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VULNERABILITY OF BUILDINGS AND CIVIL INFRASTRUCTURE TO TROPICAL CYCLONES

A preliminary review of modelling approaches and literature

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Version	Release history	Date
1.0	Initial release of document	22/02/2017

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Publisher:
Bushfire and Natural Hazards CRC

February 2017

Citation: Mason M, Parackal K (2015) Vulnerability of buildings and civil infrastructure to tropical cyclones: A preliminary review of modelling approaches and literature, Bushfire and Natural Hazards

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1. Introduction

Disasters, even those termed *natural disasters*, are largely man-made events (World Bank & United Nations, 2010). Although often caused by natural phenomena, a disaster occurs when some form of stressor negatively impacts people, communities and/or the built environment that protects them. Impacts are felt most acutely through direct damage to structures, e.g. housing, hospitals, power systems, transport networks, to name a few, but also indirectly through the resultant impact on activities that rely on these structures, e.g. business operations, supply chains or loss of general accommodation. In a broad sense the severity of a disaster has a causal link to the magnitude of an extreme event. However, given that damage to the built environment is how the general population will experience the lasting impacts of an event, there is also a strong relationship between the geographic location where an event occurs and the characteristics (e.g. quality of construction, levels of network redundancy) of the town, city or community impacted. For example, a tropical cyclone that makes landfall on a remote part of the coastline may impact a small number of people and their activities, but it is hardly considered a disaster. On the other hand, should that same event make landfall in a densely populated city, say Cairns, Darwin or Brisbane, the potential impacts will be far greater, as too will be the need for emergency services. Therefore any rational assessment of the risk of natural hazards must not only consider the hazard but also the exposure—buildings and infrastructure in the path of the tropical cyclone, say—and how exposed assets respond to the hazard when impacted. This can be expressed graphically through the classic Venn diagram given in Figure 1, or mathematically as in Equation 1 (after Stewart & Deng, 2015) where the product of the hazard probability, P(H), and the conditional probability of loss given a specified hazard level, P(L|H), is summed over all assets under consideration.

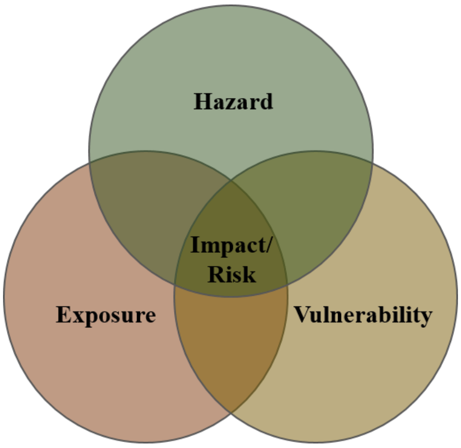

Figure 1: Venn diagram showing the intersection of hazard, exposure and vulnerability that determine natural hazard risk and impact

$$\text{Impact} = \sum(P(H) \times P(L|H)) \tag{1}$$

Equation 1 has been expressed in a probabilistic form because any type of impact or risk assessment is essentially probabilistic in nature. This is because there is still much unknown about how individual assets or systems of assets respond to hazard loading. This being the case, the estimated impacts can only be (defensibly) described by a probability density distribution of possible outcomes and this is true even when considering an individual realization of a set of potential hazards. Due to the complexity of the built environment, application of Equation 1 is not straight forward, and it is generally done using a simulation/modelling approach, often termed a catastrophe model (Grossi, Kunreuther, & Windeler, 2005; Woo, 1999, 2011). These models comprehensively analyse the entire hazard-loss chain in a probabilistic manner and in full acknowledgement of the uncertainties introduced at each step (Edwards & Challenor, 2013). Models can, be run to assess the impacts of individual hazard scenarios—as shall be the case for this project—or, given the information is available, be run for all possible scenarios to assess the potential impact of all possible hazard outcomes.

This report focuses on the P(L|H) component of equation 1, which is a description of the loss or impact that will occur conditional upon the occurrence of a specific hazard metric. This is termed the *vulnerability* and can refer to an individual asset, a network system or even a community and its population. As will be demonstrated later, vulnerability can play a crucial role in defining the overall impact felt by a community during any given event and understanding how it is quantified within risk assessment models is important for determining the level of certainty that should be placed in outputs. A wide range of vulnerability models have been employed, and it is the review of these models, as they pertain to tropical cyclone hazards, that is the subject of this review.

Tropical cyclones generate a range of concomitant hazards that any complete assessment of risk should account for. These include: wind, wind-driven rain, coastal inundation (generally termed storm surge) and inland (riverine) inundation. Wind and wind-driven rain are hazards of all tropical cyclones and impact both coastal and inland areas. Coastal and riverine flooding only impact areas near to these water bodies. In some areas of the world, landslides associated with heavy rainfall may also be locally devastating.

This report will focus predominantly on the response of assets to extreme wind and flood (coastal and inland inundation) and each asset/network class will be further investigated under the following categories.

- Buildings
    - Residential buildings
    - Other building types, e.g. commercial, industrial
- Civil infrastructure
    - Power systems
    - Road and transport
    - Water supply
    - Telecommunication

Given the broad scope of this field, we do not attempt an all-encompassing overview of all works ever undertaken on the topic (particularly for civil infrastructure), but instead focus on those models of most benefit to the scenario analyses required of this project. Because many of the models have been developed internationally, a primary question to be answered is whether they are applicable to Australian conditions.

This document forms a key component of the BNHCRC project "*Using realistic disaster scenario analysis to understand natural hazard impacts and emergency management requirements*" and is structured as follows. First we begin with a brief introduction to the theory and concepts involved in vulnerability modelling. Existing building and civil infrastructure vulnerability models are then reviewed in sections 3 and 4, with the sub-hazards of wind and flood addressed separately where appropriate. Recommendations outlining suitable tools/models for implementation will be made, with a summary of literature presented in tabular form at the end of each section. The concept of network interdependence will be briefly reviewed in section 6 as it applies to network infrastructure and a summary of all recommendations will be provided in 7.

2. Vulnerability Modelling

Vulnerability models are, in essence, mathematical tools that allow impact metrics to be estimated based on hazard metrics. They were first introduced by the insurance industry in the 1960s and have evolved considerably since that time. Pita et al. (2015) succinctly outlines the evolution of wind hazard vulnerability models—as they relate to building structures—over this period, and defines five major types of vulnerability models. Despite originally framed for wind hazard, this list is broadly representative of models developed across the range of hazards under consideration in this report.

1. Past loss data-based
2. Past loss data-based enhanced with expert judgment
3. Heuristic
4. Component-based
5. Simulation-based

The first two of these are essentially empirical models, where 'past loss data' was typically insurance claims information and the impact metric a repair or replacement cost. To develop these models information on damage cost and the causal hazard metrics from previous events are compiled and a regression technique used to relate the two variables (Pita, Pinelli, Gurley, & Hamid, 2013). Provided data is available, these models are simple to understand and apply, but they inherently make the assumption that vulnerabilities that existed for the event/s used to build the model exist for any future applications of it. In practice this is not the case as factors such as local building practice and materials can play a significant role in changing the vulnerability of otherwise similar structures. For this reason the second sub-set of models were developed. These models are essentially the same as the first, but have some level of data disaggregation prior to regression. This can be done using the variables discussed above, or any factor that will significantly influence how an otherwise identical asset would behave. While these models do not provide much information about why damage is occurring, the fact that they are routed in actual, real-life data, makes them appealing. This said, more recent research has tried to use complex statistical or data mining approaches to draw greater causal information from damage/loss data (e.g. Merz, Kreibich, & Lall, 2013).

Heuristic models are solely based on expert judgement. They are developed when no empirical damage information is available or as an interim step when developing a more complex simulation or component-based model. Most of these models rely on assessments of subjective damage probabilities conditional on hazard levels made by experienced practitioners, who through their experience purport to offer insight into vulnerabilities (Pita et al., 2015). This approach allow some level of engineering 'knowledge' to be implanted into the model, but validation against some form of data, be it experimental tests or loss data, is required before these models should be applied.

Building on the heuristic model concept is the component-based vulnerability model—referred to as potential damage model when dealing with flood vulnerability (Smith, 1994). In principle these models are similar to the generic heuristic model, in that they are often developed using expert judgement, but instead of building the model to directly predict an overall level of damage to a structure they estimate damage to individual components of a system and aggregate these up to estimate the overall level of damage. This concept builds on traditional reliability engineering theory (Pita et al., 2015) and often requires either additional information so the correlation of damage and progressive load and failure paths within a structure can be adequately considered. Full scale information is not always available for these types of models, so laboratory testing and engineering judgement are used to help build them. As with general heuristic models, component-based models require validation if they are to be believed. However, substantially more 'engineering' goes into a component-based model than either a system level heuristic or empirical model, so more information about how damage is occurring can be drawn from it. This also means these models can be used to assess the efficacy of component level mitigation measures or changes to building practice.

The most recent (and complex) type of vulnerability model is what Pita et al. (2015) refers to as a simulation-based model. These models attempt to simulate time-dependent hazard loading, load transfer and resultant damage to a structure in a probabilistic manner, with progressive elemental failure and load path updating undertaken. These models are generally developed within a Monte Carlo type simulation environment, where multiple realisations of the hazard and response are simulated. These can then be aggregated to develop mean vulnerability relationships, together with uncertainty bounds. Given the level of information often simulated, it is also possible in these models to simulate secondary damage causing mechanisms, such as debris impact (e.g. Chung Yau, Lin, & Vanmarcke, 2011) or water ingress (e.g. Dao & van de Lindt, 2010) during tropical cyclones. Again, these models require validation using loss data or damage survey information, but it seems that many researchers are moving towards developing this type of vulnerability model. This is unsurprising given that simulation-based models provide the greatest level of understanding when it comes to damage causation, which provides great explanatory and comparative capabilities when issues such as mitigation efficacy (from a safety and financial view point) are of interest.

The models described above are largely discussed in terms of building damage, but they are equally applicable to the estimation of interior and contents damage within a building. Contents damage estimation has received significant attention from the insurance industry, but relatively little—when compared with building damage—from the engineering fraternity. This is out of line with the cost of repair or replacement of contents and interior fixings following tropical cyclones, but is understandable in the sense that these damages are largely material damages and not the type of structural failures that engineers tend to deal with. This paradigm is changing thought and a number of detailed engineeringbased models of internal damage are surfacing (e.g. Dao & van de Lindt, 2010). Models for assessing both building and interior/contents damage are reviewed in this article.

Physical damage to a building and its contents is considered to be ‘direct’ damage (Merz, Kreibich, Schwarze, & Thieken, 2010). This type of damage is the primary concern of this report but it should be acknowledged that ‘indirect’ damages also occur, and can be similarly costly. Indirect damage may include interruption to business operations because a warehouse has been damaged or a road has been cut. This carries financial impacts to both the supplier and the customer.

Another type of indirect damage that is felt more widely is the cost of finding alternate accommodation when a residential home has been damaged and cannot be immediately inhabited. These types of damages are important when trying to understand the long-term impact on the wider community impacted by natural hazards. However, given the modelling of such impacts is a complex multi-variate (and multi-disciplinary) problem that doesn’t easily lend itself to generalization, this type of vulnerability modeling is not addressed in this report.

There is uncertainty in all vulnerability models, but few model descriptions include a detailed assessment of the uncertainty embedded within them. To a degree this is understandable as it is often difficult to quantify this variable given the large number of uncertain factors and processes that lead to damage occurrence—especially for empirical models where limited data is available for validation. Where uncertainty is described it is generally approximated by a probability density function that is dependent on the mean extent of damage. Truncated normal, Beta or Gamma distributions are common types assigned throughout the literature (Egorova, van Noortwijk, & Holterman, 2008; Walker, 2011).

Where probabilistic engineering-based approaches are used to develop mean vulnerability relationships the uncertainty may not conform to any particular distribution and may not be symmetrical. The scale of assessment is another important consideration when considering the modeling of uncertainty. A different spread of potential damage levels is required if attempting to simulate damage at an individual building level than when trying to understand the variability of damage aggregated over communities. In the latter case the aggregated damage should approach the mean loss for a given level of environmental stress and particular building class as suggested by the Central Limit Theorem. Most of the discussion throughout this article is around mean vulnerability relationships, but for the application of any of these a measure of uncertainty must be considered.

Irrespective of the type of vulnerability mode, each can be assessed in terms of its maturity – from conceptual to a widely used product. This is an important aspect to understand as it provides information about how easily a model could be implemented, and indirectly offers some insight into the validity of a model. Throughout this document level of maturity has been assessed using four categories (refer to the summary tables at the end of each section):

- Research – the model is conceptual without vetted application in real-world domains
- Development – Product has been validated against real world applications but is still undergoing substantial development.
- Mature Analytic – A high level of stability with analysis used in external reports. However, its usage is largely internal to the organisation.
- Mature Commercial – A widely used, often open-access, product.

3. Vulnerability of Building Structures

3.1 Wind

Wind applies a range of loads to a structure that could each potentially lead to damage and/or total failure. Most directly wind applies pressure to the external fabric of a building that can lead to failure of individual components of the envelope (e.g. windows, roof sheeting), which in turn can lead to subsequent failures or secondary damages (e.g. water ingress). Less directly, wind can transport debris such as building material or foliage at speeds close to the wind speed itself and the impact of which can also lead to structural damage. As with pressure loading, debris impact can also cause building envelope failure with resultant cascading damage again occurring. Debris impact may also take the form of treefall, which is a common mode of building damage observed even during weak storms.

In addition to direct pressure and debris loading, wind-driven rain is an ever-present hazard during tropical cyclones. Even without failure of a building envelope wind pressures force water through façade openings, irrespective of how small (Boughton et al., 2011). Wind-driven rain is the primary reason for contents damage (with respect of wind) that may contribute significantly to the over loss to a household. Even in the absence of major structural damage, loss of personal effects may mean that residents or building owners have to vacate premises for extended periods of time.

3.1.1 Residential buildings

Wind vulnerability models have largely been developed for hurricanes and tornadoes (e.g. Hart, 1976) in the United States and tropical cyclones in Australia (Crompton & McAneney, 2008; Ginger, Henderson, Edwards, & Holmes, 2010; Henderson & Ginger, 2007; Leicester & Reardon, 1976; Walker, 2011; Wehner, Ginger, Holmes, Sandland, & Edwards, 2010).

Walker (2011), Pita et al., (2013) and Pita et al., (2015) provide extensive overviews of vulnerability models developed for residential buildings subject to severe wind loading, primarily in Australia, USA and Japan. These reviews detail the historical development of modelling capacity from the early empirical models developed by Friedman (1975) to the engineering-based simulation models now being developed for public risk modelling frameworks in the USA (i.e. HAZUS and the Florida Public Hurricane Loss Model) and Australia. These review articles are an excellent source of information and provide extensive model references beyond the (largely) Australian models discussed herein.

A range of different models have been built for Australian residential construction. The earliest were developed based on observed damage to housing during Tropical Cyclone Tracy (1974), with Leister and Reardon (1976) doing so based on damage survey information collected following the event (Figure 2), and Walker (1995) (cited in Crompton & McAneney, 2008) doing so based on insurance loss data. Walker additionally studied loss data from Tropical Cyclone Althea (1971) and Winifred (1986) and derived mean vulnerability curves for Queensland housing built prior to the introduction of new building regulations in 1981 (Mason & Haynes, 2010), and those built after this point (Figure 2). Both these models were empirically derived, but also draw on engineering judgement. Importantly, these models disaggregate building and contents loss, highlighting the appreciation of the importance of the latter to overall impact. The Walker (1995) model is still used widely throughout the insurance industry as a benchmark for wind vulnerability models and Khanduri and Morrow (2003) and Walker (1995) have developed techniques to adapt these existing empirical models to other countries.

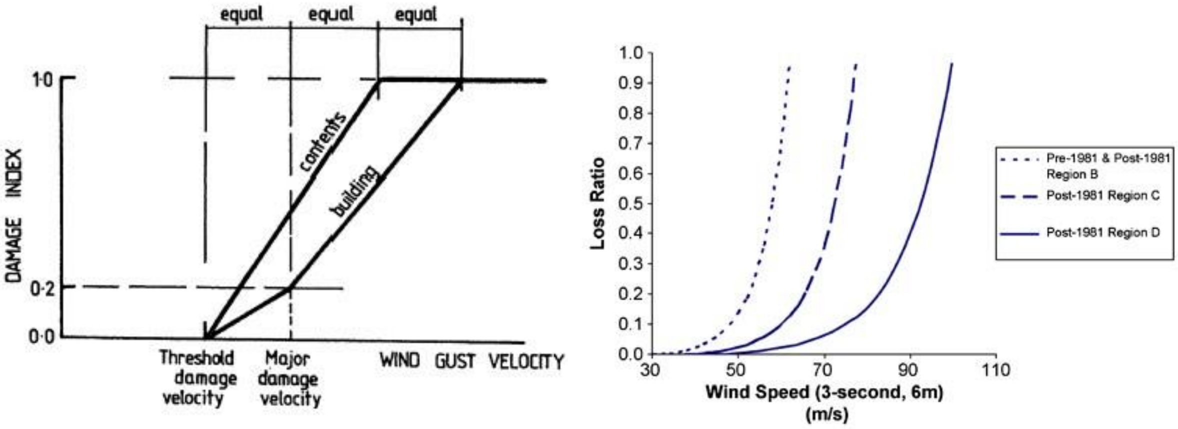

Figure 2. Early vulnerability curves for residential housing in Australia, a) Leicester and Reardon (1976) and b) Walker (1995) (Pre-1981 and post-1981 are the Walker curves).

Henderson and Harper (2003) developed a suite of probabilistic vulnerability curves for six different building types, based on assumed modes of failure and internal pressurisation. These models estimate the probability of structural damage occurring to a population of housing based on maximum wind speed to the region. In this sense they differ from the Leicester and Reardon (1976) and Walker (1995) in that they estimate the percentage of buildings that suffer ‘damage’, they do not estimate the average damage to a population of buildings. Irrespective, the model was tested by the authors against damage survey information collected following Tropical Cyclones Althea, Tracy, Winifred and Vance, with reasonable agreement. Henderson and Ginger (2007) extend this model specifically to high-set timber housing, again generating vulnerability curves that estimate the percentage of housing within a region to suffer damage based on component failure probabilities and assumed failure progressions (Figure 3). Jayasinghe and Ginger (2011) and Jayasinghe et al. (2013) later improved the component failure probabilities within this framework, particularly focusing on the performance of the roof sub-system.

In an attempt to develop a national risk assessment model, a suite of heuristic vulnerability curves was developed by Geoscience Australia through a series of expert-workshops (Ginger, Henderson, et al., 2010). These models were developed for a range of different housing types, considering the potential influence of different load bearing systems, wall cladding and roof types. Figure 4 shows an example of the mean vulnerability relationships between loss (i.e. repair cost/total cost) and maximum gust wind speed at a given location, derived for housing built in different parts of the country. Each curve utilises a two-parameter equation, with fitting parameters provided for each. This heuristic set of (mean) vulnerability models is currently being refined through the development of component-based fragility models that will allow aggregation of damage information into fully engineered vulnerability models for the range of different building types (Wehner, Ginger, et al., 2010). Some level of validation against existing damage data has been undertaken (Wehner, Ginger, et al., 2010), but this is limited to only a small subset of building types and there is some indication based on insurance loss data that these curves systematically overestimate damage levels (Ginger, Henderson, et al., 2010). Despite this comment, the Geoscience Australia curves present the only publically available set of vulnerability models for the range of housing types across Australia. It should also be noted that the Bushfire and Natural Hazards CRC project “*Improving the resilience of existing housing to severe wind events*” is contributing to the improvement of this suite of models.

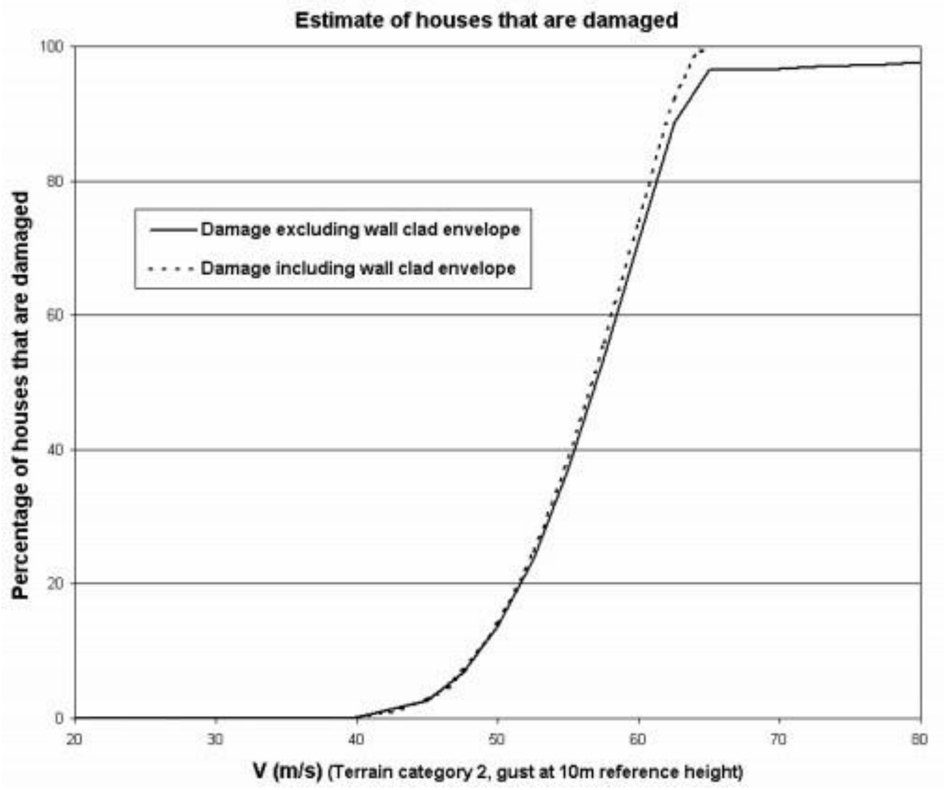

Figure 3: Vulnerability model for high-set timber housing (Henderson & Ginger, 2007).

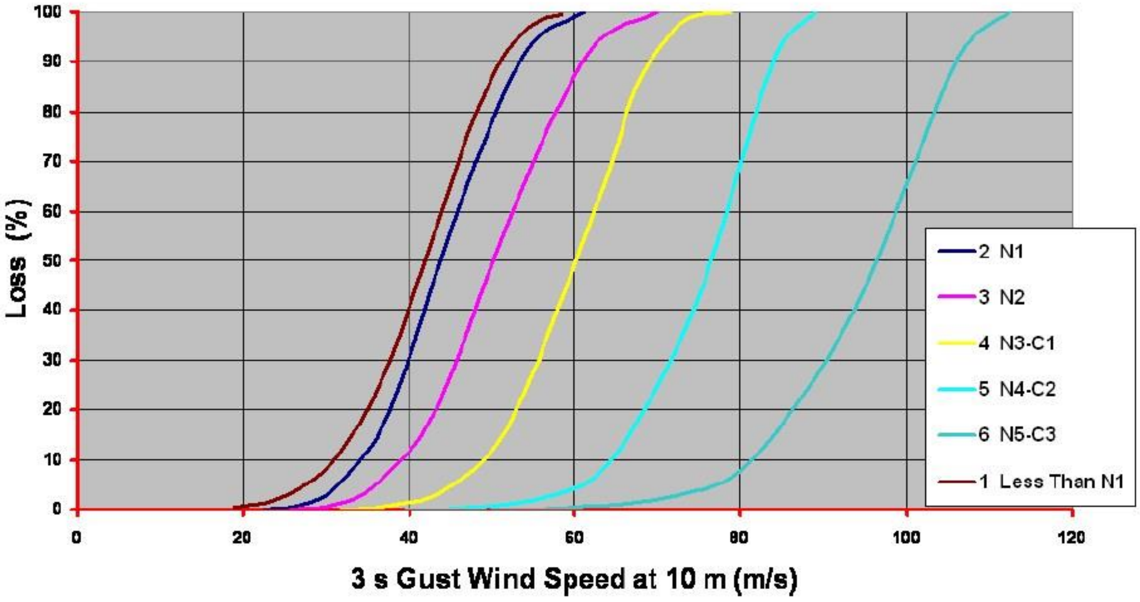

Figure 4: Geoscience Australia's suite of mean wind vulnerability models for new housing in different parts of Australia. N1 to N5 represent regions with increasing non-cyclonic wind hazard, and C1 to C3 represent regions with increasing cyclonic wind hazard (refer to AS4055 (Standards Australia, 2012) for further details).

An issue with heuristic and simulation models is their reliance on wind pressure (or the consideration of wind pressure) as the sole contributor to structural damage. As outlined earlier in this section, windborne debris impact and wind-driven rain are also contributing factors to overall damage levels experienced during tropical cyclones. While the impact of these sub-hazards are considered implicitly in empirical vulnerability models, and to some extent in heuristic models, in a strictly engineeringbased models these hazards must be explicitly simulated. This can only really be done in a simulationbased model with consideration to the building's surroundings (e.g. other buildings and foliage) and the broad wind/rain fields surrounding the building. Explicit inclusion of this information makes the modelling task complex. Holmes (2010) provides a thorough review of existing debris impact models developed internationally.

For the simulation-based Australian models (e.g. Henderson & Ginger, 2007; Wehner, Ginger, et al., 2010) wind-borne debris has been considered. The Henderson and Ginger (2007) model included debris impact through conditional probabilities that change the simulated internal pressure loadings based on an assumed state of debris penetration of the building envelope. Holmes et al. (2010) and Wehner et al (2010) describe development of a debris risk and impact model that estimates the cost of damage to walls based on the estimated extent of damage plus the resulting change in internal pressures when envelope breaches occur.

In addition to debris generated from buildings, considerable debris results from trees and other foliage. Few models could be found that describe this hazard, but the HAZUS hurricane risk model includes a sub-model (FEMA, 2009b; Vickery et al., 2006) that simulates tree fall and its impact. This model was developed based on research primarily by the forestry industry and nuclear weapons researchers.

The discussion to this point has primarily been concerned with estimating damage to the exterior façade and structural system of a building itself. However, repair or replacement of the interior elements (e.g. wall sheeting) and/or contents of a building comprise a major component of repair costs following a tropical cyclone. Referencing numerous international studies, Pita et al. (2015) report that the major cause of internal damage is wind-driven rain, not wind pressure or wind-borne debris, though these do play some role. This is corroborated in an Australian setting with numerous post-cyclone damage investigations (Boughton et al., 2011; Henderson, Ginger, Leitch, Boughton, & Falck, 2006).

It is unclear whether any of the Australian models outside that of Leicester and Reardon (1976) shown in Figure 2 consider damage to interior and contents in a systematic manner, or even at all. No published models could be found, but in the author's experience researchers have historically modelled contents losses as a direct consequence of building damage and subsequently follow similar trends to those shown previously. Stewart (2013) went one step further, and proposed a method for relating direct physical damage to indirect damage costs loosely based on aggregated loss data from Hurricane Katrina, Cyclone Tracy and Hurricane Rita. This differs from interior/contents damage because it attempts to account for wider reaching community-based losses, such as business interruption and clean-up costs, but the approach to modelling (i.e. its dependence on direct building damage) is similar. Empirical models for contents damage are widely used within the insurance industry, but as with buildings models, these are not publically available.

Internationally interior and contents damage has been modelled more explicitly. For example, Sparks and Bhinderwala (1994)studied the relationship between direct building losses and total loss statistics and found that at lower wind speeds contents losses were approximately equal to building losses, but as wind speeds increased the proportion of interior and contents loss increased. More explicit rain-flow modelling approaches have started to be used (Dao & van de Lindt, 2010; Pita et al., 2012) where volumetric estimates of rain entering a building are derived and these volumes are used as the hazard metric within a sub-assembly heuristic model to more precisely estimate contents damage. Explicit modelling of interior and contents damage is undertaken in both the HAZUS and FPHLM modelling frameworks.

3.1.2 Other building types

Significantly less research and modelling is available for other building types, such as commercial and industrial buildings. In principle the general performance of these buildings should be reasonably similar to that of residential buildings constructed to the same standard and return period. Different importance factors for some types of buildings (e.g. hospitals) will extend the return period used for design, so it could be expected that those buildings will be less vulnerable at a given wind speed than a general warehouse type industrial building.

No empirical models were found for Australian residential building types, and only limited componentbased simulation (engineering) models were found. Ginger et al. (2010) developed fragility curves for different components of a metal clad industrial shed-type building but did not extend this to full building vulnerabilities. They do, however, suggest that the developed fragility curves could be used within the Geoscience Australia simulation tool.

Internationally there is still a relative dearth of vulnerability models outside of residential construction (Walker, 2011). However, Unanwa et al (2000), using a decision tree style approach to prescribe progressive failure modes, developed mean building vulnerability models for commercial, institutional, mid-rise and residential type construction (Figure 5). At least conceptually this study shows that relatively little difference exists when comparing the bulk performance of residential and commercial buildings, but the same cannot be said for their contents.

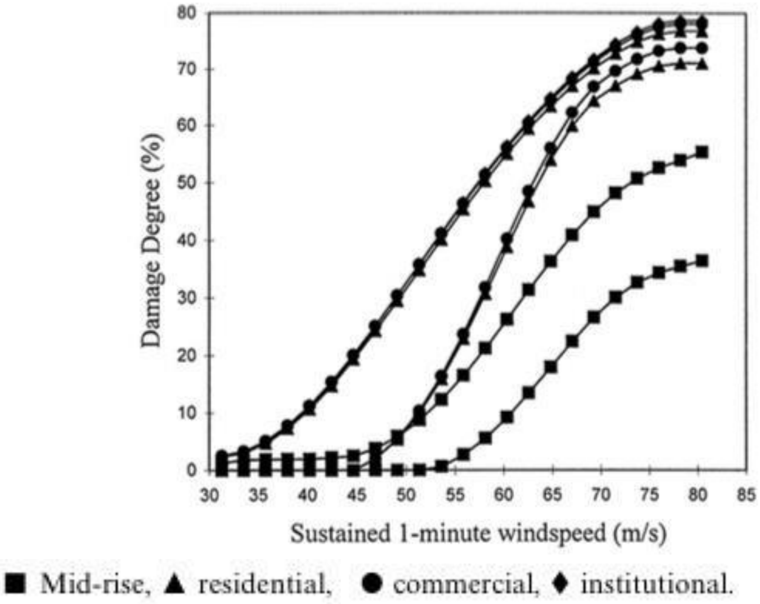

Figure 5. Upper and lower bounds of mean vulnerability curves for commercial, institutional, mid-rise and residential buildings (Unanwa et al., 2000).

Considering the wide variety of other building types it may be inappropriate to consider all these buildings together, and indeed the simulation-based vulnerability curves developed for the HAZUSMH Hurricane model (FEMA, 2009b) show a spread of mean curves for commercial and industrial buildings with different structural and cladding systems. Pita (2012) also describes the range of vulnerability curves implemented in the FPHLM for commercial and multi-story style buildings. While these mean vulnerability models are not directly applicable to Australian buildings the relative relationships between vulnerability curves may be instructive for manipulating existing residential curves so they were more representative of commercial and industrial building types.

No vulnerability models describing damage to interiors or contents were found for Australian ‘other’ buildings. This is understandable in the sense that commercial/industrial contents will vary widely between buildings and it may not be sensible to try and apply a uniform curve across the entire population. This is a particular problem faced with flood vulnerability models and is discussed further in section 0.

3.1.3 Summary table and recommendations

Empirical models of residential housing vulnerability have been implemented widely by the insurance industry dating back from the 1970’s (Friedman, 1975). Despite their complexity, most recent studies have focussed on developing engineering-based residential vulnerability models, with fewer for other building types. Several vulnerability models were found for Australian residential buildings and it is recommended that these be utilised within the disaster scenario modelling framework. The models proposed by Geoscience Australia are most directly applicable across a broad range of housing types, and are recommended for use. This said, some issues with the validity of these models were raised (Ginger, Henderson, et al., 2010), so some level of validation should be undertaken. One possible way of doing this will be to compare with the proprietary Risk Frontiers residential building vulnerability models (not discussed here). Similarly, the empirical relationship between building and contents damage within the proprietary Risk Frontiers models should be compared with ratios found by other authors (e.g. Sparks & Bhinderwala, 1994). This will allow a simplified method of modelling interior and contents damage based on external building damage in the absence of a more detailed simulation approach.

For buildings other than residential no vulnerability models were found that could be directly applied. As such it is recommended that the residential vulnerability curves proposed above be used as the base for estimating damage to other buildings, but some modification based on building characteristics, e.g. height, should be applied based on the relative vulnerability found in the HAZUS model. Further research is required to understand and develop a method for simulating interior and contents damage in these other building types.

Short summaries of some of the articles discussed throughout this section are listed in Table 1.

Table 1: Summary table of wind vulnerability research and models

PAPER	**NOTES**	**MATURITY**	**COUNTRY**
Empirical Models			
Khanduri and Morrow (2003)	***Vulnerability of buildings to wind storms and insurance loss estimation*** • Presents a method to translate known vulnerability curves of one region to another based on engineering judgment, observations from damage surveys and insurance loss data. Additionally to 'disaggregate' general vulnerability curves from insurance loss data into curves based on building classes based on occupancy, construction material and height • As an example the vulnerability of buildings of Puerto Rico in the Caribbean is assessed.	Research (Reputed)	USA
Friedman (1975)	***Computer simulation of natural hazard assessment*** Considered as one of the first (empirical) hurricane vulnerability models	Mature Analytic. Pioneering Work	USA
Leicester and Reardon (1976)	***Statistical analysis of the structural damage caused by cyclone Tracy*** • Includes a derivation of the wind field of Cyclone Tracy • Estimates of relative performance of several types of building structures	Mature Analytic	AUS

Sparks and Bindarwala (1993)	***Relationships between residential insurance losses and wind conditions in Hurricane Andrew.*** • Vulnerability model of a typical single family house in Florida, USA • Based on detailed records of insurance losses.	Mature Analytic	USA
Walker (1995)	***Wind vulnerability curves for Queensland houses*** • Model based on Sparks and Bindarwala (1993) adapted for northern Australia. • Calibrated using data from Cyclones Tracy, Althea and Winifred.	Mature commercial	AUS
<u>Engineering Based Models</u>			
Vickery et al. (2006), FEMA (2009)	***HAZUS-MH hurricane model methodology*** • Physical damage to a building is modelled using engineering based load and resistance approach - i.e. reliability concepts • Several sized representative houses, industrial buildings and commercial buildings can be used in the model. These are all rectangular in shaped with gable or flat roofs. • Able to model effects of progressive failure and internal pressures. As well as effects due to changes in wind speed and direction. Additionally damage from debris impact is also modelled. • Losses are estimated from empirical methods based on categorizing levels of damage into 'damage states' • Contents loss is also calculated based on an empirical model. • HAZUS has been validated using loss data from several Hurricanes in the United States such as Andrew, Hugo, Erin and Opal.	Mature Commercial	USA
Hart (1976)	***Estimation of Structural damage due to tornadoes*** • An early example of and engineering based model • Considered a ‘quasi-engineering’ approach as it relied on expert engineering judgment to estimate levels of damage	Research	USA
Stubbs and Boissonade (1993)	***Damage simulation model for building contents in a hurricane environment.*** • Used a similar ‘quasi-engineering’ approach to Stubbs and Boissonade (1993)	Research	USA
Sciaudone et al. (1997)	***Development of objective wind damage functions to predict wind damage to low-rise structures.*** • Early model to recognize the probabilistic nature of damage to extreme loading, incorporating structural reliability concepts	Research	-
Unanwa et al. (2000)	***The development of wind damage bands for buildings*** • A detailed model accounting for the probabilistic nature of component strengths. • Uses ‘fault trees’ to account for failures of components due to failures of interconnected components • Considers residential, commercial and industrial building types	Development	USA
Pinelli et al. (2004)	***Hurricane damage prediction model for residential structures*** • A vulnerability model of a typical Florida house based on methods developed by Unanwa et al. (2000). • Described interaction between different failure modes with Venn diagrams	Development	USA
Henderson and Ginger (2007)	***Vulnerability model of an Australian high-set house subjected to cyclonic loading*** • A component-based simulation vulnerability model of a typical northern Australian house built prior to the adoption of current building standards. • Many capabilities including accounting for progressive failure, internal pressurization and debris damage	Development	AUS

Apirakvoropinit and Daneshvaran (2009a, 2009b)	***Hurricane damage analysis using a wind damage simulator for low-rise structures with gable roof A study of debris effects on damage functions of low rise wood structures*** • A similar model to that of Henderson and Ginger (2007) for a typical wood framed house of the United States.	Development	USA
Wehner et al (2010)	***Development of methods for assessing the vulnerability of Australian residential building stock to severe wind*** • A modelling suite making use of heuristic vulnerability curves that are incorporated into simulation software. • The simulation tool accounts for shielding, building orientation, debris and water ingress amongst other factors.	Development	AUS
Wind-borne debris models			
Lin and Vanmarcke (2010), Lin et al. (2010)	***Windborne debris risk analysis Parts I and II*** • A Study published in two parts, the first describing a debris generation model based on Poisson random measure theory. The second describing the interaction between debris and structure	Research	-
Holmes et al (2010)	***Modelling damage to residential buildings from wind-borne debris—Part 1 methodology*** • Description of the debris model within the Geoscience Australia Windsim model	Development	AUS
Twisdale et al. (1996)	***Analysis of hurricane windborne debris impact Parts I and II*** • A study similar to Lin et al (2009), incorporated into the HAZUS hurricane models	Mature Commercial	USA
Tree blow down models			
Twisdale et al (1989a)	***Forest Blowdown and Debris Transport Methodology*** • Model implemented in HAZUS	Mature Commercial	USA
Twisdale et al (1989b)	***Update and Application of the BLOWTRAN Methodology to Forest and Damage Prediction (Version 2.3)*** • Model implemented in HAZUS	Mature Commercial	USA
FEMA (2009)	***HAZUS-MH hurricane model methodology*** • Most recent implementation of HAZUS tree blow down model	Mature Commercial	USA

3.2 *Flood*

Tropical cyclones generate two types of flooding. First, when cyclones move close to the coastline they generate a surge of water that can inundate low lying areas. This type of flooding is characterised by fast moving floodwaters that may also have significant wave actions associated with them. The second type is more associated with inland locations, and this is slow rising riverine flooding that typically occurs when tropical cyclones move on-shore and generate large volumes of rainfall in catchments as they decay. This rain subsequently finds its way to rivers and streams and significant flooding can ensue. An example of the latter is the 1974 Brisbane floods, which were largely driven by the decay of tropical cyclone Wanda.

Unlike wind damage where the primary damage mechanism is mechanical, the primary mode of damage during most Australian floods is material driven. That is, floodwaters come into contact with building and contents causing degradation or failure—the latter is a particular problem for electronics. Structural failure is less of an issue, except if there is significant flow velocity associated with the floodwaters—i.e. hydrodynamic loading. For riverine flooding (e.g. 2011 Queensland floods) this is generally not a problem, but is so for tropical cyclone storm surge inundation (e.g. Tully Heads, Tropical Cyclone Yasi, Figure 6).

Figure 6. Damage to home caused by storm surge inundation during Tropical Cyclone Yasi.

Mason et al. (2012) and Kelman and Spence (2004) outline the range of potential flood loading mechanisms that may cause damage or failure of a building. These include hydrostatic, hydrodynamic, buoyancy, debris impact, water contact and geotechnical loading (e.g. scouring around foundations). In addition, several authors believe contaminant loading in floodwaters can significantly increase damage levels (Soetanto & Proverbs, 2004; Thieken, Müller, Kreibich, & Merz, 2005). At a given building, the flood characteristics that lead to these types of damages, or can influence the extent to which they impact a building include, inundation depth, flow velocity, duration of inundation, rate of inundation, contaminant loading, size and amount of debris, time of inundation (i.e. night or day), frequency of inundation (as a metric for flood experience).

Several authors have sought to determine which of these characteristics were of most importance when it determining damage levels. Thieken et al. (2005) using a Principle Component Analysis approach and Merz et al. (2013) opting for a tree-based assessment approach. Both conclude that inundation depth is often the key explanatory factor, however when flow velocities exceed 1-2 m/s, hydrodynamic loading becomes important. In addition, these studies also show the importance of building characteristics to the resultant damage, along with factors such as warning time, building size and value (Smith, 1994; Thieken et al., 2005). All this said, Merz et al. (2013) conclude that while considering a range of flood and building variables when analysing damage data, any gains in explanatory power are often lost when applied through vulnerability models to real-world applications. They conclude therefore that there is no comprehensive and transferable methodology for including anything other than inundation depth in a flood vulnerability model for low velocity flooding.

Considering these points, flood vulnerability models are mostly based on the concept of a stage-damage relationship. This relates the depth of inundation to the level of damage at a structure. Smith (1994) and Merz et al. (2010) presents a review of urban stage damage methods and provides a sound introduction to the concept, its advantages and limitations. Less research has been undertaken when flow velocities are high (e.g. storm surge or flash flooding), but some observational data has been assessed and are discussed below.

3.2.1 Residential buildings

The majority of available data and subsequent vulnerability model development has been undertaken for residential housing (Merz et al 2010). These models were developed for numerous countries around the world, with several models developed for Australian housing.

Probably the earliest introduction of flood vulnerability curves to Australia was through the development of the ANUFLOOD model (Smith & Greenway, 1988). This model used a series of ‘whatif’ assumptions to estimate the extent of damage given different levels of inundation. This approach is often termed ‘synthetic’ or ‘potential’ damage estimation, but is in essence a heuristic approach which drew largely from the development of similar models for UK housing by (Penning-Rowsell & Chatterton, 1977). These mean vulnerability curves directly related inundation depth to an absolute dollar loss value, and have subsequently been used by several authorities around the country (with modified loss values) for assessing flood risk (e.g. NRM, 2002). Modifying factors that include warning time, regional flood experience and building size were proposed and used in conjunction with the ANUFLOOD model (NRM, 2002; Smith & Greenway, 1988).

More recently the NSW government developed a set of flood vulnerability curves for residential buildings based on work undertaken by Risk Frontiers (Blong & McAneney, 2003) of insurance loss data (NSW Government, 2007). These mean vulnerability functions are publically available and assess building and contents damage to single and two-storey housing. Several material and building cost inputs are required, but Figure 7 shows an example of the mean vulnerability curves developed by the model. It is seen that a multi-linear curve is the result with step changes coinciding with physical changes in building properties (e.g. storey heights).

A further series of heuristic vulnerability curves were developed for a much broader range of building types (11 types) by Geoscience Australia (cited in Mason et al., 2012). The broader scope of building types attempts to take into account the range of materials and construction practice used in contemporary Australian housing. Mean curves were developed for both building and contents damage, with moral hazard also considered as a variable. Conceptually the approach taken to develop these curves was the same as for existing heuristic models, and a quantity surveyor was used to cost all damages. Unlike those models though, normalised loss ratios are provided in place of absolute loss values. In an attempt to validate the model outputs Mason et al. (2012) used adjusted insurance loss data collected after the 2011 Queensland floods to determine model performance. By doing so adjustment factors for different building and contents types were developed and a new series of adjusted vulnerability curves were developed (Figure 8). These curves allow building and contents damage ratios to be determined on a simplified set of four housing types. Additionally, Mason et al. (2012) provides a method for estimating the range of possible damage values around mean vulnerability curves.

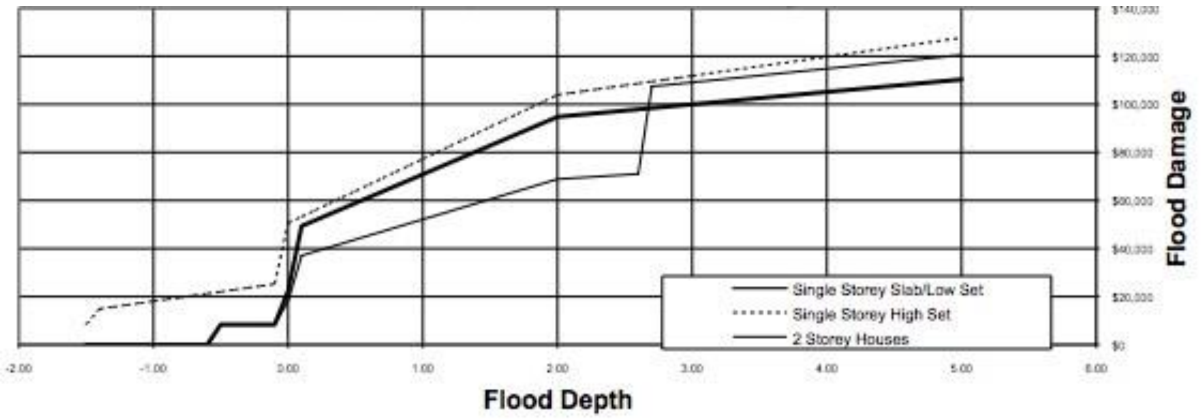

Figure 7: Residential vulnerability curves for typical housing in NSW (NSW Government, 2007).

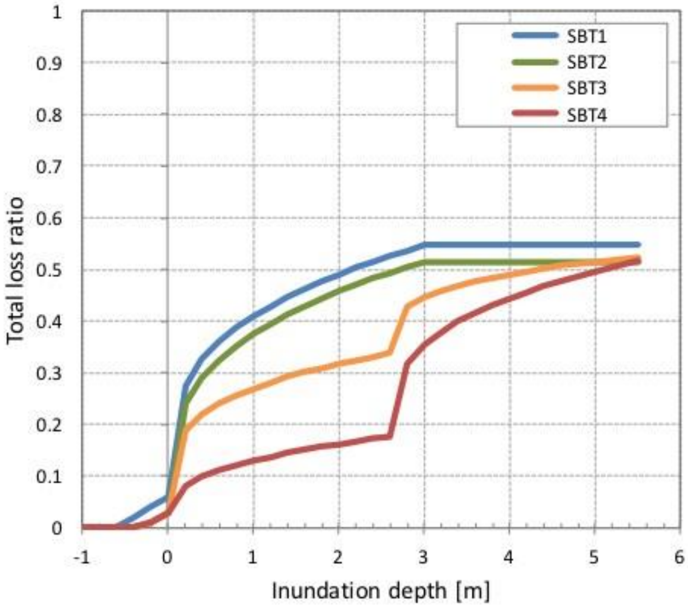

Figure 8: Total loss vulnerability curves developed by Mason et al. (2012) based on heuristic vulnerability curves developed at Geoscience Australia and insurance loss data.

All models discussed thus far have made the assumption that flow velocity is small. This is a reasonable assumption for most floods in Australia. Dale, Edwards, Middelmann, and Zoppou (2004) however, following models developed in the USA, developed vulnerability curves that assess damage when considering flow velocity as well as inundation depth (Figure 9). Unlike other flood vulnerability curves, the Dale curve is in essence a curve that describes damage states; if a point lies above the line it fails, if it below it does not. So it cannot be used in the same manner as those discussed previously, but can be used to assess whether flow velocity will be an important factor when assessing damage.

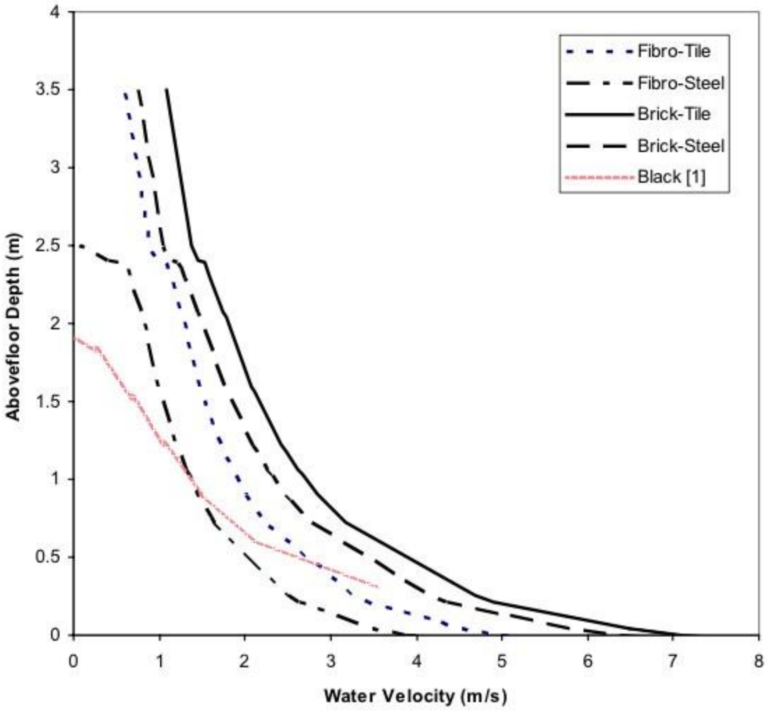

Figure 9: Threshold curves for the assessment of building failure under combinations of inundation depth and flow velocity for four typical Australian building types (Dale et al., 2004).

Other researchers have attempted to more directly associate flow velocity with building damage by combining the velocity and depth variables into a single value (e.g. Kreibich et al., 2009; Pistrika & Jonkman, 2010) through calculation of a direct product (i.e. depth x velocity) or calculation of a hydraulic head. Conflicting results were found, but it appears that a velocity threshold may exist, below which velocity plays little part in instigating damage and above which it is an important variable. Whether this threshold is purely related to velocity or is a combination of depth and velocity is still not well understood. Zerger and Wealands (2004) and Smith and Greenaway (1994) have also attempting to account for the influence of flow velocity on building damage.

3.2.2 Other building types

If only limited research into residential flood losses has been undertaken in Australia, the situation is even worse when it comes to commercial and industrial property. In one of only a very few recent studies, Risk Frontiers surveyed businesses three times in the first six months after the 2001 Kempsey floods (Gissing & Blong, 2004). Gissing and Blong (2004) found wide differences in the vulnerability of businesses and little relationship between direct damage and over-floor depth. Simple averaging or the use of stage-damage curve loss estimation methods ignored the wide variance in the actual losses and resulted in inaccurate estimates. This outcome is understandable given that 85% of the damage costs were to contents. Moreover the incurred losses depended upon a large number of factors including the degree to which contents and machinery can be moved, are perishable and the extent of contamination. As just one example of the variance, damage incurred by car repair businesses ranged between $100 and $150,000.

Nonetheless several models have been developed (the reader is referred to Merz et al. (2010) for further details), and a number of these applied in Australia. ANUFLOOD includes modification factors that are industry and building specific, as too does NRM (2002). Again these follow on from methods developed in the UK by Penning-Rowsell et al. (2010), but are subject to significant levels of uncertainty given the highly variable nature of business operations, even within the same sector. The modelling approach utilised is the same as for residential buildings and inundation depth is the primary flood variable of interest once industry type and building size are determined.

Internationally the HAZUS-MH Flood Model (FEMA, 2009a; Scawthorn et al., 2006) does use different vulnerability curves for ‘other’ building types, including hospitals and industrial buildings and their inventory. These models can be drawn upon for the scenario modelling but are not expected to be directly applicable for Australian building stock. HAZUS also includes a method for estimating the impact of flow velocity using an approach similar to Dale et al. (2004) where a failure threshold is provided.

3.2.3 Summary table and recommendations

A range of vulnerability models have been developed for assessing the impact of flood on buildings. Most have focused on estimating damage to residential buildings, but several modifications have been made to these for use in estimating damage to ‘other’ building types. Direct building and contents damage models exist. Most such models have been developed heuristically, with some work done to validate them.

For residential buildings either the Mason et al. (2012) or NSW Government (2007) set of models are recommended for initial application in the disaster scenario analysis. These models have advantages over the larger suite of Geoscience Australia curves (though these are embodied within the Mason model) because they have been validated against recent observational data. While the ANUFLOOD models have previously been utilised and validated, they are no longer being actively updated. For estimating damage to non-residential building types, modifications used within the HAZUS and

ANUFLOOD frameworks as well as Gissing and Blong (2004) should be used to generate appropriate models.

For all these models uncertainty around individual building damage levels is high and should be considered in detail when applied within the scenarios. Proprietary flood vulnerability curves developed by Risk Frontiers should be used as an additional source to validate/modify any models used.

Short summaries of some of the articles discussed throughout this section are listed in Table 2.

Table 2: Summary of select flood vulnerability models and papers

PAPER	**NOTES**	**MATURITY**	**COUNTRY**
Stage Damage Models			
Scawthorn et al (2006)	***HAZUS-MR4 Flood vulnerability Model*** ▯ Based on stage damage relationships from: ▯ Federal Insurance and Mitigation Administration (FIMA) – FIA Credibility weighted depth-damage curves. o US army corps of engineers o US army corps of engineers Institute of water resources ▯ Velocity damage relationships from US army corps of engineers. ▯ Model describes damage to building and contents for residential, commercial, industrial and special building types.	Mature Commercial	USA
ANUFlood, Smith and Greenway (1988)	***An Interactive program designed to asses urban flood damage*** • Originally developed by ANU • Developed during the 1980's and 1990s • Based on stage damage curves for residential and commercial property	Mature Commercial	AUS
HOWAD Neubert, Naumann, Hennersdorf, and Nikolowski (2014)	***The Geographic Information System-based flood damage simulation model HOWAD Germany*** ▯ A developed software package that assesses damage via synthetic stage-damage curves. ▯ Novell features include a system of identifying building types from satellite imagery or via manual input.	Mature Commercial	GER
The Multicolored Manual, PenningRowsell and Chatterton (1977)	***The benefits of flood alleviation: a manual of assessment techniques*** • Developed by Middlesex University Flood Hazard Research Centre • A series of 'what-if' scenarios considered to develop potential damage curves for building and contents. • Models available for a wide variety of building types	Mature Commercial	UK
Smith (1994)	***Flood damage estimation – a review of urban stage-damage curves and loss functions*** • A review article providing a sound introduction to flood damage modeling and the development of stage damage functions. • Provides a range of adjustment factors for accounting for flood or building properties other than inundation depth.	Research [review article]	AUS

Middelmann - Fernandes (2010)	***Flood damage estimation beyond stage damage functions: an Australian example*** • A critique of stage damage functions and their limitations, also acts as a useful review article of stage-damage as well as non-stage-damage methods. • Recommends a method that combines the use of traditional stage-damage functions and velocitystage-damage functions	Research	AUS
NSW Government (2007)	***Residential flood damages*** • Set of residential vulnerability curves for NSW (and wider Australian) housing. • Three simplified building types available with different building fabrics. • Available as excel spreadsheet	Development	AUS
Geoscience Australia	***Suite of potential flood damage vulnerability curves*** • Heuristic set of stage-damage functions for Australian residential building stock. • Includes a wide range of building types. • Slow moving floodwaters only.	Development	AUS
Mason et al (2012)	***Analysis of damage to buildings following the 2010-11 Eastern Australia floods*** • Semi-empirical models developed for four generic building types based on adjusted versions of the Geoscience Australia curves. • Modification based on analysis of damage observation and insurance loss data. • A measure of uncertainty is provided.	Research	AUS
Gissing and Blong (2006)	***Accounting for variability in commercial flood damage estimation*** • Assessed the importance of a range of flood and building variables based on damage information from Kempsey flood. • Investigated commercial building damage and provide example vulnerability curves	Research	AUS
<u>Non Stage Damage Models</u>			
FLEMOps+r), Elmer, Thieken, Pech, and Kreibich (2010)	***Influence on flood frequency on residential losses.*** • An alternative method: a regression model based relating damage to recurrence interval of a flood event.	Research	GER
Merz et al (2013)	***Multi-variate flood damage assessment: a tree-based datamining approach*** • Another alternative approach, making use of a data mining technique to determine relationships between flood damage and several factors including the effect of early warning and socio economic status of the household. • An application to a case study found it outperformed traditional stage damage functions as well as FLEMOps+r	Research	GER
Smith and Greenaway (1994)	***Tropical storm surge damage and emergency planning A Pilot Study for Mackay, Queensland.*** • A case study outlining the development of a model for storm surge damage	Development	AUS
Black (1975)	***Flood proofing rural residences*** • Considered one of the first studies to incorporate forces such as hydrostatic pressure, dynamic pressure and buoyancy into flood damage modeling	Research [pioneering work]	USA
Dale et al (2004)	***Structural flood vulnerability and the Australianisation of Black's curves***	Research	AUS

	• A study that adapts methods used by Black (1975) for use on structural systems of Australian housing

4. Occupant death, injury and displacement

4.1 Casualty Models

Little research was found in the academic domain mathematically relating deaths and injuries during cyclone or flood events. The HAZUS flood model was initially intended to incorporate a sub-model to account for deaths and injuries (FEMA, 2009a). This, however, is not currently included in the suite of HAZUS models because limited data and difficulty calibrating results with past events meant too much uncertainty was embodied in the results. Despite this, a description of the proposed model is outlined in the HAZUS-MR4 Flood model Technical manual (FEMA, 2009a). The proposed flood model considered 3 types of casualties:

1. Casualties that occur in floodwater as a function of rate of inundation e.g. rapid, moderate and slow rise.
2. Casualties occurring in buildings during flooding or during flood cleanup, related to warning times, flood depth and occupancy of structures.
3. Rain-related motor vehicle casualties for low medium and high rainfall.

The HAZUS-MH MR4 Earthquake model (FEMA, 2003) provides a more detailed model for accounting for deaths and injuries. This is based on the level of damage at a structure and also the level of occupancy of the structure—which is dependent on the time of day that an earthquake occurs. A similar modelling approach could be applied to point 2 above for both cyclone and flood hazards, but significant research into causal factors such as occupant behavior during these events would be required. Fortunately given the reasonably long warning times and good rates of evacuation that are now present during both riverine flood and tropical cyclone event, loss of life is generally low and it is only when high velocity flash flooding occurs that life safety is a major concern.

4.2 Population displacement models

Such models aim to determine the number of people that would be unable to reach or live in their homes following a tropical cyclone, and therefore the number of people that would require emergency shelter. In addition to building damage, these models are highly dependent on sociological factors such as age, race, gender and income. All these factors must be considered when estimating displacement.

The HAZUS, flood, hurricane and earthquake models (FEMA, 2003, 2009a, 2009b) all include submodels to determine population displacement. These rely on empirical relationships that consider, not only building damage, but also factors such as warning time, age, gender and income of certain populations. As such, these models are highly reliant on demographic information as well as simulated event-based building damage. Displacement is not simulated on an individual building scale but requires damage information to be aggregated over a region. Similarly, demographic information is only required on a regional scale and not down to the individual household. A detailed and simplified modeling approach for single and multi-family residential dwelling is provided. An example of the displacement vulnerability curve for tropical cyclones is shown in Figure 10. Similar to building damage the final vulnerability model is directly related to wind speed.

In the Australian context, Mason et al. (2012) developed a model for estimating the probability of short- and long-term displacement for residential properties based on heuristic arguments and estimated building damage levels during flood events (Figure 11). This model made use of empirical damage survey information collected after the Queensland floods in 2011, and the building vulnerability curves developed based on this same set of damage data (section 3.2.1). Unlike the HAZUS model this model does not consider socio-cultural factors, but these could be incorporated through further research. No similar models for tropical cyclones were found specific to Australia but could be developed utilizing the method described in the HAZUS manuals.

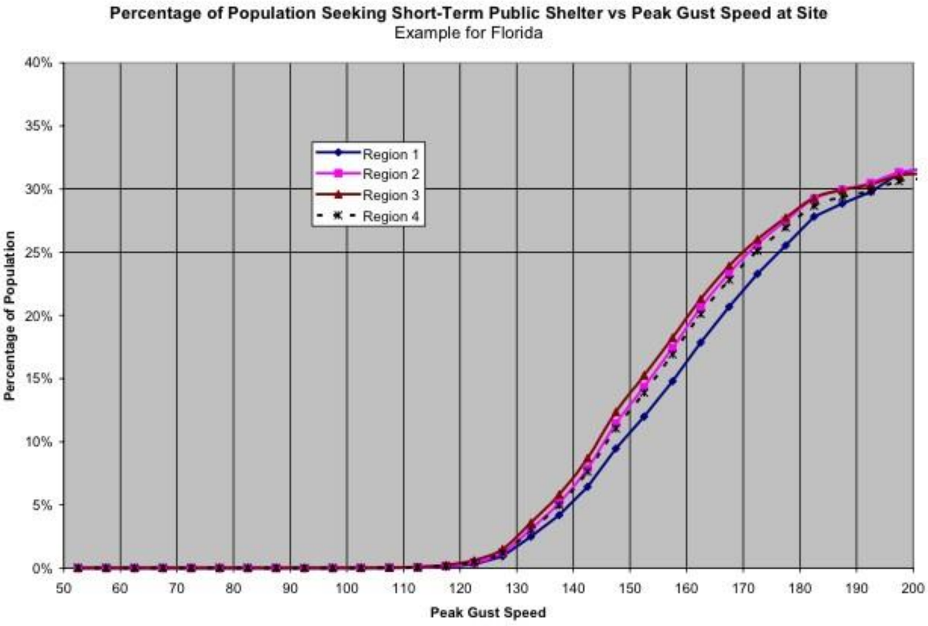

Figure 10: HAZUS vulnerability model for short-term displacement during tropical cyclones (FEMA, 2009a).

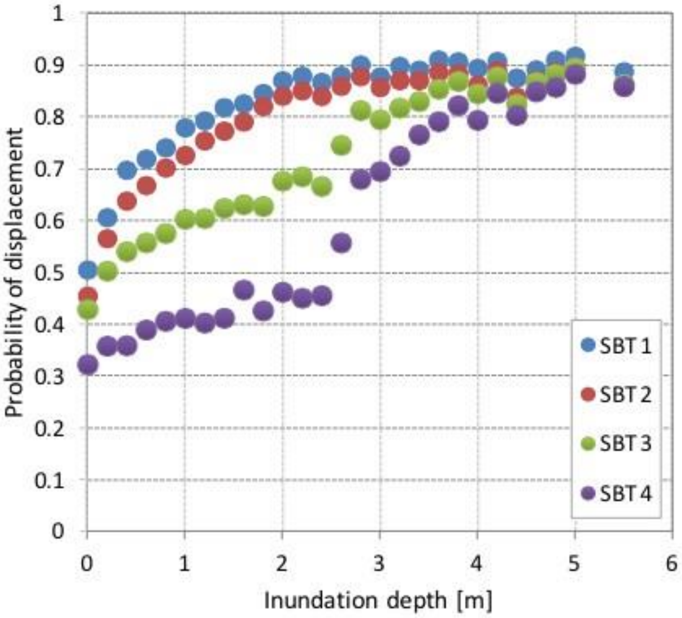

Figure 11: Probability of short-term displacement mean vulnerability curves for four generic residential building types during flood events (Mason et al., 2012).

4.3 Recommendations

Estimating casualties and population displacement are important for understanding the impact a natural hazard has on a community. The HAZUS model provides a method for estimating these impacts based on a range of building damage and sociological variables, which may be modified for application to the Australian context. Mason et al. (2012) is an example of this being done to a limited extent. Similar modelling approaches should be developed/extended for this project for both wind and flood hazards.

5. Civil Infrastructure

Networked infrastructure such as the power grid, water supply, roadways and telecommunications are essential for the proper functioning of society and hence often described as ‘lifelines’ (O'Rourke, 2007). They are particularly important in the aftermath of a natural disaster for the coordination of emergency services, supply of food and water. However, many lifelines are vulnerable to natural hazards and their disruption greatly affects the severity of a ‘disaster’.

Only a small amount of literature focuses on the effect of a particular hazard on infrastructure systems. For example, a limited number of articles examined the vulnerability of power networks to wind events and a similar number investigated roadway response to floods. Moreover, no studies could be found that examined the impact of flooding on power supply or wind hazard on water supply, even though these infrastructural networks are indeed impacted by these hazards. Flooding can also damage underground pipelines and contaminate drinking water.

Infrastructure networks can be examined on several levels: at the component level; the network level; and the interdependency between different infrastructure networks. Thus, for networked infrastructure, four types of modelling and analysis were reported.

1. Network modelling: Often commercial software that allows engineers and designers to design and maintain a network and identify potential problems. Examples include: TRANSCAD for transport networks (Caliper Corporation) REALM for water infrastructure (Victorian Government) and ns-2 for telecommunications modeling. These are not vulnerability models in and of themselves, but allow damage impacts to be propagated through a network of assets.
2. Network Vulnerability Analyses: These are most often academic studies of methods to assess the ‘weakest link’ within a network and the impacts of failure of these links. These can be general or related to a specific hazard (Reed, 2008; Taylor, Sekhar, & D'Este, 2006).
3. Network Component models: An infrastructure network is made up of several components. Similar to the component-based models discussed earlier for estimating building vulnerability, each component of an infrastructure network can be simulated individually and then aggregated to assess the vulnerability of an entire system. In the case of a power grid, the system could be broken down into the individual components of generators, transmission towers/lines and distribution poles/lines. Literature on water supply pipelines often focus on earthquake hazards (e.g. Adachi & Ellingwood, 2008) rather that wind or flood.
4. Modelling of the interdependency of networks: modern infrastructure networks are highly dependent on each other; e.g. telecommunications systems and water pumping stations require electrical power to run. Although some academic literature does exist, most work in this field are national programs funded by governments as ‘critical infrastructure protection programs’.

The following sections outline the available modelling tools and academic literature for power grids, water supply, transportation and telecommunication. Finally, an overview of several critical infrastructure protection programs and network interdependency studies is presented.

5.1 Power Systems

Almost all facets of modern society are reliant on electrical power in some way. Most other networked infrastructure also relies on electrical power. Power supply can be directly impacted by wind events through the downing of transmission towers and distribution poles and also indirectly due to fallen trees and debris impact. Power supply is generally less vulnerable to flood events but damage and disruption can still occur through scour around underground cables and inundation of electric switchboards and distribution centres.

The majority of vulnerability studies on power grids are general network vulnerability models (Albert, Albert, & Nakarado, 2004; Dueñas-Osorio & Vemuru, 2009). Several studies do relate extreme wind events to power network disruption. However, no work has been found that directly relates power grid vulnerability to flood events.

The power grid can be examined at the level of its individual components that are: Generation, transmission and distribution. Of these, the distribution stage is the most vulnerable to wind damage followed by transmission (Nateghi & Guikema, 2011). Holmes (2001) provides an introduction to the theory of wind loading on transmission lines and towers as well as associated vulnerability models. This includes an overview of methods for determining loads on communications infrastructure such as cellular towers and satellite dishes.

5.1.1 Distribution

Distribution poles are often not designed to withstand extreme winds. Bjarnadottir, Li, and Stewart (2014b) present a framework to assess the vulnerability of a network of distribution poles based on simple wind load arguments for poles and wires (Figure 12). They also include within their model a component that assessed the influence of pole age by explicitly modelling the probable degradation of strength. Using this model Bjarnadottir et al. (2014b) assessed the efficacy of a number of mitigation and replacement strategies for distribution within the Miami-Dade region of Florida. Ryan, Stewart, Spencer, and Li (2014) developed and apply a similar vulnerability model, with Bjarnadottir, Li, and Stewart (2014a) also describing vulnerability to tropical cyclone induced storm surge.

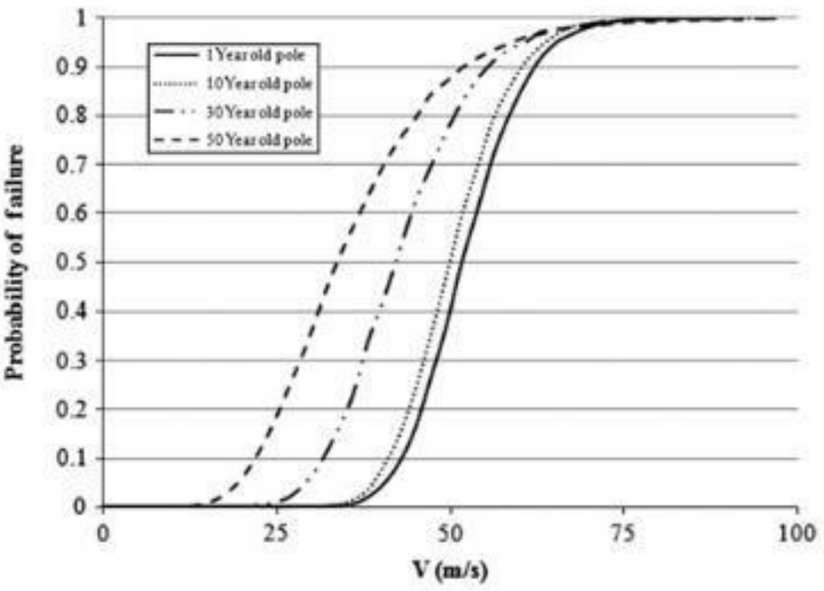

Figure 12: Example of vulnerability curve for power distribution poles (Bjarnadottir et al., 2014b).

5.1.2 Transmission

Numerous researchers have investigated wind loading of transmission towers subject to extreme wind events, predominantly during thunderstorm downbursts (e.g. Chay, Albermani, & Wilson, 2006). These however are essentially deterministic studies and their complexity does not lend itself to probabilistic simulation when considering a network of these towers. Ahmed, Arthur, and Edwards (2010), though, present a simplified method for estimating the probability of failure of single transmission tower based on the estimated loads applied under a given loading scenario. Heuristic information was gathered to estimate tower capacity and loading was assumed based on wind speed at the tower site. Considering the ratio of these two values a probability of tower failure was assigned, and once this probability exceeded a given threshold the tower was assumed failed. Figure 13 shows an example of a fragility curve developed for a given tower design. The Ahmed and Arthur model could be utilised if the full suite of curves were made available and tower designs were representative of the region being modelled. Similar simplified wind speed based mean vulnerability models have been developed for estimating risk to transmission lines under downburst wind loading (e.g. Letchford & Hawes, 2000).

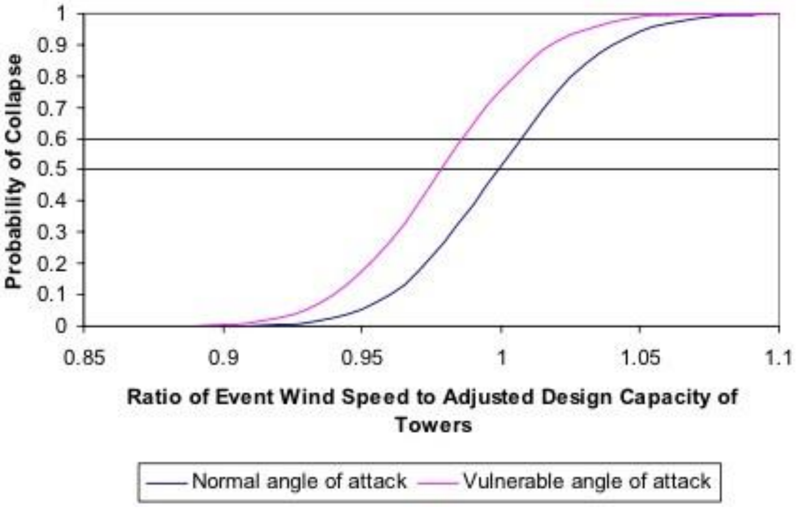

Figure 13: Example of fragility curve for single transmission tower for two different wind directions.

5.1.3 Generation

Generation plants are generally considered high importance level buildings and are designed to resist longer return period winds than typical structures (e.g. housing). They may also be quite unique in their design so do not lend themselves to generic development of vulnerability relationships. The location of the generation plant can affect its vulnerability, e.g. proximity to the ocean. There are, however, indirect vulnerabilities of generation plants such their dependence on transport networks and on water supply for cooling. No literature was readily found on the subject of power generation vulnerability in Australia. Literature from other countries focused on vulnerabilities due to terrorist threats or water security for cooling of coal fired power stations. Depending on the types of structures used to house generation facilities modified versions of the building vulnerability curves may possibly be utilised, but more research is required to ascertain their suitability. This comment is aimed primarily at wind actions, with flood impacts expected to be severe in any instance.

5.1.4 Network Modelling

Network modelling software such as the EMACS (Electricity Market Complex Adaptive System) and DEW (Distributed Engineering Workstation) have been used by engineers to maintain and design power grids. These modes allow the user to assess the impacts of failure of branches or nodes within the network. However, these tools generally have no connection to the cause of failure or a particular hazard type. Nevertheless, such modelling tools can still be used when planning for a set of disaster scenarios, if models skilled practitioners were made available.

More specialised modelling studies have developed methods of assessing the resilience of a power grid. For example, Reed, Kapur, and Christie (2009) developed a model to estimate the time taken for the system to recover from a disruption using an empirically determined parameter for ‘rapidity’ of recovery using methods adapted from Haimes et al. (2005). Such techniques can also be extended to other infrastructure types.

Reed (2008) and Park, Glagola, Gurley, and Son (2014) developed techniques to assess the vulnerability of a power grid to wind hazards, with Barben (2010) providing a thorough review of literature in the area. In general all these vulnerability assessment methods allow for the identification of weak links or critical paths in a power network. Commercial Software such as EMACs and DEW can be used to assess the number of customers or other infrastructure likely to be affected. Finally, resilience models, such as Albert et al. (2004) can be used to estimate recovery time. No flood specific vulnerability models related to power grid disruption were identified.

5.1.5 Summary table and Recommendations

Several commercial network-modelling tools exist for the modelling power grids, such as DEW and EMACs, however these are not easily accessible and require significant expertise to run. More useful to the development of new system vulnerability models are methods presented in studies such as those of Albert et al. (2004) and Reed et al. (2009). For wind hazards, Barben (2010) provides a good review for interested researchers. When examining individual components of a power grid to high winds, the method proposed by Ahmed et al. (2010) for transmission towers; and Bjarnadottir et al. (2014b) for distribution poles could be used within a scenario model without significant modification. Modification of the HAZUS approach to estimating flood damage to the electricity network will be possible but further research will be required.

Short summaries of some articles discussed throughout this section are listed in Table 3.

Table 3: Summary table of models and research on vulnerability of power networks

PAPER	TITLE AND NOTES	MATURITY	COUNTRY
Bjarnadottir et al. (2014)	***Risk-based economic assessment of mitigation strategies for power distribution poles subjected to hurricanes*** A reliability analysis of distribution poles to hurricane winds, several mitigation strategies to improve distribution lines are assessed using the method.	Research	USA
Nateghi et al. (2010)	***A Comparison of Top-Down Statistical Models with BottomUp Methods for Power System Reliability Estimation in High Wind Events*** A comparison of statistical vs. engineering based models for reliability analysis distribution networks	Research	USA
Park et al. (2014)	***Performance assessment of the Florida electric power network system against hurricanes*** A statistical model to analyse the vulnerability of the power distribution system. Accounts for failures due to wind loads and tree fall	Research	USA
Ahmed et al. (2010)	***Collapse and Pull – Down Analysis of High Voltage Electricity Transmission Towers Subjected to Cyclonic Wind***. Presents a method to analyze the cascading failure of neighboring transmission towers due to the failure of a single tower.	Research	AUS
DEW	**Distributed Engineering Workstation** A software tool that allows the modeling of an entire power network with additional tools to perform fault analysis and load estimation	Mature Commercial	USA
EMACS	**Electricity Market Complex Adaptive System** Software to model power networks that also has the capability of estimating electricity demand based on the current market situation.	Mature Commercial	USA
Albert et al. (2004)	***Structural vulnerability of the North American power grid*** Presents a method to assess the level of redundancy within a power grid	Research	USA
Barben (2010)	***Vulnerability assessment of electric power supply under conditions*** *[PhD Thesis]* • A study that analyses vulnerability based on selected event scenarios of extreme weather. The most vulnerable paths of the network can be identified and mitigated. • Also presents an excellent review of other vulnerability models	Research	***extreme weather***

Reed (2008)	***Electric utility distribution analysis for extreme winds*** • A reliability analysis of a power network accounts for wind loads and tree fall. Also models time taken for restoration of power supply	Research	USA
Winkler, DuenasOsorio, Stein, and Subramanian (2010)	***Performance assessment of topologically diverse power systems subjected to hurricane events*** • A reliability analysis of a power grid as a whole, including modeling fragility of generation, transmission and distribution stages. The topology of the network is found to be the biggest influence on the reliability of the system: influenced by level of redundancy, centrality and clustering.	Research	
Duenas-Osorio (2009)	***Cascading failures in complex infrastructure systems*** • Similar to Winkler's (2010) study, however power redistribution after initial failure and subsequent progressive failure is also accounted for. Can be used for multiple hazard types	Research	
FEMA (2010)	***HAZUS flood vulnerability model*** • Stage-damage type curves described for estimating damage to a range of components of the power network.	Mature, Commercial	USA

5.2 Roads and Transportation

Roadways are required for the normal functioning of a community as well as immediate emergency response and post-disaster recovery efforts. Roadways and other land transport links are most directly affected by flood events through inundation or overtopping of bridges. Additionally, they can be damaged by erosion and scour. Roads are still indirectly vulnerable to extreme wind events due to tree fall and downing of power lines, direct wind loading of roadways is not an issue although it can be for bridges. Traffic can be also disrupted by the loss of electrical power to traffic lights.

Of all the infrastructure types, transport networks appear to have the most number of commercially available modelling packages. These include TRAGIS (Transportation Routing Analysis Geographic Information System) and TransCAD. Although these do not directly consider wind and flood hazards they still allow the assessment of impacts due to disruption of the network. Sohn (2006) and Dawod, Mirza, and Al-Ghamdi (2012) both assess transport network vulnerability to flood hazards using these models.

Transport Networks are not directly vulnerable to wind hazards, however, roads can be made unusable by fallen trees, power lines and debris form structures. Road networks can also be disrupted by the failure of traffic signals and rail networks by loss of power. The modelling of such secondary effects can be adapted from wind-borne debris models and transmission and distribution line vulnerability models described earlier. Additionally, network interdependency can be modelled using tools described in the next section.

For direct flood disruption, the simplest approach is to determine whether inundation has occurred at any point of the road network. If it has, one can almost certainly assume that particular road segment is disrupted, at least for the duration of inundation. How this inundation relates to damage of the road surface or underlying foundations is, however, unknown. Substantial data sets on road damage following the 2011 (and subsequent) Queensland floods have been gathered by the Queensland Reconstruction Authority, and future research should aim to investigate the potential for transforming these data into vulnerability models. The additional damage that occurs when inundation waters are moving rapidly during a cyclone induced storm surge should also be studied.

Taylor et al. (2006) and Du, Aiura, Nakatsuji, and Kishi (2014) developed methods to assess vulnerability in terms of the ‘weakest link’ in a network using a measure known as an ‘accessibility index’. Taylor and D’este (2003) also presents an excellent introduction to the theory of network vulnerability.

5.2.1 Summary table and Recommendations

For the creation of disaster scenarios, techniques such as those reviewed by Murray, Matisziw, and Grubesic (2008) are most useful for identifying critical transport links. Scenarios can then be created for the failure of these—likely under flood loading of some description—and impacts could be assessed by network modelling software such as TransCAD. It is not anticipated that this type of modelling will be undertaken for initial scenarios. Vulnerability models for direct damage under flood loading (inundation and flowing water) should be developed so longer term impact assessment can be undertaken.

Short summaries of some articles discussed throughout this section are listed in Table 4.

Table 4: Summary of research and models describing road and transport network vulnerability

PAPER	TITLE AND NOTES	MATURITY	COUNTRY
Dawood et al (2012)	***GIS-based estimation of flood hazard impacts on road network in Makkah city, Saudi Arabia*** • A study that integrates a hydrological model with a road network model to determine impacts of flooding on transportation	Research	UAE
Sohn (2006)	***Evaluating the significance of highway network links under flood damage: An accessibility approach*** • Presents a method to evaluate the level of disruption to a road network based on and ‘accessibility index’, a measure of the number of alternate paths available to reach a certain location.	Research	USA
Taylor et al. (2006)	***Application of accessibility based methods for vulnerability analysis of strategic road networks.*** • A similar study to that of Sohn (2006), but for an Australian context. Also provides good review and introduction of the concepts of network reliability and network vulnerability.	Research	AUS
Murray et al (2008)	***A methodological overview of network vulnerability analysis*** • A review article of various methods used in network vulnerability analyses	Research	USA
Taylor and D’este (2003)	***Concepts of network vulnerability and applications to the identification of critical elements of transport infrastructure*** • A more compact introduction to network vulnerability analyses	Research	AUS
Berdica (2002)	***An introduction to road vulnerability: what has been done and should be done*** • Another review article that offers a critique of current models and further research that is required.	Research	SWE
Du et al (2014)	***Transportation network vulnerability: Vulnerability Scanning Methodology Applied to Multiple Logistics Transport Networks*** • Presents the development and implementation of an efficient algorithm used to identify vulnerable links in a transport network	Research	JAP
Zerger and Wealands (2004)	***Beyond modeling: linking models with GIS flood risk management*** • Presents a model that allows the consequences of different flooding scenarios to be assessed. Particularly suited for coordination of emergency services.	Research	AUS

5.3 Water Supply

Supply of clean drinking water is a basic necessity, even more so during a post disaster recovery period when communities are most vulnerable. Water supply is also required for, for example, cooling of coal fired power stations and the functioning of sewers. Water pipelines can be affected by floods through the scour around underground pipelines, but are generally not vulnerable to extreme winds except through the loss of electrical power or debris and tree damage to overground pipelines.

From this review it is apparent that minimal work has been done modelling vulnerability of water supply infrastructure when compared with power and roadways. In Australia and in other countries the majority of research into vulnerability of water supply and networks has been in response to droughts. Little or no literature relating water networks to hazards of wind and flood was identified.

Modelling of water supply networks can be performed with Software such as eWater Source or REALM (The Resource Allocation Model), both developed in Australia. These software packages are commercially available with detailed manuals and non-commercial versions are freely available to the public.

Vulnerability analysis methods such as those presented by Pinto, Varum, Bentes, and Agarwal (2010) and Bentes et al. (2011) allow for the determination of weak or critical links in a network by drawing parallels with structural reliability theory.

5.3.1 Summary table and recommendations

Given the complexity of complete network modelling, and the need to incorporate external simulation software, water network vulnerability should not be simulated for initial scenarios. The simplified approach used by the HAZUS models and deals with direct structural damage should, however, be considered.

Short summaries of some articles discussed throughout this section are listed in Table 5.

Table 5: Summary of research and models relating to water system vulnerability

PAPER/MODEL	TITLE AND NOTES	MATURITY	COUNTRY
WISE	***Water Infrastructure Simulation Environment*** Software package for modeling, simulating, and analyzing interdependent water infrastructures. Developed by the Los Alamos National Laboratory	Mature Commercial	USA
eWater Source	***eWater Source*** A water resources management software combined with water policy and governance Developed by eWater; originally a CRC but now a publicly listed company	Mature Commercial capabilities.	AUS
REALM	***The Resource Allocation Model (REALM):*** Software package that can simulate the operation of both urban and rural water supply systems. Developed by the Victorian Department of Environment and Primary Industries, available free of charge.	Mature Commercial/academic	AUS
HAZUS-MR4 flood, FEMA (2010)	***HAZUS flood vulnerability models*** Incorporates fragility relationships for treatment plants, pump stations, telecom and substations. These are developed by the HAZUS team and are not based on outside academic literature.	Mature Commercial	USA

Pinto (2010)	***A theory of vulnerability of water pipe networks*** • Presents a vulnerability assessment method based on similar concepts in structural reliability theory	Research	-
Bentes (2011)	***A new tool to assess water pipe network vulnerability and robustness*** • Presents a set of examples of the implementation of the method developed by Pinto (2010)	Research	
Wagner, Shamir, and Marks (1988a, 1988b)	***Water distribution and reliability: Analytical methods*** ***Water distribution and reliability: Simulation methods*** • Two pioneering works in network modeling. Provides a review of early modeling tools as well as fundamental theory.	Research [pioneering work]	-

5.4 Telecommunications

Telecommunication infrastructure is important for operation of radios, telephones, internet and cellular services for general communication as well as banking and commerce. During severe weather events telecommunication networks are also necessary for the coordination of emergency services and informing the public of critical information.

Telecommunication infrastructure is primarily impacted by natural hazards through the likely loss of electrical power, but wind loading of assets themselves (e.g. cellular towers) could also potentially be an issue. Electricity is required not only for transmission of data but also for the air-conditioning of spaces that house certain telecommunications equipment. Overhead telephone lines as well as radio antennae and satellite dishes are vulnerable to high wind events and debris impact.

Flood events can also damage junction boxes as well as underground cables through erosion and scour. The damage to a main Telstra fibre-optic cable due to floods during Cyclone Oswald (2013) is a prime example of the latter which caused significant disruption of landline, cellular, and internet services as well as to ATM networks and EFTPOS services at retailers.

Numerous commercial as well as open source software packages are available for modelling telecommunications networks. Sarkar and Halim (2011) review this software providing guidelines for researchers on selecting the most appropriate modelling software for the task.

Telecom networks are also highly dependent on electrical power. However, studies by Kwasinski (2010) appear to be one of the few works studying the vulnerability of communications networks and impacts of power failure due to natural disasters. No vulnerability models were, however, found that directly linked flood and wind hazards to telecommunications networks. These studies also consider the necessity of ancillary facilities such as air-conditioning in the operation of telecommunications equipment and consider the interdependency between the power and telecommunications network using reliability analysis methods.

5.4.1 Summary table and recommendations

Telecommunication damages are not expected to be simulated in initial scenarios. Whether this lifeline will be considered for future scenario analyses will require further research in full consideration of the findings of Sarkar and Halim (2011) and Kwasinski (2010).

Short summaries of some articles discussed throughout this section are listed in Table 6.

Table 6: Summary table listing research and models relating to telecommunication vulnerability

PAPER	TITLE AND NOTES	MATURITY	COUNTRY

Sarkar and Halim (2011)	***A Review of Simulation of Telecommunication Networks: Simulators, Classification, Comparison, Methodologies, and Recommendations*** • An excellent review article on available network modelling tools. • Includes a section to assist researchers in choosing the appropriate software for their needs	[Review Article]	NZ
Kwasinski (2010)	***Analysis of vulnerabilities of telecommunication systems to*** • A study that focuses on the vulnerability of a telecommunications network and its interdependency the electrical power network	Research	- ***natural disasters***
Network simulation software	NS (network simulator) Georgia Tech Network Simulator—(open source) AKOROA—(open source) OPNET—(commercial) NetSim—(commercial) MIITS—(commercial) NetQUAD—(commercial)	Mature Analytic	Many

6. Interdependency of Infrastructure Networks

As shown, several vulnerability models for the different infrastructure types have been developed. However, a critical aspect of civil infrastructural networks is that they are heavily interconnected. Thus, the vulnerability of a certain type of infrastructure, e.g. water supply, cannot be examined in isolation of power supply. Similarly, telecommunications networks are heavily dependent on electrical power for both data transmission as well as air-conditioning of computer hardware.

Literature on critical infrastructure interdependency is usually in the form of reports that have been commissioned by governments or the military. Examples include the RAIN Project (Risk Analysis of infrastructure Networks) in Europe, CIPMA Program (Critical infrastructure protection and modelling analysis) in Australia and NISAC (National Infrastructure Simulation and Analysis Centre) in the United States

The United States is a leader in the modelling of its critical infrastructure. Three National Laboratories are associated with NISAC, including the Sandia, Idaho and Los Alamos National Laboratories (LANL). A range of software packages have been developed by the LANL for the modelling of a wide range of infrastructure systems to a range of hazards. A well maintained website is available for the review of the packages (http://www.lanl.gov/programs/nisac/tools2.shtml). Australia has an equivalent modelling software CIPMA, however no web-based information is provided. Further information on this model is currently being sought.

Pederson, Dudenhoeffer, Hartley, and Permann (2006) provide a review of academic and commercial modelling tools. Software is reviewed based on modelling type, intended users, hardware and software requirements and more importantly the level of maturity. A reputed modelling tool from this review is the Inoperability Input-Output Model (IMM) that allows the modelling of interdependency of various infrastructure types.

Little academic literature on the subject of infrastructure interdependency, as it related to natural hazards, was found. One notable exception though, was Zhang, Song, Zhang, and Liu (2014), who modelled the interdependencies of the Shanghai railway system and power and communications networks. Murray and Grubesic (2007) also provides a broad overview of the topic.

6.1.1 Summary table and Recommendations:

Most work that has been done on network interdependency was through government backed ‘critical infrastructure protection programs’. Outcomes from these programs are not freely accessible to academics and researchers. Pederson et al. (2006) is a one good source of information on the selection of the appropriate modelling tool. Of those reviewed, the Inoperability Input-Output model developed by Haimes et al. (2005) appears to be the most flexible and is published in academic literature. Other recommended techniques include those by Reed et al. (2009) and Zhang et al. (2014). Given the scope of the current project it is not expected that full network interdependency will be incorporated into scenario analyses, but the incorporation of larger system vulnerability models into future scenario analyses should be explored.

Table 7: Summary of research and models of infrastructure network interdependency.

PAPER/MODEL	TITLE AND NOTES	MATURITY	COUNTRY
NISAC	***National Infrastructure Simulation and Analysis Center*** • A US- Based research program directed by the Department of Homeland Security and run by the Los Alamos and Sandia National Laboratories. • Has developed and is currently developing several modelling and simulation tools for the analysis of critical infrastructure networks.	Mature Commercial	USA

CIPMA	***Critical Infrastructure Program for Modeling and Analysis*** • An integrated modelling and database suite for energy, telecommunications and banking and finance. • Developed by the CSIRO and Geoscience Australia, managed by the Attorney-General's Department.	Development	AUS
RAIN Project	***Risk Analysis of Infrastructure Networks in Response to Extreme Weather*** • A multinational and multidisciplinary research project funded by the European Union and coordinated by Trinity College Dublin • Focuses on transport, energy and telecommunications infrastructure vulnerability and modelling	Development	EUR
Haimes et al (2005)	***Inoperability Input-Output Model*** • An analytical framework for modeling the interconnectedness of critical infrastructure such as: Oil and gas, electric power, telecommunications and banking. Developed by the University of Virginia	Mature Commercial	USA
IEISS	***Interdependent Energy Infrastructure System*** • A simulation tool for modeling interdependent infrastructure, useful for both natural hazards as well as terrorist/military attack	Mature Commercial	USA
Pederson et al. (2006)	***Critical infrastructure interdependency modelling: A Survey of U.S. and International research*** • Review of various modeling tools and software useful for network modeling as well as network interdependency modelling	[Review Article]	USA
Zhang et al. (2014)	***An Approach for modeling vulnerability of a network of networks*** • A thorough study presenting techniques for modeling the Shanghai metro network along with power and telecommunications network	Research [recent]	CHINA
Murray and Grubesic (2007)	***Critical Infrastructure – Reliability and Vulnerability*** • A comprehensive text, presenting an introduction to concepts and theory of critical infrastructure protection	[BOOK]	

7. Conclusions and Recommendations

A broad overview of vulnerability modelling for buildings and civil infrastructure exposed to the tropical cyclone hazards of wind and water has been presented. Key concepts have been highlighted and notable modelling software and tools identified.

Moving forward with this project decisions must be made about what assets and impacts will be simulated within the tropical cyclone scenarios. Table 8 provides recommendations for the most suitable models to be used for initial simulations, with comments on essential and desirable modifications provided. Models developed by Geoscience Australia and modified versions of those within the HAZUS modelling framework make up the bulk of those to be implemented, but care must be taken to modify these so that they provide sensible estimates of damage and loss. Detailed network simulation is not recommended initially, but the potential for incorporating physical damage outputs into a detailed network simulation model (e.g. CIPMA) should be explored.

Table 8: Recommendations for initial model implementation within scenario analysis

HAZARD	ASSET TYPE	BASE MODEL	COMMENTS

Wind	Buildings	Geoscience Australia	The suite of Geoscience Australia models should be used as the base for both residential and other building types. These should be modified based on relationships between different building types (and building/contents) seen in the HAZUS vulnerability models and when assessing proprietary models held by Risk Frontiers based on insurance loss data. New models developed by the Cyclone Testing Station through the BNHCRC project will also be used.
Wind	Civil (power)	HAZUS	The HAZUS methodology will be updated to consider infrastructure modelling by Ahmed et al. (2004) on transmission tower failure and, e.g., Bjarnadottir et al. (2014) on distribution system failure.
Wind	Civil infrastructure (other)	HAZUS	Little information is available for the updating of the HAZUS modelling procedure with respect of the nonpower infrastructure assets. Not all will be implemented at the initial stage of the project and further research will be required to determine whether external network modelling software can be incorporated into the project.
Flood	Buildings	Mason et al (2012), Geoscience Australia NSW Govt (2007), ANUFLOOD	The Mason et al (2012) (based on the models) and NSW Govt (2007) models will be implemented for residential buildings. Similar models will be implemented for other building structures, but care will be required when (if) attempting to model contents loss. Insurance loss data (Risk Frontiers) and the ANUFLOOD and HAZUS models will help inform decisions around the latter.
Flood	Civil infrastructure	HAZUS	As with wind there is little readily available modelling data that will allow updates to models provided in HAZUS. These will be implemented where deemed reasonably representative. Note that network modelling won't be performed at the initial stage so not all infrastructure damages will be modelled.
Wind, Flood	Death and displacement	HAZUS	The HAZUS approach should be followed closely for initial simulation.

Finally, a number of other Bushfire and Natural Hazards CRC projects within the 'Hardening Buildings and Infrastructure' cluster are working towards developing improved vulnerability models that can and should be incorporated into this project. The output of these projects will be monitored and when improved models become available they will be assessed and included if beneficial.

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