likely need to be following the event due to lack of suitable accommodation. Fortunately buildings classes in DS3 appear to be confined to the Harvey Bay/Fraser Island areas and the Sunshine Coast and Brisbane have only small numbers structures damaged to this level.

Aggregating damage state counts over the entire impacted area it is found that more than 50,000 buildings were classed as DS2 and nearly 8,000 as DS3. Of the DS2 building approximately 70% were pre-1981 vintage, while this building type made up nearly 90% of buildings classed as DS3.

POPULATION DISPLACEMENT

Using the method set out in the Methodology section, building damage information has been coupled with population data to estimate the number of residents displaced from their homes following the storm. This impact metric builds on the previous section and considers not only the MDI and the number of damaged residential buildings, but also the density of population within those buildings. Figure 14 shows plots of the three impacted regions with Table 4 listing the twenty statistical areas with the highest displaced populations. Table 4 also highlights the percentage of each statistical area's total population displaced.

Harvey Bay was found to suffer the greatest number of displacements. The suburbs along the northern beaches, including Torquay, Scarness, Urangan, Pialba are relatively densely populated with both permanent residents and hotel/apartment accommodation, and were worst affected. Each of these areas were damaged to the extent that up to 60% of the local area's population suffered damage that would necessitate significant periods of displacement. An even larger proportion of the Fraser Island-Burrum statistical area is shown to be displaced, with almost 70% of that area's population requiring post event accommodation. This number should probably be treated with some caution though, as this statistical area includes both Fraser Island, which is large, and the area to the west of Harvey Bay, which is also large. Combined, this is an extremely large area that in reality will not experience a uniform maximum wind speed, as has been simulated here. This is a resolution issue and will attempt to be addressed in future simulations. This aside, the fact that such a high proportion of the region's population would be displaced means that careful consideration must be given to the possibility of pre-event evacuations from Fraser Island. This would include notifying people in an area where camping and similar activities are common, which may make communication difficult.

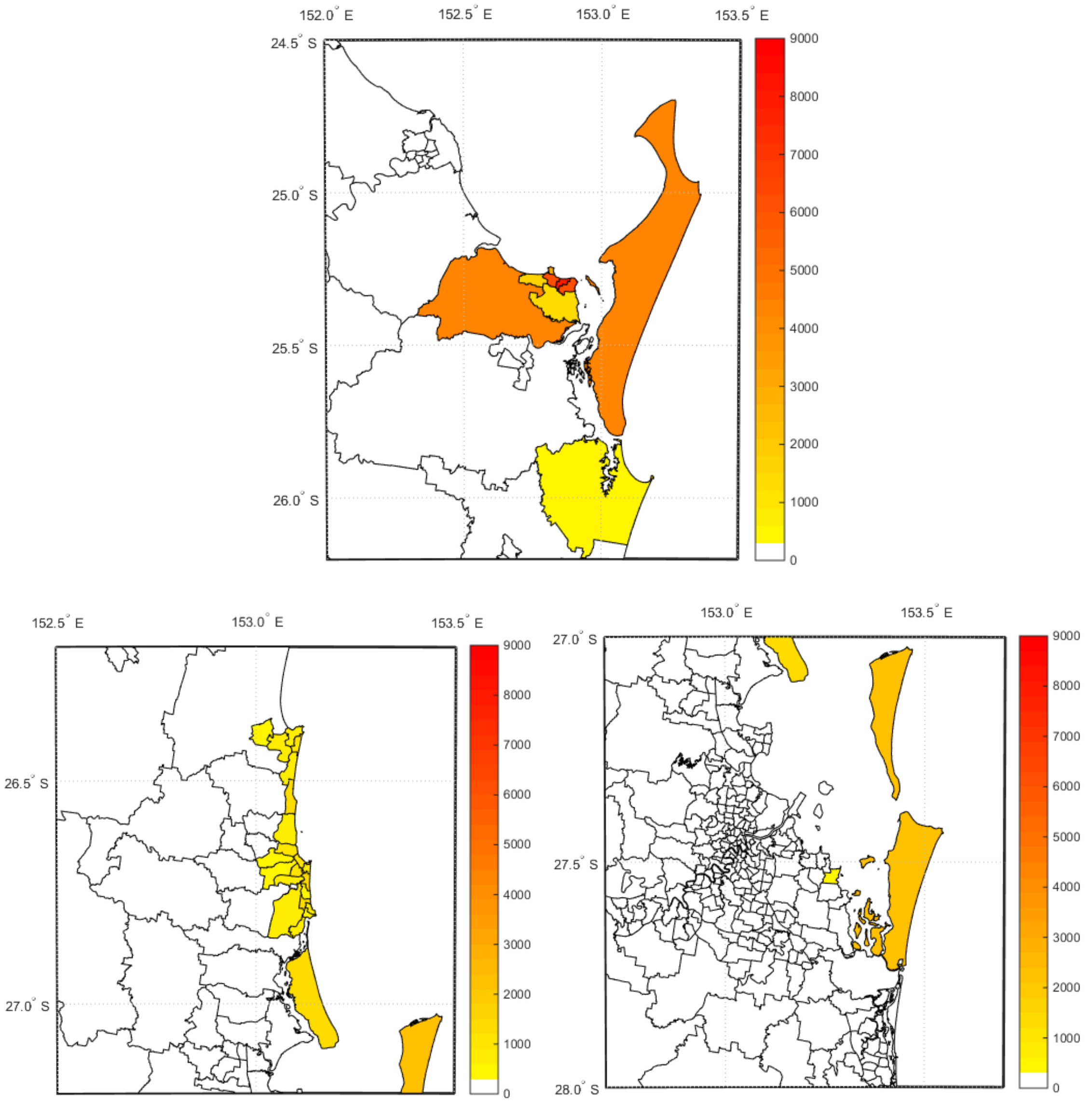


FIGURE 14. DISPLACED POPULATION FOR GREATER HARVEY BAY (TOP), SUNSHINE COAST (LOWER LEFT) AND BRISBANE (LOWER RIGHT) REGIONS. WHITE COLOURING REPRESENTS DISPLACED POPULATIONS WITHIN A STATISTICAL AREA OF LESS THAN APPROXIMATELY 250.

The Sunshine Coast and Bribie Island are also shown to experience notable levels of population displacement. While levels are not as high as in Harvey Bay, some SAs are expected to have greater than 1000 people needing accommodation. The relative percentage of total population in these area is of the order of 5-15%, which may still present accommodation sourcing issues. For a tourist area such as the Sunshine Coast it may be possible to accommodate such numbers locally, but it may also be required that some travel south to Brisbane. To some degree the severity of impact in these areas would be seasonal. Tropical cyclones occur during warmer and holiday months where the local population may swell beyond the permanent populations simulated here. As such displacement numbers may be larger and should be planned for.

TABLE 4. DISPLACED POPULATION.

Rank	SA2 Name	Displaced population	% Displaced
1	Torquay - Scarness - Kawungan	8082	61%
2	Pialba - Eli Waters	6328	61%
3	Urangan - Wondunna	6194	63%
4	Burrum - Fraser	4590	70%
5	Point Vernon	2704	51%
6	Redland Islands	2178	12%
7	Craignish - Dundowran Beach	1755	47%
8	Bribie Island	1265	8%
9	Aroona - Currimundi	1233	13%
10	Parrearra - Warana	1189	13%
11	Booral - River Heads	1134	36%
12	Coolum Beach	1001	7%
13	Sunshine Beach	921	13%
14	Mountain Creek	845	12%
15	Caloundra - West	841	6%
16	Mooloolaba - Alexandra Headland	828	7%
17	Peregian	797	9%
18	Golden Beach - Pelican Waters	739	7%
19	Maroochydore - Kuluin	723	4%
20	Noosaville	656	8%

Displacement numbers are relatively low in the Brisbane region, but the Redland Island (e.g. North Stradbroke) region is again expected to suffer considerable damage and subsequent displacement. As discussed above, the fact that many of these residents will not reside on the mainland may present issues with pre and post event evacuation and housing, which must be considered.

In total approximately 50,000 people are simulated to be displaced due to the scenario event. Around 30,000 of these are from the Harvey Bay/Fraser Island region with much of the remainder from the Sunshine Coast down to Bribie Island. Around 40,000 of the displaced occupants come from pre 1981 housing, with around 10,000 from post 1981 buildings. As with building damage, time will reduce the number of pre 1981 buildings and subsequently reduce the estimated number of displacements. To put the numbers discussed here in perspective, the aggregate count of 50,000 displaced is greater than the number of residents displaced following Cyclone Tracy, so any such event would be catastrophic.

BUILDING LOSSES (STRUCTURAL)

The NEXIS database includes estimates of the aggregate value of residential, commercial and industrial buildings, excluding contents, in each statistical area. Distributing this data to each statistical building within the area and coupling with damage index values (at each statistical building), an estimate of repair/reconstruction costs can be made. At this stage these values should be treated in relative terms as they only represent damage costs to building structures and do not include any contents or other non-structural damage costs. Additionally, they do not include any indirect losses such as cost of temporary accommodation, business interruption or any larger macroeconomic effects (e.g. Stewart, Wang et al. 2014, Walker, Mason et al. 2015). As such values only present a proportion of the total financial impact of the scenario. This said, it is instructive to understand where geographically the largest losses may occur, and to understand the relativity of losses between building types.

Similar to displacement, the largest residential building losses occur in the Harvey Bay region. The area with largest simulated loss is the Torquay-Scarness-Kawungan area, which has a total residential building loss estimated to be three quarters of a billion dollars. The aggregate expected loss to the wider Harvey Bay region (including Fraser Island-Burrum) is on the order of $3 Billion. Several areas on the Sunshine Coast also experience large losses, with values exceeding $100 Million in populous areas such as Coolum, Bribie Island, Caloundra, Mooloolaba and Noosa. While wind speeds are much lower in these areas than in Harvey Bay, the exposed assets are more numerous and in some cases more valuable and thus present more of a concern for loss estimation.

Inspecting estimated commercial losses, Urangan in Harvey Bay is shown to have a loss estimate of greater than $1.3 Billion, significantly higher losses than any other statistical area. In fact it is of the order of 5 times higher and represents nearly half the total event losses for commercial buildings. While there are several commercial resorts in this area, which will experience high wind speeds and subsequent damage, the disparity with surrounding areas raises alarm. Looking further into the underlying building statistics, NEXIS reports 222 commercial addresses in this area with a combined structural value of approximately $5.5 Billion. On average this suggests each commercial address is valued at around $25 Million, which is roughly ten times higher than its neighbouring statistical area. Further work is required to verify the validity of this value estimate, but at this point loss values will be treated as calculated.

In addition to Urangan an additional four areas have commercial losses exceeding $100 Million. These are again from Harvey Bay, but Caloundra, on the Sunshine Coast also has this level of loss. Multimillion dollar losses are reported for coastal areas spreading south to Brisbane suggesting businesses all throughout southeast Queensland will be affected. A similar distribution of loss is observed with industrial buildings, but values are an order of magnitude lower than for commercial buildings.

For the scenario a total structural building loss of $12.4 Billion is simulated. Of this value, $9.2 Billion is due to damage to residential buildings, $3 Billion to commercial buildings and a further $0.2 Billion to industrial buildings. This implies that nearly three quarters of building losses should be expected to be through damage to residential properties, while most of the remainder is due to damage to commercial properties. Industrial building damage only represents a small proportion of the total loss. However, it must be borne in mind that here we present only loss statistics for building damage and not any of the indirect impacts (including damage to building contents) that occur following a storm passage. These indirect costs tend to be a greater proportion of actual losses for commercial and industrial businesses and therefore when included could change the relativities significantly from what has been presented. Additionally, naively we have assumed that all commercial and industrial buildings perform structurally in a manner similar to residential buildings (as these are the buildings engineers have historically had the most data to build their vulnerability models from). It is not clear what the implications of this are and a more detailed treatment of these buildings should be explored.

TABLE 5. AGGREGATED LOSSES FOR EACH STATISTICAL AREA DIVIDED INTO RESIDENTIAL, COMMERCIAL AND INDUSTRIAL BUILDING TYPES. NOTE THAT VALUES ONLY REPRESENT DAMAGE TO BUILDINGS STRUCTURES AND DO NOT INCLUDE ANY CONTENTS OR INDIRECT DAMAGES.

	Rank	SA2 Name	Losses [$Mill, 2011]
Residential	**1**	Torquay - Scarness - Kawungan	738
	2	Urangan - Wondunna	638
	3	Burrum - Fraser	562
	4	Pialba - Eli Waters	550
	5	Redland Islands	410
	6	Point Vernon	251
	7	Bribie Island	212
	8	Craignish - Dundowran Beach	196
	9	Coolum Beach	164
	10	Booral - River Heads	152
Commercial	**1**	Urangan - Wondunna	1,329
	2	Pialba - Eli Waters	243
	3	Caloundra - Kings Beach	222
	4	Burrum - Fraser	168
	5	Torquay - Scarness - Kawungan	143
	6	Bribie Island	73
	7	Bargara - Burnett Heads	71
	8	Cooloola	48
	9	Maryborough (Qld)	39
	10	Peregian	35
Industrial	**1**	Craignish - Dundowran Beach	24
	2	Pialba - Eli Waters	23
	3	Brisbane Port - Lytton	10
	4	Buderim - North	10
	5	Parrearra - Warana	8
	6	Noosaville	8
	7	Eagle Farm - Pinkenba	7
	8	Moffat Beach - Battery Hill	7
	9	Caloundra - West	7
	10	Urangan - Wondunna	6

Use of loss statistics are important for financial disaster management agencies, such as re/insurers and governments. They are also important for engineers as they provide a means by which decisions about post (and pre) event reconstruction can be justified. In the long term they may also be useful for justifying decisions around modifications to building codes and practice. For these applications, though, it is not enough to simply know the aggregate level of damage to a population of buildings, it is important to know what is causing losses. With the current vulnerability models we are not able to pinpoint the exact structural mechanisms that are causing failure, but it is possible to see what levels of damage are causing the greatest loss. In other words, we're able to see what proportion of the loss for any building type is coming from different damage states.

Figure 15 shows the cumulative density functions of loss with respect to damage index for the three building types. It is shown that around 40% of residential building loss is driven by buildings in damage state 1, or those suffering only minor damage. Commercial buildings have approximately the same proportion of losses coming from minor damage, but for industrial buildings this number increases to 70%. When looking at the contribution of structures in damage state 3, or major damage, to overall loss it is seen that they contribute only around 10 – 15%. The remainder, or around half in the residential and commercial cases, is driven by moderate damage (DS2), which in many instances is made up of small levels of structural damage.

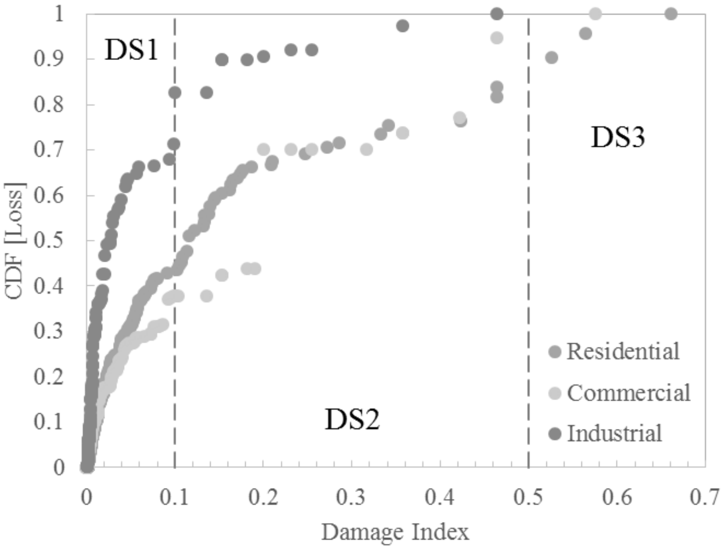


FIGURE 15. CUMULATIVE DISTRIBUTION FUNCTIONS FOR RESIDENTIAL, COMMERCIAL AND INDUSTRIAL BUILDING TYPES ACROSS THE ENTIRE IMPACTED REGION.

The shape of curves in Figure 15will vary from storm to storm and location to location. As such, similar plots for multiple storms would be required to get a more complete assessment of how differing levels of building damage contribute to tropical cyclone losses. However, some broad lessons can be learnt. The first being that significant levels of loss are caused by the aggregation of many small losses. Considering this, significant inroads could be made to reducing the impact of future storms by addressing the root causes of some of these minor damages (e.g. loss of guttering, flashing etc.). Secondly, only a relatively small proportion of loss appears to come from DS3, or major structural damage. While this may not always be the case, it does suggest that changing things like design wind speeds in buildings codes, which do little to minimise low levels of damage, but do improve performance at higher levels, may be an inefficient solution for reducing overall impact. Of course more research is required to state this conclusively, but this scenario appears to suggest this fact.

SENSITIVITY ANALYSIS

The scenario described thus far is only a single realisation of a major event impacting southeast Queensland. While the primary aim of developing disaster scenarios is to develop a plausible deterministic set of impact data that can be used for disaster management planning activities, it is useful to also have an understanding of how different storm parameters, e.g. size, small track perturbations, may influence the overall level of impact. This can provide the end-user with a greater sense of how their requirements may change depending on variability in storm characteristics, which in practice can vary significantly over very short time frames. This information is also useful when attempting to predict impacts prior to landfall. It is also important from a modelling perspective as it allows us to understand which model parameters are of most importance when developing (or revisiting) future scenarios. To this end a small number of 'alternate' scenarios are simulated and the spread of model output discussed. We focus solely on the variability in displaced persons here, but the discussion would be similar for the other variables previously described.

Sensitivity of building vulnerability

The first sensitivity test is simply a rerunning of the scenario holding everything identical to the scenario event, but allowing all random variables to be resampled. Currently the only randomness within the simulation is in the building vulnerability model, so this exercise describes the uncertainty in resulting population displacement due to variability in damage modelling.

Figure 16 shows a histogram of total displaced persons for 2000 realisations of the scenario. The range of possible displacement numbers is relatively narrow band, with all estimates sitting between 48,500 and 51,500. This represents only a few percent of the mean simulated displacement value and intuitively seems small. However, when we consider that much of the uncertainty in building damage at an individual structure level is averaged out when aggregating over large numbers it is not unexpected that the results will tighten in such a way. Additionally, by only allowing the damage component to resample we inherently assume that all exposure data provided through NEXIS is certain, which is not the case. We also assume that the uncertainty models we have implemented accurately represent the true spread of both mean and sub-region values, which as has already been stated is not the case. At any rate, Figure 16 provides an estimate of the spread of displacements to be compared with those generated in subsequent sections.

As outlined in Table 2, tests S1 and S2 are designed to test the sensitivity of results to changes in storm intensity and size. In these simulations the storm maintains the same track and central pressures as in the original scenario, but the size is reduced from 18 km down to 12 km in S1 and up to 25 km in S2. Coupled with this is an increase and decrease, respectively, of the peakedness factor B, conforming to the notion that small storms are more intense than larger ones. The net result of these changes on the wind speeds felt over land are an increase in maximum wind speed from 60 m/s to 63 m/s in S1 and a reduction to 54 m/s in S2. Damage causing winds are more widespread in S2 than S1, though, due to its increased size.

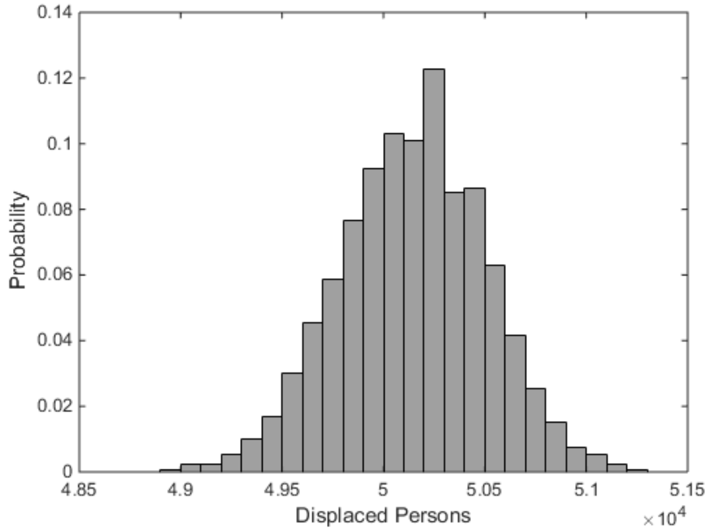


FIGURE 16. HISTOGRAM SHOWING THE PROBABILITY AN INDIVIDUAL REALISATION OF THE SCENARIO WILL GENERATE A TOTAL NUMBER OF DISPLACED PERSONS WITHIN EACH OF THE BINS SHOWN.

Storm size and maximum wind speed sensitivity

Figure 17 shows probability density functions of the resultant displaced populations for S1 and S2 as well as that the original scenario. The mean numbers of displaced persons shown in this plot are approximately 50,000, 45,000 and 23,000 for the original scenario, S1 and S2, respectively. S1 generates roughly equivalent numbers of displaced people because the areas around Harvey Bay most affected in the original scenario still experience high levels of damage in this event. For S2 however, although high winds are felt over a larger region than in the original scenario, the reduction in peak wind speeds has meant that damage and therefore resulting displacements have dropped by approximately 50%. This considered, S2 generates over 20,000 displaced people, which is by most metrics an extremely severe event.

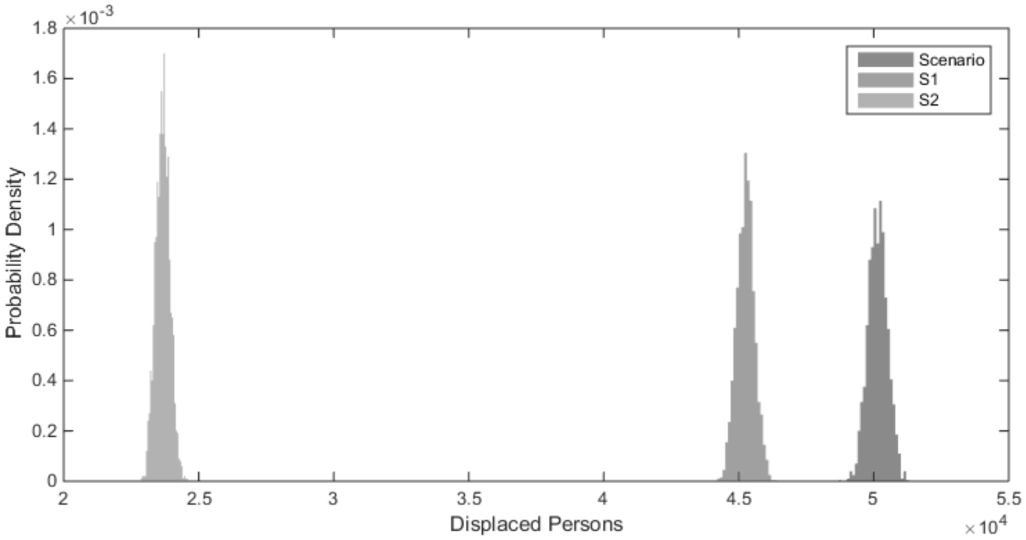


FIGURE 17. PROBABILITY DENSITY FUNCTIONS FOR TOTAL NUMBER OF DISPLACED PERSONS IN THE ORIGINAL SCENARIO, S1 (RMW = 12 KM, B = 1.4) AND S2 (RMW = 25 KM, B = 1.0).

The influence of storm size and intensity is clearly greater than that driven by the vulnerability model alone, as outlined in the previous section. This is shown in Figure 17 where the shift in mean displacements between scenarios is in each case greater than the spread of data simulated within each scenario run (2000 realisations). It is evident, therefore, that great care must be taken if this, or any other scenario model is used in an operational sense to assess impacts of an actual event without first sourcing the best quality information about the storm itself. Further, given the uncertainties associated with cyclone intensity forecasting discussed earlier, caution will need to be used when/if attempting to assess possible impacts prior to a storm so mobilisation can commence, or evacuations can be ordered based on forecast track statistics.

Track sensitivity

Sensitivity tests S3 and S4 investigate the influence of track position. Figure 3 shows the two scenario tracks simulated for this analysis, with S3 being the westerly track and S4 the easterly. As outlined in the Methodology section, the intensity (central pressure) of the westerly track deviates from the original scenario, in that it decays while over land based on empirical decay functions. Scenario S4 maintains the same central pressure time history as for the original event and roughly approximates the track of Tropical Cyclone Dinah.

The original scenario, as with any cyclone that tracks parallel to a coastline, is highly sensitive to track position. Small deviations in track can be the difference between a storm making landfall or not. This turned out to be the case with these sensitivity tests, with approximately twice the number of displaced people simulated in S3 than in the original scenario. In contrast, two orders of magnitude less displaced persons were simulated for S4. That is, approximately 100,000 displaced people in S3 and less than 1000 in S4. These two cases present extremely different levels of impact and subsequently two very different situations for emergency managers. To add to the complexity of the situation, both S3 and S4 would be considered probable outcomes in a forecast sense based on the storm position 24 hours prior to landfall (or the nearest passage in this case). Again, this makes estimating storm impacts prior to landfall a difficult proposition and one that requires great care if it is to be perused.

In the current set of sensitivity analyses the track location had the biggest influence on displacement results. This will not always be the case though (e.g. track detail is less important if it is perpendicular to the coast and impacting a uniformly populous region) and a full probabilistic analysis of all possible alternate tracks would provide a much more detailed assessment of risk. Such an analysis should be explored in future scenarios so a detailed understanding of which variables play the largest role in impact magnitudes and estimation errors can be built.

CONCLUSIONS AND FUTURE RESEARCH

CONCLUSIONS

When tropical cyclones occur they cause widespread and long lasting damage to affected communities. It is therefore imperative that potential impacts are understood prior to occurrence so they can be minimised. Some understanding of how to do this can be drawn from historical experience, but in order to understand the impacts and subsequent management requirements of events larger than those experienced, simulation techniques can be used. So called realistic disaster scenario modelling is a simulation technique widely used throughout the financial sector to gain insight into catastrophic event impacts and has been employed here to assess the impact of a hypothetical category 4 tropical cyclone tracking through southeast Queensland. Only wind-induced damage has been addressed in this work, with the compounding impacts of rainfall and coastal inundation to be explored in future research.

Consequences of the simulated storm were shown to be catastrophic. Estimates of the number of people displaced due to residential building damage number around 50,000. In some of the worst affected areas 60 – 70% of the local population would require emergency accommodation, with the added complication that a number of these would originate from the islands (e.g. Fraser and North Stradbroke) and may require pre-event evacuation. Driving this displacement is widespread destruction of housing, with around 8,000 homes suffering major damage, many of which will require complete reconstruction. In addition, a further 50,000 homes had damage levels classified as moderate, which means they will have likely sustained some level of structural damage but can feasibly be repaired, though to do this many will require their owners to seek temporary accommodation. Financially, losses due to structural damage to buildings runs into the billions, with a total aggregated loss estimated to be around $12 Billion.

In addition to the deterministic scenario simulation a small number of sensitivity analyses were undertaken to exemplify the importance of storm size, intensity and track location when it comes to estimating impacts. It was shown that for this particular storm, and the alternatives explored, track location had the largest influence on impact and small variations in track position could alter the number of displaced persons by 100 times. This highlighted the importance of incorporating high quality event information into any scenario work that extends beyond the hypothetical.

FUTURE RESEARCH

This scenario is the first in a compounding series of simulations that is working toward the development of a fully integrated tropical cyclone scenario risk and impact model. A preliminary wind field simulation tool has been developed along with damage and impact simulation models. Future work will build on and improve these two model components as well as adding capacity through the incorporation of rainfall and coastal inundation hazard models as well as subsequent impact modelling (vulnerability) tools to be used with them.

In particular future work will seek to:

- Add a synoptic wind field component to the current wind hazard model,
- Improve the treatment of surface roughness and topography in the wind hazard model,
- Increase simulation resolution to enable better estimates of wind speeds across regions,
- Incorporate new building vulnerability models as made available through other CRC projects,
- Add disruption of power supply to the impact modules,
- Build and implement rainwater and inundation hazard modelling capabilities,
- Source and implement inundation vulnerability models for estimating buildings and infrastructure damage as well as population displacement.
- Explore the use of scenario models as a tool for doing real time damage assessment and service requirements.

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APPENDIX A

TABLE A1. RANKED LIST OF DAMAGE STATE (RESIDENTIAL, COMMERCIAL + INDUSTRIAL), DISPLACEMENT AND LOSS FOR BUILDINGS/POPULATIONS. RANK BASED ON DISPLACED POPULATION.

Rank	SA2 Name	Max Gust (V3) [m/s]	DS 1 (Res)	DS 2 (Res)	DS 3 (Res)	DS 1 (C&I)	DS 2 (C&I)	DS 3 (C&I
1	Torquay - Scarness - Kawungan	57.7	605	2882	1985	21	52	17
2	Pialba - Eli Waters	56.4	453	2222	1502	150	241	38
3	Urangan - Wondunna	58.4	388	2227	1582	53	137	36
4	Burrum - Fraser	60.3	244	1518	1530	7	16	25
5	Point Vernon	56.5	390	1380	578	0	0	0
6	Redland Islands	52.4	6220	5894	150	13	9	0
7	Craignish - Dundowran Beach	53.6	263	926	309	46	37	1
8	Bribie Island	47.6	4856	2645	8	191	34	0
9	Aroona - Currimundi	47.8	2054	1840	18	34	6	0
10	Parrearra - Warana	48.6	1911	1607	23	406	41	0
11	Booral - River Heads	55.6	338	878	142	0	0	0
12	Coolum Beach	47.3	3679	1858	3	81	8	0
13	Sunshine Beach	49.0	1631	1484	29	0	0	0
14	Mountain Creek	47.3	1294	1301	9	25	0	0
15	Caloundra - West	45.0	2847	1648	0	217	2	0
16	Mooloolaba - Alexandra Headland	48.1	2239	1161	4	185	23	0
17	Peregian	47.2	2176	1318	7	58	5	0
18	Golden Beach - Pelican Waters	46.8	2857	1397	5	38	2	0
19	Maroochydore - Kuluin	46.1	3866	1346	0	445	23	0
20	Noosaville	46.3	2259	1474	4	424	13	0
21	Sippy Downs	45.7	1446	999	0	14	1	0
22	Buddina - Minyama	49.1	1683	942	8	70	10	0
23	Noosa Heads	48.7	1377	953	19	112	18	0
24	Moffat Beach - Battery Hill	48.8	2226	989	15	108	60	0
25	Marcoola - Mudjimba	45.8	2753	1051	2	130	1	0
26	Wurtulla - Birtinya	47.9	1375	818	3	0	0	0
27	Buderim - South	44.1	3726	1152	0	74	0	0
28	Caloundra - Kings Beach	48.5	489	361	8	992	273	0
29	Buderim - North	43.9	4625	1115	0	719	5	0
30	Cooloola	46.0	2385	787	2	12	0	0
31	Tewantin	43.8	3431	599	0	49	0	0
32	Cleveland	42.6	4739	629	0	316	0	0
33	Wellington Point	42.3	3591	341	0	96	0	0
34	Beachmere - Sandstone Point	42.1	4824	401	0	25	0	0
35	Bli Bli	42.4	1920	221	0	0	0	0
36	Victoria Point	41.5	4606	285	0	28	0	0
37	Ormiston	42.7	1844	211	0	27	0	0
38	Maryborough (Qld)	43.2	6422	248	0	316	4	0
39	Scarborough - Newport	42.4	3842	218	0	0	0	0
40	Granville	44.3	1023	122	0	0	0	0

41	Thornlands	41.0	3521	200	0	0	0	0
42	Redcliffe	42.5	3136	128	0	106	1	0
43	Alexandra Hills	40.5	5673	171	0	0	0	0
44	Birkdale	40.4	4757	147	0	29	0	0
45	Tinana	42.1	1460	126	0	0	0	0
46	Eumundi - Yandina	41.0	1973	130	0	353	0	0
47	Diddillibah - Rosemount	42.0	791	87	0	0	0	0
48	Rothwell - Kippa-Ring	40.4	5444	103	0	203	0	0
49	Margate - Woody Point	41.7	4144	63	0	16	0	0
50	Noosa Hinterland	39.6	6109	92	0	137	0	0