Coastal Vulnerability to Multiple Inundation Sources

COVERMAR project

Literature Review Report

(Second Edition)

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Coastal Inundation.
COVERMAR Project.

Coastal Vulnerability to Multiple Inundation Sources Project (COVERMAR)

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This report *Coastal Vulnerability to Multiple Inundation Sources – COVERMAR project – Literature Review (Second Edition)* was prepared for the **Sydney Coastal Councils Group Incorporated** by Dr. Filippo Dall'Osso [1,2] and Associate Professor Dale Dominey-Howes[1].

[1] Australia-Pacific Tsunami Research Centre and Natural Hazards Research Laboratory, University of New South Wales, Sydney
[2] MEDINGEGNERIA S.r.l, Hydraulic and Coastal Engineering, Italy

This is the second of three reports. The other two reports are:

1. Hazard Assessment Report.
2. Final Outcomes Report

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Enquiries

Sydney Coastal Councils Group

www.sydneycoastalcouncils.com.au/Contact_SCCG

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Executive Summary

This report provides background knowledge and information to set the context and define the boundaries of the Coastal Vulnerability to Multiple Inundation Sources (COVERMAR) Project. It reviews past, existing and emerging work relevant to the project, divided into five sections:

Section 1 – SCOPE

In November 2011, the Sydney Coastal Councils Group Inc. (SCCG) partnered with the University of New South Wales (UNSW) Australia – Pacific Tsunami Research Centre & Natural Hazards Research Laboratory (UNSW APTRC) in respect of a two-year research project addressing COastal VulnERability to Multiple inundAtion souRces (COVERMAR project).

The COVERMAR project will develop a tool ('COVERMAR tool') for assessing the vulnerability of coastal buildings and infrastructure to extreme inundations, including tsunamis and storm surges. The COVERMAR tool will be built upon the existing PTVA model (Papathoma Tsunami Vulnerability Assessment), an index-based tool offering a GIS-based estimate of building vulnerability to tsunami inundations.

Within this project, the newest version of the PTVA model (i.e. the PTVA-3) will be upgraded, to include:

a. Findings from the newest approaches based on tsunami fragility curves;

b. A numerical simulation of the tsunami inundation process;

c. An improved weighting procedure of the physical attributes influencing the overall vulnerability of different building types (see Section 5.2.5).

A new module will then be added to the new version of the PTVA model to assess the vulnerability of buildings and coastal infrastructure to extreme storm surge events (multi-hazard approach). The COVERMAR tool will be field tested in three study areas in New South Wales, under present and future climate conditions.

Section 2 – RISK, HAZARD, VULNERABIITY AND EXPOSURE

This section contains an overview of the key concepts of risk analysis and natural hazard science, including internationally adopted definitions of Risk, Hazard, Vulnerability and Exposure.

Section 3 – EXTREME INUNDATION EVENTS

Extreme inundations may occur as a result of different hydro-meteorological or geophysical processes, such as storm surges (and storm tides) and tsunamis.
The section provides an introductory description of these hazards, their generating mechanisms, the inundation processes and exposure in Australia and NSW.

In Australia, some 80% of the population lives within the coastal zone (Chen & McAneny, 2006). Locally in NSW, the Australian Industry Group (AIG) has estimated that more than 200,000 properties are classified as at 'risk' from coastal hazards. Chen and McAneny (2006) estimated that within the Sydney basin, some 20,000 properties are most at risk, being located <1km from the shoreline and at no more than 3m above sea level.

NSW coastal exposure to storm surges is very high. In NSW, storm surges are generally associated with East Coast Lows (ECLs). ECLs are intense low-pressure systems that occur frequently along the east coast of Australia, causing extreme winds and waves, heavy rainfall and coastal inundations. The Australian Department of Climate Change (2009) estimated that in NSW between 40,800 and 62,400 residential buildings may be at risk of inundation from a sea-level rise of 1.1 m and storm tide associated with a 1/100 year storm. This section reports a list of the most significant ECLs that have occurred in NSW since 1850 (NSW Regional Office, June 2007) and a record of significant tidal anomalies in Sydney and Coffs Harbour, recorded from 1966 to 1990 (McInnes & Hubert, 2001).

With regard to tsunami exposure, tide-gauge records show that historically, only small events have affected the NSW coastal region (Dominey-Howes, 2007). Reported geological evidence however, suggests that megatsunamis many times larger than the 2004 Indian Ocean Tsunami (IOT) may have occurred repeatedly during the last 10,000 years of the earth's history, a period known as the Holocene (Bryant and Nott, 2001). Recently, a bathymetric survey carried out by Geoscience Australia (Glenn et al., 2008) revealed that the continental slope of NSW has experienced widespread underwater sediment slide failure through time, which could have generated locally significant tsunamis.

Climate change is expected to increase the intensity and frequency of coastal inundations as an effect of sea level rise. Available sea level rise projections and climate change effects on extreme inundations in NSW are here presented and discussed. In response to the most recent Intergovernmental Panel on Climate Change projections (IPCC 2007), the NSW Sea Level Rise Policy Statement (DECCW 2009) has adopted planning benchmarks corresponding to an increase above 1990 mean sea levels of 40 cm by 2050 and 90 cm by 2100. In terms of climate change effects on extreme NSW storms, McInnes et al. (2007) estimated that this could result in an increase in their frequency by as much as 48% in 2070, and of their significant wave height (Hs) by up to as much as 32%. Further, McInnes et al. (in review) have recently generated future inundation scenarios (i.e. year 2100) associated with 1/1 year and 1/100 year storms along the Sydney coastal zone.

Section 4 – NSW POLICY FRAMEWORK ON COASTAL AND FLOOD RISK

This section outlines the NSW policy context relevant to the aims of the COVERMAR project. It includes a description and a flow-chart of the main regulations and guidelines dealing with extreme inundations in the fields of Emergency Management, Coastal and Floodplain Risk Management, Strategic Planning & Development Assessment. Specifically, these include:

NSW Emergency Management:

- NSW State Emergency and Rescue Act (1989);
- NSW DISPLAN (2010);
- Flood Sub-Plan;
- Storm Sub-Plan;
- Tsunami Sub-Plan.

Coastal Risk Management:

- NSW Coastal Protection Act (1979) and 2010 amendments;
- NSW Coastal Policy (1997);
- NSW Coastal Protection Regulation (2011);
- NSW Sea Level Rise Policy Statement (2009);
- NSW Guidelines for Coastal Zone Management Plans (2010);
- NSW Coastal Risk Management Guide (2010).

Floodplain Risk Management:

- Flood Risk Management Guide (2010);
- Floodplain Development Manual (2005);
- Practical Considerations for Climate Change (2007).

Strategic Planning & Development Assessment:

- Environmental Planning and Assessment Act (1979);
- Relevant Environmental Planning Instruments (SEPP, LEP, DCP) Coastal Planning Guidelines (2010).

Section 5 - REVIEW OF METHODS FOR ASSESSING THE VULNERABILITY OF BUILDINGS AND INFRASTRUCTURE TO EXTREME INUNDATIONS

The recent IPCC report on extreme events (IPCC 2012) outlined the critical importance of developing new multi-hazard tools, enabling risk managers and stakeholders to compare the threats posed by different processes and adopt balanced mitigation measures. However, existing methods for assessing the vulnerability of coastal assets to extreme inundations have developed independently, according to the inundation source considered. This section provides a comparative review of these methods, noting their advantages and main limitations.

Section 5.1 focuses on methods for storm surges (and storm tides) vulnerability assessment. Storm surges can affect coastal buildings and infrastructure in two main ways: (1) eroding sand dunes and reducing building foundation capacity; and (2) inundating low lying coastal areas, either with waves overtopping or breaching coastal barriers (foreshore inundation) or flooding through tidal waterways (estuaries, lagoons). In NSW, damage to coastal structures due to storms is primarily associated with the scouring effect of waves around building foundations, rather than to direct wave impact during storms. In this case, the most widely used method is the one proposed by Nielsen et al (1992) that includes a stability analysis of the coastal dunes, based on the selected design storm erosion demand.

In case of storm surges causing foreshore or tidal inundation, potential damage to buildings is generally estimated using fragility curves. Specifically, most of the existing approaches use stage-damage curves, which estimate the damage as a function of the expected water depth and primary building features (Suleman et al., 1988; Penning-Rowsell et al., 2003; Messner et al., 2007). However, Middlemann-Fernandes (2010) outlines that the use of these curves underestimates the damage when the flow velocity is higher than 1 m/sec, and in these cases it is recommended that use is made of combined stage-damage functions and stage-velocity-damage functions. A similar approach was adopted by Pistrika and Jonkman (2009) that generated stage-velocity curves for buildings damaged by hurricane Katrina in New Orleans (US).

Section 5.2 reviews existing methods for tsunami vulnerability assessment. It contains a critical summary of scientific literature describing the main index-based approaches, focusing on the PTVA model, its core idea, the three different versions of the model that have been developed so far and their applications in different coastal contexts, including Greece, the United States, the Maldives, Italy and Australia. The section describes the main PTVA-3 limitations that this project will address, and outlines the reasons why the PTVA-3 model is considered the best available approach to be used as a starting-point for the development of the COVERMAR tool. These include: (a) the flexibility of the PTVA-3 model, able to be applied in different coastal regions; (b) the implementation of a multi-criteria approach based on the Analytic Hierarchic Process (AHP); and, (c) the use of a Geographic Information System (GIS) platform, which facilitates the management of a large geographic database and the generation of thematic maps.

One of the main limitations of the recent applications of the PTVA-3 model is the lack of a numerical simulation of the tsunami propagation and inundation process. In fact, the PTVA-3 model generates the inundation layer using a static 'bathtub' approach, which can significantly affect the accuracy of tsunami hazard maps (in terms of tsunami demand parameters – e.g. flow depth – acting on different exposed buildings).

The PTVA-3 model was developed using qualitative information about the level of damage experienced by different building types during real tsunami events. However, it does not directly implement any of the existing building fragility curves for tsunamis, largely because these were not available when the original PTVA model was first developed. As a consequence, the PTVA-3 model provides a relative assessment of the building vulnerability. That is, it allows identification of buildings which are 'more' or 'less' vulnerable than others, but it cannot predict their absolute damage level should a given tsunami scenario occur.

To address these issues, the COVERMAR tool will use state-of-the-art models for the simulation of tsunami generation, propagation and inundation. Specifically, we will model selected earthquake-generated tsunami scenarios through the ComMIT system (Community Model Interface for Tsunamis), recently developed by the NOAA Center for Tsunami Research (NCTR) (Titov et al., 2011). Globally, this is the most widely used tool.

Further, the large tsunamis that have occurred in the last decade have allowed the scientific community to start developing tsunami fragility curves for the most common building types. These curves generally link the tsunami flow depth to the expected level of absolute damage (Valencia et al., 2011). The COVERMAR project will integrate these fragility curves into the PTVA-3 model, to increase the objectivity of its outputs and further increase its reliability. In this report section, we summarise and cross-compare all the currently available building fragility curves for tsunamis. One of the newest and most comprehensive approaches is the one provided by Valencia et al. (2011), who generated a set of damage curves for four types of buildings, using a database of building damage observed in over 4500 structures after the 2004 IOT in Banda Aceh, Indonesia.

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GLOSSARY

Analytic Hierarchy Process: a multi-criteria decision making tool allowing a systematic comparison between several options.

Bathtub filling' approach: a static method used to generate inundation maps without the use of a specific hydrodynamic inundation model. The "bathtub" method makes the assumption that a water level modelled at the coast will infill terrain at lower elevation to the same level (McInnes et al., in review).

Barometric surge: the increase in mean sea level caused by a decrease of atmospheric pressure.

Building fragility curve (for inundation): a mathematical function associating a parameter measuring the inundation intensity – for example the flow depth, or the flow velocity – with the corresponding level of damage that buildings with different engineering attributes are expected to suffer.

ComMIT: an internet-enabled interface to a community tsunami model developed by the NOAA Center for Tsunami Research (NCTR), in response to a recommendation of the Intergovernmental Coordination Group for the Indian Tsunami Warning System (ICG/IOTWS) to create a web-based community tsunami model.

Exposure: people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses. Measures of exposure can include the number of people or types of assets in an area. These can be combined with the specific vulnerability of the exposed elements to any particular hazard to estimate the quantitative risks associated with that hazard in the area of interest (UNISDR, 2009).

Extreme climate event: the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable (IPCC, 2012

Extreme inundation: inundation of coastal areas caused by extreme sea levels.
Extreme sea level: the highest or lowest elevation reached by the sea during a given period (IOC 1985–2006).

Foreshore inundation: coastal inundation caused by breaching or overtopping of the dune system or coastal protection.

Hazard: a threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area (UN, 1992).

Multi-hazard assessment: a study able to consider simultaneously the effects of different hazard types.

Probable maximum loss: the largest possible loss, which it is estimated in regard to a particular risk, given the worst combination of circumstances (Bennett, 1992).

Papathoma Tsunami Vulnerability Assessment model: an index-based computer tool offering a GIS-based approach to estimating the vulnerability of different building types to a potential tsunami threat.

Risk: the combination of the probability of an event (...) and its negative consequences (UNISDR, 2009).

Storm bite: erosion of unconsolidated coastal soil resulting from a single extreme storm event or from several very severe storm events in close succession with cumulative impacts (NSW Coastal Risk Management Guide, 2010).

Storm surge: the temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place (IPCC, 2012).

Storm tide: a storm surge developing on top of astronomical tide (Helmann et al., 2010)

Tidal inundation: inundation caused by overbank flows along estuaries and tidal waterways.

Tidal range: the vertical difference in high and low water level once decoupled from the water level residuals (Simm et al., 1996).

Tsunami: a Japanese term meaning wave ('nami') in a harbour ('tsu'). A series of traveling waves of extremely long length and period, usually generated by disturbances associated with earthquakes occurring below or near the ocean floor (IOC, 2008). Tsunamis can be triggered by submarine earthquakes, submarine landslides, submarine volcanic activity, cosmogenic sources (ex. asteroid impact) or man-induced processes (ex. submarine explosions).

Vulnerability: the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UNISDR, 2009).

Wave runup: the ultimate height reached by waves after running up the beach and coastal barrier (see also wave setup). (Ministry for the Environment, 2008).

Wave setup: the super-elevation in water level across the surf zone caused by energy expended by breaking waves (see also wave runup). (Ministry tor the Environment, 2008).

Wind setup: the increase in mean sea level caused by the 'piling up' of water on the coastline by wind (mhl, available at http://new.mhl.nsw.gov.au/data/realtime/wave/glossary).

ACRONYMS

AHD	Australian Height Datum
ARI	Average Recurrence Interval
COVERMAR	Coastal Vulnerability To Multiple Inundation Sources
DISPLAN	Disaster Plan
ECL	East Coast Low
FEMA	Federal Emergency Management Agency
FRM Plan	Floodplain Risk Management Plan
GIS	Geographic Information System
CZM	Coastal Zone Management
IOC	Intergovernmental Oceanographic Commission
IOT	Indian Ocean Tsunami
IPCC	Intergovernmental Panel On Climate Change
PTVA Model	Papathoma Tsunami Vulnerability Assessment Model

1. SCOPE

1.1 BACKGROUND AND AIM

The aim of the COVERMAR project is to develop and test a semi-quantitative, multi-hazard tool for the assessment of the vulnerability of buildings and selected infrastructure to extreme inundations, caused by coastal storms (and associated floods) and tsunamis.

The tool – named **COVERMAR** – will enable the generation of high-resolution interactive GIS maps (up to a scale of approximately 1:5000), showing the level of relative vulnerability of single buildings and infrastructure to selected inundation scenarios (Figure 1).

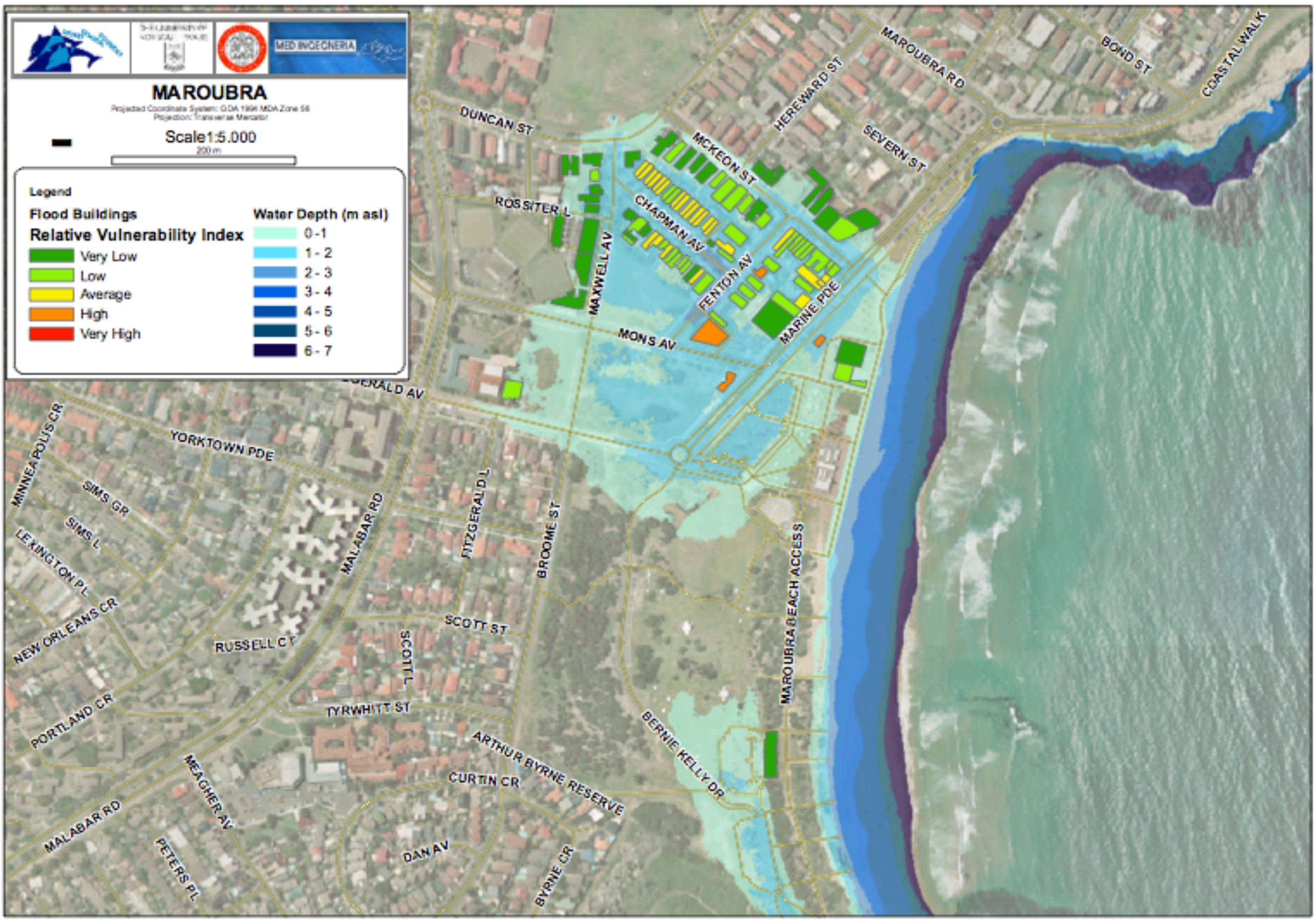

Figure 1. Example of a vulnerability map of the area of Maroubra beach (Sydney, NSW), obtained using a previous version of the COVERMAR tool (the PTVA-3 Model). The map shows the relative vulnerability of single building units to a selected tsunami inundation scenario (Dall'Osso et al., 2009a).

This project builds upon the 2009 SCCG project titled "A Method for Assessing the Vulnerability of Buildings to Catastrophic (Tsunami) Marine Flooding" (Dall'Osso & Dominey-Howes, 2009). However, COVERMAR will introduce significant methodological improvements, including the capability of the tool to deal with storm surges (other than tsunamis) and a more accurate analysis of the selected inundation scenarios.

The COVERMAR tool will be built using the newest version (i.e. version #3) of the `**Papathoma Tsunami Vulnerability Assessment (PTVA-3) Model'** as its foundation.

The PTVA-3 model

The PTVA-3 model is the newest version of the PTVA model, an index-based computer tool offering a GIS-based approach of estimating the vulnerability of different building types to a potential tsunami threat (Papathoma, 2003; Papathoma & Dominey-Howes, 2003; Dall'Osso et al., 2009a; Tarbotton et al., 2012).

The model calculates a Relative Vulnerability Index (RVI) for every building within an expected inundation zone as a function of its attributes (e.g. number of storeys, material), surroundings and expected flow-depth.

In the absence of fully validated building fragility curves for tsunamis, the PTVA-3 provides an effective means of identifying vulnerable buildings and estimating the potential loss.

However, recent studies have highlighted the following shortcomings of the PTVA-3 Model, to be addressed in the COVERMAR tool project:

- Tsunami impact is assessed using only the depth of flow expected to hit the building. There is no numerical simulation of the inundation process and flow velocity is not considered;
- Building fragility curves for tsunami damage (e.g. velocity/stage-damage functions) are not included, largely because they were not available when the model was originally developed;
- The AHP and pair-wise comparisons between building attributes have only been carried out by Dall'Osso et al (2009b) and require further validation with experts from different sectors; and
- The PTVA focuses solely on the vulnerability of buildings and does not include coastal infrastructure (e.g. harbours, streets, bridges).

A more detailed description of the PTVA Model and other index-based methods is provided in Section 2.1.

The aim of COVERMAR will be achieved through pursuing three Objectives:

1. **Generate a new improved version of the PTVA model (the PTVA-4 model)** for assessing tsunami vulnerability. This will be achieved by upgrading the current version of the PTVA model (version #3) to include:
    a. Numerical simulations of tsunami flooding;
    b. Findings from the latest tsunamis and recently published building fragility curves for tsunami damage;
    c. An improved weighting procedure of the physical attributes of buildings affecting their vulnerability to tsunamis; and
    d. A new module for assessing the vulnerability of coastal infrastructure to tsunamis.
2. **Develop and add a new module (called the 'STORM' module) to the PTVA4 Model.** The STORM module will enable the assessment of the vulnerability of buildings and selected infrastructure to coastal storms (and associated flooding in estuarine/deltaic areas). The integration of the STORM module into the PTVA-4 will generate the new multi-hazard COVERMAR tool.
3. **Test the COVERMAR tool at three study sites in NSW.** This will require selecting and generating a set of credible storm surge and tsunami inundation scenarios at each of the case-study locations. Study areas along the NSW coast will be selected based on exposure and vulnerability to marine inundations. Inundation scenarios will include a 1/100 year design storm and the worst credible case of tsunami, under present and future climate conditions (i.e. 2100 AD). Specifically, tsunami scenarios will be simulated using the latest hydrodynamic modelling techniques developed by UNESCO/IOC and the US Federal Governments NOAA, namely the Community Model Interface for Tsunami (ComMIT) system. Storm surge scenarios will utilise outputs from the SCCG's 'Mapping and Responding to Coastal Inundation Project'.

1.2 EXPECTED OUTCOMES

1. Enhanced scientific understanding of single and multi-hazard scenarios, incorporating storm and tsunami hazards, impact and vulnerability;
2. Improved risk assessment capacity of local government and emergency services in relation to individual and multiple hazards, infrastructure, disaster preparedness (including education and evacuation) and recovery and response;
3. Knowledge to underpin decision making and planning;
4. Improved community resilience to and education regarding coastal hazards and disasters;
5. Better transferability of technology to local government.

1.3 DELIVERABLES

The COVERMAR project is expected to generate the following deliverables:

1. High-resolution (scale 1:5000) GIS exposure maps showing inundation extent, flow depth and exposed assets for each of the selected scenarios;
2. High-resolution (scale 1:5000) GIS vulnerability maps, showing the relative vulnerability of buildings and infrastructure to the selected inundation scenarios;
3. Estimates of Probable Maximum Loss for each scenario event modelled;
4. Recommendations for Government addressing long term risk mitigation;
5. A GIS dataset including detailed geo-referenced information about single buildings and infrastructure characteristics (i.e. material, number of storeys);
6. A step-by-step user's manual and tutorial for applying the model to other coastal areas.

2. RISK, HAZARD, VULNERABILITY AND EXPOSURE

There are many definitions of risk. In most cases it has been defined according to the aims of the science sector in which a disaster management technique was required. Despite the high number of definitions that can be found in the literature, the concept of risk as a function of 'hazard' and 'vulnerability' appears to be the most accepted and widely used.

The AU/NZS ISO31000 (2009) risk management guidelines provide a comprehensive definition of risk, which is described as *the effect of uncertainty on objectives, with 'effect' being a deviation from the expected positive or negative*. The guidelines add that risk is often characterised by reference to potential events and consequences, or a combination of these.

If we narrow the focus to natural events, the available definitions include further details on the main risk components. According to White and Burton (1980), *risk is the product of the probability of the occurrence of a hazard and its societal consequences*. Tarrant (1987), as well as Ansell and Wharton (1992), simply define risk as the product between likelihood and consequences. At an international level, a more complete definition has been given by the United Nations (1992). The UN defines risk as *expected losses (of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period*. For the International Strategy for Disaster Reduction (UNISDR, 2009), risk is the *combination of the probability of an event* (i.e. the hazard) (...) *and its negative consequences* (i.e. exposure and vulnerability).

Thus, the identification and analysis of risk involves different evaluations about hazard, exposure and vulnerability. A large group of similar definitions can also be found for these three concepts. The UN (1992) defined **hazard** as *a threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area*. Deyle et al. (1998) gave a definition of natural hazard, as an extreme natural event that poses risks to human settlements. The United States Federal Emergency Management Agency or FEMA (FEMA 1997) defines it as *an event or physical condition that has the potential to cause fatalities, injuries, property damage, infrastructure damage, agricultural loss, damage to the environment, interruption of business, or other types of harm or loss.*

With regard to **vulnerability**, there is wide agreement in defining it as *the potential for damage*. Godshalk (1991) described it as *the susceptibility to injury or damage from hazards*, while according to Mitchell and Cutter (1997) vulnerability is *the potential for loss or the capacity to suffer harm from a hazard. It can generally be applied to individuals, society, or the environment.* The UN (1992) described vulnerability as *the degree of loss (from 0% to 100%) resulting from a potentially damaging phenomenon*. The UNISDR (2009) defines vulnerability as *the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.*

While 'vulnerability' is used to describe the susceptibility of a given element to be damaged by a specific hazard, the term **'exposure'** generally refers to the 'quantity' of the elements – or the 'extent' of a geographic area – at risk from a given hazard. UNISDR (2009) defines 'exposure' as *people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses. Measures of exposure can include the number of people or types of assets in an area. These can be combined with the specific vulnerability of the exposed elements to any particular hazard to estimate the quantitative risks associated with that hazard in the area of interest.* In the case of natural hazards, such as coastal inundations, the exposure is given by all the elements (assets, people, and socio-economic aspects) that would be affected by the selected hazard scenario. Each of these elements would then respond to the hazard according to its vulnerability. For example, a single-storey wooden house is more vulnerable to inundation than a multi-storied concrete building. However, both buildings would be "exposed" to the hazard, as long as they are situated within the inundation zone.

The vulnerability of a coastal area includes a wide range of factors or parameters. Due to its multifaceted nature, vulnerability is difficult to quantify and there is no global consensus yet on how it should be measured (Thywissen, 2006). However, according to UN guidelines (United Nations, 1992), vulnerability can be assessed as a percentage of the expected losses resulting from the occurrence of a given hazard.

According to this definition of risk (and related concepts), it is obvious that risk reduction can be achieved by altering either the physical hazard or the vulnerability of the subject/system that is exposed to it. In the case of storm surges or tsunamis, the hazard itself is not avoidable and hardly predictable. Therefore, mitigating vulnerability is the only way in which risk can be realistically reduced. In this context, the IPCC (2012) recommends that future risk studies should:

a. Acknowledge the crucial role of vulnerability in the definition of the overall risk from extreme events;

b. Undertake detailed vulnerability assessments, other than hazard analysis;

c. Propose effective vulnerability reduction strategies and tools;

d. Adopt a comprehensive approach assessing simultaneously the vulnerability to multiple-hazards, rather than to single hazard types, as *considering multiple types of hazards reduces the likelihood that risk reduction efforts targeting one type of hazard will increase exposure and vulnerability to other hazards, in the present and future* (IPCC, 2012).

Within the present work, vulnerability and related concepts are defined and measured in accordance with UN (1992), UNISDR (2009) and the AU/NZS ISO31000 (2009) guidelines. As such, the vulnerability of coastal buildings and infrastructure is assessed with respect to multiple inundation sources (storm surges and tsunamis).

3. EXTREME INUNDATIONS EVENTS

Coastal zones are especially vulnerable to the impact of extreme inundation events associated with storms, floods and tsunamis (Nicholls et al., 2008). The IPCC (2012) defines 'extreme weather and climate events' as *the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable.*

In the case of extreme sea levels, the above-mentioned 'variable' becomes the sea level along the shore, and thus *extreme coastal high water depends on average sea level, tides, and regional weather systems. Extreme coastal high water events are usually defined in terms of the higher percentiles (ex. 90th to 99.9th) of a distribution of hourly values of observed sea level at a station for a given reference period* (IPCC, 2012).

A more comprehensive definition is provided by the Intergovernmental Oceanographic Commission (IOC) (2006), which describes 'extreme sea level' as *the highest or lowest elevation reached by the sea during a given period.* This definition is one of the most widely used, and it is adopted in Australia and NSW (Manly Water Lab, http://new.mhl.nsw.gov.au/data/realtime/oceantide/Glossary#S).

In this study, we will refer to 'extreme inundations' as those inundations caused by 'extreme sea levels' (specifically, by 'the highest' sea levels), as defined by the IOC (2006). The time-period we will consider extends until year 2100, in line with the 2012 IPCC guidelines on extreme events and with NSW Coastal Risk Policy, Regulation and Guidelines (see Section 4).

Extreme inundations, as with all extreme climate events, are characterised by a relatively low frequency, but high energy and potentially disastrous consequences on coastal assets and communities. Storm surges and tsunamis are very different processes: they have different causes, hydrodynamic characteristics, frequencies and intensities. However, each of them has the potential to cause extreme inundations and widespread damage to coastal communities and assets.

3.1 STORM SURGES AND STORM TIDES

Storm surges are described as the temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place (IPCC, 2012).

Storm surges associated with astronomical tide level are known as 'storm tides' (Helmann et al., 2010). During storm tides, the increased water level has the potential to cause significant inundation of inland areas.

The main factors contributing to sea level extremes during storm tides can be summarised as (Figure 2):

a. Tidal variation: depending on the local tidal range. In the Sydney area (Middle Head tide gauge), the maximum tidal range is 1.829 m (MHL, 2008);

b. Barometric surge: sea level can increase up to 1cm for every hPA fall (McInnes et al., in review);

c. Wind setup: the increase in mean sea level caused by the 'piling up' of water on the coastline by wind (MHL, available at http://new.mhl.nsw.gov.au/data/realtime/wave/Glossary). This effect is higher when the continental shelf is relatively wide and shallow (e.g. North-West Australia, Mexican Gulf). In NSW this contribution is minor as the edge of the continental shelf is relatively close to the shore;

d. Wave setup: The super-elevation in water level across the surf zone caused by energy expended by breaking waves (Ministry for the Environment, 2008);

e. Wave runup: The ultimate height reached by waves after running up the beach and coastal barrier (Ministry for the Environment, 2008). The vertical distance above still water level reached by the uprush of water from waves across a beach or up a structure, with 'still water level' being the sum of tidal variation, barometric surge, wind and wave setup. Wave runup does not contribute to the overall still water level, as waves are transitory. However, during a storm tide, waves developing on top of an increased still water level can cause significant damage to onshore infrastructure and buildings.

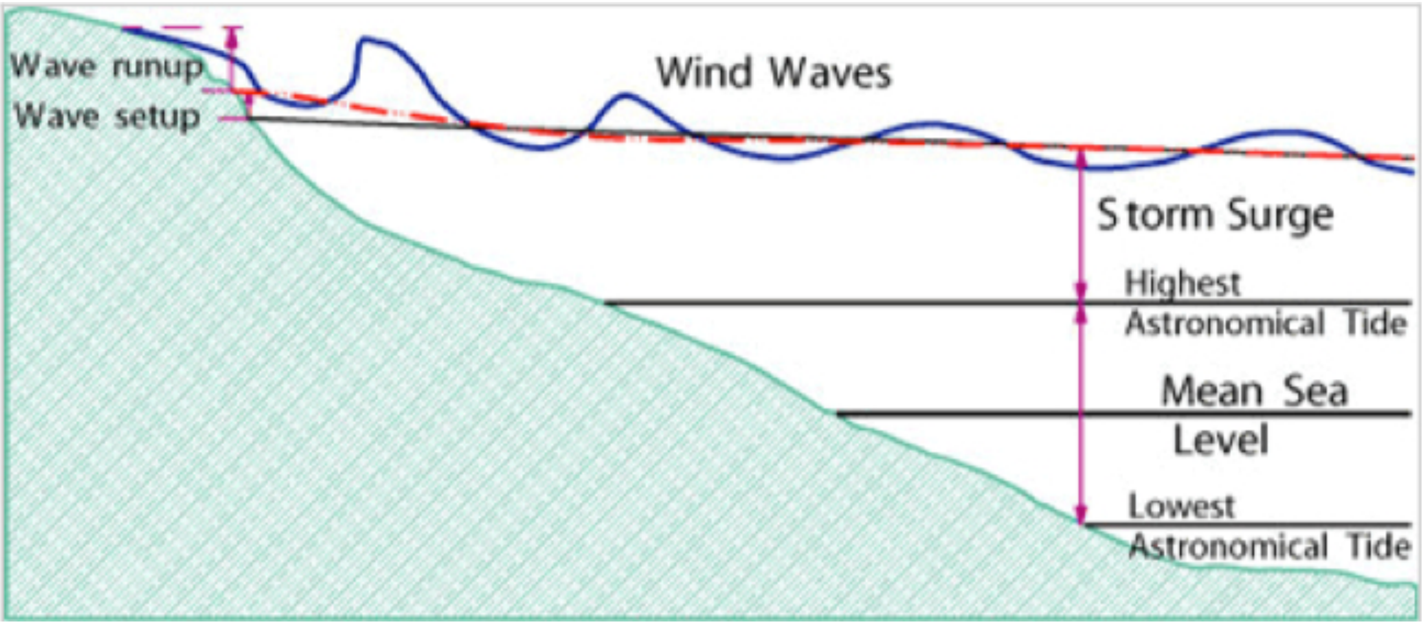

Figure 2. Contributions to extreme sea levels during a storm surges (McInnes et al., in review).

3.2 TSUNAMIS

According to the IOC (2008), a tsunami is *a series of travelling waves of extremely long length and period, usually generated by disturbances associated with earthquakes occurring below or near the ocean floor.* Similarly, NOAA (2012) defines a tsunami as *a series of ocean waves generated by sudden displacements in the sea floor, landslides, or volcanic activity.* Although both these definitions are accurate, it is important to emphasise that the 'vertical displacement' of the water column must be impulsive – or 'sudden' – in order to be able to generate a tsunami. According to Boschi and Dragoni (1999) this impulse must be in the order of 100s at the most. The physical processes that have the potential to generate this type of underwater impulse – and thus a tsunami – are only submarine earthquakes, large submarine landslides or coastal rockfalls, volcanic eruptions and the impact of cosmic bodies, such as meteorites (IOC, 2008).

As reported by Pattiaratchi (2012), 82% of the recorded tsunamis were caused by an earthquake, 6% by a submarine landslide or coastal rockfall, and 5% by volcanic activity (Figure 3). A minor proportion was caused by meteorological drivers, namely abrupt atmospheric pressure changes. Most of the tsunamis are therefore earthquake-generated. However, not every submarine earthquake generates a tsunami. Major tsunamis are produced by large (Magnitude equal to a figure greater than 7 on the Richer scale), shallow focus (< 30 km depth in the earth) earthquakes associated with the vertical movement of oceanic and continental plates (NOAA, 2012).

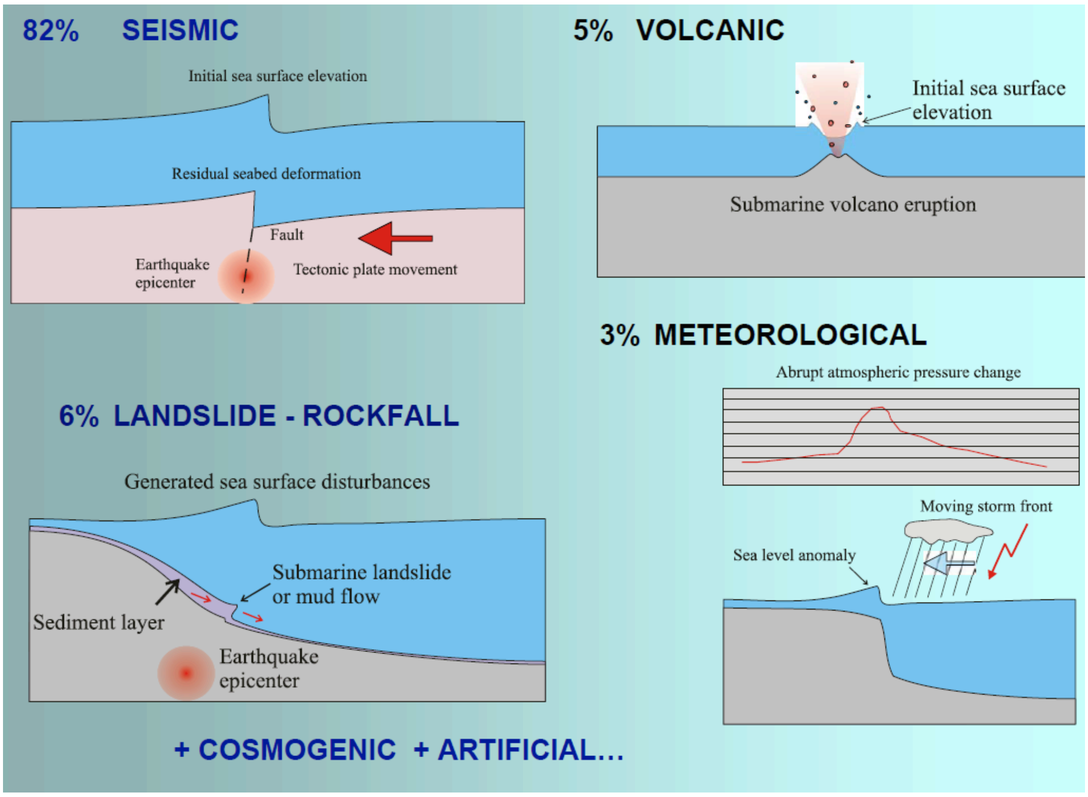

Figure 3. Tsunami generation mechanisms (Pattiaratchi, 2012).

Once energy is transmitted by the triggering impulse to the water column, a set of anomalous waves originates and starts propagating. This wave train – which in fact is a tsunami – may have wavelengths in excess of 100 km and periods of minutes to over an hour, depending on the generation mechanism (IOC, 2006). Given the relatively high ratio between the wavelength and the typical depth of ocean basins (about 4000 m), a tsunami in open-ocean behaves like a shallow-water wave and its velocity is described by the following equation:

$$V = (d \times g)^{1/2}$$

where V is the tsunami velocity in open ocean, d is the water depth and g is the acceleration of gravity ($9.8\ m/s^2$). This means that a tsunami in open-ocean can travel at about 6–700 km/h, with typical wave amplitude of 1 m at the most (IOC, 2008). As the tsunami approaches the coast, its velocity decreases (as the water depth decreases) and the wave amplitude increases (as an effect of the energy conservation principle). When impacting the shore, tsunami waves can be as high as 10 to over 30 m. Further, wave refraction, caused by segments of the wave moving at different speeds as the water depth varies, can cause extreme amplification in localised areas (IOC, 2006). Where coastal bathymetry is relatively flat compared to the wavelength, tsunami waves can break before reaching the shore. In this case, they appear as a turbulent bore with an abrupt front (Boschi & Dragoni, 1999).

3.3 AUSTRALIA AND NSW EXPOSURE TO EXTREME INUNDATIONS

Geoscience Australia (unpublished data) has estimated nationally that within 200 m of the coast, there are some 559,000 residential addresses with a replacement value $104 bn (and an additional 'contents' exposure valued at $128 bn), plus 24,000 commercial and small to medium sized industrial buildings with a replacement value of $33.5 bn, all at 'risk' to coastal hazards.

The Australian Industry Group (AIG) has estimated that more than 200,000 NSW properties are classified as at 'risk' from coastal hazards. Chen and McAneny (2006) estimated that within the Sydney basin, some 20,000 property addresses are most at risk, being located <1 km from the shoreline and at no more than 3m above sea level. Further, Pyper (2007) estimated that the value of coastal properties at risk from erosion or flooding in NSW over the next century would be about $1 bn (in 2005 prices), with this figure increasing yearly due to the growing trend in property values.

Globally climate change is expected to increase the intensity of extreme meteorological events able to cause coastal inundations, such as storm surges or storm tides (IPCC, 2012). Although tsunamis are a geological hazard and do not depend on meteorological processes, the exposure of coastal zones in the future will increase due to sea level rises.

The following sections summarise the available literature about the exposure of NSW to storm surges and tsunamis, and the expected increase in the risk of these events as a consequence of climate change.

3.3.1 Storm Surges

In eastern Australia, storm surges are normally associated with tropical cyclones or to East Coast Lows (ECLs), with the latter typically developing in middle-latitude regions, such as New South Wales. ECLs are described by Verdon-Kidd et al. (2010) as *intense low pressure systems, which occur several times a year off the east coast of Australia. They tend to form between latitudes 20°S and 40°S, often with some motion parallel to the eastern coastline of Australia. ECLs can occur at any time of the year, but tend to be more common in autumn and winter. These large-scale storms can result in gale force winds along the coast and adjacent waters, heavy rainfall leading to widespread flooding, and rough seas and prolonged heavy swells causing damage to the coastline. ECLs have a high interannual variability, with some years experiencing several ECLs while during other years only a few will develop. ECLs are responsible for approximately 16% of all heavy rainfall events and 7% of major Australian disasters [Hopkins and Holland, 1997]*. During an ECL, the increased water level associated with the storm surge overlaps with daily tidal variation, generating a storm tide (Helmann et al., 2010). The 'still' water level of a storm tide is then further increased by the action of waves, causing wave setup and wave runup.

In NSW, typical non-tidal contributions to extreme sea levels (including barometric and wind setup) with 1/1 year recurrence sum up to ~0.42 m (MHL, 2011). With regard to wave setup during storms, this can vary between 0.7 to 1.5 m (NSW Gov., 1990). The most significant contribution to temporary inundation during NSW storms comes from wave runup, which can reach 4.0 to 8.0 m above the still water level (NSW Gov., 1990). This is partly due to the characteristics of the NSW continental shelf, which is relatively narrow. Impacts of storm surges associated with ECLs on NSW coast may include (NSW SES, 2007):

a. Water damage to building contents (interior linings, furnishings, appliances, equipment and plant);

b. Possible contamination of building interior from sewage, soil and mud;

c. Undermining and/or destruction of foundations, potentially leading to structural collapse;

d. Salt spray on coastal buildings, affecting most materials' durability; and

e. Coastal erosion (in some areas likely to be severe), resulting in loss or damage to property.

According to the Australian Department of Climate Change (2009), the exposure of New South Wales to storm surges is very high. The key findings of the 2009 DCC report on Climate Change Risks to Australia's Coast – focusing on NSW – outlined that:

- *Between 40,800 and 62,400 residential buildings in New South Wales may be at risk of inundation from a sea-level rise of 1.1 m and storm tide associated with a 1/100 year storm;*
- *The current replacement value of the residential buildings at risk is between $12.4 billion and $18.7 billion;*
- *Local government areas (LGA) of Lake Macquarie, Wyong, Gosford, Wollongong, Shoalhaven and Rockdale represent over 50 per cent of the residential buildings at risk in New South Wales;*
- *New South Wales has fewer residential buildings located within 110 m of 'soft' erodible shorelines than many other states. There are approximately 3,600 residential buildings located within 110 m and 700 buildings within 55 m of 'soft' coast.*

On top of that, climate change is likely to increase the intensity of future extreme events, including East Coast Lows and associated storm surges (IPCC, 2012) (see section 3.4). Callaghan and Helman (2008) listed all the main storm events (including tropical cyclones) that have affected the east coast of Australia since 1770. Extreme sea water levels occurring in NSW have been studied by Watson and Lord (2008) (Table 8). Table 1 shows a list of the most significant ECLs that have occurred in NSW since 1850 (NSW Regional Office, 2007).

Table 1. Most recent East Coast Lows that affected NSW (NSW Regional Office, 2007, modified).

DATE	DESCRIPTION
June 2007	• Five east coast lows (ECL) occurred during June 2007 which was rare but not unprecedented, with other notable years including 1974 and 1950. During June 2007, the NSW Regional Office issued over 750 warnings including Severe Weather Warnings, Flood Warnings and Marine Wind Warnings. In terms of impacts on the NSW mainland, the first event (June 8-9) was the most serious. Offshore, the third event (June 19-20) was the most intense with a minimum central pressure of approximately 982 hPa. Fortunately the full impact of this low was not felt over land areas. • The main impacts of the June 8-9 event were: (a) nine fatalities, major flooding in the Hunter Valley, gale force winds and flash flooding in Newcastle and Central Coast; (b) The 76,000 tonne bulk ore carrier Pasha Bulker grounded on Newcastle Beach; (c) Major flooding in Paterson, Williams and Hunter Rivers; (d) Beach erosion at many Sydney beaches caused by huge swells; (e) Cremorne Wharf collapsed into Sydney Harbour due to large waves. The maximum wave height recorded at Sydney Waverider Buoy was 14.1 m at 2am Saturday. This was the highest recorded since records began in 1992; (f) Flooding and high winds caused loss of power to over 200,000 homes in Sydney-Newcastle area. • Globally in NSW more than 90,000 insurance claims were filed at an estimated cost of A$1.35bn, making the event the eighth most expensive in Australia's history (Carpenter, 2007).
10 July 2005	
22-23 March 2005	
2 October 2004	• Moderate rainfalls were recorded in the Illawarra, Central Tablelands and South Coast and isolated heavy falls over parts of the Metropolitan and Hunter districts. The highest were 132 mm at Wyong and 62 mm at Kurrajong Heights and 89 mm at Castle Cove. • Gale to storm force winds were recorded along parts of the coast. • Mean wave heights off Sydney were 5 m with around 10 m maximum wave heights and heavy swell on the 1st and 2nd of October. • Central pressure dropped 6hPa from about 1004hPa to 998hPa over the 24hr period to 10am 2 October.
27-28 July 2001	• Showers developed along the coast, with an isolated heavy fall of 91 mm at Nelson Bay on the 28th. Rainfall in Sydney area varied from 10-30 mm. • Strong southerly winds at 50-60 km/h reached gale force at times with gusts over 100 km/h in coastal Sydney. • Significant Wave height from 4 to 6 m. • An inland low-pressure trough deepened under an upper air disturbance. Central pressure dropped 16hPa from 1011hPa at 10am on the 27th to 995 at 10am on the 28th.
7-8 August 1998	• Rainfall totals over the four days (6-9 August) were greater than 300 mm at many locations in the Metropolitan and Illawarra districts. • Highest totals were 420 mm at Beaumont and 401 mm at Kangaroo Valley.
30-31 August 1996	• Central pressure dropped 12hPa in 12 hours between 9pm and 9am • Highest rainfall total 386 mm at Darkes Forest. • Cost 2 lives and caused almost $20 million damage. • Maximum wind gust was 64 knots near Wollongong.
5 August 1986	• 24 hour rainfall totals: over 300 mm in Sydney area. • Major flooding on the Nepean-Hawkesbury and Georges Rivers • Mean wind-speed up to 40 knots at Norah Head • Observatory Hill - Highest daily rainfall total on record: 328 mm.
26 May 1974 - "Sygna" storm	• Wind gusts at Newcastle Nobbys around 165 km/h. • The wreck of the Sygna, driven onshore during the storm, still lies on Stockton Beach, near Newcastle.
20 August 1857 - "Dunbar" storm	• The Dunbar, a sailing ship carrying 122 people from England, was wrecked off South Head while trying to seek shelter in Sydney Harbour. There was only one survivor.

Before the NSW Regional Office (2007), McInnes and Hubert (2001) published a list of significant tidal anomalies in Sydney and Coffs Harbour, recorded from 1966 to 1990 (Table 2, Table 3). It must be noted that the data shown in Table 2 and Table 3 represents only storm surge contributions to the increase of the mean sea level, as the effect of astronomical tides is not considered.

Table 2. Ranked tidal anomalies at Sydney for 1966–1990. In cases where the synoptic situation consists of a cut-off low, column 6 gives the approximate location of the cut-off low centre at the time of the peak surge based on daily manual weather charts from the Australian Bureau of Meteorology. The meteorological conditions reported during the surge event are shown in the last column. Definitions of wind conditions are as follows; strong breeze, 11–14 m s^{-1}; gale force wind, 17–20 m s^{-1}; and storm force wind, 24–28 m s^{-1}. Finally, (F) indicates whether floods were reported during the event. This data represents storm surge contributions to the mean sea level, and therefore are calculated by subtracting out the predicted astronomical tide heights (McInnes & Hubert, 2001).

RANK	PEAK (m)	TIME & DATE OF PEAK SURGE (EST)	DURATION (hours)	SYNOPTIC SITUATION	LOCATION OF LOW CENTRE	WIND STRENGTH FLOODS REPORTED (F)
1	0.59	0200, 26 May 1974	93	Cut-off low	157°E, 32°S	Strong to gale force (F)
2	0.54	0400, 2 June 1978	48	Cut-off low	150°E, 35°S	Gale force (F)
3	0.52	1800,10 June 1974	75	Cut-off low	162°E, 35°S	Gale force (F)
4	0.51	1200, 13 June 1966	80	Cut-off low	-	Gale force (F)
5	0.45	2300, 27 April 1990	212	Cut-off low	Not identifiable	Gale force (F)
6	0.44	0600, 21 June 1975	29	Cut-off low	154°E, 34°S	Gale to storm force (F)
7	0.43	1100, 15 June 1978	42	Cut-off low	161°E, 33°S	Gale force
8	0.40	0800, 1 May 1966	73	Front	-	Gale force
9	0.38	1100, 3 August 1990	18	Cut-off low	158°E, 33°S	Gale force (F)
10	0.38	2200, 21 May 1996	31	Cut-off low	-	Gale force (F)

Table 3. Ranked tidal anomalies at Coffs Harbour for 1971–1990 (as for Table 2) (McInnes & Hubert, 2001).

RANK	PEAK (m)	TIME & DATE OF PEAK SURGE (EST)	DURATION (hours)	SYNOPTIC SITUATION	LOCATION OF LOW CENTRE	WIND STRENGTH FLOODS REPORTED (F)
1	0.69	0100,11 June 1974	70	Cut-off low	165°E, 35°S	Strong
2	0.63	1100, 20 August 1973	17	Front	-	Strong
3	0.57	1600, 28 May 1974	48	Cut-off low	170°E, 40°S	Strong to gale force (F)

RANK	PEAK (m)	TIME & DATE OF PEAK SURGE (EST)	DURATION (hours)	SYNOPTIC SITUATION	LOCATION OF LOW CENTRE	WIND STRENGTH FLOODS REPORTED (F)
4	0.49	2200, 18 May 1977	70	Cut-off low	159ºE, 29ºS	Gale force (F)
5	0.48	2300, 1 Feb 1973	29	Front	-	-
6	0.44	1600, 15 June 1978	21	Cut-off low	162ºE, 33ºS	Gale force (F)
7	0.43	0100, 10 July 1985	56	Cut-off low	158ºE, 34ºS	Gale force (F)
8	0.42	1500, 13 June 1974	21	Cut-off low	165ºE, 35ºS	Strong
9	0.42	1800, 1 June 1978	21	Cut-off low	153ºE, 32ºS	Strong to gale force (F)
10	0.40	1000, 28 June 1977	34	Low	-	Strong
11	0.39	2000, 8 March 1990	54	Cut-off low	160ºE, 33ºS	Strong
12	0.37	1100, 21 May 1985	45	Cut-off low	165ºE, 32ºS	Strong to gale force
13	0.37	0600, 8 August 1986	18	Cut-off low	166ºE, 37ºS	Gale force (F)
14	0.35	0900, 27 March 1976	35	Cut-off low	164ºE, 38ºS	Strong to gale force
15	0.34	0900, 25 July 1971	51	Cut-off low	162ºE, 36ºS	Strong to gale force
16	0.345	0900, 2 July 1980	49	Front	-	Gale force
17	0.34	1300, 5 July 1984	29	Low	-	Gale force
18	0.34	1400, 15 Dec. 1984	42	Benign	-	-
19	0.32	0900, 21 May 1974	57	Low	-	-
20	0.32	2100, 9 August 1976	20	Cut-off low	162ºE, 35ºS	Strong
21	0.32	2200, 18 March 1977	20	Cold Front	-	-
22	0.32	0500, 27 Sept. 1987	48	Low	-	Gale to storm force
23	0.32	0300, 10 August 1988	19	Front	-	Strong to gale force
24	0.31	1200, 30 May 1979	31	Anticyclone	-	-
25	0.31	1400, 1 May 1981	30	Low	-	Strong

Interestingly, McInnes and Hubert (2001) outlined that *though the amplitudes of these residuals are relatively low compared with the storm surges that sometimes occur in tropical regions due to tropical cyclones, their duration is of the order of a day or more with the longest event lasting over nine days. Clearly, events of such duration will encounter tidal maxima, which will further elevate sea level by up to 1m, depending on the coastal location. Also, the long duration could potentially increase the likelihood of elevated sea level coinciding with floods produced by the excessive run-off, particularly if the elevated sea levels occur in the vicinity of a flooded river system.*

A detailed record of the NSW storms from 1880 to 1980 is provided by Blain et al. (1985), who reported an estimate of significant wave height (i.e. the highest one third of waves) for each event and included information on the affected coast sector (north, mid-north, central, south). The report shows that since 1880, the NSW coast has been hit by 280 storms classified as strong to extreme (i.e. with significant wave height greater than 5 m). Further, Shand et al. (2011) showed that the significant wave height (one hour exceedance) associated with the 1/100 year storm along the mid NSW coast is 9.0 m at Sydney and 9.1 m at Botany Bay. These values decrease in the north and south NSW coast, with Batemans Bay and Byron Bay exhibiting the lowest extreme heights of 7.7 and 7.6 m respectively.

3.3.2 Tsunamis

For the coast of NSW, tide-gauge records show that historically, only small tsunamis have affected the region (Dominey-Howes, 2007). Reported geological evidence however, suggests that megatsunamis many times larger than the 2004 Indian Ocean Tsunami (IOT) may have occurred repeatedly during the Holocene (the last 10,000 years of earth's history) (Bryant et al., 1992a, b; Bryant & Young, 1996; Young, et al., 1995, 1996; Nott, 1997, 2004; Bryant, 2001; Bryant & Nott, 2001).

This geological work has led to the development of what has been referred to as the 'Australian Megatsunami Hypothesis' or AMH (Goff et al., 2003). The evidence for the AMH is very controversial (Felton & Crook, 2003; Goff et al., 2003; Noormets et al., 2004). First, some of the proposed evidence for megatsunamis has clearly been incorrectly interpreted (Dominey-Howes et al., 2006). Second, there appears to be a disjunct or mismatch between the historic record of small frequent events and the Holocene record of large infrequent tsunamis (Dominey-Howes, 2007). Last, no independent verification of the sources of these events has been undertaken – a vital component for understanding risks (Dawson, 1999). Bryant (2008) however, advocates a cosmogenic source for these events although this hypothesis also remains to be proven. If the AMH can be independently validated, it has profound implications for the coastal vulnerability of NSW and government agencies.

In Australia, the only Probabilistic Tsunami Hazard Assessment (PTHA) available is the one proposed by Burbidge et al. (2008). That study associated tsunami offshore wave amplitude with its probability of occurrence, considering possible contributions from all the tectonic sources around Australia. Due to the low geographical scale of the assessment, these hazard maps are defined only at the offshore depth contour of -100m. Near-shore tsunami propagation and inland inundation are not provided. Although work is being undertaken (Garber et al., 2011), currently no PTHAs including inland inundation are available in Australia. Furthermore, it should be noted that the study by Burbidge et al. (2008) considers only earthquake-generated tsunamis and does not estimate the probability of other tsunami-genic events, such as underwater landslides.

Recently Glenn et al. (2008) confirmed the risk of tsunamis generated by submarine landslides along the NSW continental slope. In fact, a bathymetric survey carried out by Geoscience Australia along the NSW coast in 2008 provided a much better understanding of the morphology and history of the continental shelf and any associated underwater sediment slides. The survey focused on the region between Jervis Bay and Forster. Geoscience Australia's survey data revealed that the continental slope of NSW has experienced widespread underwater sediment slide failure through time even though the rate of sedimentation on the continental shelf is very low. Swath bathymetry has revealed the architecture of slope failures and the slip-plane geometry of a number of submarine mass failure sites. Sites that have failed include the Bulli (~20 km^3), Shovel (~7.97 km^3), Birubi (~2.3 km^3) and Yacaaba (~0.24 km^3) slides (Figure 4) (Glenn et al., 2008).

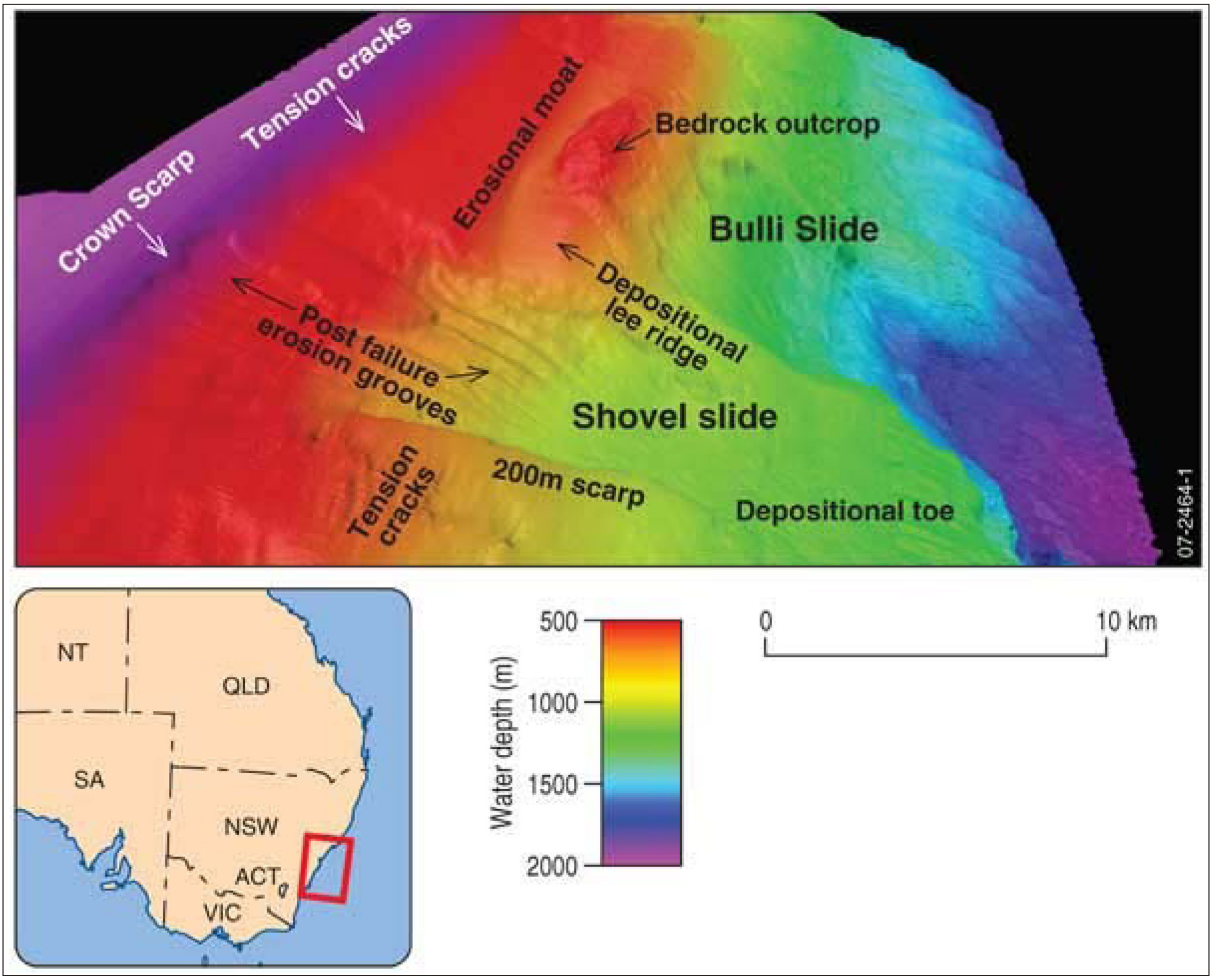

Figure 4. The slope failure architecture and slip-plane geometry of the Shovel Slide. Location of the large Bulli Slide is also indicated. Insert – the area of the NSW coast surveyed by Geoscience Australia (Glenn, 2008).

Within the Sydney area, the vulnerability to tsunamis is very high. As discussed by Dall'Osso and Dominey-Howes (2009) in the SCCG project titled *A Method for Assessing the Vulnerability of Buildings to Catastrophic (Tsunami) Marine Flooding*, a tsunami of 5m impacting the coastal zone of Manly during high astronomical tide would have the potential to inundate over 1200 buildings. However, it must be noted that Dall'Osso and Dominey-Howes (2009) did not simulate the tsunami inundation using a numerical model, but adopted a less accurate 'bathtub filling' approach. Within the present project, this issue will be addressed by adopting state-of-the-art modelling techniques simulating tsunami generation, propagation and inundation.

3.4 CLIMATE CHANGE EFFECTS ON EXTREME INUNDATIONS

The most direct effect of climate change on the risk to extreme coastal inundations is given by the expected rise of the sea level (Australia Department of Climate Change, 2009). The IPCC Fourth Assessment Report (2007) provided a range of possible future global sea level scenarios accounting for the expected changes in ocean heat content and thus ocean thermal expansion, changes in glacier mass, surface mass balance changes for the ice sheets and changes in ice-sheet flow (Figure 5).

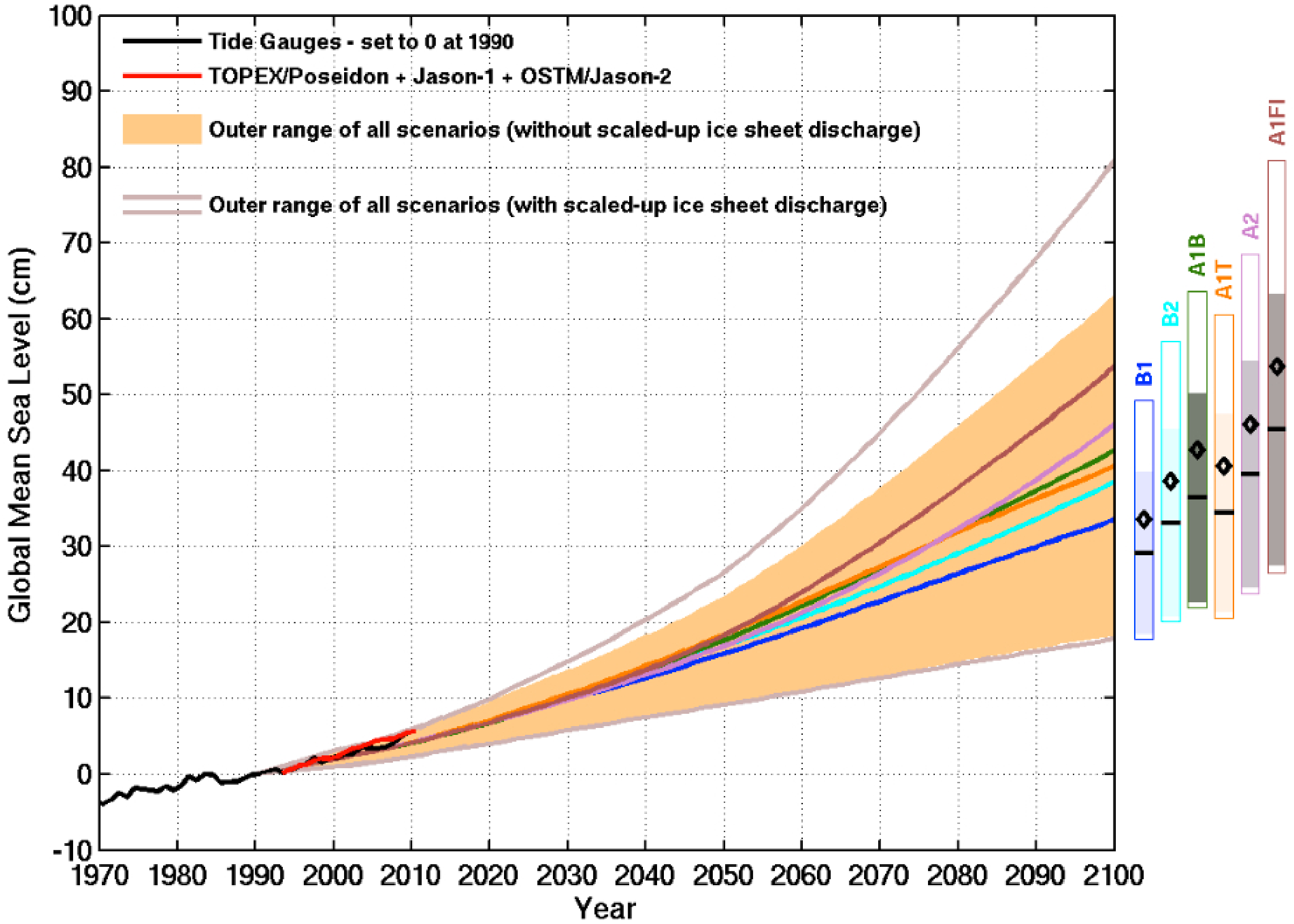

Figure 5. This figure shows projections of global-average sea-level rise for the greenhouse gas scenarios from the IPCC Special Report on Emission Scenarios (SRES) to 2100 with respect to 1990 (IPCC, 2007).

As a consequence of the rise in sea level, the frequency and intensity of extreme meteo-marine events (including storm surges) is likely to increase (IPCC, 2007), as shown in Figure 6.

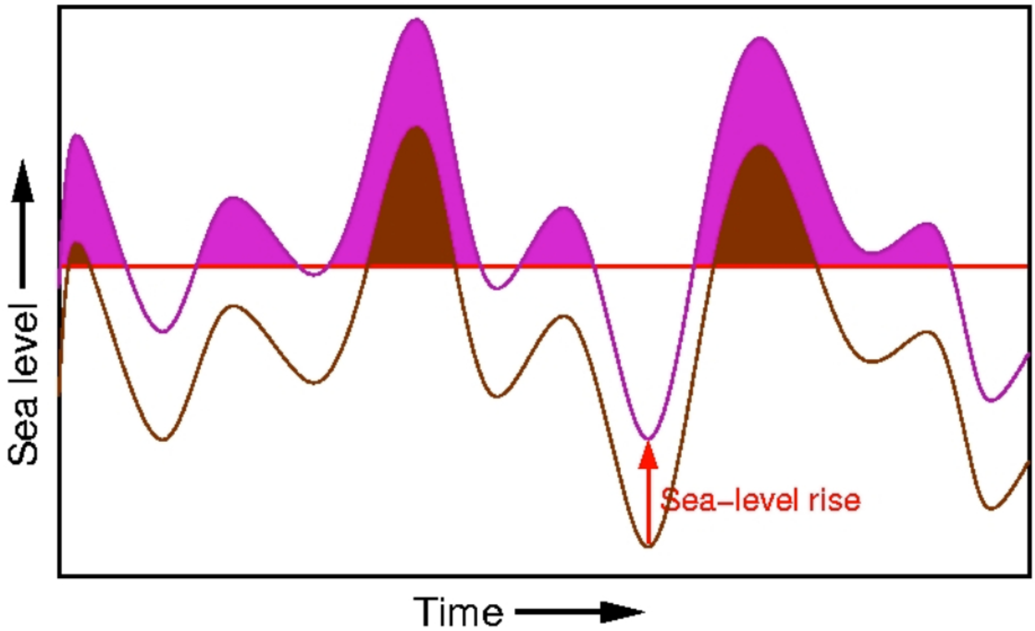

Figure 6. The effect of sea level rise on the frequency and intensity of extreme events (IPCC, 2007)

In Australia, this process has already been observed and measured by Church et al. (2006) (Table 4).

Table 4. Average Recurrence Intervals for given sea levels for the pre-1950 and post-1950 periods (Church et al., 2006).

LEVEL	FORT DENISON Average Recurrence Interval (years)		LEVEL	FORT DENISON Average Recurrence Interval (years)	
	Pre-1950	*Post-1950*		*Pre-1950*	*Post-1950*
2.1 m	1.7	0.6	**1.5 m**	1.6	0.5
2.2 m	11.4	3.4	**1.6 m**	3.7	1.4

With regard to tsunamis, since most of them are generated by geological processes such as earthquakes, there is no connection to the climate system and as such, there is no expected change in their frequency. It is however logical to assume that the same tsunami event, occurring with increased sea level, would be able to inundate further inland.

In response to the IPCC projections, the 2009 report of the Australia Department of Climate Change titled *Climate Change Risks to Australia's Coast stated that over the last 6,000–7,000 years sea level around Australia has been relatively stable, which has generally allowed current landforms and ecosystems to persist without large scale modifications. Since 1788 settlements have been built along our coast in expectation that sea level would remain broadly unchanged. Significant settlement of low-lying areas has occurred, and structures were designed and built to standards defined by a relatively narrow period of experience. Those conditions are now changing. A new climate era driven by global warming will increase risks to settlements, industries, the delivery of services and natural ecosystems within Australia's coastal zone. Scientific observations and modelling are pointing to changes in the climate system at the upper end (or above) of projections in the 2007 report of the Intergovernmental Panel on Climate Change (IPCC). The IPCC report estimated global sea-level rise of up to 79 cm by 2100 (in the worst case scenario), noting the risk that the contribution of ice sheets to sea level this century could be substantially higher.*

Different jurisdictions around Australia have adopted sea-level rise benchmarks for land use planning based on the IPCC's 2007 projections. The NSW Sea Level Rise Policy Statement (2009) has adopted SRL planning benchmarks corresponding to an increase above 1990 mean sea levels of 40 cm by 2050 and 90 cm by 2100 (Table 5).

Table 5. Components of the NSW sea level rise planning benchmarks (Department of Environment, Climate Change and Water NSW, 2008).

COMPONENT	Year 2050	Year 2100
Sea level rise	30 cm	59 cm
Accelerated ice melt	(included in above value)	20 cm
Regional sea leve rise variation	10 cm	14 cm
Rounding*	-	-3 cm
Total	40 cm	90 cm

Further, the NSW Office of Environment and Heritage (OEH), in partnership with the Climate Change Research Centre at the University of New South Wales (UNSW), has recently developed regional climate projections for NSW based on preliminary analyses of global modelling data (Department of Environment, Climate Change and Water NSW, 2010). The aim of that report was to provide a regional 'snapshot' of how the state could be affected by climate change in 2050, based on the IPCC A2 scenario (Table 6).

So far, few studies have considered the effect of climate change on the frequency and intensity of storm surges. The recent IPCC report on extreme events (IPCC, 2012) outlined that so far *trends in extreme coastal high water across the globe reflect the increases in mean sea level, suggesting that mean sea level rise rather than changes in storminess are largely contributing to this increase, and that while changes in storminess may contribute to changes in sea level extremes, the limited geographical coverage of studies to date and the uncertainties associated with storminess changes overall mean that a general assessment of the effects of storminess changes on storm surge is not possible at this time* (IPCC, 2012). Nonetheless, in Australia some analyses have already been undertaken. For example, McInnes et al. (2007) simulated the effect of climate change on future severe weather events associated with coastal erosion (future storms frequency and wave heights, surge heights and local sea level rise) at the planning horizon of 2030 and 2070, at two locations along the NSW coastline (Batemans Bay and Wooli River). The simulation was performed using two different sets of boundary conditions (CCM2 and CCM3), both derived from the IPCC A2 emission scenario. McInnes et al. says the *CCM2 simulation was nudged towards the results of the CSIRO Mark 2 GCM forced by the A2 emission scenario and the CCM3 simulation was nudged towards those of the CSIRO Mark 3 GCM also forced by the A2 emission scenario.* The expected change in the key parameters of future storms occurring at these locations are shown in Table 7 for the 2030 and 2070 planning horizons. Results of the two simulations show opposite trends: CCM3 outputs predict a significant increase of future storm frequency and intensity, while CCM2 outputs show an average decrease.

A later study undertaken by Hemer et al. (2010) attempted to assess the effect of climate change on wave climate along the east coast of Australia. For the 2081–2100 time interval, *results showed a robust decrease in mean significant wave height along the east Australian coast relative to present climate conditions. The magnitude of the projected change was relatively small (less than 0.2 m), but significant, and increased northwards along the NSW coast. A relatively small (~5°) anticlockwise rotation in mean wave direction is projected to occur over the same period.*

Watson and Lord (2008) analysed the recurrence intervals of extreme water levels based on records from the Fort Denison tide gauge, and made projections for years 2050 and 2100 accounting for the expected sea level rise in NSW (Table 8). McInnes et al. (in review) recently used that data to generate storm surge inundation maps of the Sydney area under present and future climate conditions (year 2100). This was achieved through a numerical simulation of the 1/1yr and the 1/100yr design storms, using the projected sea level benchmarks adopted by the NSW Sea Level Rise Policy Statement (2009). The simulation calculated the increased still water level along the shore and included the contribution of wave-setup. The inland inundation layer was then generated using a static bathtub-filling approach. Although this assessment has some important limitations – e.g. it did not consider the contribution of wave runup and implications of future shoreline retreat – it represents the best available attempt to assess exposure to storm surge inundation within the Sydney area.

Table 6. Expected 2050 climate change effects in the coastal regions of NSW (Department of Environment, Climate Change and Water NSW, 2010).

<table>
<tr><th></th><th></th><th colspan="2">NORTH COAST</th><th colspan="2">HUNTER</th><th colspan="2">SOUTH COAST</th></tr>
<tr><td rowspan="4">RAINFALL</td><td>Spring</td><td colspan="2">No change</td><td colspan="2">5-20% increase</td><td colspan="2">5-20% increase</td></tr>
<tr><td>Summer</td><td colspan="2">5-20% increase</td><td colspan="2">10-50% increase</td><td colspan="2">20-50% increase</td></tr>
<tr><td>Autumn</td><td colspan="2">5-10% increase</td><td colspan="2">5-10% increase</td><td colspan="2">5-10% increase</td></tr>
<tr><td>Winter</td><td colspan="2">5-10% decrease</td><td colspan="2">5-20% decrease</td><td colspan="2">20-50% decrease</td></tr>
<tr><td rowspan="4">RUNOFF</td><td>Spring</td><td colspan="2">6-9% decrease</td><td colspan="2">0-3% decrease in the NE of the region
3-6% decrease in the rest of the region</td><td colspan="2"><9% decrease</td></tr>
<tr><td>Summer</td><td colspan="2">>9% increase</td><td colspan="2">>9% increase</td><td colspan="2">>9% increase</td></tr>
<tr><td>Autumn</td><td colspan="2">0-3% increase</td><td colspan="2">3-6% increase</td><td colspan="2">3-6% increase</td></tr>
<tr><td>Winter</td><td colspan="2">3-6% decrease</td><td colspan="2">3-6% decrease</td><td colspan="2">6-9% decrease from the ACT south</td></tr>
<tr><td rowspan="3">SEA LEVEL RISE & COASTAL IMPACTS</td><td>SLR (above 1990 mean sea level)</td><td>0.4 m in 2050</td><td>0.9 m in 2100</td><td>0.4 m in 2050</td><td>0.9 m in 2100</td><td>0.4 m in 2050</td><td>0.9 m in 2100</td></tr>
<tr><td>Coastal Recession</td><td>20-40 m in 2050</td><td>45-90 m in 2100</td><td>20-40 m in 2050</td><td>45-90 m in 2100</td><td>20-40 m in 2050</td><td>45-90 m in 2100</td></tr>
<tr><td>Other Impacts</td><td colspan="2">Coastal flooding, dune erosion and soil decline are likely to increase, while saltwater from sea level rise is very likely to affect subsoils on coastal plains.</td><td colspan="2">Significant increased coastal dune erosion, increased flood risk to property and infrastructure with developments near coastal lakes, estuary entrances and on coastal floodplains. Saline intrusion.</td><td colspan="2">Inundation and saline intrusion will impact on low-lying coastal ecosystems and threaten some estuarine communities.</td></tr>
<tr><td rowspan="3">NATURAL HAZARDS</td><td>Flash Floods</td><td colspan="2">The incidence of flash flooding may increase.</td><td colspan="2">The incidence of flash flooding may increase.</td><td colspan="2">The incidence of flash flooding may increase depending on location.</td></tr>
<tr><td>Riverine Floods</td><td colspan="2">The incidence of riverine flooding is likely to increase with changing community profiles and development density and more flood-producing rain events. Exposure is expected to increase for settlements in catchments in lower coastal areas and lakes/ lagoons.</td><td colspan="2">The incidence of riverine flooding may increase. Rising sea levels and catchment-driven flooding is likely to increase flood frequency, height and extent in lower portions of coastal floodplains.</td><td colspan="2">Exposure to riverine flooding is expected to increase in settlements in lower coastal areas and around coastal lakes and lagoons.</td></tr>
<tr><td>Storm Surges</td><td colspan="2">Still-water levels will increase, wave height and period is projected to increase, and wave direction likely to change, resulting in unknown changes to shoreline recession rates. Shoreline recession due to SLR will increase.</td><td colspan="4"></td></tr>
<tr><td colspan="2">IMPACTS ON COASTAL ECOSYSTEMS</td><td colspan="2">Significant wetlands in the region that are likely to be threatened by climate change include Everlasting Swamp and freshwater wetlands in Bundjalung National Park.</td><td colspan="2">Inundation and erosion of the foredunes may impact on coastal ecosystems, such as freshwater lagoons, maritime grasslands and forested wetlands.</td><td colspan="2">Freshwater wetlands close to the coast are very likely to be completely transformed by increased salinity.</td></tr>
</table>

Table 6. Expected 2050 climate change effects in the coastal regions of NSW (Department of Environment, Climate Change and Water NSW, 2010).

		CENTRAL COAST	SYDNEY REGION	ILLAWARRA
RAINFALL	Spring	10-20% increase	5-20% increase	5-20% increase
	Summer	20-50% increase	10-50% increase	20-50% increase
	Autumn	No significant change	5-10% increase	5-10% increase
	Winter	10-20% decrease	5-20% decrease	20-50% decrease
RUNOFF	Spring	3-6% decrease	0-3% decrease in the NE of the region 3-6% decrease in the rest of the region	<9% decrease
	Summer	>9% increase	>9% increase	>9% increase
	Autumn	6-9% increase	3-6% increase	3-6% increase
	Winter	0-3% decrease	3-6% decrease	6-9% decrease from the ACT south
SEA LEVEL RISE & COASTAL IMPACTS	SLR (above 1990 mean sea level)	0.4 m in 2050 0.9 m in 2100	0.4 m in 2050 0.9 m in 2100	0.4 m in 2050 0.9 m in 2100
	Coastal Recession	20-40 m in 2050 45-90 m in 2100	20-40 m in 2050 45-90 m in 2100	20-40 m in 2050 45-90 m in 2100
	Other Impacts	Coastal flooding, dune erosion are likely to increase; saltwater is very likely to affect subsoils on coastal plains.	Coastal flooding and dune erosion are likely to increase; saltwater is very likely to affect subsoils on coastal plains.	Coastal flooding and dune erosion are likely to increase; saltwater is very likely to affect subsoils on coastal plains.
NATURAL HAZARDS	Flash Floods	The incidence of flash flooding may increase. The impact is variable depending on location, although risk is expected to increase with changing community profiles and due to sea level rise.		The incidence of flash flooding may increase and is exacerbated by the influence of the Illawarra escarpment.
	Riverine Floods	Development density and settlements around catchments will be exposed to an increased risk of riverine flooding, particularly in lower coastal areas and coastal lake/lagoon areas where ocean levels and catchment flooding will contribute to risk.		Average exposure is expected to increase for settlements around catchments in lower coastal areas, lakes and lagoons.
	Storm Surges	Residential and commercial beachfront properties and critical infrastructure, such as ports, airports and sewage works, are likely to be affected by sea level rise. Areas at risk include Collaroy, Narrabeen, North Entrance and Avoca.		
IMPACTS ON COASTAL ECOSYSTEMS		Ecosystems on foreshores are likely to be affected by coastal recession and rising waters, and other low-lying coastal ecosystems are at risk from saltwater intrusion into water tables and up-river systems.		Affected ecosystems are likely to include coastal swamp forests, coastal floodplain wetlands, wallum sand heaths, littoral rainforests, coastal heath swamps and coastal dune dry sclerophyll forest.

Table 7. Ranges of climate-change driven changes in key wave parameters simulated in Wooli and Batemans Bay for 2030 and 2070, using two different emission scenarios. The CCM2 simulation was nudged towards the results of the CSIRO Mark 2 GCM forced by the A2 emission scenario and the CCM3 simulation was nudged towards those of the CSIRO Mark 3 GCM also forced by the A2 emission scenario (McInnes, 2007).

Location	WOOLI				BATEMANS BAY			
Planning Timeframe	2030		2070		2030		2070	
Model	CCM2	CCM3	CCM2	CCM3	CCM2	CCM3	CCM2	CCM3
Changes to Swell waves from dominant direction (135° to 180° from North)								
Direction	+0.3°	-0.8°	+1.2°	+0.1°	-0.4°	0.3°	+0.1°	-0.5°
Average Hs	0%	+8%	-7%	+8%	0%	8%	-8%	+8%
Changes to Stroms from S-SE direction (135° to 180° from North)								
Frequency Of Occurrence	-8%	+13%	-20%	+48%	-6%	+28%	-23%	+41%
Hs Max Of Storms	+3%	0%	-15%	+9%	+7%	+11%	-6%	+32%
Changes to 100 year strom surge (above Mean Sea Level)								
Surge Height	-1%	+1%	-3%	+4%	-1%	+1%	-3%	+1%
Local sea level rise (SLR) above projected global average sea level rise								
Model	Mark2	Mark3	Mark2	Mark3	Mark2	Mark3	Mark2	Mark3
Variation	0	+8 cm	0	+12 cm	0	+4 cm	0	+12 cm

Table 8. Sydney Harbour extreme still water levels associated with different recurrence intervals under present and future climate conditions (Watson & Lord, 2008, as modified by McInnes et al., in review).

ARI (years)	Maximum Sea Water Level		
	2010	**2050**	**2100**
	m AHD	**m AHD**	**m AHD**
0.02	0.97	1.31	1.81
0.05	1.05	1.39	1.89
0.10	1.1	1.44	1.94
1	1.24	1.58	2.08
5	1.32	1.66	2.16
10	1.35	1.69	2.19
50	1.42	1.75	2.25
100	1.44	1.78	2.28

4. NSW POLICY FRAMEWORK ON COASTAL AND FLOOD RISK

A comprehensive summary and description of the NSW coastal risk and climate change legislation is provided by Gibbs and Hill (2011). In this section we offer a brief overview of the aspects relevant to the aims of the project. Appendix I includes a flow chart of the framework and main connections between different regulations and guidelines.

4.1 EMERGENCY MANAGEMENT AND RESPONSE

The **NSW State Emergency and Rescue Management Act 1989 (SERM Act)** establishes the legislative base for disaster management and emergency services in NSW. Namely, the SERM Act:

a. Provides a definition of 'emergency' as *an actual or imminent occurrence which endangers or threatens to endanger the safety health of persons or animals in the State or destroys or damages or threatens to destroy or damage property in the state being an emergency which requires a significant coordinated action*;

b. Sets powers and responsibilities of public authorities during emergencies, including the Minister for Police and Emergency Services, a State Emergency Operations Controller and Centre, the State Disaster Council and the State Emergency Management Committee (SEMC);

c. Provides for the preparation of a State Disaster Plan (DISPLAN).

The **NSW Disaster Plan (DISPLAN)** – prepared in 1989 and amended in July 2010 provides for the coordination of emergency response in NSW. It establishes the role, responsibilities and tasks of State, District and Local Agencies during different emergency types. With regard to flood and storms, Paragraph 116 of the NSW DISPLAN states that *Subject to the requirements and provisions of the State Emergency and Rescue Management* Act, *1989 (as amended), and under the provisions of the State Emergency Service Act, 1989 (as amended), for the emergencies of flood and damage control for storms, including the coordination of evacuation and welfare of affected communities, the overall control of operations in response to these emergencies is vested in the Director General of the State Emergency Service*. Under the NSW DISPLAN, there are a number of State Sub-Plans, addressing emergencies caused by specific hazards.

The **NSW State Storm Sub-Plan** was prepared in 2007. It provides specific indications for prevention, preparedness, warning, response and initial recovery arrangements for severe storm events occurring in NSW. For each of these services, the Storm Sub-Plan outlines the responsibilities of different agencies and organisations (Part 2). In terms of prevention, section 3.1 – Paragraph 3.1.1 states that *while it is not possible to prevent severe storms from occurring, actions to minimise risk to life and reduce property damage can be undertaken*.

Section 3.2 – Paragraph 3.2.1 states that the Local Councils have the responsibility for preparing Coastal Zone Management Plans addressing the risk of coastal erosion, while SES *will contribute on an opportunity basis to building codes related to reducing the impacts of storm phenomena on buildings, such as those included in the Building Code of Australia* (Paragraph 3.2.2). The Storm Plan includes three informative annexures respectively titled:

a. Types of severe weather and their impacts in New South Wales;

b. Some severe storm events in New South Wales history;

c. Coastal Erosion and Inundation.

The NSW State Flood Sub-Plan (released in 1989 and amended in July 2008) has the same aims and structure as the State Storm Sub-Plan. It defines the roles and responsibilities of different State agencies in the various phases of an emergency caused by a flood, including mitigation and floodplain management, preparation, warning, operation, response and first recovery arrangements. With regard to flood management, Paragraph 3.1.2 states that *the arrangements for managing flood prone land in New South Wales are detailed in the State Government's Flood Prone Lands Policy and the Floodplain Development Manual (2005) which covers floodplain management matters gazetted under the Local Government Act 1993*. However, the NSW SES will take part in the management process as it *is to be represented on relevant floodplain risk management committees established by local councils* (Paragraph 3.1.3).

In terms of flood preparation, NSW SES is responsible – among other tasks – to develop and maintain a flood intelligence system (Paragraph 4.1.2), a tool able to describe *flood behaviour and its effects on the community* (Section 4.2). Paragraph 4.2.2 specifies that *flood intelligence is obtained by gathering and assessing information, over the full range of possible flood types and severities, so that the likely effects of developing floods can be assessed. Intelligence is used to facilitate operational decision making and the provision of warnings and information to agencies and the public*. To this aim, NSW SES will develop and maintain:

a. *Information about the potential effects of flooding on communities at risk; and*

b. *Community characteristics (including the social and demographic nature of flood prone communities)* (Paragraph 4.2.4).

The **NSW Emergency Tsunami Sub-Plan** (December 2008) adopts an approach similar to the State Storm and Flood Sub-Plans, as it identifies roles and responsibilities of agencies and organisations in terms of preparedness for and response to tsunamis and the initiation of recovery coordination arrangements following a tsunami impact. The combat agency designed for tsunami emergency is the NSW SES (Paragraph 1.2.2), as tsunamis are managed as a type of flooding.

In terms of preparedness, the Tsunami Sub-Plan has a particular emphasis on community education (Section 3.2), which in the case of low-frequency and large magnitude hazards such as tsunamis is crucial. Paragraph 3.2.1 states that *education of the community is necessary so that people at-risk of tsunami can recognise the threat, know what actions should be taken in response to a tsunami warning, and know how agencies will assist them to manage the risk*. It is the responsibility of the NSW SES to develop and deliver tsunami education programs to the exposed communities (Paragraph 3.2.2).

Section 3.3 is about tsunami warning. Paragraph 3.3.1 outlines that *the official tsunami warning centre for Australia is the Joint Australian Tsunami Warning Centre*, which shall warn NSW SES in case a tsunami threat is detected. In this case, the *SES is responsible for directing the dissemination of Tsunami Watches, Tsunami Warnings, evacuation warnings and evacuation orders at Regional and Local levels* (Paragraph 3.3.2).

Section 3.6 is about evacuation planning. It firstly provides an overview of the tsunami exposure in NSW (Paragraph 3.6.1), which includes *between 250,000 and 1.5 million people, depending on tsunami magnitude, time of day and season*. Paragraph 3.6.4 states that evacuation centres will need to be located in areas *1 kilometre from the coast and above ten m above sea level*. Very importantly, for those areas that cannot be evacuated in time, *the upper floors of rigid multi-story buildings may provide refuge […]. Most homes and small buildings are not designed to withstand tsunami impact and therefore should not be used as a refuge* (Paragraph 3.6.5). It is therefore imperative to know in advance which buildings and high structures would be suitable for vertical evacuation during a tsunami alert. This information and other data required for the management of the emergency shall be stored into a *Tsunami Intelligence System, which will be complementary to its existing Flood Intelligence System. This system will manage intelligence on tsunami risk areas on the NSW coast. This system will be applied to determine areas requiring specific planning for warning and evacuation, education and operational readiness. In a response context this system will be applied to show areas needing to be warned, evacuated, monitored and restored by recovery operations.* (Paragraph 3.11.1).

Under Part 5 – 'Response' – Paragraph 5.9.1 states that *essential resources required to respond to the impacts of tsunami will be protected*. Specifically, *land and marine resources required to deal with the effects of a tsunami impact will be protected by removing them to locations outside the likely impact area* (Paragraph 5.9.3). It is therefore implicitly assumed that the extension of the tsunami impact area must be known, as well as the location and vulnerability of the buildings hosting *resources required to deal with the effects of a tsunami*.

4.2 COASTAL AND ESTUARY RISK MANAGEMENT

The **Coastal Protection Act (CP Act, 1979)** is the main coastal protection law applying to NSW coastal zones. It is administered by the Minister of Environment and the NSW Office of Environment and Heritage (OEH), and must be read in conjunction with the Environmental Planning and Assessment Act (EP&A Act, 1979). The CP Act provides the first comprehensive legal approach acknowledging the value and vulnerability of the NSW coastal zone and direction for preservation from unsustainable development and exploitation. As outlined by Gordon et al. (2011), the Act laid down the fundamental tenet that development should not adversely impact on the natural processes of the coast or be adversely affected by those processes.

With regard to the aim of this project, the CP Act is critically important as:

a. It gives an univocal geographical definition of 'coastal zone' (an area of land depicted on maps approved by the Minister), where the CP Act itself applies;

b. It enables and incentivises Councils to develop Coastal Zone Management Plans (CZM Plans) (Part 4a), that must address a set of defined key-criteria. Specifically, a CZM Plan must make provision for various matters relating to coastal protection including protecting and preserving beach environments and amenity, emergency actions carried out during periods of beach erosion, the management of risks arising from coastal hazards and the impacts from climate change on risks arising from coastal hazards (Gibbs & Hill, 2011). CZM Plans must be prepared in accordance with specific Minister's guidelines (i.e. Coastal Zone Management Guidelines, 2010).

In 2010 the CP Act was amended by the **Coastal Protection and Other Legislation Amendment Act (CPAOLA – 2010)**. This includes new provisions about coastal protection works, the creation of the NSW Coastal Panel and improved the arrangements for preparing coastal zone management plans.

The **2011 NSW Coastal Protection Regulation** was mainly introduced to support the CP Act amendments, not covered by the previous (2004) Regulation. In addition, Part 4 of the 2011 CP Regulation introduces the concept of Coastal Hazard Risk Categories: the Minister can categorise coastal land according to its vulnerability to coastal hazards. The CP Regulation details the following three Coastal Hazard Risk Categories:

1. Area currently exposed to coastal hazards;
2. Area that will be exposed to coastal hazards in 2050;
3. Area that will be exposed to coastal hazards in 2100.

The relevant CZM Plan must provide the information required by the Minister for risk zoning. The resulting risk categories have to be acknowledged when planning under the EP&A Act.

The **NSW Coastal Policy (1997)** – developed by the Department of Planning and Infrastructure – defines a broad framework for strategic planning, coastal management and protection in NSW, but does not apply to the regions of Sydney, Illawarra, Central Coast and Newcastle. The Policy aims to integrate economic growth and development with the protection of coastal resources and natural environment, through the application of sustainable development principles. The Policy requires the impacts of coastal hazards to be assessed in Coastline and Estuary Management Plans, which shall account for new insights on climate change and sea level rise, although the Policy does not contain specific instructions or procedures in this regard (Gibbs & Hill, 2011). In the preparation of Local Environmental Plans (LEPs), Councils are required to include provisions consistent with the Coastal Policy, unless justified by specific environmental studies.

Given the need for incorporating future projections on sea level rise in NSW into coastal management plans, the Department of Environment, Climate Change and Water (now the Office of Environment and Heritage) has released the **NSW Sea Level Rise (SLR) Policy Statement (2009)**. The Statement provides an overview of the Government approach to sea level rise and associated coastal risk to developed areas. Most importantly, the Statement builds upon the fourth IPCC assessment report on Climate Change (2007) and defines the NSW sea level planning benchmarks for the time horizon years of 2050 and 2100. The benchmarks set a rise relative to year 1990, of 40 cm by 2050 and 90 cm by 2100, and must be adopted for land use planning, development assessment as well as coastal and floodplain risk management in NSW.

Following the NSW SLR Policy Statement, the Office of Environment and Heritage has prepared the **Coastal Risk Management Guide (the 'Coast Guide', 2010)** and the Flood Risk Management Guide (the 'Flood Guide', 2010). The Coast and the Flood Guides contain more detailed instructions on how to implement the SLR benchmarks into coastal and flood risk assessment studies. In terms of coastal hazard assessment, the Coast Guide focuses on coastal inundation and shoreline erosion, as these will be directly exacerbated by sea level rise. The Coast Guide recommends that these studies consider long-term exposure to erosion and inundation, including the 2050 and 2100 time periods and the relevant SLR benchmarks as advised in the NSW Sea Level Rise Policy Statement (2009).

The Coast Guide notes that in addition to underlying recessionary trends (of certain shorelines), sea level rise will increase the predicted recession over the adopted planning period, resulting in a landward movement of coastal hazard areas over time. In this context, the future position of unconsolidated shorelines shall be identified using the Bruun Rule (Bruun, 1962, 1988) or more sophisticated modelling techniques accounting for the projected sea level rise. Once the future shoreline position is identified, the impact of extreme storm events on coastal building and infrastructure should be assessed in terms of the storm erosive potential (also known as 'storm bite') and the associated reduced foundation capacity of buildings, as described by Nielsen et al (1992). To this aim, future still water levels associated with extreme storm events are provided by Watson and Lord (2008). These values include the contribution of SLR in 2050 and 2100 and should be used in the areas of Sydney, Newcastle and Wollongong for both infrastructure design and coastal inundation assessments.

With regard to coastal inundation, the Guide outlines that in most instances, dunal systems along the open coastline are sufficiently elevated that episodic threat from oceanic inundation due to wave runup and overtopping of coastal dunes or barriers is negligible. Notwithstanding, the threat of oceanic inundation along the open coast in the vicinity of low-crested dunal barriers (less than 5m Australian Height Datum (AHD)) should also be considered where this is relevant. Around lower lying estuarine foreshores, the threat from tidal inundation will be significantly exacerbated with a projected rise in mean sea level. The interaction between this issue and catchment flooding is particularly important for coastal councils and has been considered in the companion document Flood Risk Management Guide – Incorporating sea level rise benchmarks in flood risk assessments (DECCW, 2010).

The Coast Guide and the NSW SLR Policy Statement are strictly connected to the **Guidelines for Preparing Coastal Zone Management Plans (2010)**. The CZMP Guidelines replaced the Coastline Management Manual (the 'Coast Manual', 1990) and the Estuary Management Manual (1992) and were prepared to support Local Councils in the drafting and implementation of CZM Plans. The guidelines state that CZMP must be based on a set of 'Coastal Management Principles' (Figure 7) that are then discussed in each section of the document.

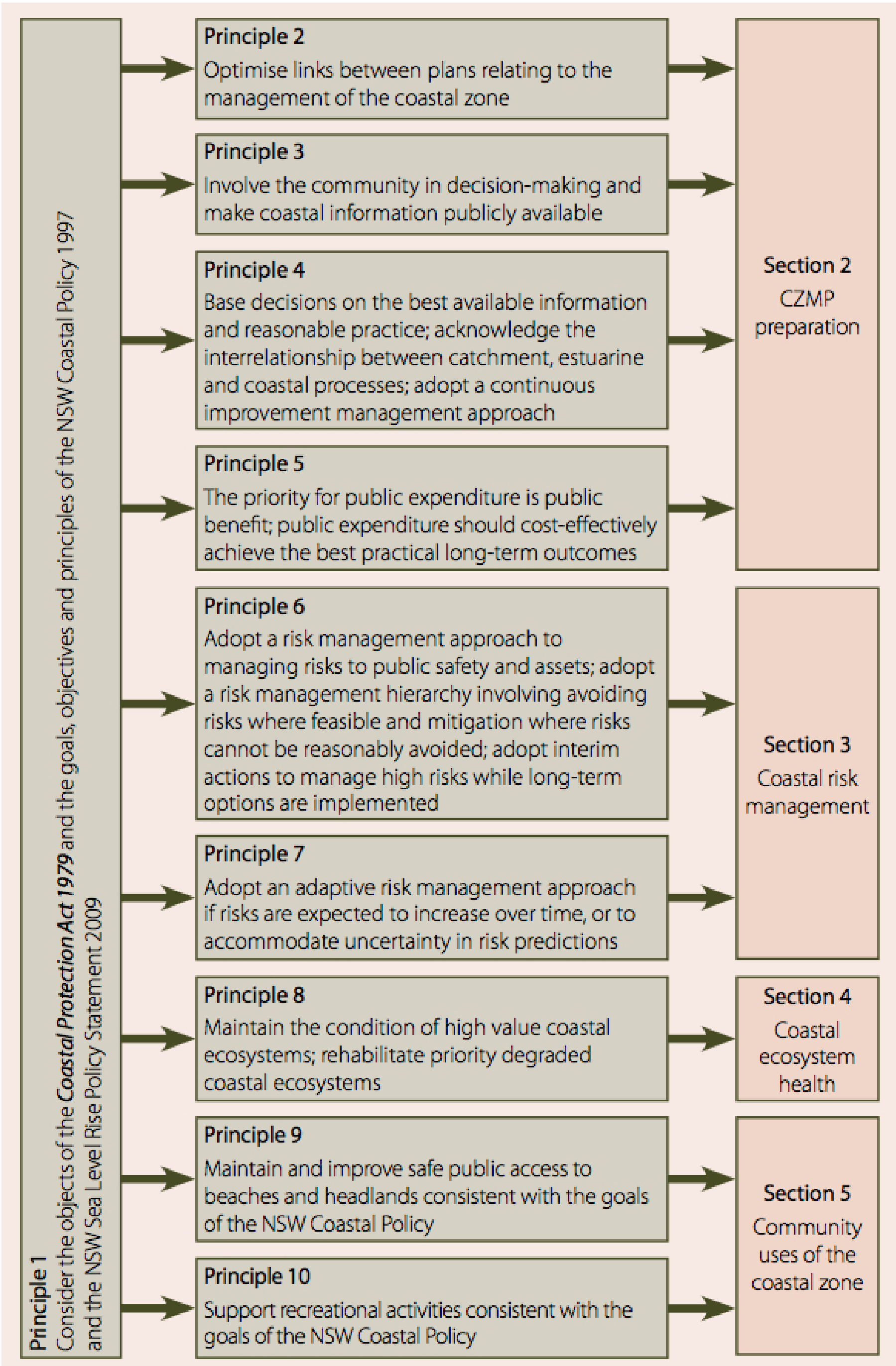

Figure 7. Coastal Management Principles for CZM Plans (NSW Government, 2010).

The CZM Plan guidelines detail the minimum requirements that CZM Plans must have in addition to those specified in the Coastal Protection Act (1979). In terms of Coastal Risk Management, these include a description of:

1. *The coastal processes within the plan's area, or at a level of detail sufficient to inform decision-making;*
2. *The nature and extent of risks to public safety and built assets from coastal hazards;*
3. *The projected climate change impacts on risks from coastal hazards. This is to include incorporation of the SLR Benchmarks from the NSW Sea Level Rise Policy Statement (2009);*
4. *Suitable locations where landowners could construct coastal protection works, subject to EP&A Act (1979);*
5. *Property risk and response categories for all properties located in coastal hazard areas.*

Section 3.2 lists a set of coastal hazards and the minimum criteria for assessing their extent (Table 9). For beach erosion, shoreline recession, coastal inundation and tidal inundation, the criteria are the same as those presented in the Coast Guide (2010) and in the Flood Guide (2010, see Section 4.3 of this report). Further, the extent of the areas exposed to each hazard should be indicated with a thematic map.

Table 9. Minimum Assessment Criteria for major Coastal Hazards (NSW Government, 2010).

HAZARD	MINIMUM ASSESSMENT CRITERIA
Beach erosion	Storm bite due to a beach erosion event with an average recurrence interval (ARI) of approximately 100 years plus an allowance for reduced building foundation capacity
Shoreline recession	Estimated recession due to sediment budget deficit and projected sea level rise*
Coastal lake or watercourse entrance instability	Qualitative assessment of entrance dynamics based on historical records*
Coastal inundation (including estuaries)	Estimate of wave run-up level and overtopping of dunes resulting from an extreme ocean strom event*
Coastal cliff or slope instability	Slpe stability assessment; see Australian Geomechanics Society (2007)*
Tidal inundation (including estuaries)	Estimate of areas inundated from still water levels with a 50 or 100 year ARI*
Erosion within estuaries caused by tidal waters, including the interaction of those waters with catchment floodwaters	Estimate of estuary foreshore erosion due to physical processes and flood events

*Assess under current conditions and projected 2050 and 2100 conditions.

In addition to the hazards listed in Table 9, Section 3.3 outlines that *a CZMP may address other risks to public safety or built assets or the environment in the coastal zone if actions are proposed by council or a public authority to reduce these risks over the CZMP's implementation period. These additional coastal risks may include […] tsunami impacts.*

The CZM Plans Guidelines define the procedure through which CZM Plans are submitted to the Minister of Environment for certification under the CP Act. Upon approval and gazettal by the Minister, the CZM Plan becomes a statutory plan enforceable by legislation. As outlined by Lord et al. (2006), *Council will merely need to establish that an activity or use is or is not in accordance with the gazetted plan. To act other than in accordance with a properly formulated and gazetted plan is an offence under the provisions of the CP Act.* Further benefits for Councils of having a gazetted CZM Plan would include (Lord et al, 2006):

- *The CZM Plan satisfies the requirements of Section 733 of the Local Government Act 1993 granting Council exculpation from liability having prepared and enacted a plan in accordance with the prescribed manual;*
- *Activities leading to the formulation and gazettal of a coastal zone management plan and activities which accord with the recommendations of a gazetted plan will be prioritised by the NSW Government for funding through the Coastal and Estuary Management Programs.*

4.3 FLOODPLAIN RISK MANAGEMENT

The NSW policy frameworks of flood and coastal risk management are in some measure symmetrical (Appendix I). At the local level, flood risk is addressed by **Floodplain Risk Management Plans (FRM Plans)** that are to be prepared by Councils as advised by the **Floodplain Development Manual** (the 'Flood Manual', 2005). The equivalent of the Flood Manual in the field of coastal risk management was the Coast Management Manual (1990), replaced by the CZMP Guidelines in 2010.

The Flood Manual aims to reduce the flood impact on exposed private and public assets by promoting a sustainable use of flood-prone land. Local Councils have the responsibility for mitigating future flood risk through the preparation and implementation of FRM Plans. Similar to CZM Plans, FRM Plans must incorporate the outcomes of specific hazard studies, assessing flood risk under present and future climate conditions. Outcomes of the FRM Plans – such as floodplain zoning – must be considered by Councils when planning under the EP&A Act.

The Flood Manual was integrated in 2007 by the **Floodplain Development Manual – Practical Consideration on Climate Change** (the '2007 Flood Guidelines'). The 2007 Flood Guidelines provide support to Local Councils on how to incorporate SLR Benchmarks into flood risk assessment studies and FRM Plans. The guidelines recommend including in the FRM Plans a vulnerability assessment of present and future development options. They apply to areas where the SLR Benchmarks are likely to have an impact on predicted flood levels, such as tidal waterways and lagoons (Gibbs & Hill, 2008). The Flood Guide recommends that flood risk assessment studies *should be undertaken using the 2050 and 2100 sea level rise planning benchmarks and should be based upon the predicted extent of the 1% AEP flood level (corresponding to 1/100 years ARI), incorporating the relevant sea level rise planning benchmark plus an appropriate freeboard (as used in the derivation of the flood planning level, such as 0.5 m).*

4.4 Strategic Planning and Development Assessment

The main regulatory instrument governing NSW planning and development assessment is the **Environmental Planning and Assessment Act** (EP&A Act, 1979). The Act is administered by the NSW Department of Planning and Infrastructure. The EP&A Act allows two types of environmental plans to be made:

1. **State Environment Planning Policies (SEPPs);**
2. **Local Environmental Plans (LEPs).**

Collectively, these plans are called Environmental Planning Instruments (EPIs). EPIs define the circumstances under which a specific type of land development is permissible, according to the characteristics of the interested land. Specifically, SEPPs are prepared for addressing development issues on a State-wide basis. For example, **SEPP 71 – Coastal Protection** seeks to protect NSW coast by requiring Local Councils to consider the impact of coastal hazards when preparing LEPs and assessing development in coastal zones, plus informing the Director General of Planning about new development applications in the coastal zone. Another relevant example is the **Infrastructure SEPP (ISEPP, 2007)**, that *assists the NSW Government, local councils and the communities they support by simplifying the process for providing infrastructure in areas such as education, hospitals, roads, railways, emergency services, water supply and electricity delivery* (http://www.planning.nsw.gov.au/infrastructure). Specifically, Section 8 of the ISEPP contains planning provisions for emergency services facilities, including: (1) the Ambulance Service of NSW; (2) NSW Fire Brigades; (3) NSW Rural Fire Service; (4) NSW Police Force; (5) State Emergency Services; (6) NSW Volunteer Rescue Association; (7) NSW Mines Rescue Brigade; and (8) an accredited rescue unit (within the meaning of the State Emergency and Rescue Management Act 1989).

LEPs regulate development issues at the Local Council-scale. This is achieved through the introduction of a specific land-use classification, allowing different development types for different classes of land. Local Councils can also prepare **Development Control Plans (DCPs)**, to define more detailed planning requirements in particular areas.

Further, the Minister of Planning and Infrastructure has power to make specific directions to Councils under **Section 117 of the EP&A Act**. For example, Ministerial **direction 2.2 (Coastal Protection)** under Section 117 requires LEPs applying to the coastal zone to be consistent with the NSW Coastal Policy, the Coastal Design Guidelines (2003) and the Coast Manual, now superseded by the CZMP Guidelines (2010). Similarly, **direction 4.3 (Flood Prone Land)** requires that LEPs are consistent with the NSW Flood Manual (2005) and the NSW Flood-Prone Land Policy.

Importantly, when planning in coastal areas under the EP&A Act, Local Councils are afforded certain protection under **Section 733 of the NSW Local Government Act**. Councils are not liable for 'anything done or omitted' in relation to the occurrence of coastal hazards or floods, provided that they acted in 'good faith'. Councils are taken, unless proven otherwise, to have acted 'in good faith' if they followed the CZMP Guidelines and the Flood Manual, as applicable. Thus, for example, LEPs must account for the coastal risk zoning made under the 2011 NSW Coastal Regulation, as well as for floodplain zoning defined within FRM Plans.

The **'Coastal Planning Guideline: Adapting to Sea Level Rise'** (2010) provides further guidance to Local Councils on how to implement sea level rise benchmarks (provided in the NSW Sea Level Rise Policy Statement, 2009) and coastal risk into strategic planning and development assessment. The guideline applies to all coastal areas in NSW and considers three main hazards:

1. Erosion, including the effect of extreme storm events ('storm bite');
2. Tidal Inundation, defined as 'flooding of land by tidal waters';
3. Coastal flooding, defined as 'catchment-related flooding of coastal areas'.

The guideline is divided into three main sections:

Section 1 – Identifying Coastal Risk Areas;

Section 2 – Strategic and Statutory Land Use Planning;

Section 3 – Development Assessment.

For every section, the guideline introduces two 'coastal planning principles' to be considered by Local Councils when planning in coastal zones (Figure 8).

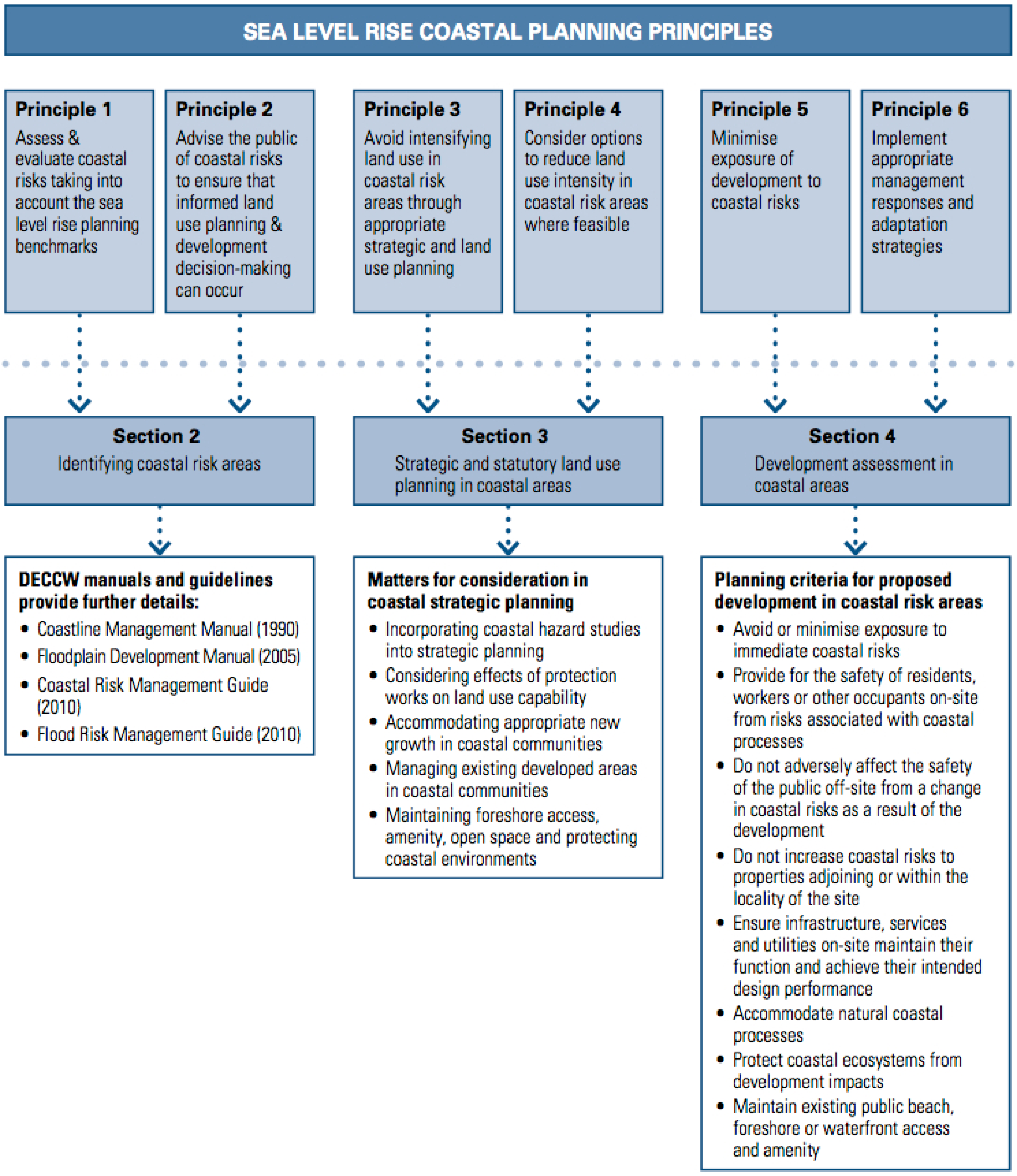

Figure 8. Coastal Planning Principles defined by the Coastal Planning Guideline (2010).

With regard to coastal and flood hazard assessment studies, the guidelines make extensive reference to the Coast Guide (2010) and the Flood Guide (2010), as well as to the Coast Manual (1990) and Flood Manual (2005), emphasising the need to account for SLR benchmarks for 2050 and 2100 in the definition of coastal and flood 'hazard lines'.

In terms of the vulnerability of buildings and infrastructure, Section 4 outlines the need to *provide for the safety of residents, workers or other occupants on-site from risks associated with coastal processes*. Although efforts are underway, in Australia there are no specific housing design standards for buildings exposed to storm surges and storm tides. The **Australian Building Codes Board** currently has recently developed a draft technical standard for the construction of buildings in flood prone areas, but the performance requirements are not applicable *to areas subject to storm surge, coastal erosion, landslip or mudslide* (Australian Government and States and Territories of Australia, 2012). In order to fill this lack of guidelines, Local Councils have to undertake specific development assessments or building vulnerability studies.

4.5 THE NSW LOCAL GOVERNMENT ACT (1993) AND COUNCILS' LIABILITY

Under **Section 733 of the NSW Local Government Act (1993)**, Local Councils are immune from liability for planning decisions under the EP&A Act, drafting CZM Plans and undertaking any type of coastal hazard or flood hazard study, as long as this is done in good faith. The NSW Local Government Act (1993) is the main regulatory instrument at the local level. It serves as an administrative and structural reference for councils. The Act provides a wide set of indications on councils' administration, financial issues, legal powers, internal rules and procedures. Section 733 of the Act provides Councils with statutory immunity from liability in respect of any advice furnished in 'good faith', or anything done or omitted in good faith, relating to the likelihood of any land being:

a. Flooded, or about the nature or extant of any such flooding;

b. Affected by a coastline hazard (as defined in the Coast Manual), or about the nature and extent of any such hazard.

In terms of coastal and flood risk, Section 733 applies to:

a. The preparation of an environmental planning instrument under the EP&A Act (1979);

b. The preparation or making of a Coastal Zone Management Plan, under the Coastal Protection Act (1979);

c. Certificates under Section 149 and the EP&A Act (1979);

d. The carrying out of flood or coastal mitigation works;

e. The provision of information relating to climate change or sea level rise.

Subsection 4 provides a definition of when a Council is considered to have acted in 'good faith': *without limiting any other circumstances in which a council may have acted in good faith, a council is, unless the contrary is proved, taken to have acted in good faith for the purposes of this section if the advice was furnished, or the thing was done or omitted to be done, substantially in accordance with the principles contained in the relevant manual most recently notified under Subsection (5) at that time.*

Subsection 5 states that the manuals must be published in the Gazette and include: (a) a manual relating to the management of flood-liable land (i.e. the Flood Manual); (b) a manual relating to the management of the coastline (i.e. the Coast Manual).

4.6 CLIMATE-CHANGE ADAPTATION IN NSW LOCAL COUNCILS

Section 733 of the NSW Local Government Act was introduced among other reasons, to act as an incentive to Councils for developing coastal and flood hazard assessment studies, or sea level rise adaptation programs. However, in NSW there are few statutory obligations on Councils to address climate change. According to Morrison et al. (2009), NSW Councils have significant discretion in deciding to undertake any adaptive activity on sea level rise or climate change, and this discretion has created confusion. In 2008, the Environment Defenders Office (EDO) report *Coastal Councils and Planning for Climate Change: an Assessment of Australian and NSW Legislation and Government Policy Provisions Relating to Climate Change Relevant to Regional and Metropolitan Coastal Councils* (EDO, 2008) underlined the critical need of Local Councils for further guidance and legislative reform on climate change. Since 2009 the NSW Government has released the Sea Level Rise Policy Statement (2009), the Coastal Risk Management Guide (2010), the Flood Risk Management Guide (2010), the Guidelines for CZM Plans (2010) and the NSW Coastal Protection Regulation (2011).

Today, the degree of commitment by Councils to undertake climate change adaptation activities has significantly increased. According to the Local Government and Shires Association (LGSA, 2010), in 2010 about 72% of NSW Councils had already started or completed at least one climate change risk assessment study. The Australian Climate Change Adaptation Research Network for Settlements and Infrastructure (ACCARNSI) is currently leading a project 'Enhancing The Effective Use Of Climate Change Adaptation Tools: A Local Government Research Initiative'. The project aims to evaluate the implementation of the available climate-change guidelines and tools in Australia LGAs, and is divided in to three 'research stages':

1. Stage 1 is described in Booth and Cox (2012a). It includes the design of a 'Reporting Template' to gather local case studies and statewide synopses on how local governments have used climate change adaptation tools. Results included a 'Portfolio of Case Studies and Synopses' (Booth & Cox, 2012b), describing the data obtained in 16 case studies and 4 statewide synopses;
2. Stage 2 used findings from the Case Studies Report (Stage 1) to design and undertake a nationwide online survey of councils and regional organisation of councils (Booth & Cox, 2012c);
3. Stage 3 (on-going) will summarise key learnings of Stage 1 and Stage 2 and generate a 'Decision Support Guide' to help local councils select the climate adaptation tool most suitable for their needs.

Interestingly, the Stage 1 Final Report (Booth & Cox, 2012a) outlined that the 'critical success factors' for Local Councils in the implementation of the available climate change adaptation tools are: (a) the ability to update data in 'living documents', that can be modified as new information becomes available; (b) the leaders commitment to incorporate the tools' outputs into a long-term Strategic Plan; and (c) the good use of scenarios and visual modelling tools (for example maps or videos) at community and stakeholder meetings. In NSW, during Stage 1 the following case studies were gathered and analysed:

1. Synopsis of adaptation tools and processes (Local Government and Shires Association of NSW (LGSA, 2010);
2. Clarence Valley Council undertook a corporate risk assessment through a set of workshops facilitated by an external consulting company (Echelon);
3. Gosford City Council developed its own 'Business Case' for managing climate change adaptation;
4. Sutherland Shire Council participated in the Sydney Coastal Council Group project named 'Systems Approach to Regional Climate Change Adaptation Strategies in Metropolises' (SCCG 2008).

In these studies, the most frequently used climate change adaptation tools were:

1. The Australian and New Zealand Standard for Risk Management AS/NZS ISO31000 (2009);
2. The Australian Greenhouse Office guidelines (AGO, 2006);
3. The LGSA Climate Change Action Planning for Local Government Workshop Package (LGSA, 2011);
4. The ICLEI Local Government Climate Change Adaptation Toolkit (ICLEI, 2008);
5. The Guide to Climate Change Risk Assessment for NSW Local Government (OEH, 2011).

At the national level, results of the survey carried out by ACCARNSI in Stage 2 outlined that in most cases, rather than specific documents or guidelines, Australia LGAs used a variety of built-for-purpose or professionally integrated tools, such as Regional Adaptation Plans, Decision Support Systems or specific studies carried out by external consultants. Nonetheless, a number of LGAs referred to the AS/NZS ISO31000 (2009), to the AGO guidelines (2006) or to Climate Change Adaptation Actions for Local Government (DCC, 2009).

4.7 RELEVANCE OF THE PROJECT TO THE NSW POLICY ON COASTAL INUNDATION

The COVERMAR methodology has been designed with the relevant NSW standards, guidelines and regulations (summarised below) in mind. Project outputs will inform, at the local and state level, many of the considerations outlined in the legislation, regulatory and policy instruments, as described in Table 10.

Table 10. Contribution of COVERMAR outputs to the application/implementation of existing NSW regulations and guidelines.

	REFERENCE	COVERMAR CONTRIBUTION
EMERGENCY MANAGEMENT	NSW STATE STORM SUB-PLAN	COVERMAR storm surge exposure and vulnerability maps will clearly show: (a) the extension of the inundation for the selected storm scenarios (in present and future – year 2100 – climate conditions); (b) the expected maximum water depth; and (c) the degree of vulnerability of the buildings or infrastructure that would be inundated, or that could suffer structural damage due to coastal erosion. This will help NSW SES identify critical areas, assess evacuation plans and undertake actions to minimise risk to life and reduce property damage (Section 3.1 – Paragraph 3.1.1). The maps will also support NSW SES by contributing on an opportunity basis to ***building codes*** *related to reducing the impacts of storm phenomena on buildings, such as those included in the Building Code of Australia* (Section 3.2, Paragraph 3.2.2).
EMERGENCY MANAGEMENT	NSW STATE FLOOD SUB-PLAN	In estuary areas, COVERMAR exposure and vulnerability maps will provide NSW SES with information to assist the updating of flood emergency plans and in developing/updating the related ***flood intelligence system***, as required at Paragraph 4.1.2. The information stored and organised within the **COVERMAR GIS database** that can be added to the intelligence system are: a high resolution digital elevation model (showing topographic elevations across the study area), the expected maximum inundation depth for the selected storm scenarios, the location, shape, orientation and main engineering characteristics of every existing building and infrastructure, including their vulnerability to tidal inundation and/or coastal erosion.
EMERGENCY MANAGEMENT	NSW EMERGENCY TSUNAMI SUB-PLAN	COVERMAR tsunami exposure and vulnerability maps will clearly show: (a) the extension of the inundation for the selected tsunami scenario (in present and future – year 2100 – sea level conditions); (b) the expected maximum water depth; and (c) the degree of vulnerability of single buildings or infrastructure that would be inundated. This high-resolution information will contribute to updating/improving the existing tsunami emergency and evacuation plans. COVERMAR outputs, including maps and tsunami simulation outputs (ex. wave propagation/inundation videos), will be suitable for use as visual aids for **education activities** that NSW SES may undertake to raise public awareness of tsunami risk (Section 3.2, Paragraph 3.2.2). Most importantly, tsunami exposure and vulnerability maps will show which buildings would safely resist the selected scenarios and which of them would be suitable for **vertical evacuation** (Section 3.6, Paragraph 3.6.5). The COVERMAR GIS database, including detailed data on coastal topography, expected tsunami inundation depth and engineering attributes of single buildings and infrastructure, could easily be used to develop/update the ***tsunami intelligence system***, as required at Section 3.6, Paragraph 3.11.11. Finally, COVERMAR vulnerability maps will include information on the 'type' and the 'use' of every building exposed to the tsunami, other than its physical attributes and vulnerability level. This will assist NSW SES to identify and protect the *essential resources required to respond to the impacts of tsunami*, including for example health services buildings (hospitals, nursing homes, ambulance stations, etc.), police stations, strategic utilities, public transport. (Paragraph 5.9.1).

COSTAL FLOODPLAN RISK MANAGEMENT	REFERENCE	COVERMAR CONTRIBUTION
	NSW COASTAL PROTECTION ACT (1979)	COVERMAR methodology is consistent with the indications and guidelines provided in the CP Act, particularly with those concerning the requirements that CZM Plans must include.
	NSW COASTAL PROTECTION REGULATION (2011)	COVERMAR outputs, including exposure and vulnerability maps, will provide critical information to assist identify and map the ***Coastal Hazard Risk Categories*** (Part 4) in present conditions (areas currently exposed to coastal hazards) and in year 2100 (areas that will be exposed to coastal hazards in 2100)
	NSW SLR POLICY STATEMENT (2009)	All COVERMAR inundation scenarios will implement the suggested NSW Sea Level Rise Benchmarks for year 2100 (+90 cm with respect to the 1990 sea level).
	NSW COASTAL RISK MANAGEMENT GUIDE (2010 COAST GUIDE)	COVERMAR methodology for assessing building vulnerability to storm surges is guided by the 2010 Coast Guide, including the identification of dune stability zones for building foundations. Section 733 of the NSW Local Government Act, may afford exemption from liability to Local Councils adopting the COVERMAR approach for storm surge vulnerability assessment studies.
	COASTAL ZONE MANAGEMENT PLANS	The COVERMAR approach is consistent with the CZMP Guidelines regarding Coastal Risk Management. COVERMAR will inform: *(a) coastal processes within the plan's area, or at a level of detail sufficient to inform decision-making; (b) the nature and extent of risks to public safety and built assets from coastal hazards; (c) the projected climate change impacts on risks from coastal hazards.* Further, COVERMAR will meet all **the minimum assessment** criteria that coastal hazard studies, addressing beach erosion, shoreline recession, coastal inundation and tidal inundation, must adhere to for consideration in Coastal Zone Management Plans (Section 3.2). In addition, COVERMAR will produce **exposure maps** showing the extent of the above-mentioned hazards in the selected case scenarios, as explicitly recommended by the CZMP Guidelines. The CZMP Guidelines do not include tsunamis in the list of those coastal hazards that must be assessed within CZM Plans. However, Section 3.3 outlines that *a CZMP may address other risks* (including tsunamis) *to public safety or built assets or the environment in the coastal zone if actions are proposed by council or a public authority to reduce these risks*. In terms of **tsunami risk reduction measures**, COVERMAR will identify tsunami-safe areas and buildings suitable for vertical evacuation. This information could be easily incorporated into the existing tsunami emergency plans and the tsunami intelligence system (see the NSW Tsunami Emergency Sub-Plan).

	REFERENCE	COVERMAR CONTRIBUTION
FLOODPLAN MANAGEMENT	NSW FLOOD RISK MANAGEMENT GUIDE (2010 FLOOD GUIDE) & FLOODPLAIN MANAGEMENT PLANS	COVERMAR will address the risk of river flood **only when this is due to storm surges causing tidal inundation along river estuaries.** In this regard, the COVERMAR approach will be consistent with the relevant indications contained in the 2010 Flood Guide, and: (a) The study will account for the 2100 sea level rise planning benchmark plus an appropriate freeboard; (b) The inundation scenarios will be based upon the predicted extent of a flood scenario with 1/100 years ARI
PLANNING AND DEVELOPMENT ASSESSMENT	SEPP 71 – COASTAL PROTECTION DIRECTION 2.2 UNDER SECTION 117 OF THE EP&A ACT	SEPP 71 requires Local Council to consider the impact of coastal hazards when preparing LEPs or assessing development in coastal zones. Ministerial Direction 2.2 (Coastal Protection) under Section 117 requires LEPs applying to the coastal zone to be consistent with the NSW Coastal Policy, the Coastal Design Guidelines (2003) and the Coast Manual, superseded by the CZMP Guidelines (2010). By reason of the use of a GIS approach, COVERMAR outputs (vulnerability and exposure maps, GIS database) will provide new geographic information that can be easily fed into strategic planning and development assessment. Further, the COVERMAR approach is consistent with all NSW Policy and Regulations mentioned in Direction 2.2.
	COASTAL PLANNING GUIDELINE: ADAPTING TO SEA LEVEL RISE (2010)	The COVERMAR methodology is consistent with the 2010 NSW Coastal Planning Guidelines. Project outputs will assist the application of each of the six Sea Level Rise Coastal Planning Principles. Specifically, COVERMAR will: (a) assess and evaluate specific coastal risks taking into account the sea level rise planning benchmarks (Principle 1); (b) generate self-explanatory exposure and vulnerability maps, that could be used to support any education and dissemination activity to advise the public of coastal risks to ensure that informed land use planning & development decision making can occur (Principle 2); (c) support coastal planners decisions about land use intensification/reduction (Principles 3 and 4) and help them minimising exposure to coastal risks (Principle 5); (d) provide recommendations for appropriate management responses and adaptation strategies (Principle 6).

5. REVIEW OF METHODS FOR ASSESSING THE VULNERABILITY OF BUILDINGS AND INFRASTRUCTURE TO EXTREME INUNDATIONS

Given the significant physical differences between possible sources of extreme inundation events, methods for assessing the vulnerability of coastal assets have developed independently. Existing approaches range from a basic identification of different risk zones to more complex tools accounting also for the physical and engineering characteristics of the exposed structures, such as fragility curves. There is however, an increasing need to compare different methods and develop comprehensive multi-hazard tools (IPCC, 2012). The following sections provide an overview of available state of the art methods, divided by the relevant hazard type.

5.1 STORM SURGES AND STORM TIDES

Storm surges (or storm tides) can affect coastal buildings and infrastructure through the following attack processes:

a. A short-term increased erosion rate caused by storm waves (**'storm bite'**). Storm bite can lead to a reduced foundation capacity for those buildings located on top of sand dunes or unconsolidated coastal soil;

b. Flooding of buildings in low lying areas, caused by:

  - **Foreshore inundation**, caused by breaching or overtopping of the dune system or coastal protection, and
  - **Tidal inundation**, as overbank flows along estuaries and tidal waterways.

The expected damage to coastal assets is therefore dependent on how their physical/engineering attributes (i.e. construction material, foundation type, and the like) react to different storm attack processes.

Wave runup does not contribute to the overall still water level, as waves are transitory. However, during a storm tide, waves developing on top of an increased still water level can cause significant damage to onshore infrastructure and buildings.

5.1.1 Methods for Assessing the Vulnerability to 'Storm Bite'

In NSW, as well as in many wave-dominated coastal areas around the world, most of the damage caused by extreme storms to coastal buildings results from the undermining of their foundations due to wave scour, rather than from foreshore inundation or direct wave impact (Nielsen et al., 1992). In this case, the most widely used approach for assessing building vulnerability is the one proposed by Nielsen et al. (1992). This is also described in the NSW Coastal Risk Management Guide (2010), which recommends applying it in conjunction with the projected sea level benchmarks for 2050 and 2100.

According to Nielsen et al. (1992), in the case of 'storm bite' the factors affecting the vulnerability of coastal buildings are: (a) the nature of foreshore materials (consolidated or unconsolidated soils); and (b) the type of building foundations and their loadings. The proposed method is based on the identification of *different stability zones* along the coastal dune system (this is named 'stability analysis'). The boundaries of the stability zones will depend on the intensity of a selected design storm scenario. Dune stability zones are schematically represented in Figure 9 and include:

1. *The Zone of Wave Impact,* where any structure would be subject to wave attack during the selected design storm event;
2. *The Zone of Slope Adjustment*, including the seaward face of the coastal dune that would slump to its natural angle of repose following sand removal by wave erosion at the base of the dune. Note that in the NSW Coastal Risk Management Guide (2010), the zones of wave impact and slope adjustment are grouped into the '**Immediate Hazard Area**' (Figure 10);
3. *The Zone of Reduced Foundation Capacity*, where building foundation would experience a reduced soil bearing capacity due to sand erosion and slump occurring in the adjoining immediate hazard area;
4. *The Stable Foundation Zone*, where no reduced capacity is expected.

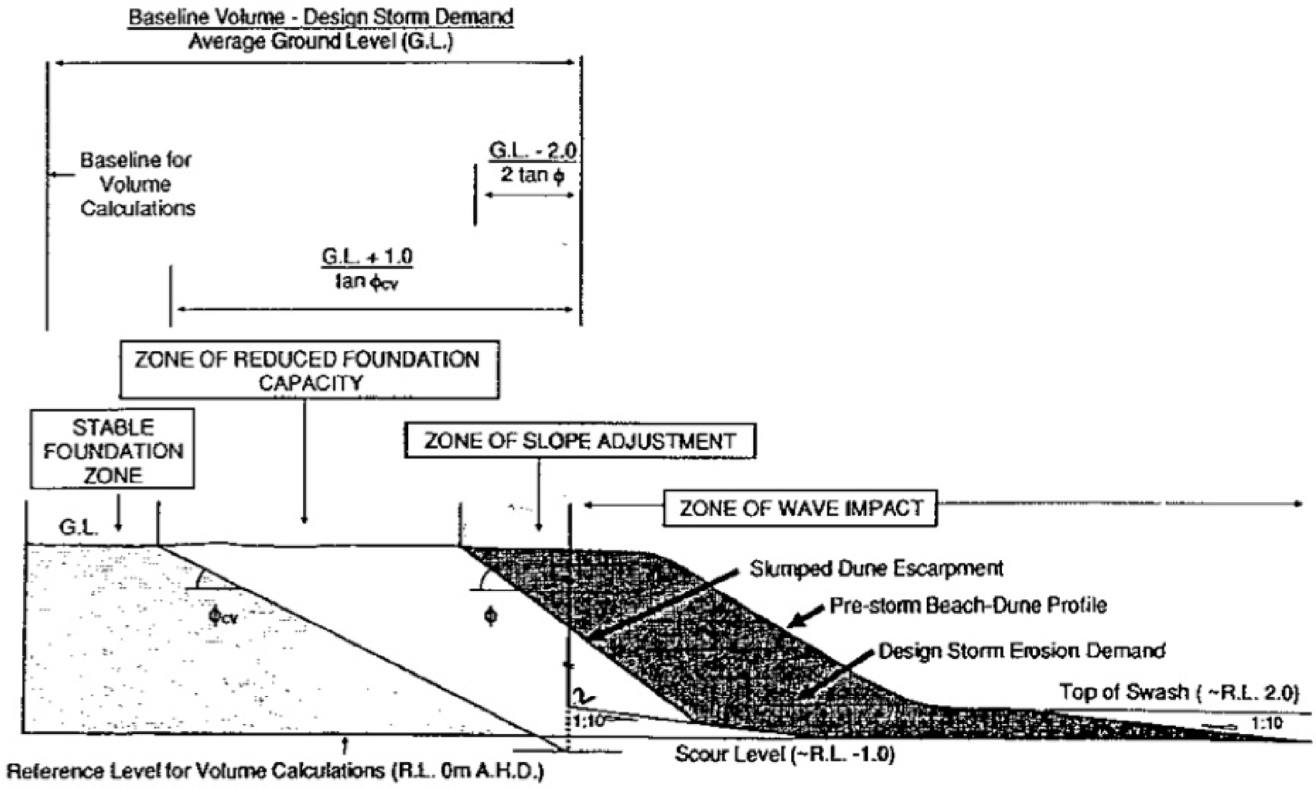

Figure 9. Dune stability schema and risk zones for a selected design storm event (Nielsen et al., 1992).

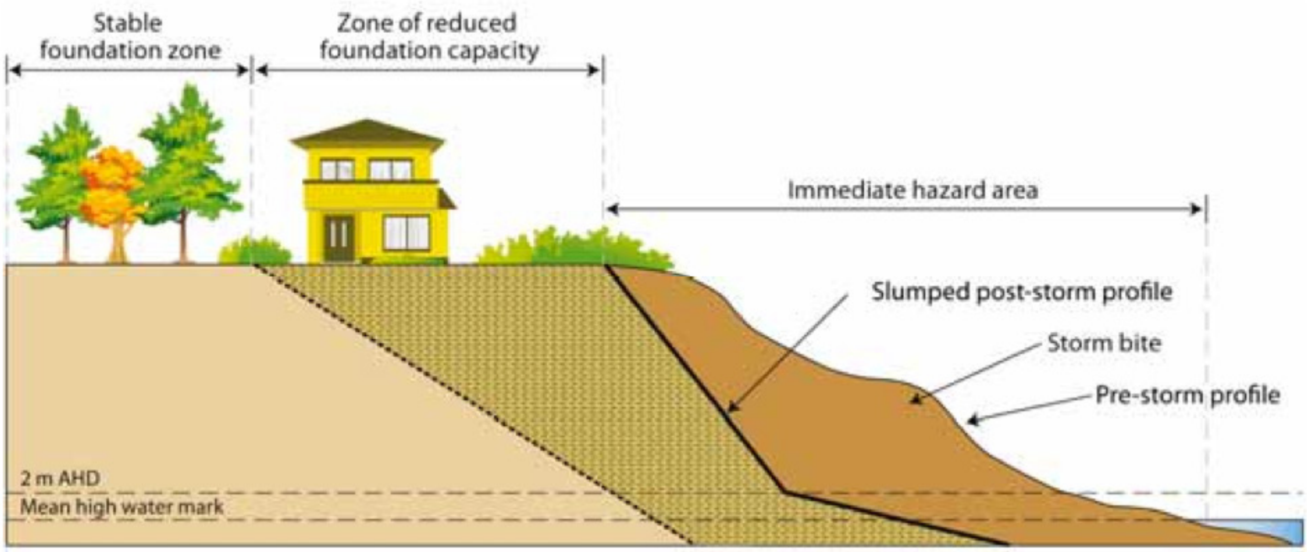

Figure 10. Idealised representation of the dune stability zones during a design storm event (NSW Coastal Risk Management Guide, 2010, after Nielsen et al., 1992).

The identification and mapping of the dune stability zones requires an assumption to be made on the *design storm erosion demand*; that is the volume of sand that the selected design storm would be able to erode from the beach. Typical values for NSW coast range from 125 to 250 m^3, depending on the selected storm ARI (Gordon, 1987) (Figure 11).

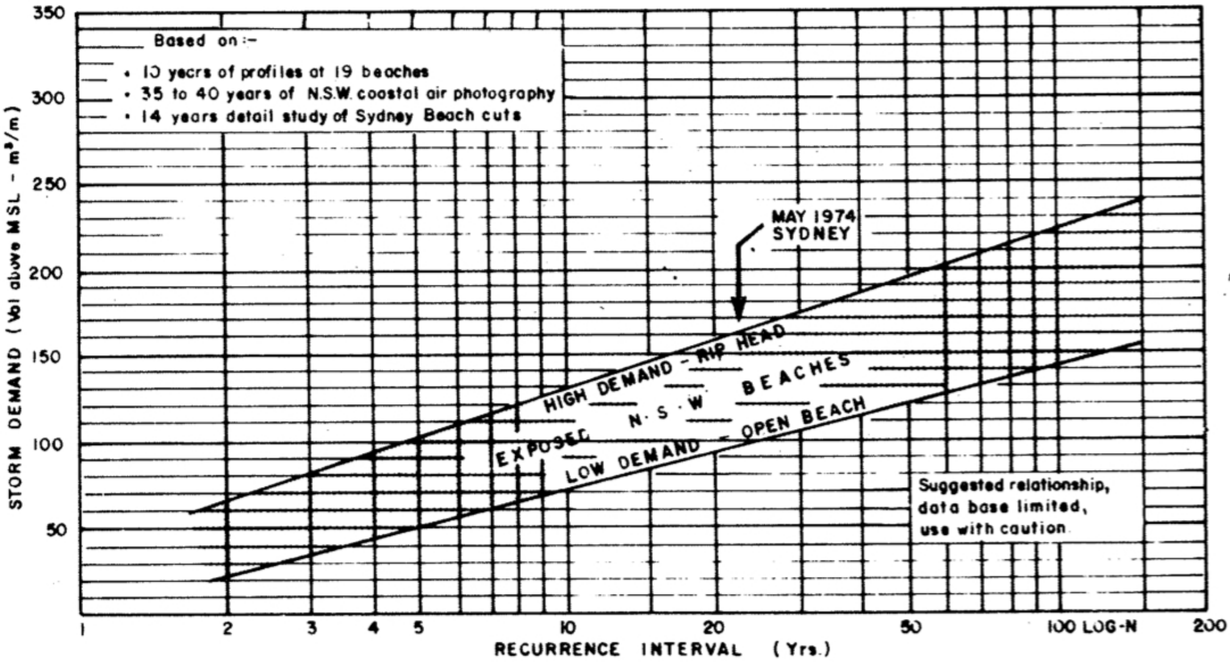

Figure 11. Typical NSW design storm erosion demand values associated with different Average Recurrence Intervals of extreme storms (Gordon, 1987).

Other than the design storm erosion demand, additional parameters required to identify the dune stability zones are:

a. The baseline volume, defined as the sand volume contained between a landward arbitrary line (baseline for volume calculations) and the pre-storm beach dune profile;

b. The average Ground Level (G.L.), that is the arithmetic mean of the ground elevation at the top of the dune seaward of the baseline;

c. The natural repose angle of the sand dune (α).

If the data is available, then the dune stability zones can be identified using the relations shown in Figure 9, considering that:

- The *top of swash zone* at low tide is taken to be approximately at 2m AHD;
- The inland limit of the is a profile starting from the inland limit of beach scour (the zone of wave impact) and rising landward to an angle $\Phi v = \tan^{-1}(\tan \alpha/1.5)$.

In the case of future storm scenarios, the stability analysis by Nielsen et al (1992) must account for the contribution of sea level rise (Figure 12). This requires recalculating the shoreline position and the pre-storm beach dune profile using the 2050 and 2100 sea level benchmarks as input, which can be done by applying the Bruun Rule (Bruun, 1962, 1988) or more sophisticated modelling techniques (NSW Coastal Risk Management Guide, 2010).

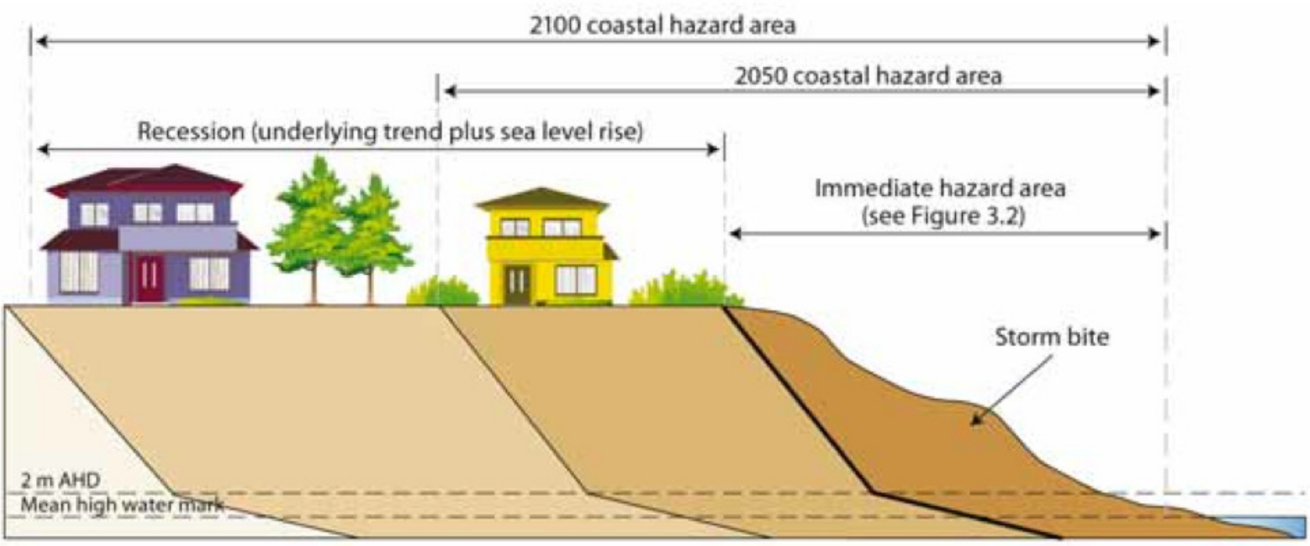

Figure 12. Retreat of the immediate hazard area associated with the projected sea level benchmarks in 2050 and 2100 (NSW Coastal Risk Management Guide, 2010).

5.1.2 Methods for Assessing the Vulnerability to Foreshore and Tidal Inundation

The NSW Coastal Risk Management Guide (2010) outlines that the NSW dune system is generally sufficiently elevated to provide adequate protection against foreshore inundation, although the risk of overtopping should be considered where coastal dunes are lower than 5m AHD. On the other hand, NSW low lying estuarine areas are prone to tidal inundation, and their exposure will increase in the future due to sea level rise.

In the case of either foreshore or tidal inundation, damage to coastal buildings and infrastructure is generally caused by:

a. Seawater inundation (prolonged contact with water), damaging building contents, fixtures, appliances, floors, and the like;

b. Hydrostatic pressure on building walls caused by a water depth differential on the two sides of the walls (inside and outside);

c. Hydrodynamic pressure caused by water currents, which could break through building walls or moving the whole building off its foundations;

d. Impact of debris and suspended sediment;

e. Waves breaking onto structures (Kelmann & Spence, 2004) – negligible in most NSW coastal areas.

Therefore, the overall damage to buildings is strictly associated with the inundation characteristics. These include water depth (Smith, 1994; Green, 2003), flow velocity (USBR, 1988), duration of inundation (Parker et al., 1987; FEMA, 2005), the rate of water rise, sediment or debris load (Haehnel & Daly, 2002; Thieken et al., 2005) and wave impact (Smith & Greenway, 1994; Kelmann & Spence, 2004). Further, the actual damage to buildings is significantly affected by their structural and design features, particularly under flow velocity higher than 1 m/s (Dale et al., 2004; Kelman & Spence 2004). Most relevant building attributes include construction material, foundation type, number of storeys, building weight and size, hydrodynamic characteristics of the ground floor, and the like (Figure 13).

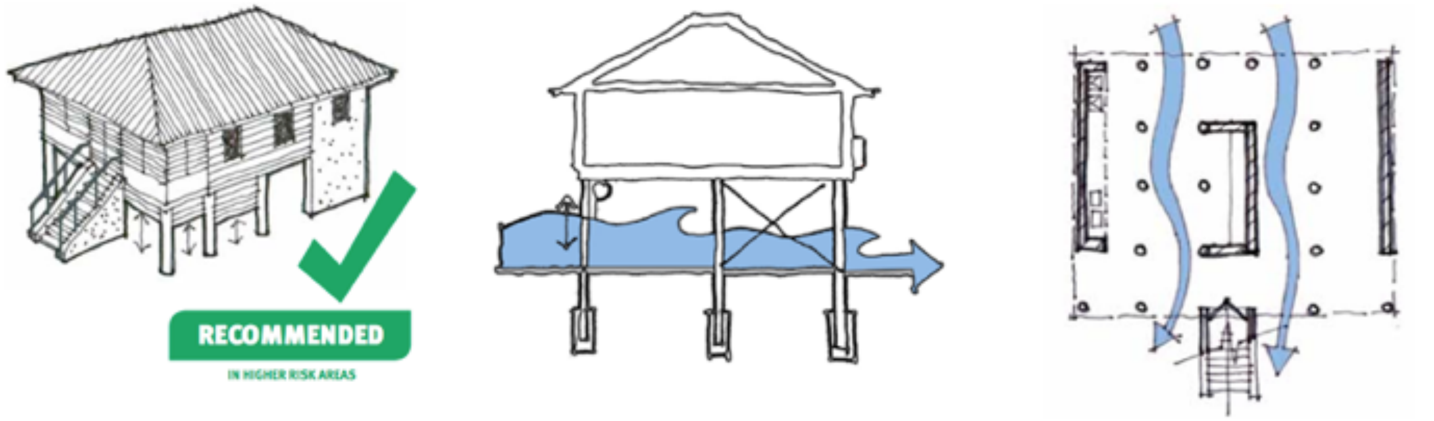

Figure 13. Example of recommended building design attributes for coastal areas exposed to storm tides. The ideal building has an elevated ground floor with a flow-through design, reinforced concrete structure and deep pile foundations (Queensland Reconstruction Authority, 2011).

Although the Australia Building Code contains provisions for buildings to resist wind loads and floods, there is a lack of design standards for extreme coastal inundations (storm surges or tsunamis). As a consequence, this gap has to be filled by specific state or local initiatives. The Queensland Reconstruction Authority (2011), for example, has recently released a series of guidelines about coastal resilience to tropical cyclones as part of a program named 'Rebuilding a Stronger, More Resilient Queensland'. Part 1 of the report, entitled 'Rebuilding in Storm Tide Prone Areas: Tully Heads and Hull Heads', provides an exhaustive overview of the main physical attributes of typical Queensland buildings influencing their vulnerability to storm tide. Resilient buildings should have an elevated ground floor (for example built on stumps) with a 'flow-through' design, deep pile foundations and rigid construction materials. Further, the document underlines the importance of natural barriers (coastal dunes and vegetation), which should be preserved from development (Figure 14). Table 11 provides a summary of the main building attributes influencing their vulnerability to storm surge inundation.

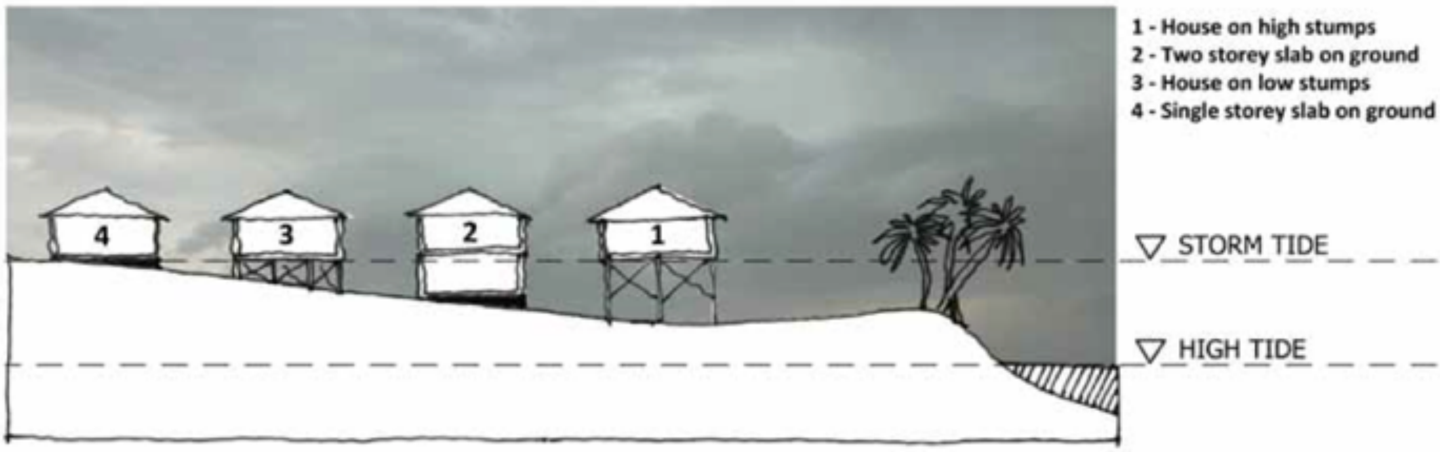

Figure 14. Example of resilient building types designed according to the expected maximum inundation depth (Queensland Reconstruction Authority, 2011). Protection provided by natural barriers, such as coastal dunes and vegetation, was found to be of critical importance.

Table 11. Performance of construction materials and design options below storm tide level (Queensland Reconstruction Authority, 2011).

COMPONENT	SUITABLE	MILD EFFECTS	MARKED EFFECTS	SEVERE EFFECTS
FLOOR, SUB-FLOOR STRUCTURE	- slab-on-ground - suspended concrete	- timber T&G (with ends only epoxy sealed and provsion of side clearance for board swellin) or plywood	- standard grade plywood	- particleboard flooring close to the ground
WALLS SUPPORT STRUCTURE	- reinforced or mass concrete - large windows low to the ground	- full brick/block masonry	- brick/block veneer with venting (stud frame) cavity brick	- inaccessible openings
WALL AND CELLING LININGS	- fibre cement sheet - face brick or blockwork - cement render - ceramic wall tiles - galvanised steel sheet - glass and glass blocks - stone, solid or veneer - plastic sheeting or tiles with waterproof adhesive	- common bricks - solid wood, fully sealed - exterior grade plywood fully sealed - non ferrous metals	- exterior grade particleboard hardboard - solid wood with allowance for swelling - exterior grade plywood	- particleboard fibreboard or strawboard - wallpaper - cloth wall coverings - standard plywood - gypsum plaster plasterboard
DOORS	- solid panel with waterproof adhesive - flush marine ply with closed cell foam - aluminium or galvanised steel frame	- flush or single panel marine ply with waterproof adhesive - painted metal construction timber frame, full epoxy sealed before assembly	- standard timber frame	- standard flush hollow core with PVA adhesives and honeycomb paper core Note: lowest cost and generally inexpensive to replace
WINDOW FRAMES	- aluminum frame with stainless steel or brass rollers	- timber frame, full epoxy sealed before assembly with stainless steel or brass fittings		- timber with PVA glues - mild steel fittings
INSULATION	- plastic/ polystyrene boards - closed cell solid insulation	- reflective foil perforated with holes to drain water if used under timber floors		- materials which store water and delay drying open celled insulation (batts etc)
BOLTS, HINGES, NAILS, FITTINGS AND CONNECTIONS	- brass, nylon/stainless steel, removable pin hinges	- galvanised stee, aluminium		- mild steel
FLOOR COVERING	- cly/ concrete tiles - epoxy or cementilious floor toppings on concrete - rubber sheets (chemically set adhesives) - vinyl sheet (chemically set adhesives)	- terrazzo - rubber tiles (chemically set adhesives) - polished floor and loose rugs - ceramic tiles	- loose fit nylon or acrylic carpet (close cell rubber underlay)	- wall to wall carpet - wall to wall seagrass matting - cork - linoleum

Most of the existing methods for assessing the vulnerability of buildings to either marine or riverine inundation are based on stage-damage curves, which estimate the total damage as a function of the expected water depth and primary building features (Suleman et al., 1988; Penning-Rowsell et al., 2003; Messner et al., 2007; Pistrika & Jonkman, 2009).

According to Messner et al (2007), there are two types of stage-damage curves: a) **empirical curves**, derived after historical floods; and b) **synthetic curves**, theoretical curves developed independently from historical floods, estimating damage not for actual properties but for standardised, typical property types. While synthetic curves depend only on a few selected flood parameters (e.g. flow depth, duration, warning time), empirical curves account for all the potentially damaging processes occurring during a flood (flow depth, flow velocity, debris, contamination, warning time, duration and so on). However, according to Middelmann-Fernandes (2010), empirical curves can be used only in the same location where they were originally developed (or in similar locations). Conversely, synthetic curves are more flexible and can be applied in different study areas, allowing a comparison between them. However, synthetic curves tend to overestimate the damage as they do not account for loss-reducing measures taken by the threatened community (e.g. lifting valuable building contents to upper floors).

Whether a curve is obtained synthetically or empirically, there are two other main options by which the damage to buildings can be assessed: a) the **'absolute damage'**, expressing the general amount of money required to completely restore the building and its content; and b) the **'relative damage'**, showing the damaged proportion of the building. An important example for a synthetically generated database of absolute damage functions is the Multi Coloured Manual (Penning-Rowsell et al. 2003) developed for 100 residential, and more than ten non-residential, property types in England (Figure 15). As described by Messner et al. (2007) *this data is derived synthetically; i.e. for residential flats first a definition and inventory of these standard property types is done. Secondly, for each of its typical building fabric and inventory components the monetary value is determined. Thirdly, expert assessors estimate the susceptibility of each item to inundation depth. So finally depth-damage functions can be constructed for each residential property type.*

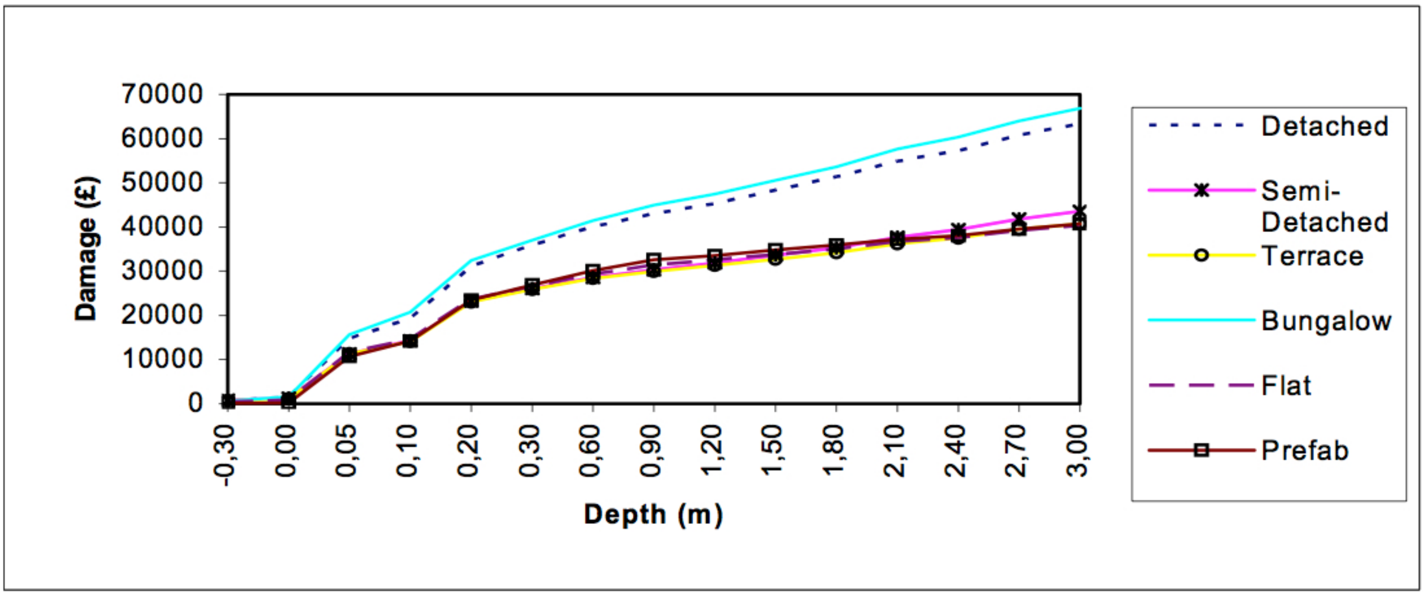

Figure 15. Synthetic absolute stage-damage curves for different residential building types in England (Penning-Rowsell et al. 2003).

In Australia, the most widely-used approach based on synthetic stage-damage functions is ANUFLOOD (Middelmann, 2005). ANUFLOOD is an interactive platform designed to assess direct damage to urban assets during floods. Input information required by ANUFLOOD includes a building-by-building description of location, ground and floor heights, construction material, value, house size, number of storeys and so on.

Whilst there are many advantages offered by these approaches, the use of stage-damage functions with flow velocity higher than 1m/s is associated with significant uncertainty, because these curves do not consider the risk of structural failure which is mainly connected with elevated flow velocity (Greenway & Smith, 1983; Middelmann-Fernandes, 2010). To address this, the latest approaches are moving towards integrated use of stage-damage and velocity-stage-damage curves, applied to different building types (Pistrika & Jonkman, 2009; Middelmann-Fernandes, 2010) (Figure 16).

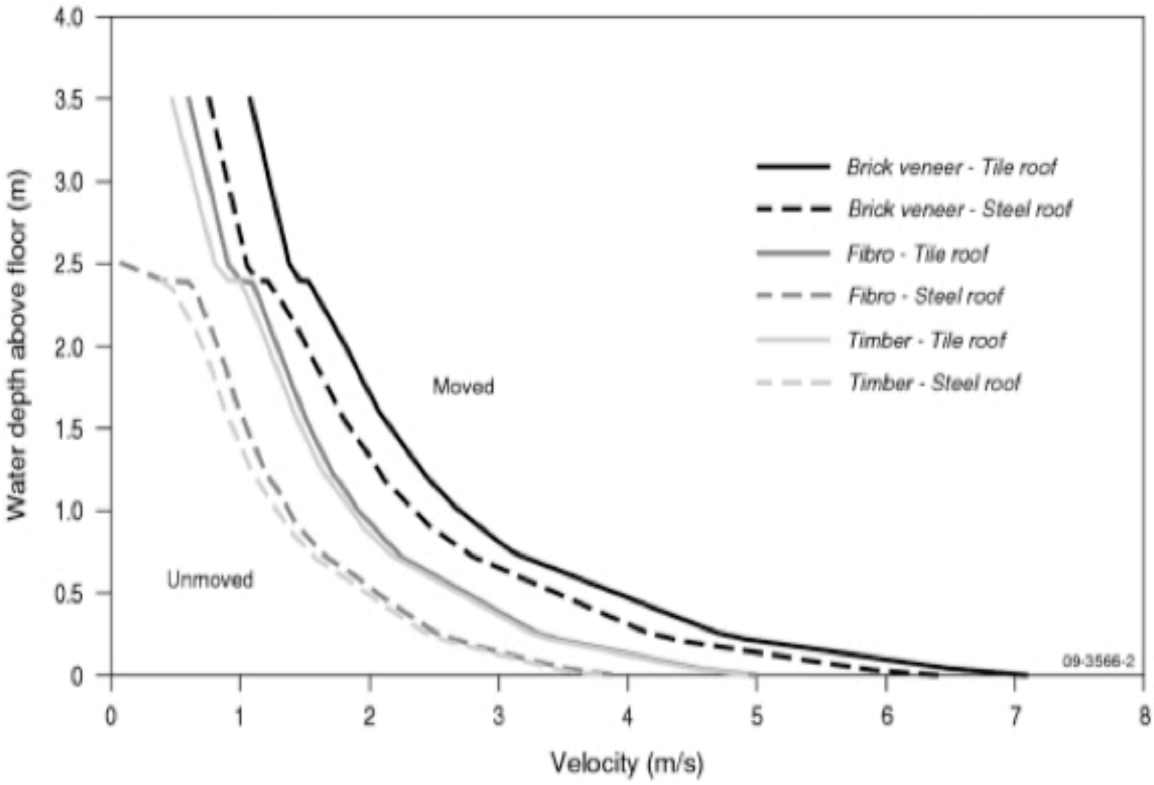

Figure 16. Velocity–stage–damage functions for single-storey detached houses (Middelmann-Fernandes, 2010).

5.2 TSUNAMIS

Various engineering and statistically-based attempts have been made to quantify the vulnerability of built structures to tsunamis. These include: investigations into the forces sustained by tsunami inundated buildings (Nistor et al. 2009) and the development of building fragility curves (Peiris, 2006; Dias et al., 2009; Koshimura et al., 2009a, 2009b). Ultimately, the aim of that work is to develop fragility curves that quantitatively relate the intensity of a hazard to the probability that a particular damage state will be reached or exceeded. However, the large return period and unpredictability of tsunamis make it difficult to obtain the field data necessary for such an approach (Douglas, 2007). Unlike other natural hazards, such as earthquakes (Rossetto & Elnashai, 2003; Calvi et al., 2006), where extensive quantitative post-event and laboratory data exists, there is limited data for tsunamis. Where data is available, it is generally qualitative and shows great variation in the type and severity of damage (Ghobarah et al., 2006; Reese et al., 2007).

At present, the development of a fully validated and site-adaptable building fragility model looks to be far from completion. In the meantime, there is a need for tools that can assess the vulnerability of structures located within expected tsunami inundation zones and provide loss estimates for future events.

5.2.1 The PTVA Model

IThe Papathoma Tsunami Vulnerability Assessment (PTVA) model was developed to address this need. In contrast to more quantitative approaches (i.e. fragility curves), the PTVA model provides qualitative scenario-based estimates of building vulnerability and potential loss. These outputs contribute to the process of risk reduction by informing decisions regarding land-use policy, building codes, evacuation plans and public education. As such, the PTVA model has the potential for playing a central role in determining the risks faced by coastal communities
(Tarbotton et al., 2012).

The PTVA Model has been successfully applied, field tested and validated in Greece (Papathoma, 2003; Papathoma & Dominey-Howes, 2003), the Maldives after the 2004 Indian Ocean Tsunami (Dominey-Howes & Papathoma, 2007), the Cascadia subduction zone region (Seaside, Oregon – USA) (Dominey-Howes, et al., 2010), Sydney (Dall'Osso et al., 2009a, 2009b) and Italy (Dall'Osso et al., 2010). The central idea behind the PTVA model is that the vulnerability of a building can be described by combining the inundation effects of a potential tsunami scenario with a series of measurable attributes relating to its design, condition and surroundings. Each attribute contributes in varying degrees to the overall vulnerability of a building and is seen as an indicator of the potential damage that would be sustained during a tsunami. By characterising these vulnerability attributes, a relationship (i.e. building vulnerability equation) is established between them and the hazard. The building vulnerability equation provides the means of calculating the 'vulnerability score' of a building (Figure 17) (Tarbotton et al., 2012).

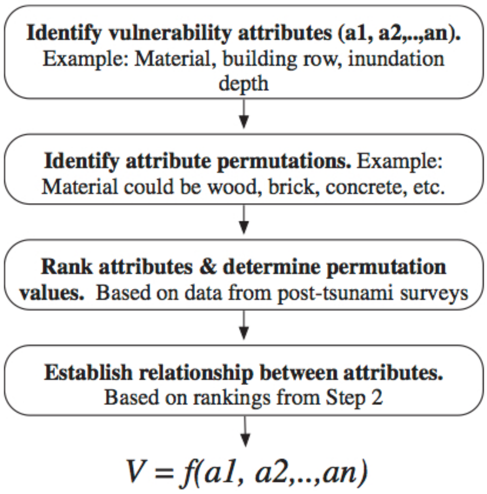

Figure 17. The PTVA model – establishing the building vulnerability equation.

The basic steps taken to conduct a PTVA model assessment are shown in Figure 18. They are conducted by combining the results of an inundation model with the vulnerability attribute data collected for each building. The outputs are presented via GIS-based database/maps, highlighting, among other things, buildings appropriate for vertical evacuation, possible evacuation routes and at-risk populations. In the majority of cases where the PTVA model has been used, the inundation scenario has been provided via a deterministic 'bathtub filling' inundation model. The one exception to this was in the Seaside, Oregon (Dominey-Howes et al., 2010) case study, where a probabilistic inundation scenario was used (Tarbotton et al., 2012).

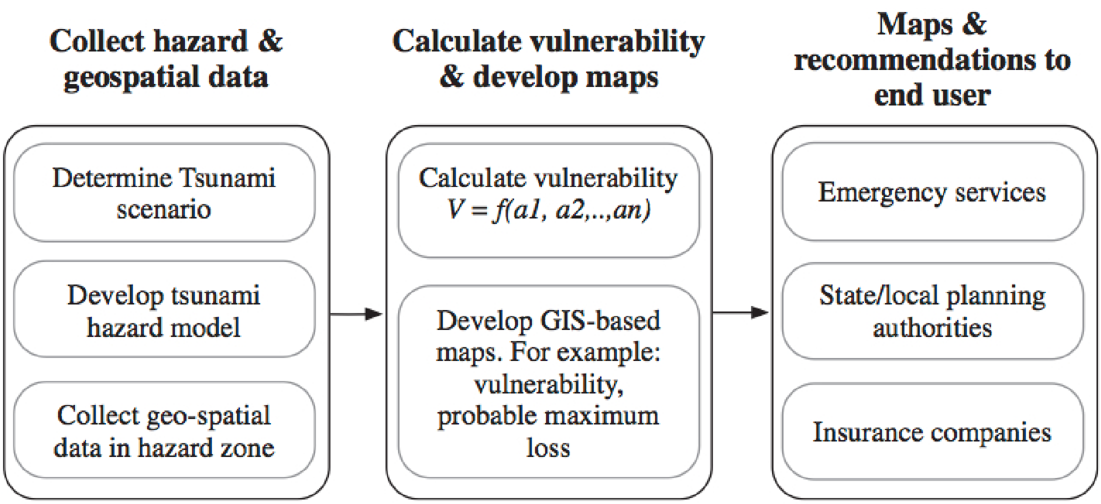

Figure 18. The PTVA model – steps in conducting a vulnerability assessment.

5.2.1.1 *PTVA-1*

The first version of the PTVA model (PTVA-1) was developed by Papathoma (2003) and published in Papathoma and Dominey-Howes (2003). The methodology was tested at two coastal sites in Greece – Herakleio, Crete (Papathoma, 2003) and the Gulf of Corinth (Papathoma & Dominey-Howes, 2003). Greece has a long record of tsunami events that date back to at least 1628BC (Papadopoulos, 1998). As such, the probability of a tsunami occurring and devastating coastal areas in Greece is not only high, it is also likely to have a larger impact than in the past due to the extensive development of coastal areas (Dominey-Howes, 2002). The PTVA-1 was developed to address these issues by providing a GIS-based method to estimate and present the vulnerability pattern within a predicted tsunami inundation zone. Based on previous records of tsunami events and their impact, seven attributes affecting building vulnerability were identified. These were ranked according to their importance through an in-depth study of post-tsunami damage observations. The PTVA-1 attributes and their relative weightings are shown in Table 12 (Tarbotton et al., 2012).

Table 12. PTVA-1 vulnerability attributes and their weightings.

n	ATTRIBUTE *(bv_n)*	WEIGHT *(W_n)*
1	Building material	7
2	Building row	6
3	Surroundings	5
4	Condition of ground floor	4
5	Number of floors	3
6	Sea defence	2
7	Natural environment	1

The vulnerability of each building (BV) in the inundation zone is calculated via a weighted sum of the vulnerability factors collected for each building.

$$BV = w_1bv_1 + w_2bv_2 + w_3bv_3 + w_4bv_4 + w_5bv_5 + w_6bv_6 + w_7bv_7 \tag{1}$$

For both case studies, a tsunami wave height of 5m, such as was achieved during the tsunamis of 1650AD in the Aegean Sea (Dominey-Howes et al., 2000) and 1963 in the Gulf of Corinth (Galanopoulos et al., 1964) was considered to be the worst case scenario. The area between the 5m contour and the coastline was identified as the potential inundation zone. The final product of the initial study using PTVA-1 included a GIS-based database and a series of vulnerability maps showing the location of vulnerable buildings (Figure 19) within the inundation zone (Tarbotton et al., 2012).

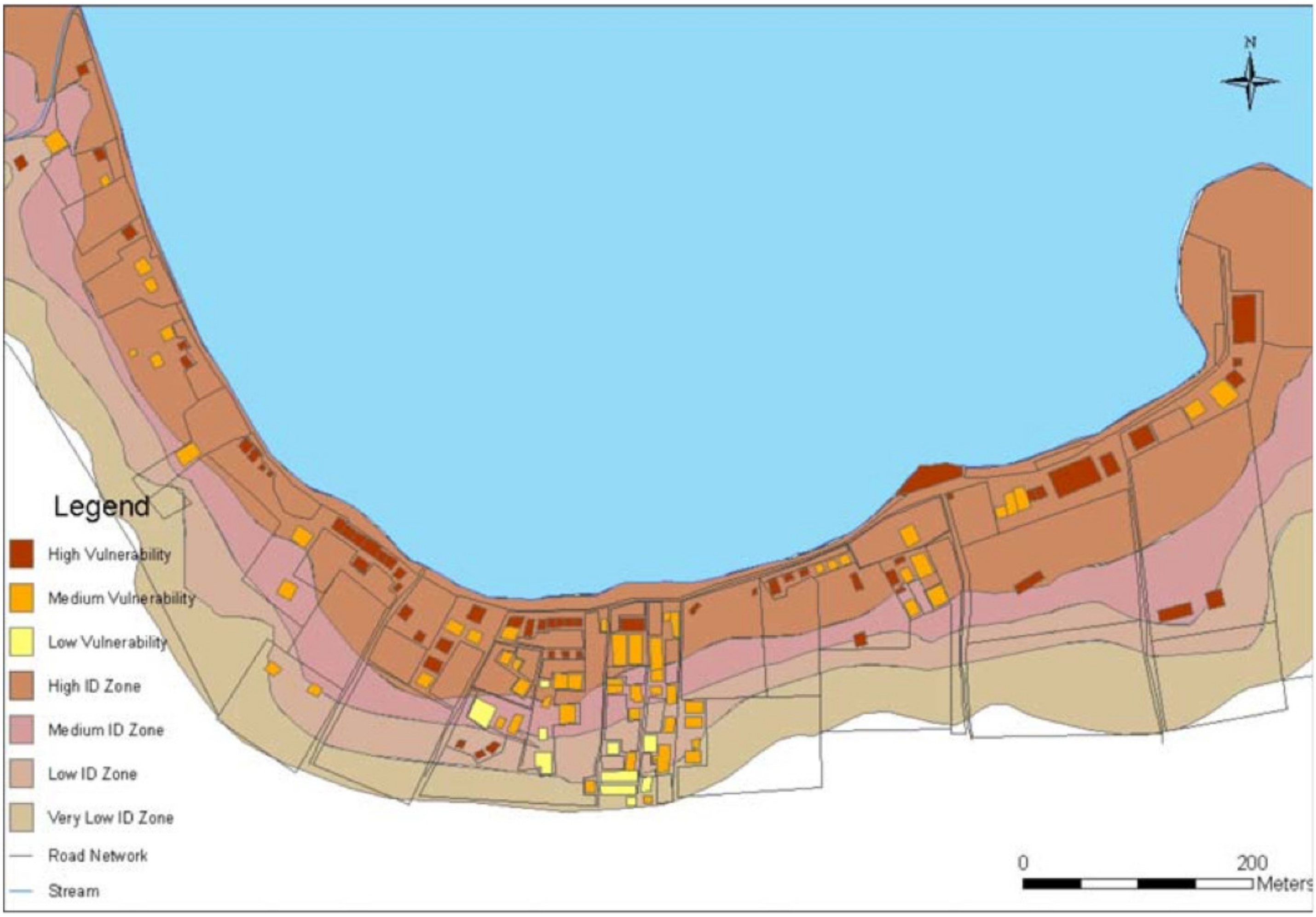

Figure 19. Building Vulnerability in Akoli, Gulf of Corinth.

The results of both studies demonstrated that in the case of a tsunami, the impact on the population and local economy would be significant. As such, the initial study using PTVA-1 not only met its aims but also it represented, at the time, a rare case where GIS was used in providing a comprehensive tsunami vulnerability assessment of the built environment (Tarbotton et al., 2012).

5.2.1.2 *PTVA-2*

A review of the PTVA-1 vulnerability attributes (Dominey-Howes & Papathoma, 2007) using post-event data from the 2004 Indian Ocean Tsunami (IOT) led to the development of a revised version of the model: PTVA-2. That study confirmed that many of the PTVA-1 attributes correlate well with the type and severity of the damage that was observed. PTVA-2 features some changes to the ranking and details of the attributes. The revised PTVA-2 vulnerability attributes and weighting were published in Dominey-Howes & Papathoma (2007) (Table 13) (Tarbotton et al., 2012). The PTVA-2 attributes are combined in a weighted sum to provide estimates of building vulnerability. The primary change featured in the PTVA-2 framework is that inundation depth is explicitly included in the calculation of Building Vulnerability (BV). In PTVA-1, BV is exclusively related to a building's characteristics and surroundings, with the worst-case tsunami scenarios being incorporated as a separate layer into the GIS database (Tarbotton et al., 2012).

Table 13. PTVA-2 vulnerability attributes and their weightings.

n	ATTRIBUTE (bv_n)	WEIGHT (W_n)
1	Water depth above ground	7
2	Building row	6
3	Building material	5
4	Number of floors	4
5	Orientation of building	3
6	Building surrounding	2
7	Land cover	1

5.2.1.3 *PTVA-3*

A major criticism of both the PTVA-1 and PTVA-2 models is that the ranking of the vulnerability attributes is based on a subjective procedure that relies heavily on the expert judgment of the authors. To address these concerns, a further version, PTVA-3, was proposed by Dall'Osso et al. (2009b). The PTVA-3 model introduces a more robust attribute ranking procedure via an Analytical Hierarchy Process (AHP), as well as additional vulnerability attributes and changes to the building vulnerability calculation. The PTVA-3 model was applied at two pilot sites: Sydney, Australia (Dall'Osso et al., 2009a) and the Aeolian Islands, Italy (Dall'Osso et al., 2010).

In the PTVA-3 model, the vulnerability score of a building is calculated via the Relative Vulnerability Index (RVI) equation (Equation 2). The RVI equation is a weighted sum of two independent scores: the Structural Vulnerability (SV) – the capacity of a building to sustain the hydrodynamic forces of a tsunami flow – and the Water Vulnerability (WV) – the extent to which it is submerged by water.

$$RVI = 2/3(SV) + 1/3(WV) \tag{2}$$

The WV term represents the first innovative aspect of the PTVA-3 model, as it considers both the structural vulnerability of a building and the damage caused by prolonged contact with water. According to Olivieri & Santoro (2000), a flooded building experiencing little or no structural damage could still lose up to 40 – 50% of its value. A higher weighting coefficient is assigned to SV because structural damage generally results in expensive repair works or complete building replacement (Reese et al., 2007). WV is calculated simply as the percentage of the floors in a building that would be inundated by the tsunami, including possible underground storeys:

$$WV = (\text{\# of inundated levels}) / (\text{\# of levels}) \tag{3}$$

Compared with WV, the computation of SV is significantly more articulated. It requires data about the building structure (BV), the expected inundation depth at the building (Ex) and the degree of protection provided by artificial and natural barriers (Prot). These three factors are multiplied together to obtain SV:

$$SV = (BV)(Ex)(Prot) \tag{4}$$

The BV term is calculated via a weighted sum of seven attributes (same as Equation 1) and the Prot term is calculated via a weighted sum of four attributes (Equation 5). The attributes and weightings for BV and Prot are shown in Table 14 and Table 15.

$$Prot = w_1 prot_1 + w_2 prot_2 + w_3 prot_3 + w_4 prot_4 \tag{5}$$

Table 14. PTVA-3 – Building Vulnerability (BV) vulnerability attributes and their weighting.

n	ATTRIBUTE *(bvn)*	WEIGHT *(Wn)*
1	Number of storeys	$W_1 = 0.236$
2	Material	$W_2 = 0.189$
3	Cround floor hydrodynamics	$W_3 = 0.149$
4	Fundation strength	$W_4 = 0.142$
5	Shape and orientation	$W_5 = 0.121$
6	Moveable objects	$W_6 = 0.109$
7	Preservation condition	$W_7 = 0.054$

Table 15. PTVA-3 – Protection (Prot) vulnerability attributes and their weightings.

n	ATTRIBUTE *(bvn)*	WEIGHT *(Wn)*
1	Building row	$W_1 = 0.332$
2	Natural barriers	$W_2 = 0.243$
3	Seawall	$W_3 = 0.243$
4	Surrounding wall	$W_4 = 0.183$

Many of the building vulnerability attributes used in the PTVA-3 model are the same as those used in previous models. However, PTVA-3 does introduce two new attributes: foundation type and preservation condition (i.e. the preservation state of the building). The foundation type, in particular, was found to be very influential in the overall vulnerability of buildings (Dalrymple & Kriebe, 2005; Reese et al., 2007). Furthermore, the manner in which the shielding term, Prot, is integrated into the vulnerability calculation represents a significant departure from previous versions of the PTVA model. As opposed to adding the shielding attributes (i.e. building row) to the weighted BV calculation, the PTVA-3 model considers Prot as a separate multiplying factor. This approach is generally consistent with the findings of Reese et al. (2007) who observed that well shielded buildings in many cases suffer much lighter damage (up to four or five fold) than buildings completely exposed to the tsunami impact. This is well represented by the SV equation (Equation 4), as a minimum score of Prot (i.e. Prot=1 is very good protection) would reduce SV up to five fold (Tarbotton et al., 2012).

As with previous versions of the PTVA model the attribute weights in PTVA-3 correspond to the relative importance that an attribute has in contributing to the total vulnerability of a building. PTVA-3, however, features a much more robust and sophisticated ranking procedure than previous versions of the model. This is achieved via an Analytic Hierarchy Process (Saaty, 1986), whereby a series of pair-wise comparisons are conducted between all the various vulnerability attributes. Each pair-wise comparison provides a measure of the relative importance that one attribute has over another in contributing to the overall structural vulnerability or level of protection of a building. A total of 21 comparisons were conducted for the seven BV attributes and seven for the four Prot attributes. Details of all the pair-wise comparisons are outlined in Dall'Osso & Dominey-Howes (2009). Comparisons between attributes were performed using M-Macbeth, a specially designed computer program for multi-criteria analysis (Bana e Costa & Chargas, 2004; Bana e Costa et al., 2004). The M-Macbeth software combines the pair-wise comparisons to determine the rankings of the attributes. This more rigorous mathematical approach avoids many of the biases typical of a ranking procedure and addresses concerns about the subjectivity and linearity of the weights used in the PTVA-2 model (Tarbotton et al., 2012).

The PTVA-3 model has been successfully field-tested in two coastal suburbs of Sydney: Manly beach (Figure 20) and Maroubra beach. Results of these studies are described in detail in Dall'Osso et al. (2009a, b). More recently, the PTVA-3 Model has been applied and validated in the Aeolian Islands, Italy (Dall'Osso et al., 2010). In this study, the model outputs were qualitatively compared with post-tsunami damage data from the 2002 Stromboli tsunami. Results of the comparison showed the PTVA-3 model to be accurate, but simultaneously highlighted some of its main deficiencies – a simplistic representation of the tsunami hazard and a highly qualitative assessment framework (Tarbotton et al., 2012).

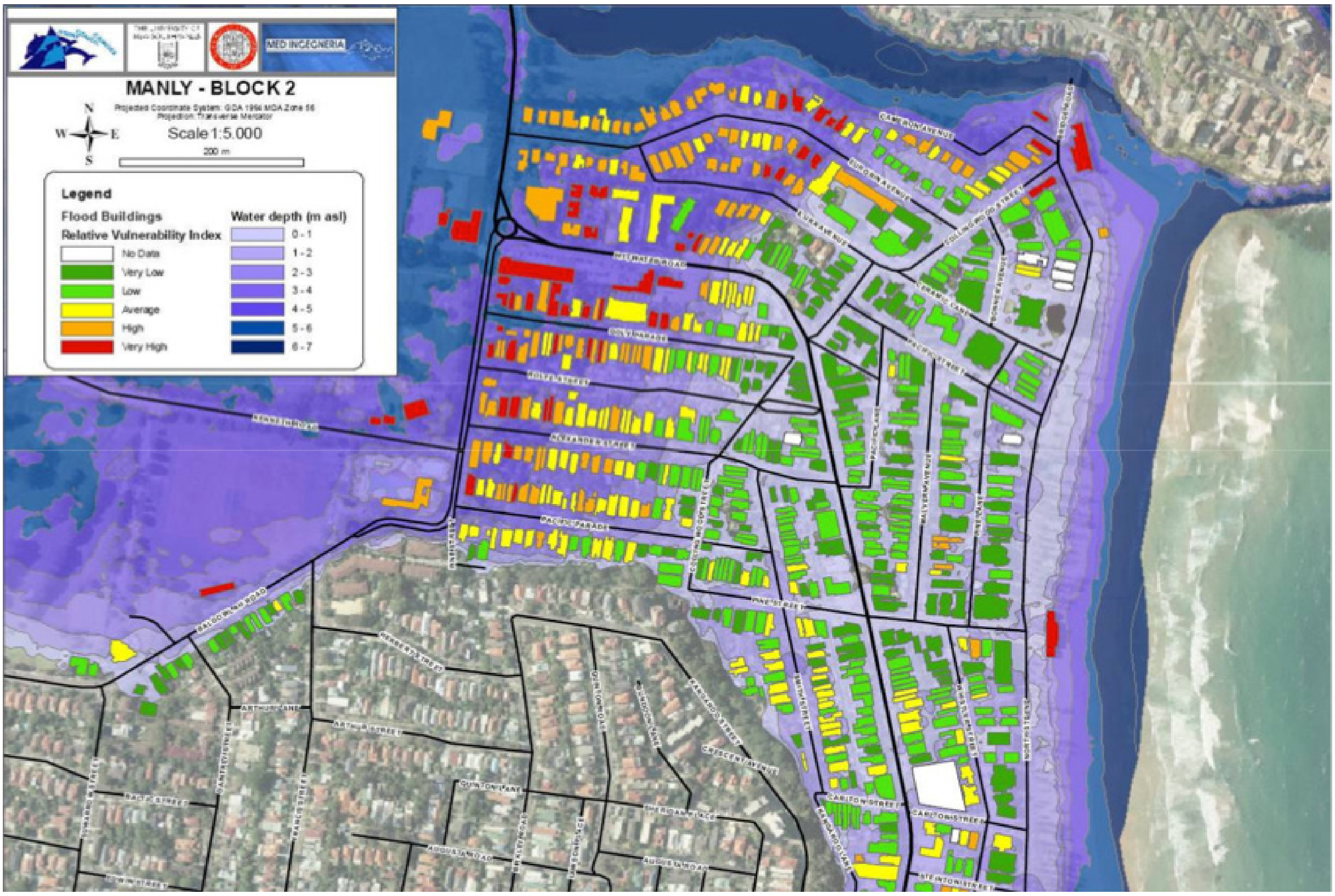

Figure 20. Tsunami inundation and water depth in the northern part of Manly. The RVI scores of buildings located within the inundation zone are indicated.

5.2.2 Other Index-Based Approaches

A review of the available literature suggests that only two other GIS-based attempts have been made to explore the vulnerability of buildings to tsunamis. These are documented in Wood and Stein (2011), Wood et al. (2002), Wood and Good (2004) and Omira et al. (2009). Table 16 compares some of the key aspects of these models with PTVA-1, PTVA-2 and PTVA-3 (Tarbotton et al., 2012).

Table 16. Key elements of the three versions of the PTVA model and competing approaches.

Model	Representation of The Hazard	No. of Vulnerability Attributes	Ranking Procedure	No. of Study Locations Used
Wood	Hydrodynamic, worst case	N/A	N/A	1
Omira	Hydrodynamic, probabilistic	3	Expert judgment	1
PTVA-1	Bathub, worst case, deterministic	7	Expert judgment	2
PTVA-2	Hydrodynamic, probabilistic	8	Expert judgment	1
PTVA-3	Bathub, deterministic	13	AHP/ Expert judgment	3

Wood et al. (2002), Wood & Good (2004) and Wood and Stein (2011) provide a framework for identifying broad areas of concern – termed as 'relative vulnerability hotspots'. The approach focuses on (1) identifying key assets and services within a community; and (2) representing the intersection of these community assets (using GIS) with worst-case hazard scenarios. This approach is effective at the regional scale but its capacity to assess the structural vulnerability of individual buildings is limited (Tarbotton et al., 2012).

The method outlined in Omira et al. (2009) offers an improvement in this respect. It provides an attribute-based methodology similar to the PTVA model, in which three vulnerability factors are used to determine the vulnerability of a building: building condition, inundation depth and the presence of a sea defence. The building condition attribute corresponds to four predefined building categories – ranging from very weakly resistant to strongly resistant. The pilot study used to test the model (Casablanca, Morocco) utilises a probabilistic hydrodynamic inundation model to represent the tsunami hazard. In comparison to the PTVA approach, Omira et al. (2009) requires significantly less input data regarding the design and condition of buildings. PTVA-3, for example, uses a total of seven attributes to describe the structural vulnerability of a building, while Omira et al. (2009) uses only one – building condition. This significantly reduces the time required for field surveys but makes it less adaptable to study locations that do not feature buildings in the defined building categories (Dall'Osso et al., 2010; Tarbotton et al., 2012).

In light of the other tsunami vulnerability assessment approaches discussed above, it is concluded that the PTVA model offers the best available technique for assessing the impact of tsunamis on the built environment. The PTVA-3 model, in particular, offers the most developed and flexible assessment framework. It can be used to analyse a wide range of different building types. As, such, the COVERMAR tool considers the PTVA-3 model as the baseline from which such work moves forward (Tarbotton et al., 2012). As previously stated, the PTVA-3 Model will be upgraded through:

a. The use of the best available hydrodynamic models for simulating tsunami propagation and inundation;

b. The implementation of recently published building fragility curves for tsunamis, to ensure a more quantitative and less relative vulnerability assessment process;

c. An improved weighting process of the factors affecting the vulnerability of buildings to tsunamis;

d. A new module for assessing the vulnerability of coastal infrastructure to tsunamis.

5.2.3 Hydrodynamic Models for Simulating Tsunami Hazard

The simplistic representation of the tsunami hazard in the PTVA model has perhaps, the most significant effect on the accuracy of its outputs (Tarbotton et al., 2012). The static 'bathtub' approach mainly used to date fails to account for the complex role that bathymetry, topography and buildings play in dictating the flow of a tsunami inundation (Liu et al. 1991). This has a profound effect on how the hazard exposure of buildings is incorporated into the model (Tarbotton et al., 2012).

In an attempt to account for variations in building exposure not represented by the static flood model, PTVA-3 uses a series of qualitative shielding factors in addition to the flood depth. These provide an approximation of how a tsunami would flow and impact the built environment without having to model it explicitly. To improve this, the COVERMAR tool will include the integration of hydrodynamic modelling results into its assessment framework. The integration of hydrodynamic modelling into the PTVA-3 results could offer a number of important improvements for the PTVA model:

- The effect of shielding features, such as, walls, buildings and natural barriers could be integrated directly into the model of the hazard. This would provide the opportunity to remove aspects of the qualitative protection term, making estimates of building exposure less reliant on qualitative factors.
- Alternative methods of representing building exposure could be investigated, which not only utilises flood depth but also the other hydrodynamic quantities produced by hydrodynamic tsunami models (e.g. flow speed and direction).
- Probabilistic vulnerability studies could be achieved by utilising probabilistic source parameters (i.e. from subsea earthquake and landslide studies) as the initial conditions to tsunami simulations.
- It builds upon a modelling tool that is already familiar and widely used by planners and emergency managers. The vulnerability assessments provided by the PTVA model would become a natural extension of inundation modelling efforts that are already taking place using hydrodynamic models. This would speed the adoption of PTVA as a planning resource for coastal communities, as well as extend the current capabilities of hydrodynamic models (Tarbotton et al., 2012).

Hydrodynamic models are capable of representing (dynamically) a tsunami event from source (generation), via propagation to inundation (Synolakis & Bernard, 2006). In models such as the Rivers and Coastal Ocean Model (RiCOM) (Walters, 2005) and the MOST model (Titov & Gonzalez, 1997; Titov & Synolakis, 1998), the effects of bathymetry, topography, and even aspects of the built and natural environment, can be integrated directly into the numerical simulations (Tarbotton et al., 2012). Specifically, MOST has been validated through analytical solutions, experimental results, and field measurements as outlined in Synolakis and Bernard (2007) and Synolakis et al. (2008) and it is the only model currently implemented into the ComMIT system (Community Model Interface for Tsunamis) (Titov et al., 2011).

5.2.3.1 *ComMIT: Community Model Interface for Tsunamis*

ComMIT is an internet-enabled interface to the community tsunami model developed by the NOAA Center for Tsunami Research (NCTR), in response to a recommendation of the Intergovernmental Coordination Group for the Pacific Tsunami Warning System (ICG/IOTWS) to create a web-based community tsunami model. ComMIT is based on the same tsunami forecast methodology currently in use at the NCTR, located within the Pacific Marine Environmental Laboratory (PMEL) in the USA (Wei et al., 2008; Tang et al., 2009; Titov et al., 2009;). Titov et al. (2011) described ComMIT as a rich graphical interface to a precomputed tsunami scenario database and to the MOST model. Through ComMIT it is possible to run numerical simulations of tsunami generation propagation and inundation (Figure 21).

The required input data include: (1) high-resolution near-shore bathymetry and topography (e.g. Lidar dataset); (2) initial and boundary conditions (i.e. source location, earthquake magnitude, bathymetry grids); and (3) some specific model parameters (spatial resolution, time step, and the like).

At the moment, ComMIT can only be used to simulate earthquake-generated tsunamis, as it only implements the MOST model. However, ComMIT allows incorporation of other tsunami models (e.g. TsunAWI – Harig et al., 2008), including models for landslide-generated tsunamis (Lovholt et al., 2010).

The main advantages of using a community-based approach for tsunami simulation are: (1) it allows nations without a significant cadre of trained modellers to build tsunami modelling capability for forecast and hazard assessment; (2) it allows nations with restrictions on sharing geo-spatial data to input that data locally and not share it with other web-based model users, but at the same time share the model results regionally or globally; and (3) most significantly, the internet-based approach creates a virtual regional and global community of modellers using the same tools and approaches to understand tsunami threats, all able to share information and insights (NCTR website, http://nctr.pmel.noaa.gov/ComMIT/background.html).

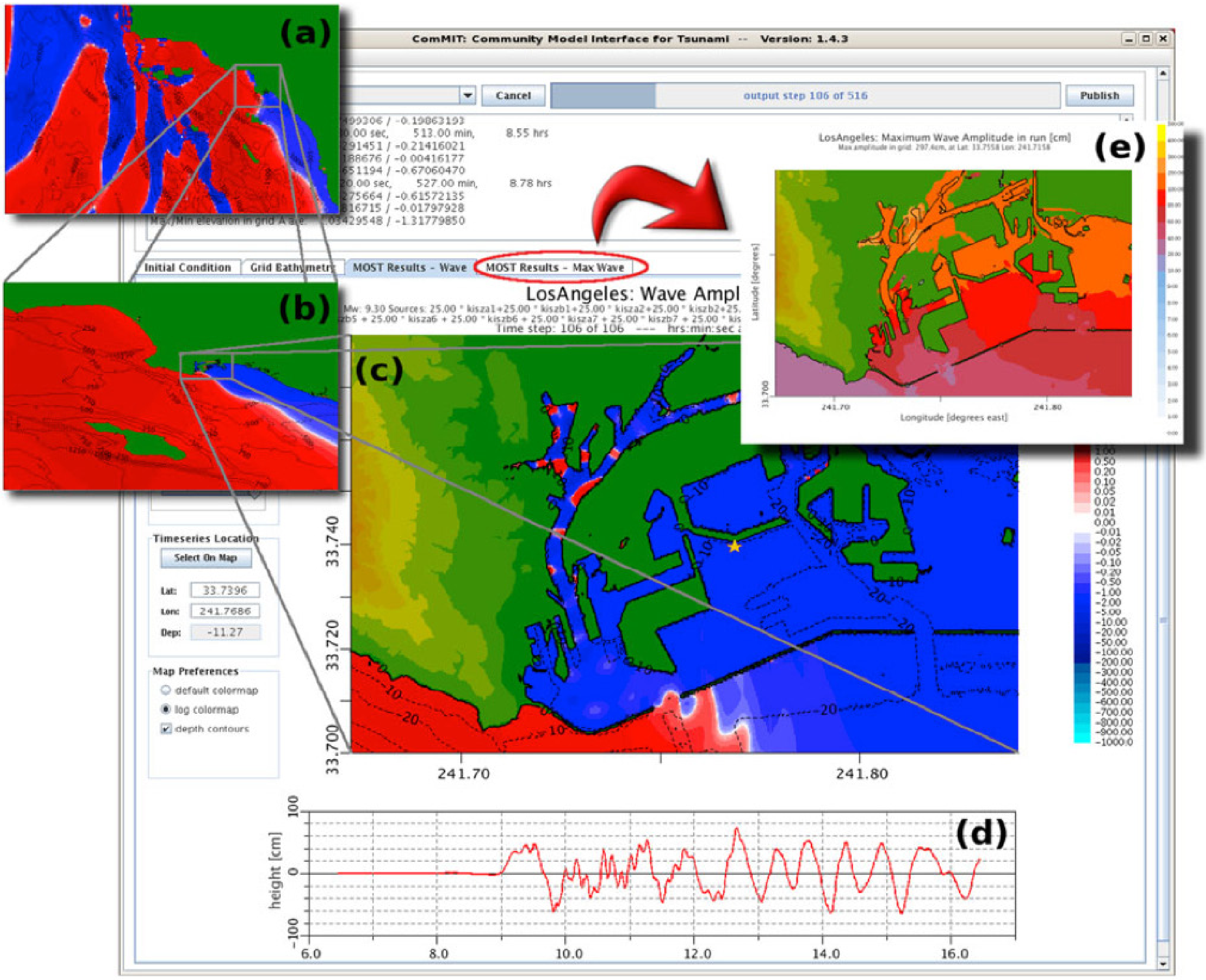

Figure 21. Snapshot of the ComMIT interface showing the outputs of a simulation onto three topobathymetric grids with increasing spatial resolution (Titov et al., 2011).

5.2.4 Existing Tsunami Fragility Curves for Buildings

Given the low incidence of destructive tsunamis that have large impacts, new observations are particularly valuable and can contribute data to better explore the relationship between tsunami characteristics and building damage, which is the theoretical foundation of the PTVA Model.

After large tsunamis occurred in the last decade (i.e. 2004 Indian Ocean, 2006 South Java, 2007 Solomon Islands, 2009 Samoa, 2010 Chile, 2011 New Zealand and 2011 Japan) an increased number of observations of the impact on buildings has become available to the scientific community.

Most of this information has been published in the form of 'fragility curves', defined as the structural damage probability with particular regard to hydrodynamic features of tsunami inundation flow (such as inundation depth, flow velocity or hydrodynamic force) (Koshimura et al, 2009a). Fragility curves associate some measure of the tsunami impact (e.g. flow depth) to the failure probability of different building types, or to their expected mean damage (in the latter case the curve is labelled the 'damage curve'). This section summarises and compares the available approaches that have developed different tsunami fragility curves.

5.2.4.1 *Peiris (2006)*

Using field survey data collected after the 2004 Indian Ocean Tsunami, Peiris (2006) developed fragility curves for typical Sri Lankan masonry residential buildings. Specifically, Peiris (2006) calculated the probability that those buildings have to suffer three defined damage levels (labelled as 'still usable', 'partially unusable' and 'complete destruction') in response to various tsunami flow depths. The fragility curves obtained by Peiris (2006) have a log-normal shape (Figure 22), like most of the curves published in subsequent research.

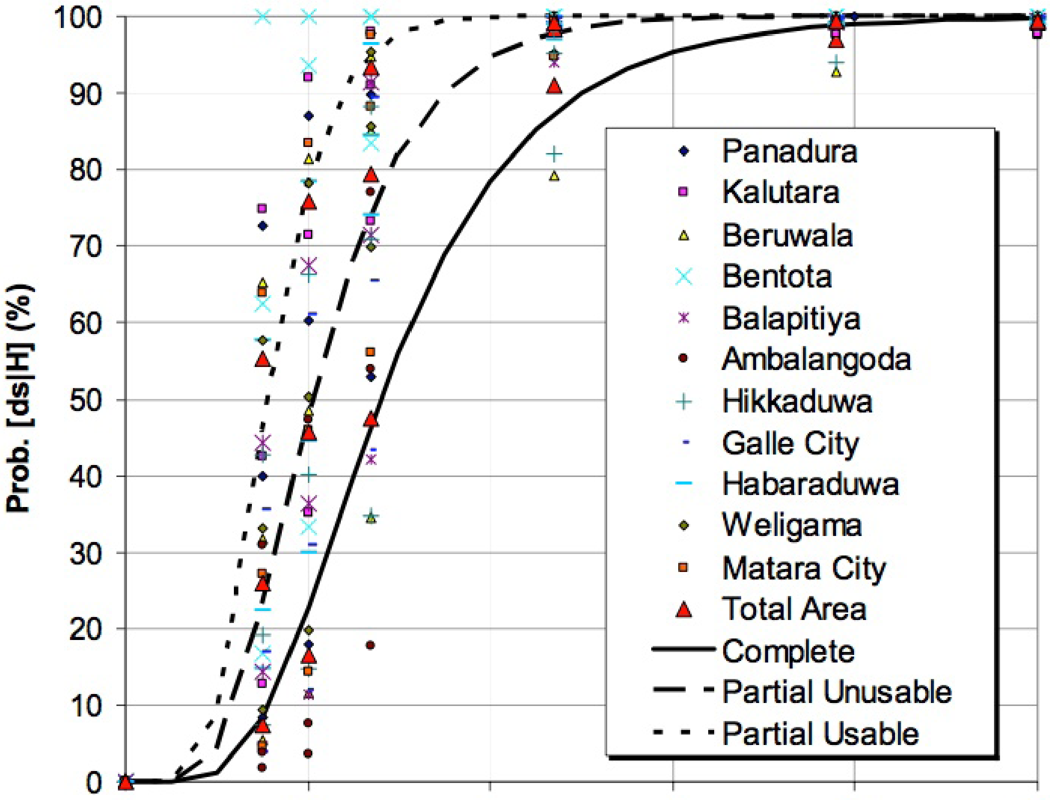

Figure 22. Fragility curves for masonry residential buildings in different Sri Lanka regions (Peiris, 2006).

5.2.4.2 *Reese et al. (2007)*

After the July 2006 tsunami in South Java, Stefan Reese guided a team of scientists from New Zealand and Indonesia on a reconnaissance mission in the field to undertake a building damage assessment. The observed level of building damage was diverse, due to a relatively wide variety of building types and construction standards. They divided the affected buildings into the following classes:

a. Light timber or bamboo construction, with a wood frame (100 x 100 mm) and light/flexible timber walls. These buildings had mainly only a ground floor and shallow foundations;

b. Single-storey residential buildings, made with a single layer of bricks, with concrete shallow foundations. Reese et al. (2007) describes them as 'weak' non-engineered constructions;

c. Non-engineered masonry structures with reinforced concrete columns (100 x 100 mm to 200 x 200 mm), concrete floors and one or two storeys;

d. Engineered buildings with reinforced concrete frames (200 x 200 mm) and brick infill walls, with two or more storeys.

According to the observed damage levels, Reese et al. (2007) developed one Damage/Ratio curve per identified building class. This type of curve describes the relationship between the inundation flow depth and the 'cost to repair/cost to replace' ratio of every building class (Figure 23). Therefore, in contrast to Peiris (2006), the curves from Reese et al. (2007) provide a more direct quantification of the damage that every building class is likely to suffer in response to different tsunami flow depths.

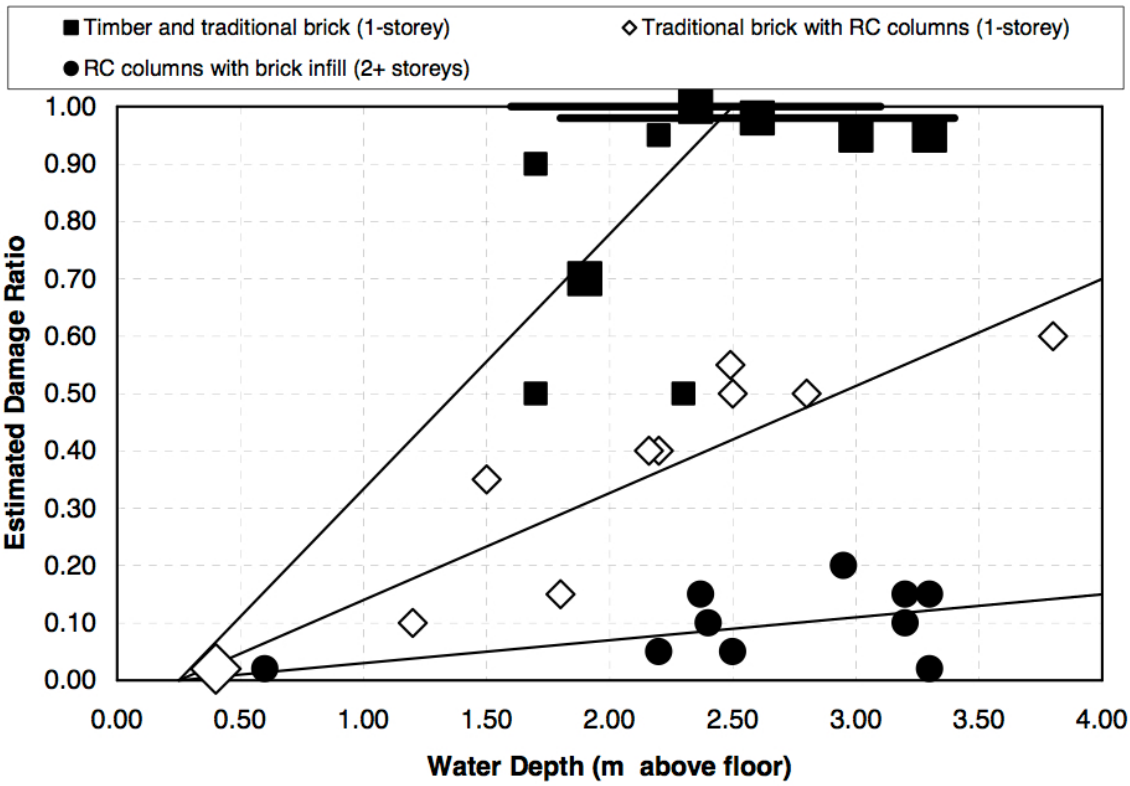

Figure 23. Damage ratio curves as a function of flow depth for different building classes in South Java (Reese et al., 2007).

Further, another important element of Reese's analysis is the quantification of the 'shielding' effect; that is the degree of protection provided to every building by artificial (e.g. other buildings, seawalls) or natural (e.g. vegetation, coastal dunes) barriers. Reese et al (2007) compared the damage ratio of buildings of the same class that were differently exposed-to/ shielded-from the tsunami inundation. Results confirmed that damage to exposed buildings may be up to five times higher than similar shielded structures (Figure 24).

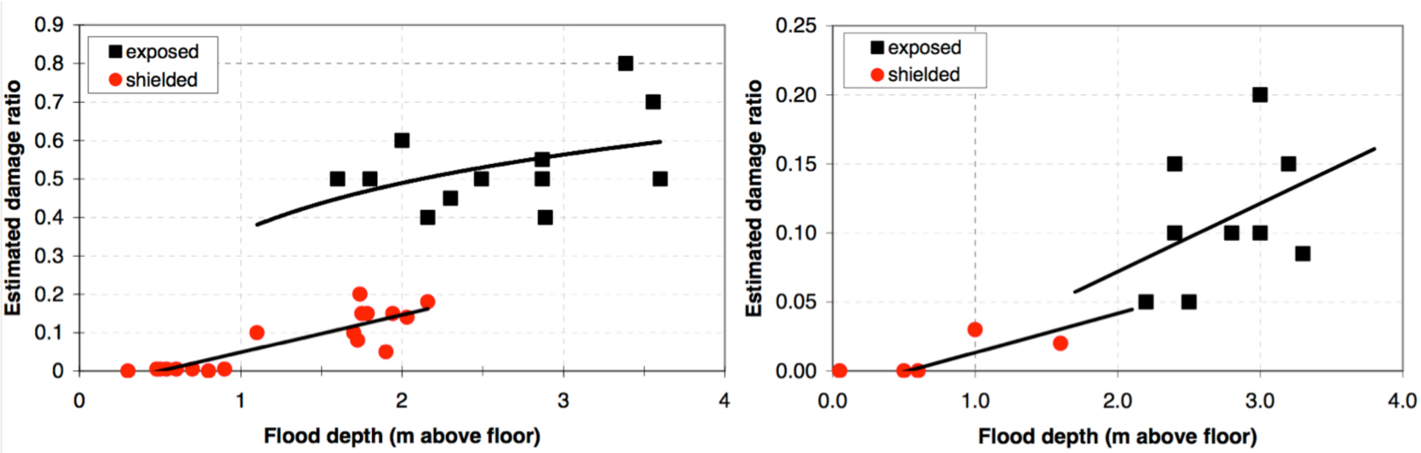

Figure 24. Damage ratio curves for: (a) brick buildings with reinforced concrete (RC) columns (on the left); and (b) Engineered buildings with RC frames (on the right). The two graphs show the difference between shielded and exposed buildings (Reese et al., 2007).

5.2.4.3 *Dias et al. (2009)*

Dias et al. (2009) used data on tsunami-damaged houses collected by the Department of Census and Statistics in Sri Lanka, after the 2004 Indian Ocean Tsunami to build new fragility curves. Dias et al. (2009) developed fragility curves showing the probability of complete damage for two main building classes:

a. Buildings with more than 50% of 'permanent' construction materials;

b. Buildings with less than 50% of 'permanent' construction materials;

where 'permanent' material refers to concrete, bricks, timber tiles and frames, and 'temporary materials' include mud, tin sheets, wood and cadjan. As shown in Figure 25, these curves have a log-normal shape. Unfortunately, Dias et al. (2009) did not provide any further detail on the physical characteristics of the surveyed buildings, inhibiting comparisons with other bounding fragility curves (BFCs).

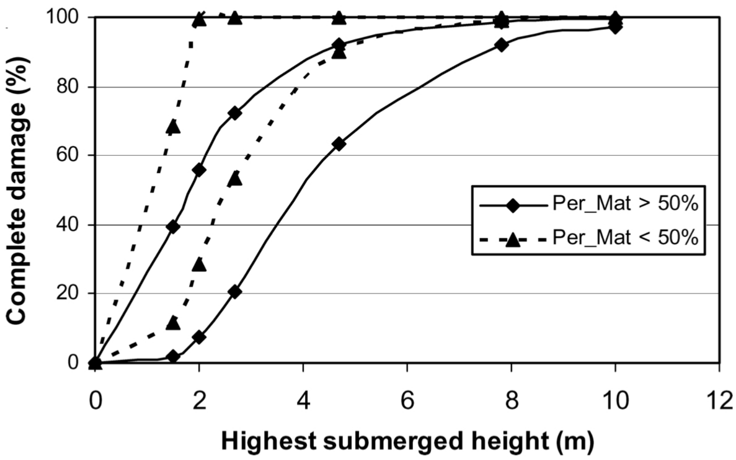

Figure 25. Bounding fragility curves for the two building classes identified by Dias et al. (2009) in Sri Lanka.

5.2.4.4 *Koshimura et al. (2009b)*

Koshimura et al. (2009b) developed a set of tsunami fragility curves starting from a dataset of over 40,000 structures affected by the 2004 Indian Ocean Tsunami in Banda Aceh, Indonesia. In contrast with previous approaches, Koshimura et al. (2009b) used three tsunami 'demand parameters' (e.g. flow depth, flow velocity and hydrodynamic pressure), which they obtained through a numerical simulation of the tsunami inundation process. The affected buildings included low-rise wooden houses, timber constructions and non-engineered reinforced concrete (RC) structures. However, Koshimura et al. (2009b) decided not to treat these building categories separately, but just generate one general curve including all of them. The curves account only for the probability of complete damage, and they all have a log-normal shape (Figure 26).

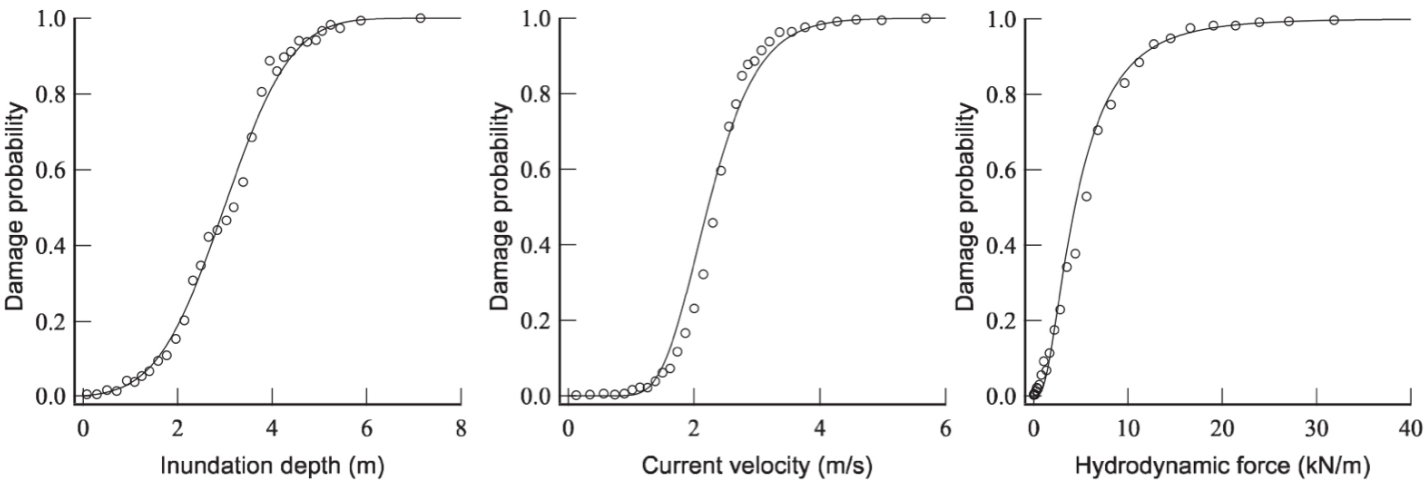

Figure 26. Fragility curves developed by Koshimura et al., 2009b. The curves describe the probability of complete damage for all the surveyed buildings (no building types distinction), as a function of three tsunami demand parameters (flow depth, flow velocity and hydrodynamic pressure).

Whilst this analysis cannot be used to investigate the response of different building types to tsunami inundation, it was the first attempt to link the probability of damage to two tsunami demand parameters (i.e. flow velocity and hydrodynamic pressure) other than the flow depth. However, Koshimura et al. (2009b) state that the best demand parameter to be used is the flow depth, as the estimation of current velocity with a numerical model is significantly affected by grid resolution, the topographic dataset, the applied friction coefficient and the accuracy of the model itself.

5.2.4.5 *Leone et al. (2011)*

Leone et al. (2011) developed tsunami damage curves using data from remote-sensing analysis and field surveys carried out after the 2004 IOT in Banda Aceh. The dataset included 6200 units that Leone et al. (2011) classified into five categories according to their damage level. The analysis was carried out assuming that most of the damage to buildings was caused by the tsunami, while the earthquake had only minor effects (Boen, 2006).

Leone et al. (2011) generated the following curves: (a) one curve accounting for all the building types (Figure 27); and (b) one curve for *Individual buildings with concrete structure, hardly strengthened (200 x 200 mm), masonry of bricks or rubble stones, 0 or 1 floor* (Figure 28). Whilst the amount of data was significant, Leone et al. (2011) developed damage curves for just one building type (i.e. buildings with a RC frame, brick walls and 0 to 1 floors), because 4095 buildings (out of a dataset of 6200 units) were completely destroyed by the tsunami, and their original construction features could not be recognised.

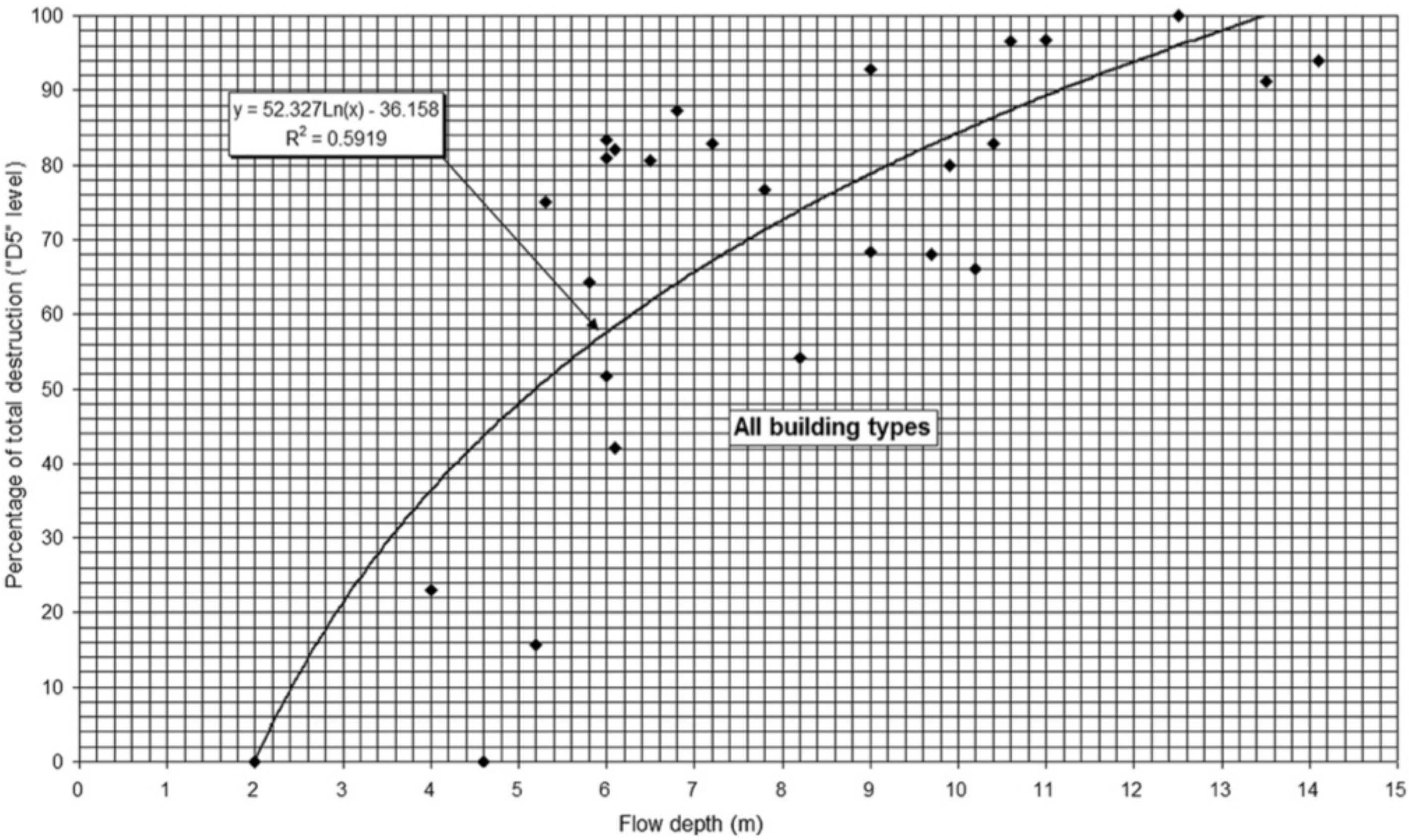

Figure 27. Mean damage curve for all building types in Banda Aceh (Leone et al., 2010).

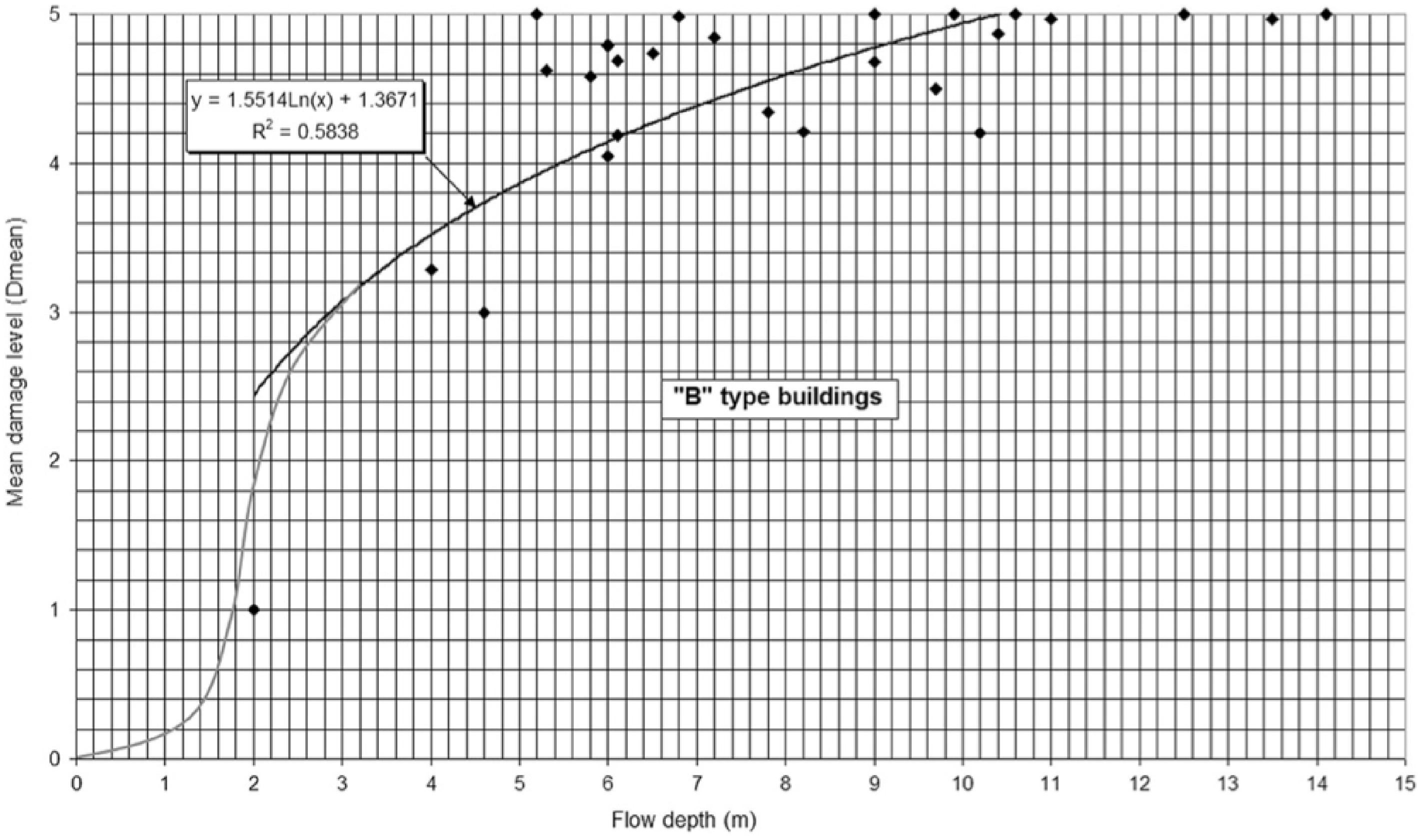

Figure 28 Mean damage curve for Banda Aceh buildings with RC frame, brick walls and 0 to 1 floors (Leone et al., 2011).

As shown by the equations reported in Figure 27 and Figure 28, Leone et al. (2011) adopted a logarithmic curve to interpolate the dataset.

5.2.4.6 *Suppasri et al. (2011)*

Suppasri et al. (2011) developed fragility curves using data extracted from visual interpretation of high-resolution satellite imagery (Ikonos) after the 2004 IOT in Thailand. Given the relatively low accuracy of a survey based on remote-sensing imagery (compared to field surveys), Suppasri et al. (2011) focused only on the probability of complete destruction of the above-mentioned building classes and could not investigate the fragility of specific building types. Similarly to Koshimura et al. (2009b), Suppasri et al. (2011) generated the tsunami demand parameters (i.e. flow depth, flow velocity and hydrodynamic pressure) using a numerical simulation (Figure 29).

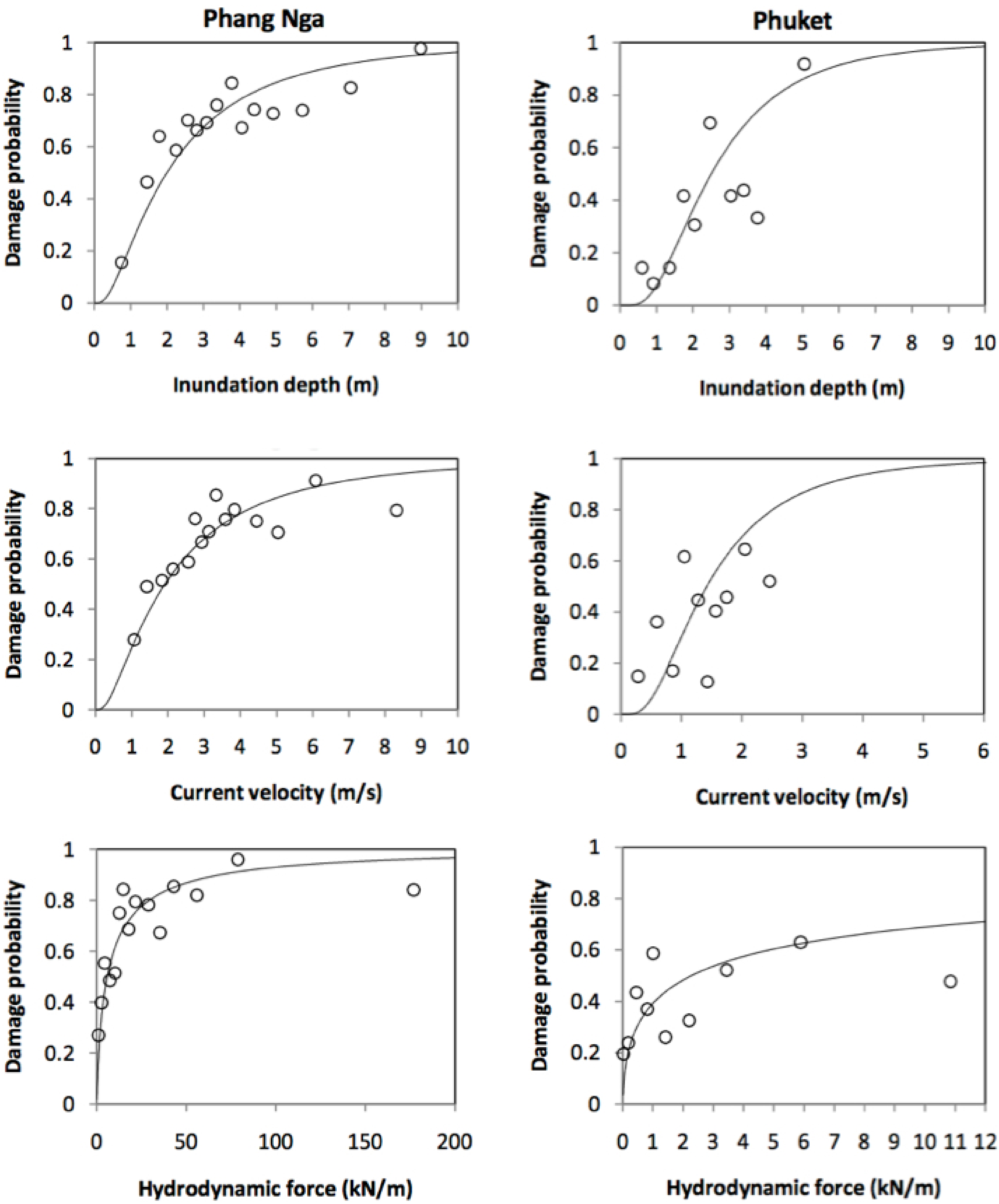

Figure 29. Fragility curves for complete destruction of buildings in Phang Nga and Phuket (Thailand) as functions of tsunami flow depth, flow velocity and hydrodynamic pressure (Suppasri et al., 2011). These curves include all building types.

Suppasri et al. (2011) link the evident gap between the curves for Phang Nga and Phuket buildings to the differences in the construction codes used in the two provinces. As a secondary result, Suppasri et al. (2011) used their database to integrate a previous study (Foytong, 2007) on the vulnerability of three different building classes in Thailand, including: (a) RC buildings; (b) mixed-type structures; (c) wooden buildings (Figure 30).

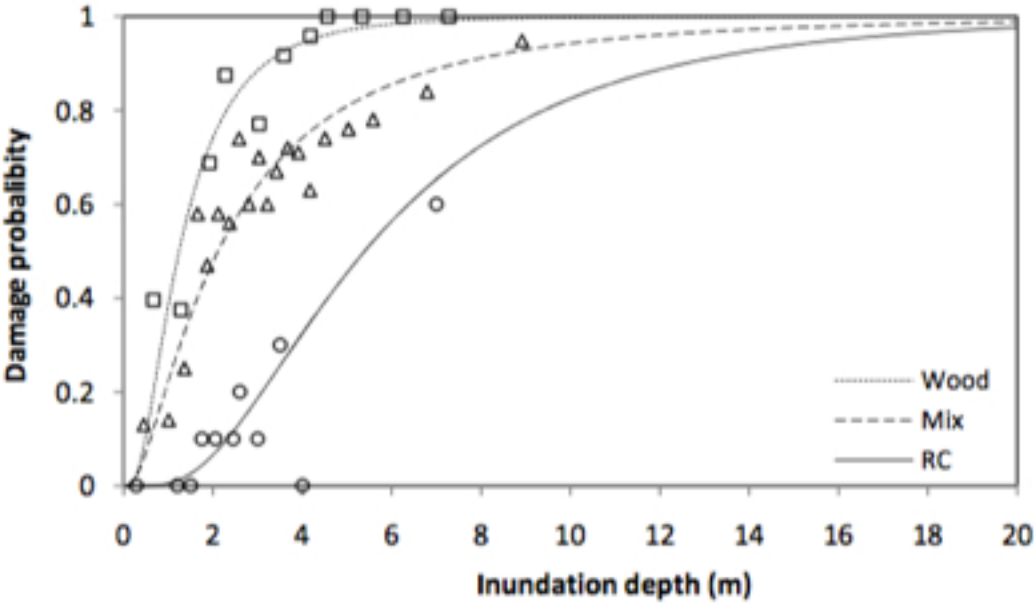

Figure 30. Tsunami fragility curves for complete destruction of three building types (reinforced concrete, mixed type and wooden) as a function on flow depth (Suppasri et al., 2011).

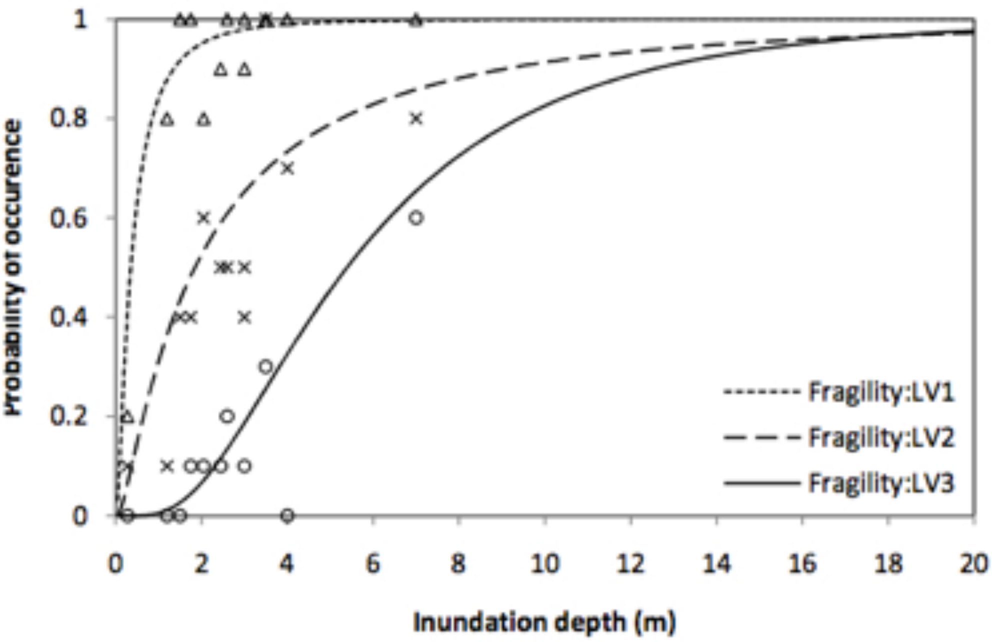

Figure 31. Tsunami fragility curves for three levels of damage as a function of inundation depth (Suppasri et al., 2011).

5.2.4.7 *Valencia et al. (2011)*

The work carried out by Valencia et al. (2011) is based on the same building dataset as Leone et al. (2011). However, Valencia et al. (2011) added to the original database new information on the 4095 buildings destroyed by the tsunami, that Leone et al. (2011) could not classify due to a lack of observations.

Valencia et al. (2011) overcame this issue through a detailed analysis of high-resolution satellite images (Quickbird), taken before the 2004 IOT in Banda Aceh. This allowed the classification of a further 2576 buildings according to their features, and the generation of a much wider set of fragility and mean-damage curves, including the following building types (Table 17).

Table 17. Building classes for which Valencia et al. (2011) developed tsunami damage curves.

CLASS	BUILDING DESCRIPTION	EXAMPLE IMAGES
A	Beachfront light constructions made of wood, timber, clay.	
B	One-storey buildings made of bricks and fieldstone, with cement mortar wall.	
C	Individual buildings, villas: brick with reinforced column and masonry filling. One or two storeys	
D	Non-engineered reinforced concrete buildings. Collective use. Two to four floors.	

The relevant 'weighted mean damage curves' – where the 'weight' corresponds to the number of buildings of the same class that suffered the same level of damage in response to the same flow depth – have a log-normal shape and are shown below (Figure 32, Figure 33, Figure 34, Figure 35).

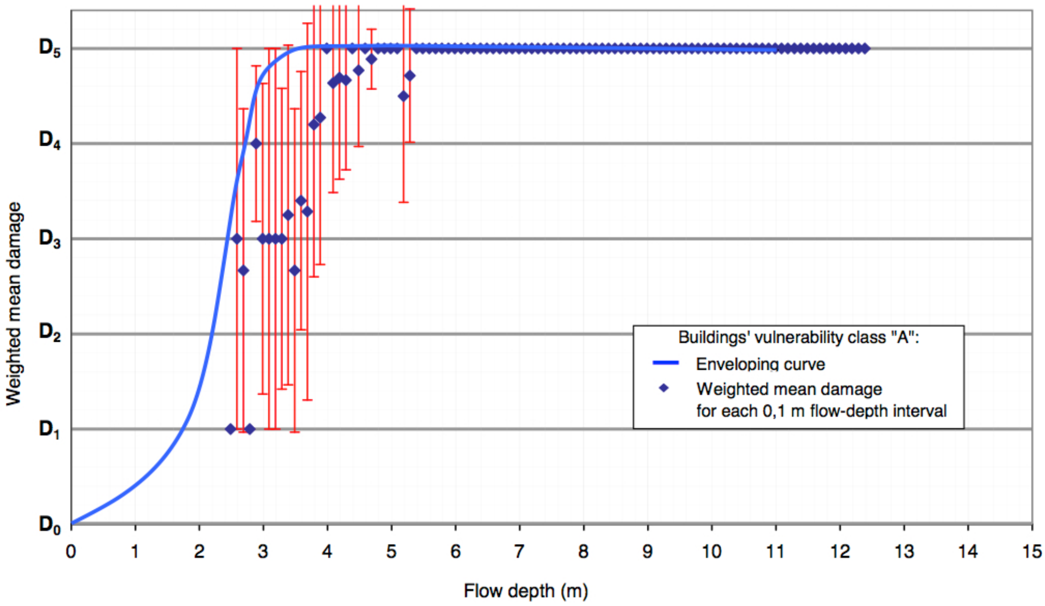

Figure 32. Enveloping curve for the weighted mean damage to buildings in class A (Valencia et al., 2011).

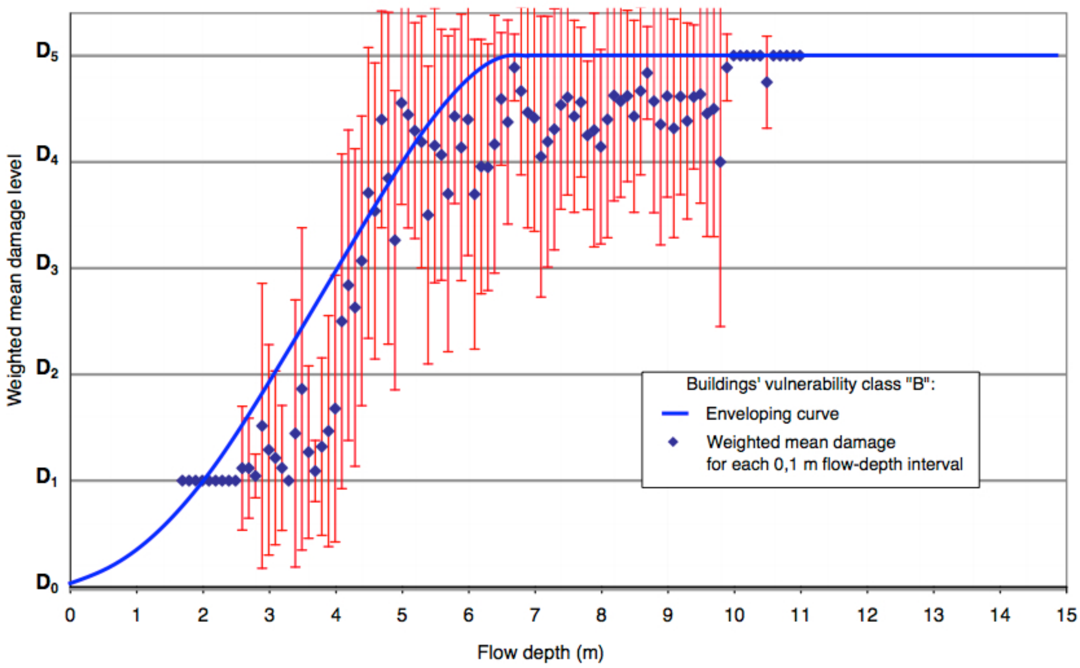

Figure 33. Enveloping curve for the weighted mean damage to buildings in class B (Valencia et al., 2011).

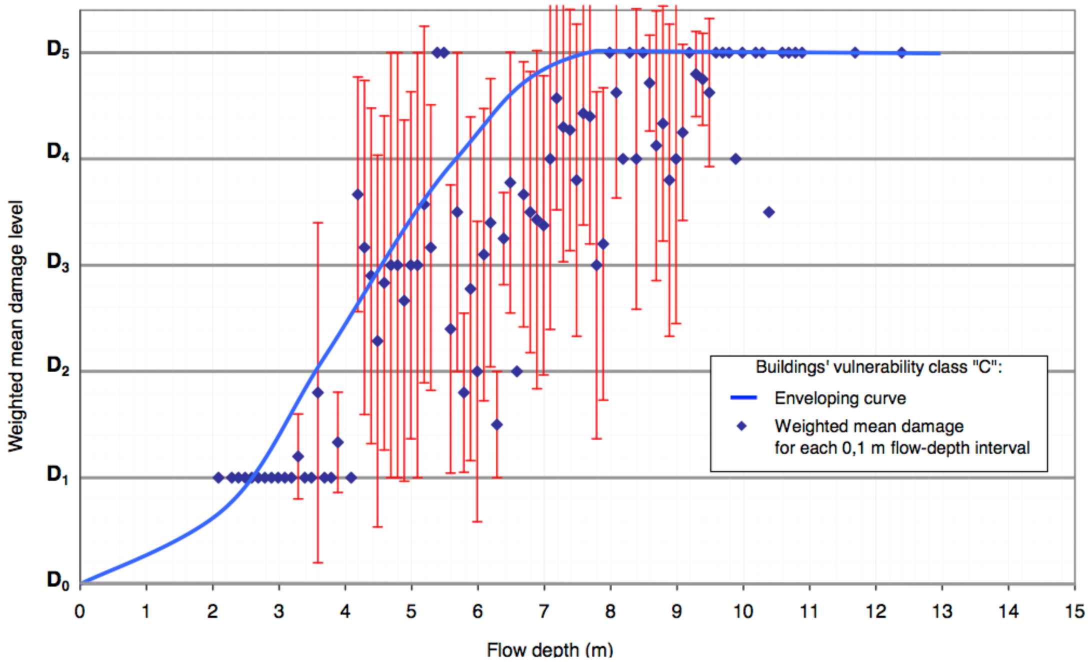

Figure 34. Enveloping curve for the weighted mean damage to buildings in class C (Valencia et al., 2011)

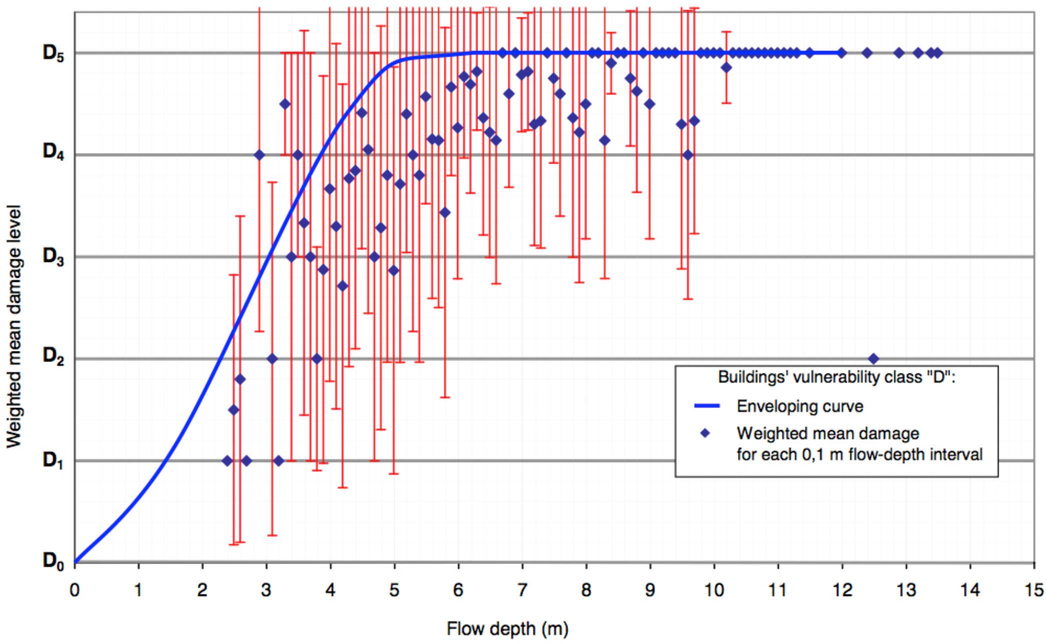

Figure 35. Enveloping curve for the weighted mean damage to buildings in class D (Valencia et al., 2011).

As can be seen from the curves, the average building resilience increases from class A to class C. However, surprisingly, buildings of class D (non-engineered reinforced concrete buildings, two to four storeys) are more vulnerable than buildings of class B (masonry construction) and C (masonry construction with reinforced columns, one or two storeys). Valencia et al. (2011) explain this unexpected finding with a possible lower performance of RC columns that are particularly vulnerable to the lateral impact of tsunami waves and debris (Saatcioglu et al., 2006). However, C Class buildings also have reinforced concrete frames and columns, but according to the survey they performed significantly better. Further, D Class buildings are taller than those of Class C, which should result in larger and stronger RC columns. Finally, it should be considered that a significant part of the damage to class D buildings could have occurred during the earthquake, rather than the tsunami itself. In fact, although Boen (2006) stated that the tsunami was responsible of most of the damage to Banda Aceh buildings, Cluff (2007) and Ghobarah et al. (2006) observed that the highest RC structures, particularly the non-engineered ones, were heavily affected by ground shaking. Specifically, Ghobarah et al. (2006) stated that the *seismic damage to the 3–5-storey high structures was substantial.*

Besides the discussion on the unexpected behaviour of Class D buildings, the work undertaken by Valencia et al. (2011) represents one of the most comprehensive examples of tsunami damage curves for different building types. This is due to (a) the relatively wide building dataset, providing the whole analysis with a strong statistical framework; and (b) the number of building classes for which the functions were developed. Further, the curves obtained for both the fragility and mean-damage functions have a log-normal shape, as most of the previous analyses (Peiris, 2006; Koshimura et al., 2009b; Suppasri et al., 2011).

However, the following assumptions and limitations can be identified:

1. Despite the huge magnitude (Mw 9.15), the effects of the earthquake on buildings are neglected, and all the observed damage is associated with the tsunami inundation. Although this is supported by the analysis of Boen et al. (2006), there might have been an overestimation of the tsunami-induced damage for those building classes most vulnerable to ground-shaking, for example Class D buildings.
2. The classification of 2576 buildings totally destroyed by the tsunami was solely based on photo-interpretation of high-resolution satellite images (i.e. Quickbird), a difficult and subjective process.
3. The enveloping 'mean weighted damage curves' were drawn manually, due to some difficulties in finding the best interpolating algorithm.
4. The analysis does not make distinctions between shielded and exposed buildings, which results in a higher variability of data and affects the accuracy of results (Reese et al., 2007; Reese et al., 2011).

5.2.4.8 *Reese et al. (2011)*

Reese et al. (2011) used field survey data collected after the 2009 South Pacific Tsunami to develop fragility curves for buildings in Samoa and American Samoa. Since the largest part of the surveyed structures were residential masonry buildings (120 out of 201), Reese et al. (2011) developed only two types of fragility functions: (a) one set of curves for all the 201 affected buildings in Samoa and American Samoa; (b) one set of curves for the residential masonry structures. Specifically, Reese et al. (2011) calculated the probability of every building class to reach or exceed six different damage levels (DS0: no damage, to DS5: total destruction) (Figure 36).

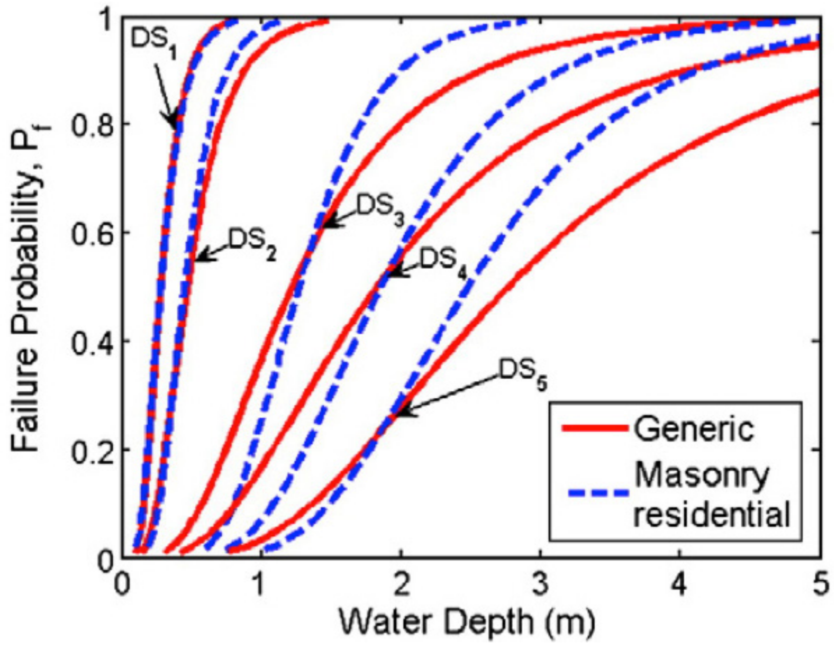

Figure 36. Fragility functions for all building types and for residential masonry buildings in Samoa (Reese at al., 2011).

Reese et al. (2011) further investigated the effects of shielding and debris, as in the 2006 Java tsunami (Reese et al., 2007). As shown in Figure 37, the effect of shielding can result in a much lower damage probability, particularly for higher damage state (DS4 and DS5). Similarly to the shielding effect, the presence of debris strongly influences building responses, especially for the highest damage levels (Figure 38).

5.2.4.9 Summary of existing tsunami fragility curves for buildings

The existing approaches for assessing the vulnerability of different building types to tsunami damage, based on fragility curves have been described in the previous sections. Table 18 summarises their main aspects.

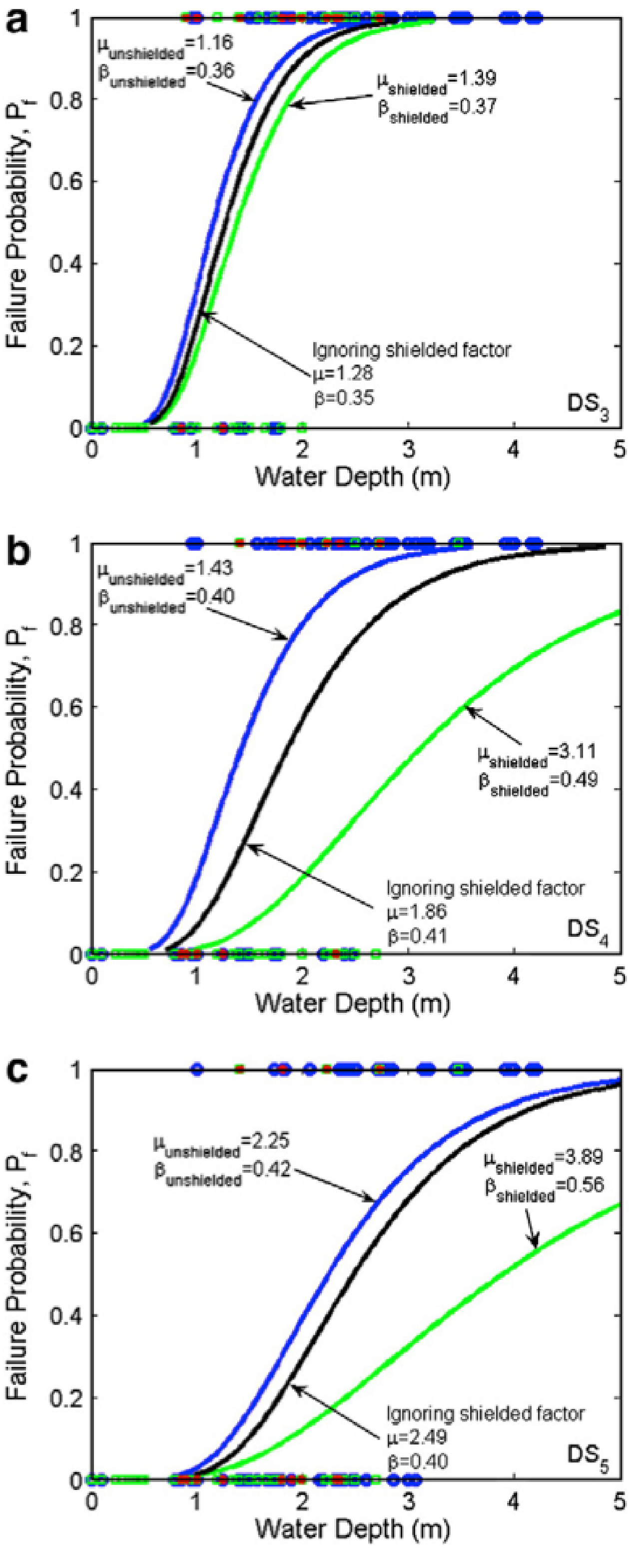

Figure 37. Effect of shielding on building fragility (Reese et al., 2011): (a) damage state DS3; (b) damage state DS4; (c) damage state DS5.

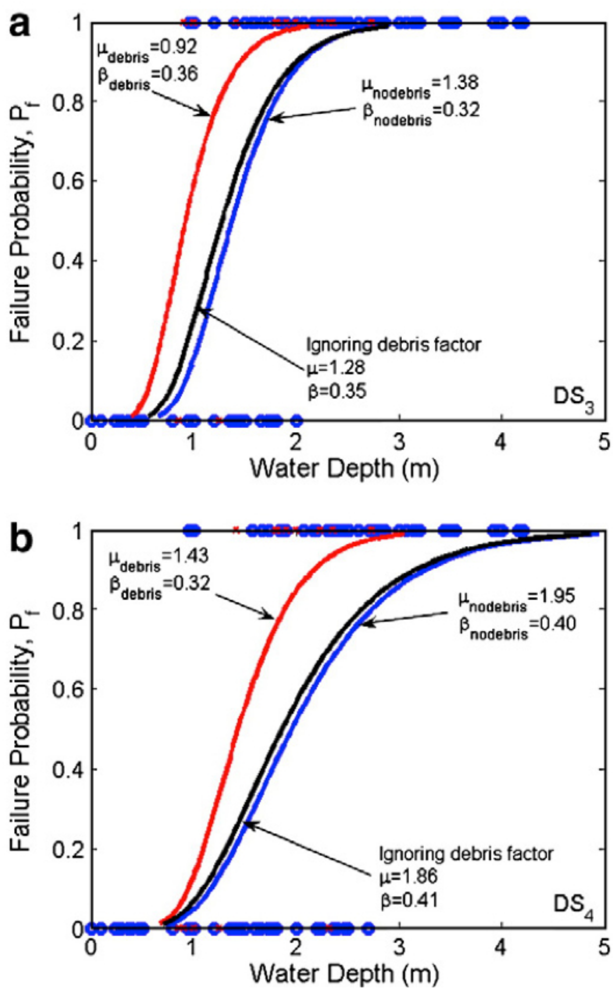

Figure 38. Effect of debris on the fragility of buildings (Reese et al., 2011): (a) Damage State DS3; (b) Damage state DS4.

Table 18. Summary of the main existing building fragility or damage curves for tsunamis.

REFERENCE	AREA	SURVEY TECHNIQUE AND BUILDINGS NO.	TSUNAMI DEMAND PARAMETER	BUILDING TYPES FOR WHICH CURVES WERE PUBLISHED	CURVE TYPES
Peiris (2006)	Sri Lanka, 2004 IOT.	Field surveys / unknown number of buildings	Flow depth	Masonry residential buildings	Fragility curves with 3 damage levels / log normal shape
Reese et al. (2007)	Java, 2006 tsunami.	Field surveys / over 1800 buildings	Flow depth	1. Timber / one floor (non-engineered) 2. Single layer of brick / one floor 3. Brick and RC columns 4. RC frames / two or more floors	Damage ratio curves / linear shape
Dias et al. (2009)	Sri Lanka, 2004 IOT.	Field Surveys / unknown number of buildings	Flow depth	1. With more than 50% of permanent materials 2. With less than 50% of permanent materials	Fragility curves for complete damage (bounding curves) / log normal shape
Koshimura et al. (2009b)	Banda Aceh, Indonesia, 2004 IOT.	Ikonos imagery / over 40000 buildings	Flow depth, velocity, hydrodynamic pressure	No classes / low rise wooden houses, timber and not engineered RC	Fragility curves for complete damage / log normal shape
Suppasri et al. (2011)	Thailand, 2004 IOT.	Ikonos imagery / 4806 buildings	Flow depth, velocity, hydrodynamic pressure	1. Wooden (after Koshimura 2009 in Japan) 2. Mixed type 3. RC	Fragility curves, with different damage level only for RC buildings / log normal shape
Leone et al. (2010)	Banda Aceh, Indonesia, 2004 IOT.	Field surveys and aerial imagery / about 1200 buildings	Flow depth	Bricks / 20 cm RC pillars / not engineered	Mean damage curves / Logarithmic shape
Valencia et al. (2011)	Banda Aceh, Indonesia, 2004 IOT.	Same dataset as Leone et al. (2010) plus Quickbird imagery / about 3800 buildings	Flow depth	1. Light beachfront wood / one storey 2. Brick not reinforced / one storey 3. Brick with RC columns / one or two storeys 4. Collective buildings, concrete not reinforced / two to four storeys, non-engineered	Mean damage curves for four building classes / log normal shape
Reese et al. (2011)	Samoa 2009	Field surveys / 201 buildings	Flow depth	1. Masonry residential 2. Mixed types	Fragility curves for 5 different levels of damage / log normal shape

5.2.5 The Weighting Process of the PTVA-3 Model

As the new version of the PTVA model to be developed as part of the COVERMAR project will still make use of expert judgment and multi-criteria analysis. The weighting procedure used in the existing PTVA-3 Model will be further improved by having the ranking process for the Analytic Hierarchy Process (AHP) (Saaty, 1986) undertaken by Dall'Osso et al. (2009a) repeated by external experts and stakeholders from different sectors involved in coastal zone management (i.e. coastal engineers, risk managers, urban planners, emergency services, environmental scientists, insurance companies). Before being submitted to the external experts, consideration will be given to converting the AHP into a questionnaire, developed using closed questions and according to the latest international scientific standards in the sector of natural hazards (Bird, 2009).

As output, every single questionnaire will provide a ranking of the physical attributes of buildings controlling their vulnerability to tsunami, calculated according to the priorities of each interviewee's area of expertise. Each questionnaire will be anonymous and contain no personal data. Finally, single rankings will be merged together using the Aggregation of Individual Priorities (AIP) approach, which is the best method for aggregating judgments within an AHP framework when interviewees have different value systems (Forman & Peniwati, 1998).

5.2.6 Vulnerability of Coastal Infrastructure to Tsunamis

Provided that enough information is available, the vulnerability of coastal infrastructure (i.e. harbours, wharfs, seawalls, streets, and the like) will be calculated by aggregating contributions made by their main structural/functional attributes (e.g. design, construction material, strategic importance during emergencies), according to the AHP-based approach used in the PTVA-3 Model. The relevant input data will be obtained from field survey reports and infrastructure damage assessments undertaken after tsunamis (Dalrymple & Kriebe, 2005; Ghobarah et al., 2006; Tinti et al., 2006; Dominey-Howes & Thaman, 2009).

6. SUMMARY AND CONCLUSION

This report has summarised the nature of extreme coastal inundations, the existing NSW policy and the relevant regulatory framework and the published information relating to methods for assessing the vulnerability of coastal assets. The following key topics have been considered:

a. Extreme Inundation Events.

This section provides a description of the natural processes able to generate destructive coastal inundations. It includes details on the generating mechanisms and inundation characteristics of storm surges and tsunamis, with a focus on the NSW context. Specifically, the section describes the main historical events that have affected the region and reports information on the current level of exposure – that is the number of people, buildings and critical infrastructure located in low-lying coastal areas. Although extreme inundations have relatively long ARIs (Average Recurrence Interval), consequences in NSW could be devastating. This condition is further exacerbated by climate change, which is likely to increase the frequency and intensity of severe coastal storms, as well as the exposure to tsunamis. Risk managers, policy makers and stakeholders need innovative multi-hazard tools to undertake accurate risk assessment studies and adopt balanced mitigation measures.

b. NSW Policy Framework on Coastal and Flood Risk.

This section includes an overview of the current NSW regulations and guidelines dealing with climate change and inundation risk. It also includes a flow chart of the main regulatory instruments, which helps provide an understanding of where and how the outcomes of the COVERMAR project will support the work of Combat Agencies, Local Councils, risk managers and other stakeholders.

c. Review of the Existing Methods for Assessing the Vulnerability of Coastal Assets to Extreme Inundations.

This section represents the core part of the report. Whilst the recent IPCC report on extreme events (IPCC 2012) emphasises the need for comprehensive multi-hazard tools, most of the existing methods are still based on single-hazard approaches. The review is therefore divided into two separate sub-sections, one about coastal storms and one about tsunamis.

In the case of coastal storms, damage to buildings can occur either though coastal erosion (causing reduced foundation capacity) or inundation, with the latter being less frequent in NSW. The best approach for assessing vulnerability to the wave scouring effect on building foundations is the one proposed by Nielsen et al. (1992), which is also recommended by the NSW Coastal Risk Management Guide (2010). Where foreshore or tidal inundation occurs, exposed buildings can be damaged by seawater contact, hydrostatic or hydrodynamic pressure on walls or even wave breaking. In these cases, vulnerability assessment methods are based on the use of fragility functions, associating the inundation depth (and/or flow velocity) with the expected level of damage.

With regard to tsunamis, there is a limited availability of validated fragility functions, as most of them have been developed only after the 2004 Indian Ocean Tsunami. The PTVA model is an index-based method that was developed with the specific purpose of compensating for the lack of fragility curves for tsunami damage. So far, the PTVA model is one of the most widely used approaches for assessing the vulnerability of buildings to tsunamis. In this section the newest version of the PTVA model (version #3) is compared with other index-based approaches, and it is concluded that the PTVA-3 model is the best available tool for the purposes of the COVERMAR project. This is due to (a) the flexibility of the PTVA-3 model that can be applied in different coastal regions; (b) the implementation of a multi-criteria approach based on the Analytic Hierarchic Process (AHP); and, (c) the use of a GIS (Geographic Information System) platform, which facilitates the management of large geographic databases and the generation of thematic maps. Recent studies have however outlined shortcomings of the PTVA-3 model. These include: (a) the lack of a numerical simulation of the tsunami propagation and inundation; (b) the recently developed building fragility curves for tsunami damage are not implemented by the model; (c) the multi-criteria analysis of the building attributes influencing their vulnerability to tsunamis requires further validation; and (d) the PTVA-3 focuses solely on the vulnerability of buildings and does not include coastal infrastructure (e.g. harbours, streets, bridges). Addressing these limitations is part of the objectives of the COVERMAR project. To this purpose, the section reviews the best available numerical models simulating tsunami generation, propagation and inundation in the Australia-Pacific area. It is concluded that the best option for the COVERMAR project is the ComMIT system. ComMIT is an internet-enabled interface to the community tsunami model developed by the NOAA Center for Tsunami Research (NCTR), implementing the MOST numerical model for tsunami propagation and inundation.

Further, this section reviews and cross-compares the newly published building fragility curves for tsunami damage. One of the most comprehensive approaches is the one provided by Valencia et al. (2011), who generated a set of damage curves for four types of buildings, using a database of building damage observed in over 4500 structures after the 2004 Indian Ocean Tsunami in Banda Aceh, Indonesia. This information will be implemented into the PTVA Model to generate a new upgraded version (the PTVA-4).

The overview of the relevant literature provided in this report is considered as the necessary scientific baseline upon which the COVERMAR project will move forward.

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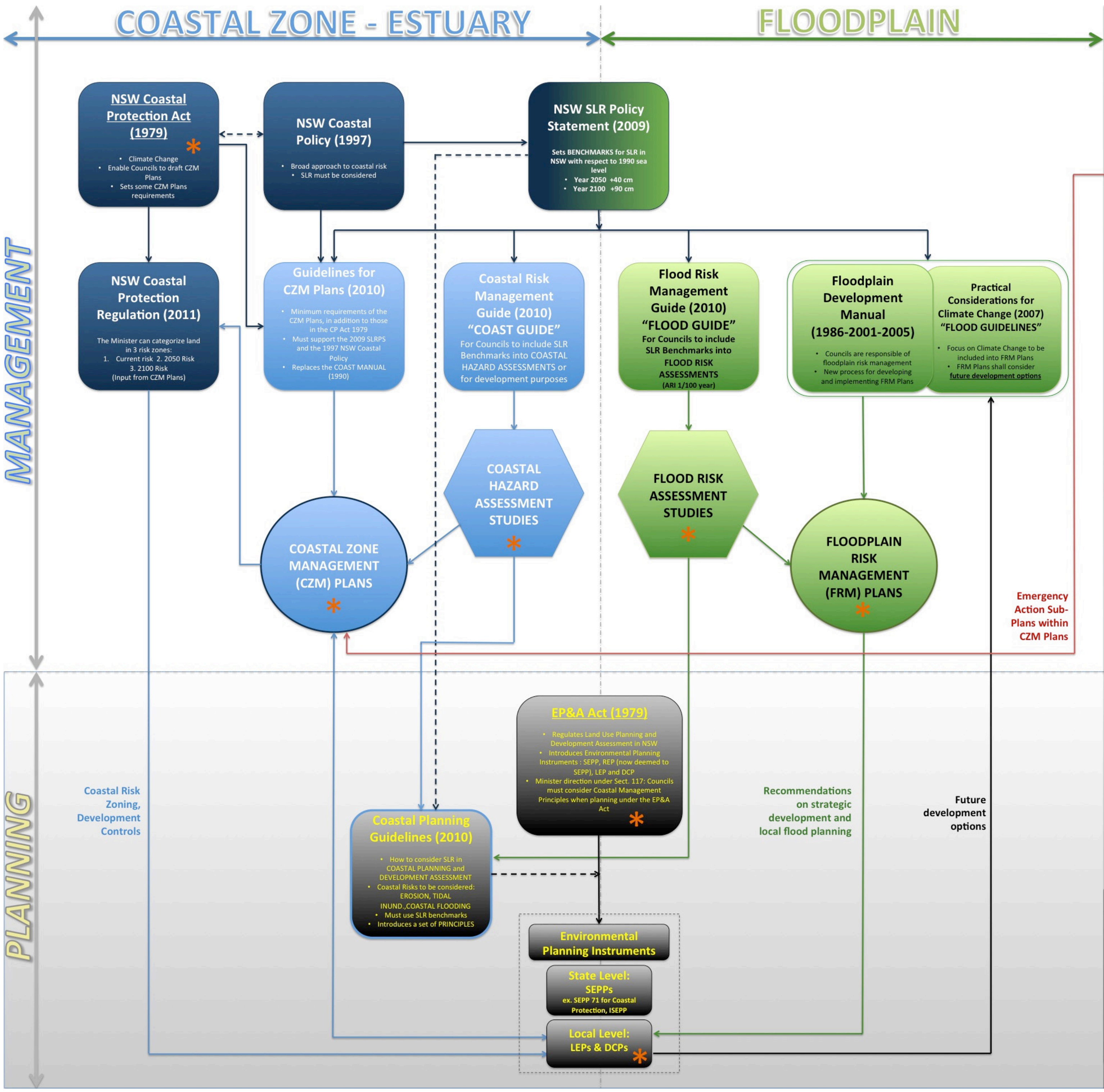
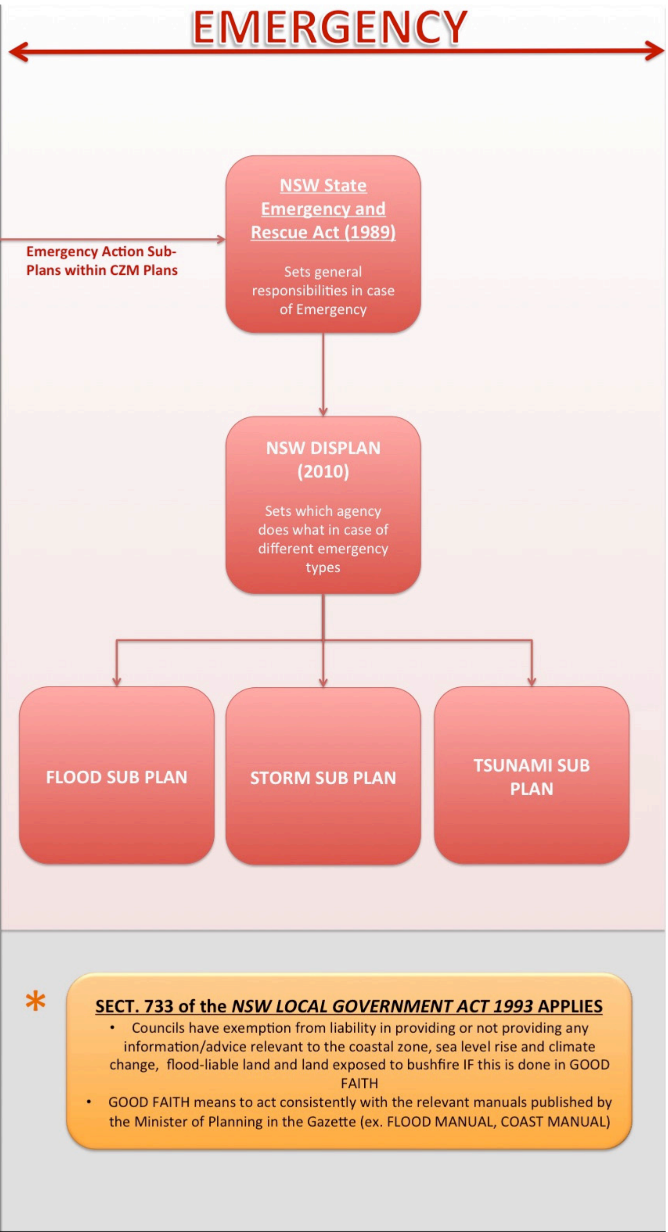
APPENDIX I - Flow-chart of NSW Regulation, Policy and Guidelines on Coastal and Flood Risk





Overview of the

NSW Legislation, Policy and Guidelines on Coastal and Flood Risk

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Prepared by
Dr. Filippo Dall'Osso
for the
COVERMAR project
f.dallosso@unsw.edu.au

UNSW
THE UNIVERSITY OF NEW SOUTH WALES
SYDNEY · CANBERRA · AUSTRALIA

SYDNEY COASTAL COUNCILS GROUP