Coastal Vulnerability to Multiple Inundation Sources

COVERMAR project

Final Outcomes Report

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SYDNEY COASTAL COUNCILS GROUP

Coastal Inundation.
COVERMAR Project.

Coastal Vulnerability to Multiple Inundation Sources Project (COVERMAR)

SYDNEY COASTAL COUNCILS GROUP

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

1. Literature Review Report
2. Hazard Assessment Report.

Copies are available from the project webpage
http://www.sydneycoastalcouncils.com.au/node/106

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Executive Summary

Background

Natural hazards such as tsunamis and 1/100 year storm surges have a low probability of occurrence, but high intensity and wide spatial distribution. Although these events are rare, their consequences for vulnerable coastal communities can be very significant.

In NSW, the risk of extreme inundation inrelation to such storm surges or tsunamis is very high. Urbanisation and sea level rise in the future are expected to further exacerbate this risk. Cascading effects, for example the trigger of a secondary hazard such as a chemical spill from a damaged industrial site, also contribute to risks. Natural hazards cannot be avoided but their impacts can be mitigated by reducing the vulnerability (susceptibility to damage) of exposed communities and assets.

Coastal Vulnerability to Multiple Inundation Sources (COVERMAR) Project

Typically the vulnerability of coastal assets to different inundation events has been calculated using a variety of approaches. This makes it difficult for decision makers and planners to understand and compare the results of different vulnerability assessments, and it also complicates the development of balanced, multi-hazard mitigation strategies. COVERMAR helps to overcome these issues by providing NSW emergency and risk managers with a tool capable of comparing the risks posed by multiple hazards, namely both tsunamis and storm surges. It has developed an innovative, multi-hazard tool for assessing the vulnerability of different types of buildings (e.g. wood, brick) and critical infrastructure (including schools, hospitals, power transmission infrastructure and council buildings) to extreme inundations. To demonstrate the efficacy of the tool, it was applied to three case study LGAs adjoining Botany Bay, Georges River (up to the Como Bridge), Bate Bay and Port Hacking, namely Botany Bay City and Rockdale City Councils and Sutherland Shire Council.

COVERMAR is Australia's first multi-hazard tool to assess the vulnerability of different building types and critical infrastructure to extreme marine inundation caused by both storm surges and tsunamis. Scenarios were simulated using state-of-the-art numerical models, under present and predicted future sea level conditions, and tested at NSW study sites spanning Botany Bay, Port Hacking and Bate Bay. Project outcomes assist NSW emergency and coastal managers and stakeholders. They have been specifically tailored to the needs of agencies and councils.

The project builds on the outputs of the 2009 SCCG study *A Method for Assessing the Vulnerability of Buildings to Catastrophic (Tsunami) Marine Flooding* (Dall'Osso and Dominey-Howes, 2009). This earlier project updated a widely used index-based tool for assessing the vulnerability of buildings to tsunamis – the Papathoma Tsunami Vulnerability Model, version 3 (PTVA-3), and applied it to two Sydney case study locations (Manly and Maroubra). COVERMAR has enhanced the tool by incorporating weighted data drawn from the expert opinion of relevant academics worldwide. It also developed that project by addressing multiple inundation sources incorporating probabilistic inundation scenarios, numerically simulated using state-of-the-art models, and integrating contemporary building vulnerability functions.

COVERMAR elements and deliverables

Key elements and deliverables of the project include the following:

Advisory Committee

Establishment of a project Advisory Committee (AC), which guided and informed each stage of the project. Membership of the AC included scientific experts, stakeholders and representatives from State and Local Government.

Literature Review and Report

Detailed Literature Review and Report outlining the scientific and legislative background including the nature of storm surges and tsunamis and their incidence in NSW. Uniquely, as part of the review, NSW regulation, policy and guidelines in coastal risk management, strategic planning and emergency management were examined and presented in a comprehensive flow-chart. The manner in which COVERMAR outputs contributed to relevant instruments, such as the NSW State Storm Sub-Plan and coastal zone management plans, were also tabulated.

Compatibility with NSW legislation

Implementing a methodology compatible with existing NSW coastal risk management, land use planning and emergency management legislation to facilitate the implementation of COVERMAR outcomes and recommendations by coastal, risk and emergency managers.

Case study selection

Selection of case study areas through a multi-criteria analysis comparing the vulnerability of the SCCG's 15 Member Councils' LGAs to extreme inundations. Each Council was scored against eight vulnerability selection criteria and a weight applied to each criterion reflecting its relative importance (as determined by the Advisory Committee).

Hydrodynamic simulations

Hydrodynamic simulation of storm surge and tsunami scenarios using state-of-the-art numerical models under different initial sea level conditions:

1. Current (2010) mean sea level
2. 2050 horizon (current msl +34 cm)
3. 2100 horizon (current msl +84 cm)

Consideration of different sea level conditions provided an understanding of changes in inundation extent with changes in sea level and tide.

Thirty nine different inundation scenarios were considered, 3 for storm surges and 36 for tsunamis. There were a greater number for tsunamis because scenarios considered three annual probabilities (1/100, 1/1,000 and 1/10,000) for both high tide and mean sea level at two source locations (New Hebrides and Puysegur). Scenarios were simulated using the model developed by the National Oceanic and Atmospheric Administration (NOAA) Centre for Tsunami Research. For storm surges, scenarios applied a single annual probability – that normally applied for extreme storm events – 1/100. Simulations used the outputs of the numerical modelling undertaken by McInnes et al. (2012), as part of the SCCG project entitled *Mapping and Responding to Coastal Inundation.*

Exposure estimates and presentation of results

To show the extent of the inundation and enable a count of exposed buildings and critical infrastructure, numerical outputs of the model were imported into a GIS system and superimposed upon aerial images and a Digital Elevation Model to generate thematic maps. The number of buildings inundated was tabulated and, for each case study area, results presented (tables and figures) in relation to inundated buildings, roads and critical infrastructure.

For the most severe storm surge (1/100 yr. + 84 cm sea level) the assessment identified that up to 3173 buildings would be exposed to inundation. For the worst tsunami event (Puysegur, 1/10,000 yr. + high tide + 84 cm sea level), 2623 buildings would be exposed. This equates to 4083 buildings being exposed to inundation from these two sources. For the least severe scenarios, the results would be 248 and 9 buildings respectively for storm surges (Puysegur, 1/100, current msl) and tsunamis (1/100, current msl).

Survey of building attributes

As the vulnerability of buildings and infrastructure to inundation is a function of their physical and engineering attributes, all 4083 exposed buildings were individually surveyed against 16 different attributes divided into 24 classes and 117 subclasses. These results together with relevant building footprints were entered into a GIS. Infrastructure was also surveyed against eight infrastructure classes (health, government, utility, education, transport, recreation and coastal), comprising 30 different elements.

Building vulnerability

To assess the vulnerability of buildings (degree of expected damage), the following work was undertaken:

1. For storm surge, two potential damage types were considered
   a) Erosion of the soil substrate undermining building foundations. In this case, vulnerability was assessed using storm erosion lines (generated by relevant councils), as recommended by the 2010 NSW Coastal Risk Management Guide.

   b) Tidal inundation (i.e. inundation along tidal waterways). Vulnerability was assessed by applying 19 contemporary building vulnerability functions developed by Geoscience Australia to the corresponding building. The functions were modified and adapted to match the buildings in the study area.

2. For tsunamis, a combined approach was utilised:
   a) Development and utilisation of an improved Papathoma Tsunami Vulnerability Assessment Model (a GIS-based vulnerability assessment tool). The determination of the weights ascribed to building attributes in the PTVA Model was improved by submitting a questionnaire to all the authors of scientific papers published in the last 10 years in the field of building vulnerability to tsunamis. Authors re-weighted the attributes of the PTVA-3 Model and included information from the 2011 Japan Tsunami. The improved model was used to generate vulnerability maps.

   b) Applying a set of contemporary building vulnerability functions developed in Japan after the 2011 Tohoku Tsunami, adapted to the case study areas to estimate economic lost to buildings. Damage to streets and carparks was assessed by reference to flow velocity.

Economic loss

The economic losses of buildings and critical infrastructure linked to the selected inundation scenarios across the three case study areas was then calculated, adopting an approach widely used in the insurance and re-insurance industry (Probable Maximum Loss, 'PML').

The vulnerability assessment identified the number of buildings that would require replacement and the number that would be in need of repair. Buildings were considered to require replacement if repair was uneconomical. For each building type, the construction cost was calculated by using the total construction cost per building type or, where this was unavailable, the construction cost per square metre used for tax depreciation purposes. The construction, demolition and replacement costs were calculated for all the 117 different building subclasses. Construction costs for roads and streets were obtained from a relevant industry costs guide.

Of the 4083 buildings surveyed across the study areas, 555 buildings were inaccessible and therefore could not be assigned to a class. To account for this, we calculated two PML estimates, one that excluded these buildings and another which assumed all inaccessible buildings to be the most frequent building type in the study area (i.e. residential, one storey, brick veneer with a raised ground floor).

For the most severe storm surge event (1/100 yr. + 84 cm sea level) the economic loss to buildings would total ~$263.3M. For the worst tsunami event (Puysegur, 1/10,000 yr. + high tide + 84 cm sea level) economic losses can total up to $728.1M. For the least severe scenarios, the results would be $26.2M and $3.1M respectively for storm surges (1/100 yr., current msl) and tsunamis (Puysegur, 1/100 yr., current msl).

Display of geographically referenced information

The vulnerability level of each exposed building was displayed on 66 thematic GIS maps, where building vulnerability is represented using a colour-coded scale.

Recommendations

Recommendations have been developed to improve hazard assessment and building vulnerability and in relation to coastal risk management, planning and development and emergency management. Future research opportunities are also identified and discussed. Key recommendations and research opportunities are detailed overleaf.

Results

Results of the exposure and vulnerability assessment demonstrated that:

1. Tsunamis triggered in Puysegur, New Zealand would reach the study area in about 2.5 hours and those originating in the New Hebrides, Vanuatu would take over 4 hours.
2. Extreme inundations, particularly those caused by tsunamis, can trigger 'cascading effects' (e.g. an inundated industrial site can release pollutants into the environment).
3. Kingsford Smith Airport and Port Botany would be heavily inundated by the most severe scenarios: storm surge 1/100 yr. + 84 cm sea level and tsunami, Puysegur, 1/10,000 yr. + high tide + 84 cm sea level.
4. Storm erosion is currently a low threat to the buildings in the study areas, but it would cause significant damage to beaches, coastal structures and transport infrastructure.
5. Sea level conditions (e.g. tide level, adjustments for predicted sea level rise) have a strong influence on the number of buildings and infrastructure inundated by both storm surge and tsunamis.
6. The exposure of buildings and infrastructure to 1/100 yr. storm surges is significantly higher than the exposure to all simulated tsunami events (i.e. 1/100 yr, 1/1,000 yr, 1/10,000 yr) under the same initial sea level conditions.
7. The average economic loss per building (Probable Maximum Loss) caused by a 1/100 yr. tsunami is three times higher than that caused by a 1/100 yr. storm surge. However, if all buildings of the study area had a raised ground-floor (+30 cm above ground level), the total PML would decrease by 44.6% (storm surge) and 29.6% (tsunami).
8. The total economic loss for building impacts caused by tsunamis and storm surges having an annual probability of occurrence of 1/100 yr. is comparable (against 1/100 yr. tsunamis, the number of buildings exposed to 1/100 yr. storm surges is higher but the damage to individual buildings is less). However, the PML caused by 1/1,000 and 1/10,000 yr. tsunamis is many times higher than that caused by 1/100 yr. storm surges.
9. Hotspots representing the most exposed and vulnerable locations within the study areas were identified by COVERMAR and are listed against each LGA. It also identified an area that may become isolated by most tsunami and storm surge scenarios and the implications for the nature of the buildings in that area.

Key recommendations

1. Undertake multi-risk assessments for all LGAs along the NSW coast using the COVERMAR methodology to understand exposure and vulnerability based upon local geomorphological and environmental conditions and local building types.
2. Increase the hazards considered via the COVERMAR methodology to include other natural hazards such as extreme rainfall, catchment runoff, landslide and bushfire.
3. Review of building codes in areas exposed to storm surge or tsunami.
4. Emergency plans and planning strategies would be enhanced by including the risk of extreme inundations and concomitant potential cascading effects.
5. As tsunamis triggered in Puysegur (New Zealand) would reach the study area in about 2.5 hours there would be limited time to evacuate 'one Km inland, or 10 m above mean sea level', as recommended by the NSW Tsunami Emergency Sub Plan (2008). For such events, multi-storey buildings identified by COVERMAR as being 'tsunami-safe' could be used for vertical evacuation.
6. During extreme inundations, conventional transport routes may be damaged or inundated and should not be considered as an option for evacuation or the transportation of aid.

7. Emergency response plans include special provisions for buildings providing critical services during emergencies (e.g. police stations) and buildings particularly vulnerable such as education and health facilities.
8. As Kingsford Smith Airport and Port Botany would be heavily inundated by the most severe tsunami and storm surge scenarios, although such events have a low probability of occurrence, the consequences would be very high and these risks should be addressed in relevant emergency plans.
9. Relevant emergency management authorities organise engaging public awareness activities for the community to test and prepare community responses to an evacuation order.
10. Local government authorities collaborate with relevant State and Federal government agencies to enhance the quality, accuracy and coverage of their building inventory databases. High quality datasets aid accurate inundation risk assessment, development and planning, and natural hazard risk assessment.

Research opportunities

Project outputs can be further developed by attending to the following:

1. Social vulnerability assessments of local communities to compliment and extend engineering focused work.
2. Additional numerical modelling to refine the storm surge inundation assessment by McInnes et al. (2012).
3. The risk of tsunamis arising from underwater submarine slides off the continental shelf is unknown but potentially high. Hazard assessment of submarine slides and their tsunami potential would be particularly useful.
4. Developing vulnerability models using building vulnerability functions specifically designed for the building stock in the study area.

This report

This report describes the methodology and results of the building and infrastructure vulnerability assessment at a NSW case study location. It also summarises and draws upon the outputs of the two previous COVERMAR stages.

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ACRONYMS

AHD	Australian Height Datum
ComMIT	Community Model Interface for Tsunamis
COVERMAR	Coastal Vulnerability to Multiple Inundation Sources
DEM	Digital Elevation Model
ECL	East Coast Low
GIS	Geographic Information System
LGA	Local Government Area
MOST	Method of Splitting Tsunamis
NCTR	NOAA Centre for Tsunami Research
NOAA	National Oceanographic and Atmospheric Administration
PML	Probable Maximum Loss
PTVA	Papathoma Tsunami Vulnerability Model
RVI	Relative Vulnerability Index
SCCG	Sydney Coastal Councils Group Incorporated

AIM AND OBJECTIVES

AIM

Enhance the capability of local government and State agencies to assess the vulnerability of the built environment to extreme marine inundation caused by storm surges and tsunamis.

OBJECTIVES

1. Develop a multi-hazard tool to assess the vulnerability of buildings and critical infrastructure to extreme marine inundations caused by both storm surges and tsunamis.
2. Generate thematic maps showing the level of vulnerability of single buildings and infrastructure to selected inundation events, allowing a comparison of the risk posed by different types of extreme inundations so as to inform long term risk reduction measures and emergency management strategies.
3. Enhance scientific understanding of single- and multi-hazard inundation scenarios, incorporating storm and tsunami hazards, impact and vulnerability.
4. Improve the modelling and risk assessment capacity of local government and emergency services in relation to individual and multiple inundation hazards, infrastructure, disaster preparedness (including education and evacuation) and recovery and response.
5. Create knowledge to underpin decision making and planning.
6. Improve community resilience to, and education regarding, coastal hazards and disasters.
7. Enhance transferability of coastal risk assessment technology to local government.

SCOPE

IN SCOPE

1. Review and synthesise published and grey literature relating to:
   a) Storm surge and tsunami;
   b) Emergency risk management in NSW pertaining to inundation;
   c) Building fragility curves;
   d) Hazard risk to NSW from tsunami and storm surge.
2. Engage key stakeholders.
3. Undertake a multi-hazard assessment for the following storm surge and tsunami scenarios:
   - 1/100 yr. storm surge, occurring under different sea level conditions (i.e. 2010 mean sea level, +34 cm and +84 cm)
   - 1/100 yr, 1/1,000 yr and 1/10,000 yr tsunamis, originating at two sources (Puysegur Trench and New Hebrides Trench), occurring under different sea level conditions (i.e. 2010 mean sea level, +34 cm and +84 cm) and with two different tide levels (i.e. mean sea level and +97 cm high tide).
4. Undertake a vulnerability assessment, applied to three local government case study areas in NSW.
5. Assess the vulnerability of buildings and infrastructure to the selected inundation scenarios in relation to streets, and critical buildings including Government (e.g. council offices, Police Stations, Fire Brigade, Surf Life Savers), utilities (e.g. public transport, power transmission, Sydney Water buildings), health (e.g. hospitals, medical centres), education (e.g. schools and kindergartens) and recreational/heritage (e.g. sports centres, theatres, heritage buildings, churches).
6. Develop a multi-hazard assessment tool.

OUT OF SCOPE

1. The consideration of wave run-up in the storm surge inundation scenarios.
2. The consideration of hydraulic processes in the storm surge inundation scenarios.
3. Tsunamis generated by submarine landslides.
4. The value of building contents (i.e. chattels and other moveable items) in the calculation of economic loss.

TARGET AUDIENCE

Local government and State agency professional staff involved in the assessment, planning and management of coastal and floodplain hazards and who are generally familiar with the concepts and matters outlined in this report. The report can also assist other stakeholders such as emergency managers and response agencies.

CONTEXT

Storm surges and tsunamis are different physical processes: the former are forced by meteorological drivers and the latter, in most instances, by geologic mechanisms. However, the impacts of these events may be similar (Figure 1).

NSW is susceptible to both storm surges and tsunamis. More than 200,000 buildings are at 'risk' from inundation and erosion. Within the Sydney basin, some 20,000 properties are located <1 km from the shoreline and at <3 m above sea level (Chen and McAneny, 2006). In addition, continued urbanisation as well as predicted future sea level rise can exacerbate exposure. Storm surges and tsunamis cannot be avoided; however impacts can be reduced by mitigating vulnerability.

Figure 1. Visual comparison of the damage caused by tsunamis and storm surges. The pictures were before and after the 2011 Tohoku Tsunami (Japan) and the 2012 Sandy Hurricane (USA) (http://www.abc.net.au/news/specials/japan-quake-2011/, http://www.abc.net.au/news/specials/hurricane-sandy-before-after-photos/)

The vulnerability of coastal assets to different inundation events has been calculated using a variety of approaches rendering it extremely difficult for decision makers and planners to understand and compare the results of different vulnerability assessments. It also complicates the development of balanced, multi-hazard mitigation strategies. COVERMAR helps to overcome these difficulties by providing NSW emergency and risk managers with a tool capable of comparing the risks posed by multiple hazards, namely tsunamis and storm surges. To demonstrate the effectiveness of the tool, it was applied to three case study LGAs within the Sydney Metropolitan Area, namely Botany Bay City and Rockdale City Councils and Sutherland Shire Council (Figure 2).

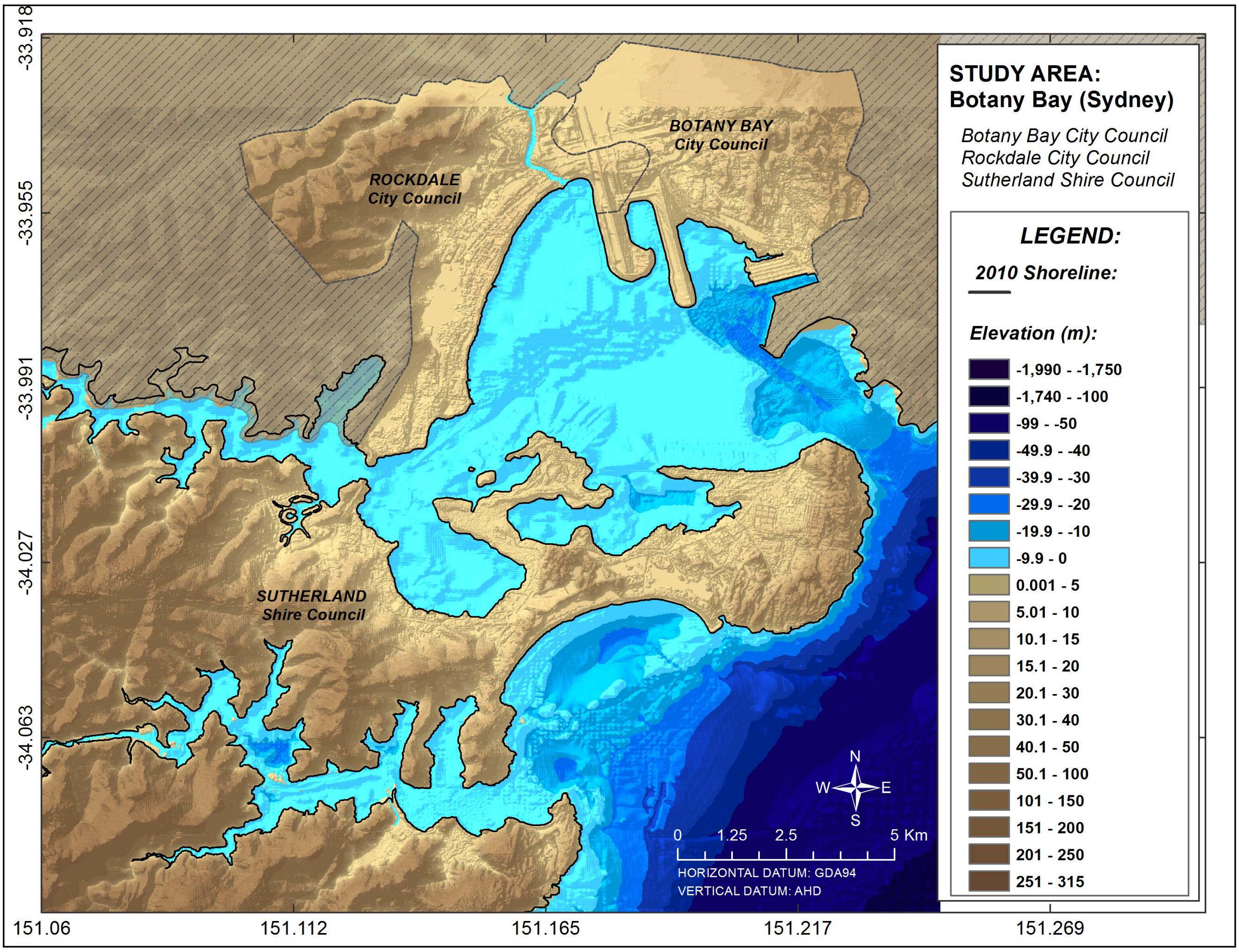


Figure 2. The selected case study locations: LGAs of Botany Bay City and Rockdale City Councils and Sutherland Shire Council. For Sutherland Shire Council, the study area covers the coastal zone of Botany Bay and Georges River (up to the Como Bridge), Bate Bay and Port Hacking.

This report represents the third and final stage of the project. The first stage Literature Review Report and second stage Hazard Assessment Report are available on the project webpage: http://www.sydneycoastalcouncils.com.au/Projects

BUILDING UPON PREVIOUS WORK

A Method for Assessing the Vulnerability of Buildings to Catastrophic (Tsunami) Marine Flooding

This project contributes to existing research. In 2009, Dall'Osso and Dominey-Howes undertook a project which developed a 'Method for Assessing the Vulnerability of Buildings to Catastrophic (Tsunami) Marine Flooding' (Dall'Osso and Dominey-Howes, 2009). This research, also funded under the Natural Disaster Resilience Program, developed a GIS-based vulnerability assessment tool (the Papathoma Tsunami Vulnerability Assessment Model, version 3) and applied it to the oceanic Sydney beaches of Manly and Maroubra to evaluate the impact of a hypothetical tsunami on buildings.

Papathoma Tsunami Vulnerability Assessment Model, version 3

The PTVA-3 model is an index-based computer tool offering a GIS-based approach to estimating the vulnerability of different building types to potential tsunami threats (Papathoma and Dominey-Howes, 2003; Dall'Osso et al., 2009a; Tarbotton et al., 2012). The model calculates a Relative Vulnerability Index (RVI) for each building within an expected inundation zone as a function of its attributes (e.g. number of storeys, material of construction, foundation type, and the like), surroundings and expected tsunami flow-depth. The advantage of index-based methods is that since they incorporate many idealised structural attributes in the calculation of the total vulnerability of a building, the differences between different building structures can be robustly and sensitively determined. To date, the PTVA Model is the world's most widely used index-based method for assessing the vulnerability of buildings to tsunamis (Tarbotton et al., 2012).

Vulnerability assessment – Manly and Maroubra

In Manly and Maroubra, Dall'Osso and Dominey-Howes (2009) identified and mapped respectively, 1200 and 300 buildings that would be inundated by a 5 m tsunami wave. They assessed the vulnerability to tsunamis of these buildings using the PTVA-3 Model, generating a set of thematic building vulnerability maps (see for example Figure 3) and provided recommendations for long-term tsunami risk management and land use planning strategies. Project outputs may be viewed online: http://www.sydneycoastalcouncils.com.au/Project/Vulnerability _of_Buildings_Tsunami_Flooding

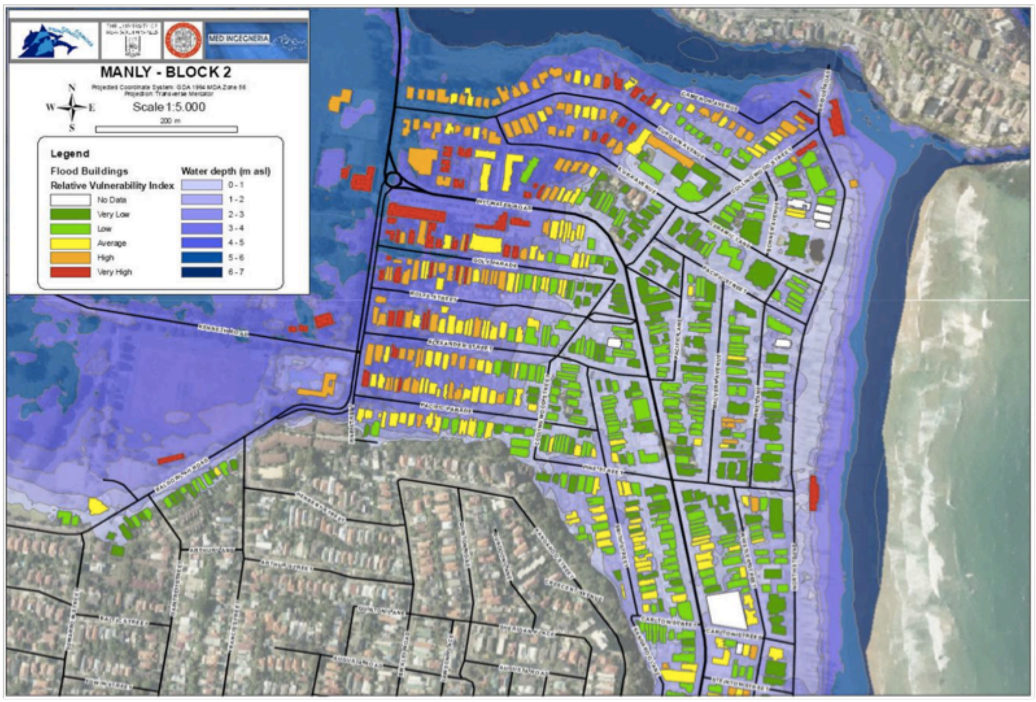


Figure 3. Tsunami vulnerability map generated by Dall'Osso and Dominey-Howes (2009). The vulnerability of each building is calculated using the PTVA-3 Model and represented using a colour-coded scale.

THE COVERMAR CONTRIBUTION

The 2009 project identified a number of areas where outputs could be enhanced. COVERMAR addresses those areas and the enhancements undertaken are detailed below:

COVERMAR	DALL´OSSO AND DOMINEY-HOWES, 2009
• Multi-hazard approach, assessing and comparing the impacts of tsunamis and storm surges with the same annual probability of occurrence.	• Focused on vulnerability to tsunamis.
• Probabilistic assessment of tsunami and storm surge hazards. All inundation scenarios that were analysed were associated with the annual probability of occurrence. This information is of utmost importance to local councils and coastal risk managers, because it allows a comparison between different hazard types.	• Deterministic approach which concentrated on the tsunami 'worst case scenario' (probabilistic estimates were unavailable).
• Hydrodynamic simulation of inundation scenarios using state-of-the-art numerical models.	• Static bathtub-filling method. Any area with a topographic elevation less than 7m AHD was assumed to be equally inundated by a flat, static water level.
• Consideration of different sea level conditions. Sea level rise and tide variations are included in the selected tsunami and storm surge scenarios. This is important as the same tsunami or storm surge with a higher initial sea level can inundate a different expanse of area.	• A single initial sea level condition, corresponding to the 2009 mean sea level, high tide conditions.
• Improved the PTVA-3 Model by including weights assigned under a multi-criteria analysis. The PTVA model calculates the contribution of different building engineering attributes to the final building vulnerability index as a weighted sum. Weights are a valuable contribution to the model because different building attributes differentially influence the final building vulnerability (e.g. the construction material is more important than the building preservation condition). COVERMAR re-weighted the building vulnerability attributes based on the judgments of leading scientists in the field, and also accounted for new knowledge generated after the 2011 Japan tsunami.	• Assignment of weights through a multi-criteria analysis based on the judgment of a restricted number of experts.
• Implemented insights from contemporary building vulnerability functions for tsunamis and storm surges. These are continuous curves that associate the intensity of the inundation (i.e. the flow-depth, or the flow velocity) to the expected response of a particular building type. The use of vulnerability functions offers important advantages over index-based methods PTVA Model. The fragility functions adopted include: (a) tsunami functions developed after the 2011 Japan tsunami by Suppasri et al. (2012), who surveyed over 252,000 damaged buildings; and (b) flood functions developed by Geoscience Australia for typical Australian buildings (Maqsood et al., 2013).	• Tsunami vulnerability functions were not considered.
• Calculated the economic losses of buildings and critical infrastructure linked to the selected inundation scenarios, adopting the approach used in the insurance and re-insurance industry (Probable Maximum Loss).	• Economic losses were not considered.
• Methodology is compatible with NSW coastal risk management, land use planning and emergency management legislation. This facilitates the implementation of COVERMAR outcomes and recommendations by local councils and coastal risk and emergency managers.	• These matters were not considered.

PROJECT DELIVERABLES

COVERMAR delivered the following:

PROJECT ADVISORY COMMITTEE (AC)

The creation and facilitation of an AC of relevant experts was a key output. The Committee was able to retain and engage key stakeholders and ensured the project outputs were of the highest quality.

The AC was established at the project's inception through a process which first identified the skill set necessary to meet the project aim and objectives and then cross-referenced this skill set against experts from international, Federal, State and local organisations involved in coastal hazards, risk prevention and mitigation. These experts were then invited to join the AC, subscribing to a comprehensive terms of reference.

Input from relevant experts throughout the project ensured that the project benefitted from considerable intellectual capital – drawing upon extensive experience and qualifications. The AC was instrumental in guiding and informing all stages of the project and value adding outputs.

LITERATURE REVIEW REPORT (DALL'OSSO AND DOMINEY-HOWES, 2013)

Published and grey literature in the following areas were investigated, evaluated and synthesised to provide context and background information on:

a) The definition of risk, hazard and vulnerability in the context of natural disasters

Despite the high number of definitions that can be found in the literature, the concept of risk as a function of 'hazard' and 'vulnerability' is accepted and widely used. The term *vulnerability* refers to the *characteristics of an asset that make it susceptible to the damaging effects of a hazard* (UN ISDR, 2009). A hazard is a *potentially damaging natural phenomenon defined by its intensity, probability of occurrence and spatial distribution* (Coburn et al., 1994).

b) Extreme inundations in NSW: storm surges and tsunamis

Storm surges are *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)* (IPCC, 2012). When storm surges are associated with a high-tide, the combined water level is known as a 'storm tide' (Helmann et al. 2010). During a storm tide, the increased water level along the shore has two main contributors:

- A rise of the 'still water' level, caused by a combination of high tide, low barometric pressure, wind and wave set-up (i.e. the piling-up of water on the coastline due to the dissipation of wind and wave energy);
- A temporary increase of water level due to the action of waves on top of the still water level (wave run-up).

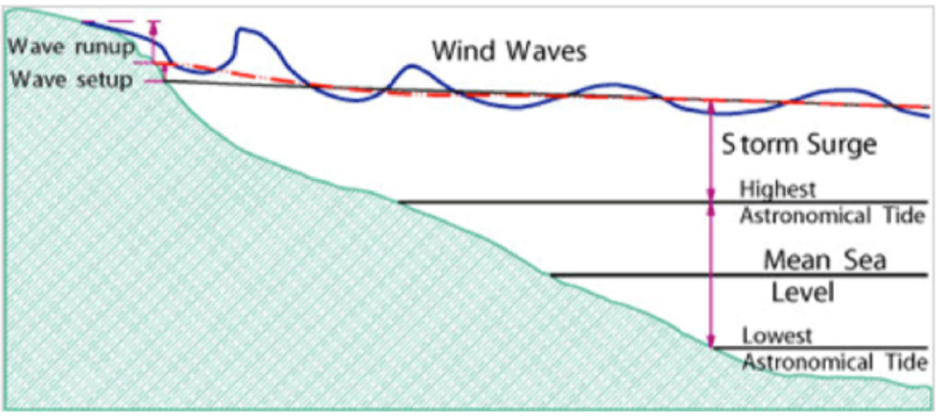


Figure 4. Contributions to extreme sea levels during a storm surge (McInnes et al., 2012).

In eastern Australia, storm surges are normally associated with tropical cyclones or East Coast Lows (ECLs), with the latter typically developing in middle-latitude regions, such as New South Wales. During East Coast Lows, the still water level along the NSW coastal fringe may increase up to about 2 m (without considering the contribution of tide), and wave run-up can reach 3–6 m (NSW Government, 1990).

Tsunamis are a *series of ocean waves generated by sudden displacements in the sea floor, landslides, or volcanic activity* (NOAA, 2012) (Figure 5). This 'wave train' may have wavelengths in excess of 100 km and periods of minutes to over an hour, depending on the generation mechanism (IOC, 2006). As a tsunami approaches the coast, its velocity decreases (with the decrease in water depth) and the wave amplitude increases (an effect of the energy conservation principle).

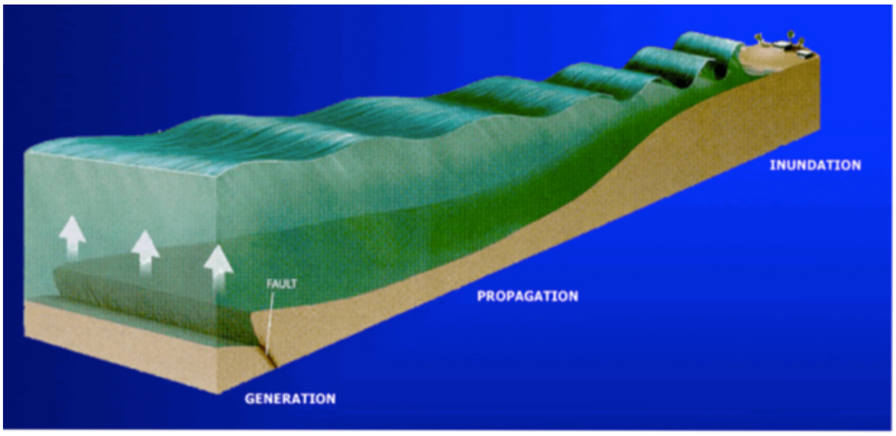


Figure 5. Earthquake-generated tsunami: generation, propagation and inundation.

When reaching the shore, tsunami waves can exceed 30 m in height.

On 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) (Bryant and Nott, 2001).

c) NSW regulation, policy and guidelines on coastal and flood risk

In NSW regulation and policy on coastal hazards is divided into three main classes:

1. Emergency Management and Response;
2. Coastal and Floodplain Risk Management;
3. Strategic Planning and Development Assessment.

Each class is discussed in detail in the COVERMAR Literature Review Report. NSW standards, guidelines and regulations were examined to ensure that the COVERMAR methodology was consistent. Project outputs inform, at the local and State level, many of the matters addressed in the legislation and policy instruments (Table 1). Further, Appendix I includes a flow-chart summarising the relationships between these classes, and among the individual legislative instruments within each class. The flow-chart has been updated to include the amendments introduced by the 2012 NSW Coastal Reforms (www.environment.nsw.gov.au/coasts/stage1coastreforms.htm), after the publication of the Literature Review Report.

Table 1. Contribution of COVERMAR outputs to the application/implementation of existing NSW regulation and guidelines.

	REFERENCE	COVERMAR CONTRIBUTION
EMERGENCY MANAGEMENT	NSW STATE STORM SUB-PLAN	COVERMAR storm surge exposure and vulnerability maps show: a) the extent of the inundation for the selected storm; b) scenarios (under different sea level conditions); c) the expected maximum water depth; d) the degree of vulnerability of inundated buildings and those that could suffer structural damage due to coastal erosion. These maps will assist 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 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).
	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 of the related flood intelligence system (Paragraph 4.1.2). The information that is stored and organised within the COVERMAR GIS database (that can be utilised by the SES intelligence system) includes: a) a high resolution digital elevation model (showing topographic elevations across the study area); b) the expected maximum inundation depth for the selected storm scenarios; c) the location, shape, orientation and main engineering characteristics of existing building and critical infrastructure, including their vulnerability to inundation.
	NSW EMERGENCY TSUNAMI SUB-PLAN	COVERMAR tsunami exposure and vulnerability maps show: a) the extension of the inundation for the selected tsunami scenario (under different sea level conditions); b) the expected maximum water depth; c) the vulnerability of single buildings or infrastructure that would be inundated. This high-resolution information will contribute to the updating/improving of existing tsunami emergency and evacuation plans. COVERMAR outputs, including maps and tsunami simulation outputs (e.g. wave propagation/inundation), are 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 show which buildings would safely resist the selected scenarios and which would be suitable for vertical evacuation (Section 3.6, Paragraph 3.6.5). The COVERMAR GIS database, which includes detailed data on coastal topography, expected tsunami inundation depth and engineering attributes of single buildings and infrastructure, can readily be used to develop/update the tsunami intelligence system, (Section 3.6, Paragraph 3.11.11). The COVERMAR vulnerability maps also include information on the 'type' and the 'use' of every building exposed to tsunamis, in addition to their physical attributes and vulnerability. This assists NSW SES 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, and the like (Paragraph 5.9.1).
COASTAL RISK MANAGEMENT	COASTAL PROTECTION ACT (1979) NSW*	The COVERMAR methodology enables a more detailed consideration of storm surge and tsunami inundation than the minimum requirements advocated in the Coastal Protection Act 1979 NSW, particularly the requirements for coastal zone management plans.
	NSW COASTAL RISK MANAGEMENT GUIDE (2010 COAST GUIDE)	The COVERMAR methodology for assessing building vulnerability to storm surges follows the 2010 Coast Guide.
	COASTAL ZONE MANAGEMENT PLANS	The COVERMAR approach is consistent with the Guidelines for Preparing CZMPs (OEH 2013). COVERMAR informs on: ***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.*** The COVERMAR methodology addresses **the minimum assessment criteria** required for addressing coastal inundation and tidal inundation components of coastal hazard definition studies (Section 3.2.1). In addition, COVERMAR produced exposure maps that show the extent of inundation in the selected case scenarios, as specifically recommended by the CZMP Guidelines. The minimum requirements for coastal risks advised in the CZMP Guidelines do not include tsunamis in the list of those coastal hazards that must be considered when preparing a CZMP. However, **Section 3.3** outlines that a CZMP may address other risks (such as 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 identifies tsunami-safe areas and buildings suitable for vertical evacuation. This information can easily be incorporated into the existing tsunami emergency plans and the tsunami intelligence system (see the NSW Tsunami Emergency Sub-Plan).

Table 1. Contribution of COVERMAR outputs to the application/implementation of existing NSW regulation and guidelines.

	REFERENCE	COVERMAR CONTRIBUTION
FLOODPLAIN MANAGEMENT	NSW FLOOD RISK MANAGEMENT GUIDE (2010 FLOOD GUIDE) and FLOODPLAIN MANAGEMENT PLANS	COVERMAR addresses the risk of river flood **where this is due to storm surges causing tidal inundation along river estuaries.** In this regard, the COVERMAR approach is consistent with the 2010 Flood Guide. Inundation scenarios are based upon the predicted extent of a flood with an annual probability of 1/100.
PLANNING AND DEVELOPMENT ASSESSMENT	SEPP 71 – COASTAL PROTECTION DIRECTION 2.2 UNDER SECTION 117 OF THE EP&A ACT	SEPP 71 requires local councils 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 and more recently the CZMP Guidelines (OEH 2013). By reason of the GIS approach, COVERMAR outputs (vulnerability and exposure maps, GIS database) provide new geographic information that can be readily incorporated 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: a) assesses and evaluates specific coastal risks **(Principle 1)**; b) generates self-explanatory exposure and vulnerability maps, that can be used to support any education and dissemination activity to advise the public of coastal risks to ensure that informed land use planning and development decision making can occur **(Principle 2)**; c) supports coastal planners' decisions about land use intensification/reduction **(Principles 3 and 4)** and helps them minimise exposure to coastal risks **(Principle 5)**; d) provides recommendations for appropriate management responses and adaptation strategies **(Principle 6)**.

d) Methods to assess the vulnerability of buildings and infrastructure to storm surges

Storm surges can damage coastal assets in two main ways:

1. Coastal erosion, which can undermine the foundations of the first row of buildings on the coast.
2. Overtopping of coastal dunes and seawalls, and tidal inundation (inundation along tidal waterways).

Vulnerability to coastal erosion is assessed by calculating the erosion lines and mapping the zones of reduced foundation capacity, as indicated in the 2010 NSW Coastal Risk Management Guide. Vulnerability to overtopping is estimated using flood vulnerability functions for different building types. These are mathematical models (curves) associating the expected percentage of damage to a building in response to different inundation depths.

e) Methods to assess the vulnerability of buildings and infrastructure to tsunamis

Available methods include either index-based methods (e.g. the PTVA Model) or tsunami vulnerability functions. Index-based methods provide a relative assessment of the vulnerability of every building (e.g. building A is more/less vulnerable than building B), whereas vulnerability functions provide absolute estimates of the expected damage (e.g. building A will suffer 70% damage if struck by a 2 m-deep tsunami flow).

Due to the low frequency of tsunamis worldwide, a relatively small volume of information about their impact on buildings is available. As a consequence, existing vulnerability functions for tsunamis possess a high degree of variability. Index-based methods are relative, but more accurate in capturing the differences between different building types. COVERMAR used an approach combining index-based methods and vulnerability functions.

The full version of the Literature Review Report is available online at the SCCG project page:
http://www.sydneycoastalcouncils.com.au/node/106

HAZARD ASSESSMENT REPORT

The Hazard Assessment report undertaken in Stage 2 of the project describes the methodology employed to select and simulate the COVERMAR inundation scenarios (tsunamis and storm surges) addressing:

a) The multi-criteria analysis undertaken by the COVERMAR Advisory Committee to select the most suitable case study locations.

b) The selected inundation scenarios.

Storm surge and tsunami events were simulated under three different initial sea level conditions with respect to the 1990 sea level. Specifically, we utilised 2010 sea level as the current condition and adopted the former NSW sea level rise benchmarks (DECCW 2009), that is +40 cm for 2050 and +90 cm for 2100 (above the 1990 mean sea level). We adjusted the sea level increases for a 2010 current condition by subtracting 6 cm based on the assumption of a mean sea level rise of 3 mm/year occurring between 1990 and 2010, resulting in a total increase of +6 cm by 2010 (McInnes et al., 2012). This equated to a sea level increase of + 34cm for 2050 and + 84 cm for 2100.

The NSW sea level benchmarks were withdrawn in late 2012 as part of the Stage 1 NSW Coastal Reforms (www.environment.nsw.gov.au/coasts/stage1coastreforms.htm). These 'reforms' transferred to local government the responsibility of selecting appropriate sea level projections. At the time of writing this report, the selected case study Councils had not formally adopted new sea level rise benchmarks. Accordingly, the former NSW sea level benchmarks were used for illustrative purposes of the multi-hazard tool, and applied as 'testing points' rather than proposed as benchmarks for specific time horizons.

The storm surge inundation scenarios used the usual return time considered for extreme storm events (1/100 yr.; Engineers Australia, 2012), occurring under the three sea level conditions above.

For tsunamis, we selected 36 probabilistic scenarios which combined two sources (North and South East of the study area), three annual probabilities (1/100, 1/1,000 and 1/10,000), the three sea level conditions, and high tide vs. mean sea level. The probability of occurrence was calculated based on the work of Burbidge et al. (2008).

c) The numerical models used to simulate the selected scenarios.

For the storm surge scenarios, we used the outputs of the numerical modelling undertaken by McInnes et al. (2012), as part of the SCCG project entitled *Mapping and Responding to Coastal Inundation*. McInnes et al. (2012) used data from a previous storm (tide, storm surge and wave setup using still water levels at Fort Denison) which corresponded to a 1/1 year event. This data was also extrapolated to a 1/100 year event (controlling for tide phasing and wind stress). The numerical modelling was undertaken using a combination of two hydrodynamic models (GCOM 2D and SWAN) to obtain the maximum water level alongshore. A modified bathtub-filling approach propagated the water level inland to generate the inundation layers.

The selected tsunami scenarios were simulated using the model developed by the National Oceanic and Atmospheric Administration (NOAA) Centre for Tsunami Research (MOST – Method for Splitting Tsunamis), accessed through the online platform ComMIT (Community Model Interface for Tsunamis) (Titov et al., 2011). MOST numerically simulates earthquake-generated tsunamis using a stepwise approach:

- Deformation of the ocean floor caused by an earthquake;
- Propagation of the tsunami across the ocean using nonlinear shallow water wave equations;
- Inundation by extending the tsunami nearshore and onshore.

d) Results of the simulations in form of GIS inundation maps.

Numerical modelling outputs were imported into a GIS system as vector layers and superimposed upon aerial images and a Digital Elevation Model provided by SCCG, with vertical accuracy of 0.25 m to show the extent of the inundation and enable a count of exposed buildings and infrastructure.

For each tsunami scenario, we generated two thematic maps – one showing the maximum flow velocity reached during the inundation and one showing the maximum water level (a total of 72 maps). We then compared these outputs against similar maps showing the storm surge inundation extent.

e) Discussion and conclusion.

Results showed that for each of the three Sydney study areas, a 1/100 yr. storm surge event would inundate an area larger than or equal to a tsunami occurring with the same initial sea level. Results were similar across all three annual probabilities of occurrence. However, tsunamis would produce flow velocities exceeding 15 m/sec, a velocity greater than that reported for storm surge of up to 4 m/sec (Oey and Wang, 2009). Flow velocity is relevant because it is likely to influence the extent of damage to built and natural assets. Further, the tsunamis triggered by earthquakes in Puysegur (New Zealand) would reach the study area in only 2h30m. The short evacuation lead times have implications for emergency management.

We presented the results of the vulnerability assessment at the 2013 NSW Coastal Conference (Dall'Osso et al., 2013).

IDENTIFICATION OF CASE STUDY AREAS

The COVERMAR tool developed was then applied to three case study areas selected through a multi-criteria analysis comparing the exposure of the SCCG's 15 Member Councils' LGAs to extreme inundations. Botany Bay and Rockdale City Councils and Sutherland Shire Council were selected through this process as the case study locations because they:

- are significantly vulnerable to inundation (Botany Bay, Port Hacking and Bate Bay);
- are within a discrete physiographic unit;
- possessed the requisite input data.

The methodology and the results of the vulnerability assessment process are described below. The vulnerability assessment process includes the following elements:

a) Survey of the buildings and infrastructure exposed to the selected inundation scenarios;

b) Construction and description of the GIS;

c) Description of the storm surge and the tsunami vulnerability models;

d) Results of the vulnerability assessment for buildings and infrastructure: the GIS vulnerability maps;

e) Estimates of PML;

f) Discussion;

g) Recommendations for long-term risk reduction strategies;

h) Conclusion.

VULNERABILITY ASSESSMENT

DATA ACQUISITION

The vulnerability of a building to inundation is a function of its physical and engineering attributes. Past inundation events have demonstrated that rigid multi-storey buildings with steel or reinforced concrete (RC) structures perform much better than single storey timber or brick veneer structures. Accordingly, the structural features of characteristic buildings in the study areas are the main input required by building vulnerability models.

The COVEMAR Hazard Assessment Report undertook a first-order estimate of the number of buildings that would be flooded by each inundation scenario. For each building, we conducted a visual survey to determine the attributes required by the building vulnerability models utilised. These attributes are listed in Table 2. A total of 4083 buildings were surveyed.

Surveys were undertaken remotely using Google Street View and high resolution aerial images provided by SCCG. Google Street View is an online system offering georeferenced images of single building units within a chosen area (Figure 6). The street level images were recorded by Google between November and December 2009, while aerial images were taken in 2011.

Our survey approach permits the rapid acquisition of data on large numbers of buildings and overcomes a significant criticism of the original PTVA model, namely the amount of time required for field surveys. A similar method was adopted by Maqsood et al. (2013). Of the 4083 buildings surveyed, 555 were not visible on Google Street View or accessible in the field. Most of these buildings were located in proximity to the water along Georges River and Port Hacking.

ATTRIBUTE CLASS	ATTRIBUTE TYPE	ATTRIBUTE OPTIONS	SURVEY TECHNIQUE
Use and Size	1.Building Use	Residential Commercial Health Government Utility Recreational Heritage	Google Street View
	2. Number of units	Number of residential or commercial units within the building	Google Street View
Building structure	3. Building Material/Style	Fibro Wood Brick veneer Full brick Reinforced concrete	Google Street View
	4. Number of Storeys	1, 2, 3, 4 or more than 5	Google Street View
	5. Foundations	Slab on ground Footings Deep pile	Google Street View
	6. Ground-Floor(GF) Hydrodynamics	GF completely closed (no windows) GF moderately closed (a few windows) GF averagely open (average number of windows and openings) GF moderately open (many windows, large glass doors) GF completely open (columns and windows, no walls)	Google Street View
	7. Ground Floor Type	Raised GF Non raised GF	Google Street View
	8. Shape and Orientation	Long footprint L-shaped footprint Rectangular footprint Square footprint Round footprint	SCCG Aerial Imagery (2011)
	9. Preservation Condition	Badly preserved Averagely preserved Well preserved	Google Street View
	10. Basement	Basement No basement	Google Street View
	11. Garage	Garage No garage	Google Street View

Table 2. Building attributes required by the COVERMAR vulnerability models. These attributes were collected remotely using Google Street View (November 2009) and SCCG High Resolution Aerial images (2011). Once completed, 10% of the data set was ground truthed using a systematic random sampling technique. The overall accuracy of the COVERMAR dataset was 94% (excluding the 555 inaccessible buildings).

ATTRIBUTE CLASS	ATTRIBUTE TYPE	ATTRIBUTE OPTIONS	SURVEY TECHNIQUE
Building Surroundings	12. Movable Objects	Proximity to areas where large movable objects are concentrated such as car parks and marinas	SCCG Aerial Imagery (2011)
	13. Natural Barriers	Degree of protection provided to the building by coastal dunes and vegetation	SCCG Aerial Imagery (2011)
	14. Building Row	1st, 2nd, 3rd, 4th or more than 5	SCCG Aerial Imagery (2011)
	15. Seawall	Degree of protection provided to the building by sea walls	SCCG Aerial Imagery (2011) and Google Street View
	16. Brick Wall	Height of brick walls around the building	Google Street View

Figure 6. Building surveys were undertaken remotely using Google Street View. Data was then ground-truthed in the field

In order to optimise the time dedicated to collecting the building attributes listed in Table 2, we generated 24 different building classes, which represent the totality of building types in the study area (Table 3). This allowed us to allocate one code per building, representing the corresponding class. For each class, building attributes numbers 3 and 4 of Table 2 are automatically determined by Table 3. The remaining attributes may vary within the same building class and were surveyed building-by-building.

Table 3. The COVERMAR building stock.

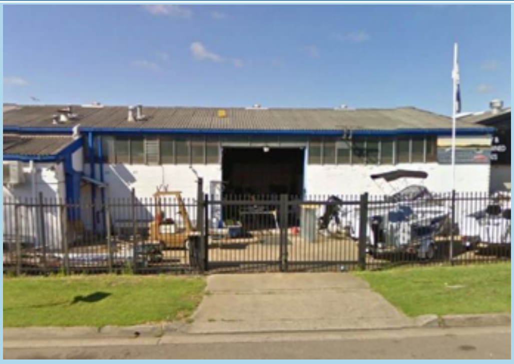
CODE	EXAMPLE	DESCRIPTION
1		1 storey, timber frame and fibro boards
2		1 storey, timber frame boards
3		1 storey, brick veneer
4		2 storeys, brick veneer

CODE	EXAMPLE	DESCRIPTION
5		2 storeys, single leaf reinforced walls, modern construction, slab on grade
6		2 storeys, modern construction, reinforced concrete frame, brick infills
7		3 storeys, brick, old construction
8		1 storey, modern style, reinforced full bricks or reinforced concrete

CODE	EXAMPLE	DESCRIPTION
9		1 storey, double brick, old construction
10		4 storeys, brick
11		2 storeys, old style, double brick
12		3 storeys, reinforced concrete, modern construction

CODE	EXAMPLE	DESCRIPTION
13		3 storeys, brick construction, large footprint
14		2 storeys, timber frame and boards
15		2 storeys, full brick, old construction, attached building
16		2 storeys, ground floor in brick veneer, first floor in wood

CODE	EXAMPLE	DESCRIPTION
17		2 storeys, timber frame and fibro boards
18		4 storeys, modern construction, reinforced concrete and full brick
19		2 storeys, ground floor brick veneer, first floor in fibro
20		More than 5 storeys, modern construction, reinforced concrete and full brick

CODE	EXAMPLE	DESCRIPTION
21		Industrial (factory, warehouse, showroom), 1 storey, old construction (brick)
22		Industrial (factory, warehouse, showroom, offices upstairs), 2 storeys, old construction (brick, corrugated iron, wood)
23		Industrial (factory, warehouse, showroom), 1 storey, new construction (concrete, steel, precast concrete, reinforced brick)
24		Industrial (factory, warehouse, showroom), 2 storeys, new construction (concrete, steel, precast concrete)

GROUND-TRUTHING

The Google Street View dataset was ground-truthed to ensure its accuracy. We examined 400 buildings selected randomly (~10% of the total number of buildings surveyed, i.e. 3,528) to verify that they corresponded with images from Google Street View (Figure 7). Results showed that 24 buildings of the 400 examined (i.e. 6%) differed from those extracted from the Google Earth database. The accuracy of Google Street View database within the study area was therefore extrapolated to 94%.

Figure 7. 400 buildings (about 10% of the total number of accessible buildings, i.e. 3,528) were randomly selected and ground-truthed to check the accuracy of the Google Street View database. The image on the right is extracted from Google Street View and represents a building in Dolls Point (Rockdale). On the left, the same building is ground-truthed during field surveys.

CONSTRUCTION OF THE GIS DATABASE

The COVERMAR input data and outputs were organised and stored in a GIS (Geographic information System) database. The database includes the following elements:

Inundation Scenarios

Outputs of the numerical modelling of each of the 39 inundation scenarios (as described in the COVERMAR Hazard Assessment Report) are included in the GIS as raster layers. For each of the 36 tsunami scenarios, two raster layers have been generated, including the maximum inundation depth and the maximum flow velocity. For storm surge, flow velocities are not available, hence only one layer per scenario including the maximum flow depth was included in the GIS.

Digital Elevation Model

The Digital Elevation Model is included in the GIS as a raster layer. This is the model utilised in the numerical modelling of the selected inundation scenarios. The DEM basic parameters are:

Spatial Resolution: 10 m

Vertical Accuracy: <25 cm

Horizontal Datum: GDA94

Vertical Datum: AHD

For further details about the DEM, refer to the COVERMAR Hazard Assessment Report.

High Resolution Aerial Imagery

Aerial images taken in 2011 with a spatial resolution of 50 cm are included in the GIS dataset.

Building and Infrastructure Dataset: the GIS Vulnerability Maps

All buildings exposed to the selected inundation scenarios were included in the GIS as a vectorial layer of polygons. Polygons represent the building footprint and contain all the building attributes listed in Table 2, as well as the vulnerability level and economic loss associated with each inundation scenario.

Building footprints within Sutherland Shire were provided by Sutherland Shire Council, whereas the 1479 buildings that fell within the LGAs of Rockdale and Botany Bay City Councils had to be manually digitised using the SCCG aerial images as a reference. Similarly, streets, car parks, bridges, coastal structures, seawalls and marinas in most of the study area were manually digitised.

Building polygons are plotted using a colour coded scale, representing the level of vulnerability.

STORM SURGE BUILDING VULNERABILITY ASSESSMENT MODEL

In NSW, storm surges can damage buildings in two ways:

1. By eroding the soil substrate and undermining building foundations. This happens primarily to the first row of buildings along oceanic beaches, and the risk is higher where coastal dunes have been removed or altered. This type of damage is less likely to occur within Botany Bay, as beaches are partially protected from wave action.
2. Through inundation caused by coastal dunes (or seawalls) being breached or overtopped, or flooding occurring through tidal waterways.

The storm surge vulnerability assessment model we adopted considers both these damage mechanisms. Buildings and streets exposed to erosion were identified through storm erosion lines, under 2010 and future sea level conditions. The storm erosion lines were generated through coastal hazard studies undertaken by local councils and made available by the SCCG. The methodology used to obtain the erosion lines is described in the COVERMAR Literature Review Report and it is consistent with the guidelines in the 2010 NSW Coastal Risk Management Guide. All buildings and infrastructure located beyond the storm erosion lines are assumed to be completely destroyed.

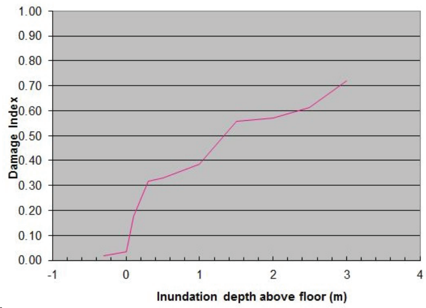
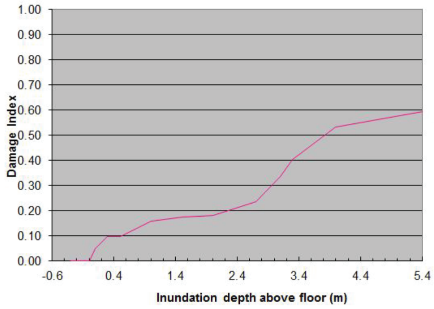
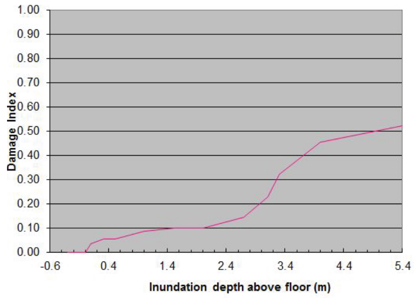
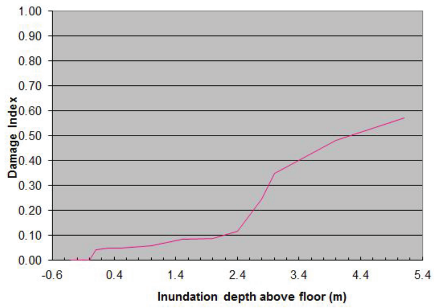
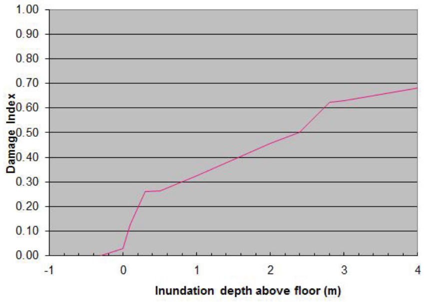
The damage caused by overtopping of coastal defences and tidal inundation was assessed using flood vulnerability functions provided by Geoscience Australia (Maqsood et al., 2013). These curves are an option for assessing the vulnerability of buildings to storm surge in NSW as they consider some of the building types typically found in NSW. The curves were generated using a mixed empirical and subjective approach combing expert judgment and observations of the actual damage caused to different building types by historical floods.

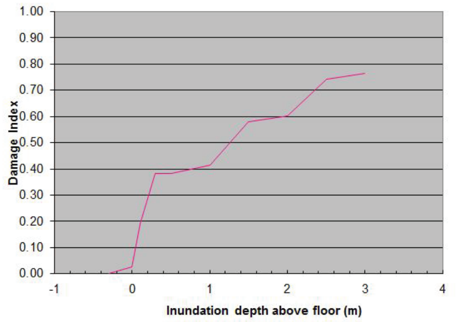
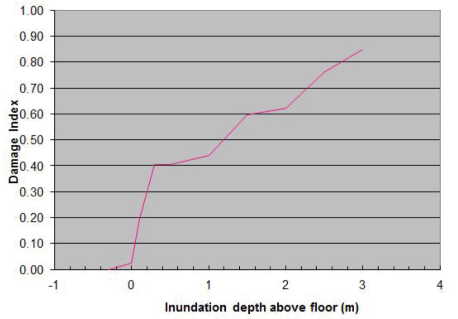
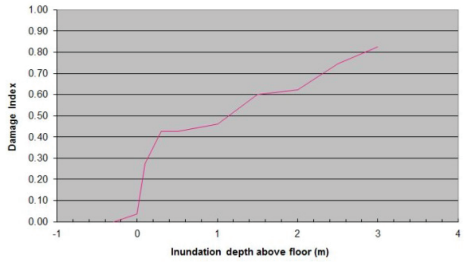
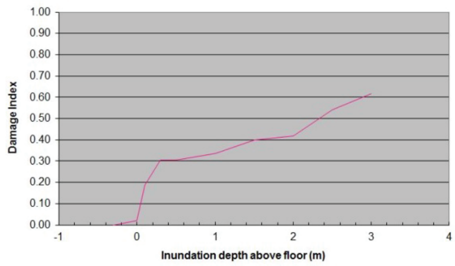
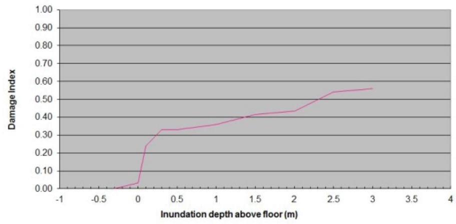
Flow velocity is assumed to be proportional to flow depth, and thus not directly considered by the model. The expected damage to buildings is estimated through a 'Damage Index' (DI). The DI represents the ratio (cost to repair/cost to replace). This is calculated for different building types, and for different values of the demand parameter. The demand parameter (i.e. a parameter of the inundation used to estimate its intensity) is the maximum inundation depth. This approach is similar to most flood vulnerability curves applied in similar studies (Dale et al., 2004; Nadal et al., 2010).

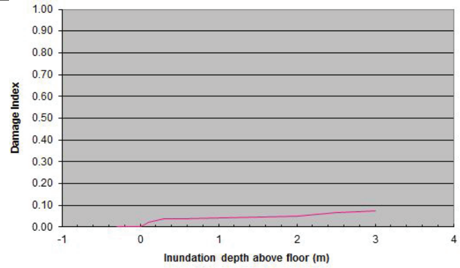
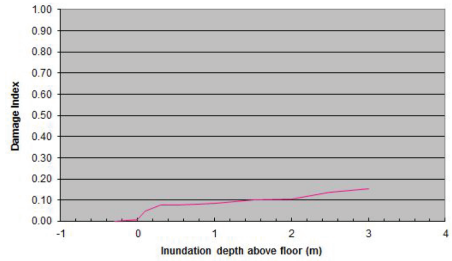
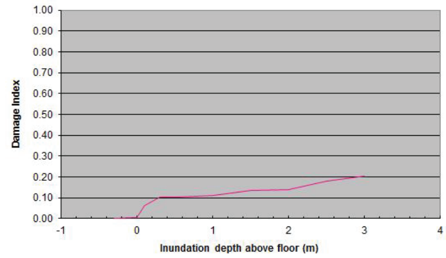
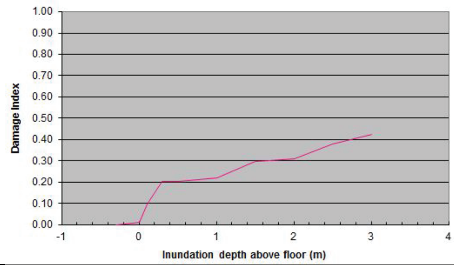
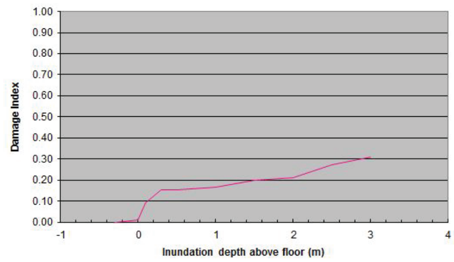
The vulnerability functions adopted to assess the damage from tidal inundation are shown in Table 4. To adjust for any differences in building characteristics, each function was applied to the most similar COVERMAR building type (Table 5). In some instances (i.e. multi-storey buildings) the functions by Geoscience Australia required modification. This is the case for functions FCM12, FCM13, FCM14, FCM15 and FCM16, which were modified by:

1. identifying the most similar one-storey construction type in the Geoscience Australia building stock;
2. dividing the Damage Index of the GA building by the number of storeys of the COVERMAR building type.

Table 4. Vulnerability functions for assessing the damage from tidal inundation (storm surge) used in COVERMAR.

GA code	Description	Photo	Vulnerability Curve
FCM1	1 storey raised timber floor, lightweight cladding, no integral garage		
FCM3	2 storeys, slab on grade bottom floor, timber upper floor, lightweight upper floor cladding, no integral garage		
FCM4	2 storeys, slab on grade bottom floor, timber upper floor, lightweight upper floor cladding, integral garage		
FCM5	2 storeys, slab on grade lower floor covering only part of the plan area, timber upper floor, integral garage on the lower floor		
FCM6	2 storeys, raised timber lower floor, timber upper floor, lightweight cladding, no integral garage		

GA code	Description	Photo	Vulnerability Curve
FCM7	1 storey, slab on grade floor, masonry veneer construction, integral garage		
FCM8	1 storey, slab on grade floor, masonry veneer construction, no integral garage		
FCM9	1 storey, raised timber floor, masonry veneer construction, no integral garage		
FCM10	1 storey, slab on grade floor, cavity masonry construction, no integral garage		
FCM11	1 storey, raised timber floor, cavity masonry construction, no integral garage		

GA code	Description	Photo	Vulnerability Curve
FCM12 (created by COVERMAR by adapting function FCM10)	More than 5 storeys, modern construction, reinforced concrete and full brick		
FCM13 (created by COVERMAR by adapting function FCM10)	4 storeys, modern construction, reinforced concrete and full brick.		
FCM14 (created by COVERMAR by adapting function FCM10)	3 storeys, reinforced concrete frame, modern construction		
FCM15 (created by COVERMAR by adapting function FCM8)	2 storeys, brick veneer		
FCM16 (created by COVERMAR by adapting function FCM10)	2 storeys, single leaf modern construction, slab on grade		

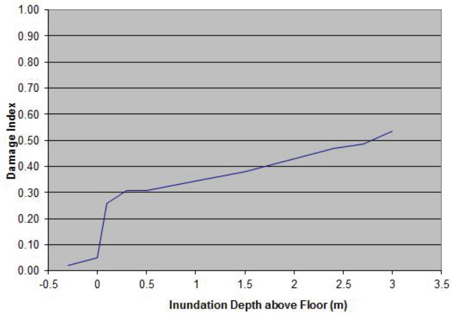
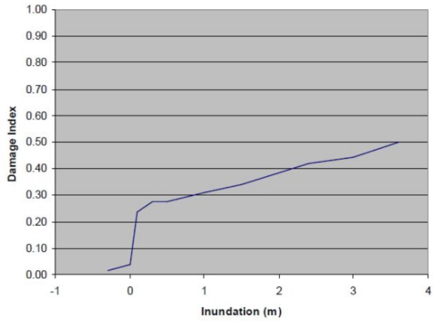
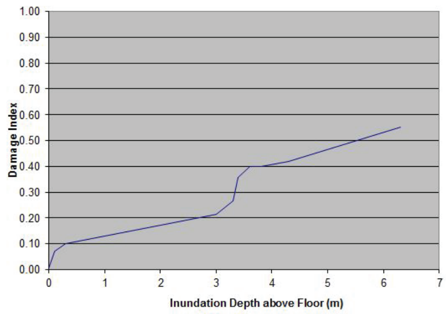
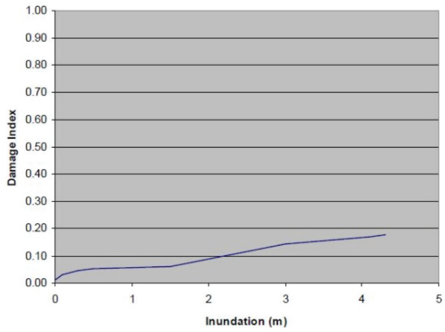
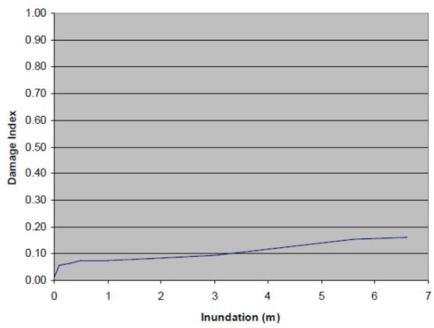
GA code	Description	Photo	Vulnerability Curve
ACFS1A	Victorian residential terrace, 1 storey, no basement		
ACSF2A	Victorian residential terrace, 2 storeys, no basement		
ACSF3	Mixed use: retail / residential, 2 storeys		
ACSF4	Showroom / Office, 2 storeys		
ACSF6	Industrial, 1 storey		

Table 5. Associations between the COVERMAR building types and the vulnerability functions listed in Table 4. 'rf'= raised ground floor, 'g'=garage, 'grf'+garage and raised ground floor, 'ggf'=ground floor entirely used for garages.

COVERMAR building type		
CLASS	SUBCLASS	Storm Surge Class
1	-	FCM1A
	rf	FCM1A
	g	FCM1A
	grf	FCM1A
	ggf	FCM1A
2	-	FCM1A
	rf	FCM1A
	g	FCM1A
	grf	FCM1A
	ggr	FCM1A
3	-	FCM8
	rf	FCM9
	g	FCM7
	grf	FCM7
	ggf	FCM7
4	-	FCM15
	rf	FCM15
	g	FCM15
	grf	FCM15
	ggf	FCM15
5	-	FCM16
	rf	FCM16
	g	FCM16
	grf	FCM16
	ggf	FCM16
6	-	FCM16
	rf	FCM16
	g	FCM16
	grf	FCM16
	ggf	FCM16
7	-	FCM14
	rf	FCM14
	g	FCM14
	grf	FCM14
	ggf	FCM14
8	-	FCM10
	rf	FCM10
	g	FCM10
	grf	FCM10
	ggf	FCM10

COVERMAR building type		
CLASS	SUBCLASS	Storm Surge Class
13	-	ACFS2A
	rf	ACFS2A
	g	ACFS2A
	grf	ACFS2A
	ggf	ACFS2A
14	-	FCM6
	rf	FCM6
	g	FCM6
	grf	FCM6
	ggf	FCM5
15	-	ACSF3
	rf	ACSF3
	g	ACSF3
	grf	ACSF3
	ggf	ACSF3
16	-	FCM3
	rf	FCM3
	g	FCM4
	grf	FCM4
	ggf	FCM4
17	-	FCM6
	rf	FCM6
	g	FCM6
	grf	FCM6
	ggf	FCM5
18	-	FCM13
	rf	FCM13
	g	FCM13
	grf	FCM13
	ggf	FCM13
19	-	FCM3
	rf	FCM3
	g	FCM4
	grf	FCM4
	ggf	FCM4
20	-	FCM12
	rf	FCM12
	g	FCM12
	grf	FCM12
	ggf	FCM12

9	-	AFCS1A		21	-	ACFS6
	rf	AFCS1A			rf	ACFS6
	g	AFCS1A			g	ACFS6
	grf	AFCS1A			grf	ACFS6
	ggf	AFCS1A			ggf	ACFS6
10	-	FCM13		22	-	ACFS4
	rf	FCM13			rf	ACFS4
	g	FCM13			g	ACFS4
	grf	FCM13			grf	ACFS4
	ggf	FCM13			ggf	ACFS4
11	-	ACFS2A		23	-	ACFS6
	rf	ACFS2A			rf	ACFS6
	g	ACFS2A			g	ACFS6
	grf	ACFS2A			grf	ACFS6
	ggf	ACFS2A			ggf	ACFS6
12	-	FCM14		24	-	ACFS6
	rf	FCM14			rf	ACFS6
	g	FCM14			g	ACFS6
	grf	FCM14			grf	ACFS6
	ggf	FCM14			ggf	ACFS6

TSUNAMI BUILDING VULNERABILITY ASSESSMENT MODEL

COVERMAR utilises a combined approach based on two standard international methods:

1. The PTVA Model which is the most accurate tool for assessing the relative vulnerability of buildings to tsunamis in countries where no specific vulnerability functions are available. COVERMAR developed a new improved version of the model: the PTVA-4 Model.
2. A set of vulnerability functions for typical Japanese buildings derived from the 2011 tsunami (Suppasri et al., 2012). The use of vulnerability functions was necessary to estimate the PML associated with the COVERMAR tsunami scenarios.

The differences between the PTVA Model and tsunami vulnerability functions are discussed in detail in the COVERMAR Literature Review Report, and summarised in the next section.

INDEX-BASED METHODS AND VULNERABILITY FUNCTIONS

The capability of a building to withstand the impact of a tsunami depends on a variety of factors, including structural elements, construction material, foundation type, the design of the ground floor and the like (IOC UNESCO, 2011). These factors or 'attributes' may coexist in numerous possible forms and combinations, making an assessment of vulnerability on a building-by-building a complicated exercise.

Before the 2004 Indian Ocean Tsunami (IOT), the only available building vulnerability model for tsunamis was the PTVA Model (Papathoma and Dominey-Howes, 2003). This model is an index method constructed on a GIS platform that calculates a vulnerability score for a building based on main structural characteristics (e.g. construction material, number of storeys, foundation type). After the 2004 IOT, the model was refined by Dall'Osso et al., (2009a, b) and validated in the Aeolian Islands, Italy (Dall'Osso and Dominey-Howes, 2010). Validation of the model showed it to be accurate in assessing the relative vulnerability of buildings to tsunamis (Tarbotton et al., 2012). A similar approach was proposed by Omira et al. (2009).

The advantage of index-based methods is that since they incorporate many idealised structural attributes in the calculation of the total vulnerability of a building, the differences between different building structures can be robustly determined. On the other hand, index-based methods are relative, so the final vulnerability scores have no stand-alone meaning and can only be used to compare different buildings within a study location.

A non-relative approach for assessing building vulnerability can be achieved via the use of vulnerability functions. These are continuous curves that associate the intensity of the tsunami (i.e. the tsunami 'demand parameter') to the expected response of a particular building type. Although this approach is widely used for other hazards (i.e. earthquakes, floods), no tsunami vulnerability functions were available before the 2004 IOT.

To date, 15 studies have proposed tsunami vulnerability functions for buildings. Most have adopted flow depth as the tsunami demand parameter, assuming that this is the main driver of building damage. However, in some instances, flow velocity and kinetic energy have also been considered (Koshimura et al., 2009).

Tsunami vulnerability functions have been developed using a variety of techniques. Some described the building damage deterministically (e.g. using the ratio 'cost to repair/cost to replace') (Reese et al., 2007; Valencia et al., 2011) whilst others adopted a probabilistic approach estimating the conditional probability that a given building type will reach or exceed a specific damage state (Koshimura et al., 2009; Reese et al., 2011; Suppasri, Koshimura and Imamurra, 2011; Suppasri et al., 2012). Most of these curves are empirical (i.e. based on observations after the actual tsunami), but some studies employed analytical techniques (i.e. referred to a theoretical building prototype, whose damage-state equation is solved for various tsunami loads) (Dias, Yapa and Peiris, 2009; Nadal et al., 2010).

Vulnerability curves offer the advantage of providing quantitative damage models, which can be used to predict if a building will collapse (or will be heavily damaged) when struck by a given tsunami flow. However, the variety of techniques employed and assumptions made renders the existing curves hard to compare and difficult to apply in locations distant from where they were developed. By way of example, in the case of empirical approaches, the curve of a masonry building developed in Samoa may differ significantly from that of a masonry building in Indonesia (Figure 8). This may be due to different building standards, survey techniques or statistical analyses adopted by researchers (Schultz et al., 2010; Gardi et al., 2011).

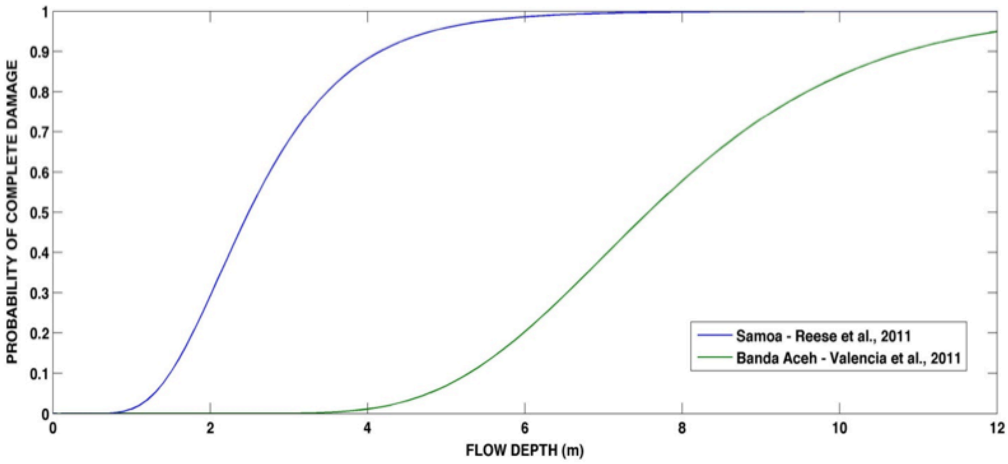


Figure 8. Example of fragility curves for residential masonry buildings developed in Samoa after the 2009 tsunami (Reese et al., 2011) and in Banda Aceh, Indonesia, after the 2004 IOT (Valencia et al., 2011). The curves express the probability of collapse at different tsunami flow depths. Although the building type is described in a similar way by the authors (i.e. residential masonry buildings for Reese et al., one storey masonry building for Valencia et al.), the resulting curves are different.

Index-based methods are still useful in areas where no vulnerability curves are available. However, these methods provide only a relative assessment of vulnerability (i.e. building A is more/less vulnerable than building B), which limits their utility. For instance, index-based methods cannot be used to estimate economic losses, as they do not provide an estimate of the absolute damage that a building may incur. To calculate economic loss vulnerability functions are more suitable.

The PTVA-4 Model

In the previous PTVA Model (V3), the relative vulnerability of buildings was calculated through a weighted sum of the contributions made by different building attributes (e.g. building material, number of storeys, foundation type). Weights were obtained through a multi-criteria analysis undertaken by Dall'Osso and Dominey-Howes (2009).

After publication, it was suggested that the model could be improved by increasing the expert input in the determination of the weights attributed to building attributes. To deal with this issue, we submitted a questionnaire to all the authors of scientific papers published in the last 10 years in the field of building vulnerability to tsunamis. We asked each author to re-weight the attributes of the PTVA-3 Model and to incorporate information from the 2011 Japan Tsunami. The questionnaire also allowed comments to be made on the model and permitted additional attributes to be suggested. Survey results are shown in Figure 9 and Figure 10.

We then formulated new weights for the model by taking the mathematical mean of weights obtained in the survey (Forman and Peniwati 1998). These new weights were incorporated into the PTVA and used to calculate the relative vulnerability of buildings in COVERMAR.

Building attributes influencing the structural vulnerability to tsunamis (building content is NOT considered)	Original Weight (0 to 100%)	Suggested Weight (0 to 100%)
Number of Stories:	100	81
Main Construction Material:	80	95
Ground Floor Hydrodynamics:	63	66
Foundation Type:	60	66
Large Movable Objects:	51	50
Shape and Orientation:	46	49
Preservation Conditions:	23	32
Engineered/Not Engineered	NA	80
Raised Gound Floor	NA	70

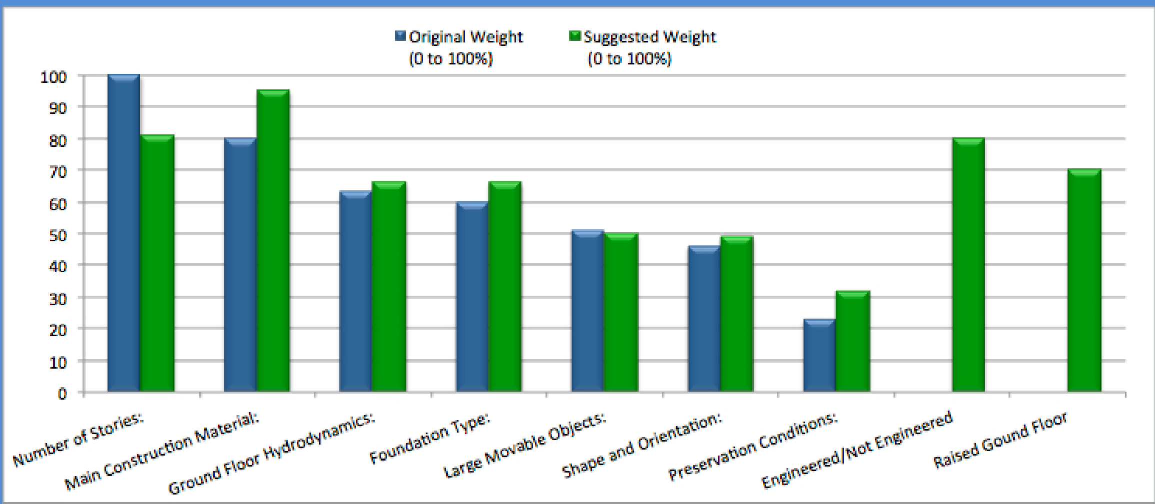


Figure 9. Results of the survey undertaken to re-weight the attributes of the PTVA-3 Model influencing the structural vulnerability of buildings to tsunamis. Blue bars represent the original PTVA-3 weights, while green bars represent the average value of the new weights indicated by the interviewees. Two new attributes were also suggested: engineered/not engineered buildings, and buildings with a raised ground-floor.

Attributes of buildings surroundings influencing the degree of protection from tsunamis	Original Weight (0 to 100%)	Suggested Weight (0 to 100%)
the Building Row	100	0
Seawall	73	0
Natural Barriers	73	0
Brick Wall around the Building	55	0
OTHER??	NA	0
OTHER??	NA	0

NOTE: Step 2 shall be considered only when the tsunami representation (e.g. numerical model) is not accurate enough to include the effect of these "shielding" elements on the flow depth and velocity impacting single buildings

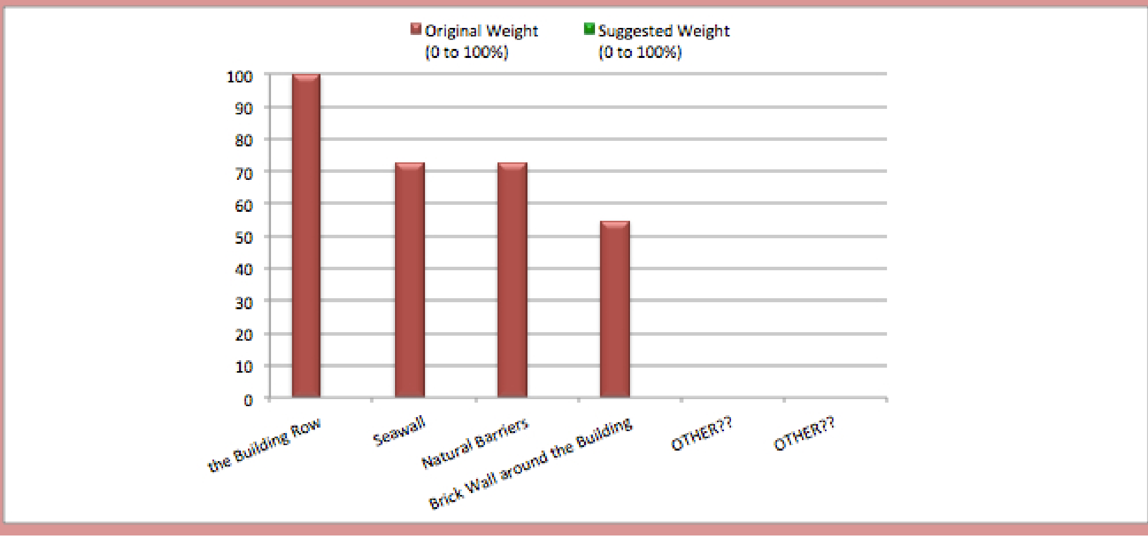


Figure 10. Results of the survey undertaken to re-weight the attributes of the PTVA-3 Model influencing the degree of protection provided to single building by their surroundings. Red bars represent the original PTVA-3 weights, while green bars represent the average value of the new weights indicated by the interviewees.

Tsunami Vulnerability Functions

We adopted the vulnerability functions developed by Suppasri et al. (2012) after the 2011 Tohoku Tsunami (Japan). These functions:

1. are the only functions available for buildings with construction standards similar to Australia;
2. are statistically robust as they were generated using a database of over 250,000 damaged structures. This is the highest number of buildings ever considered to create tsunami vulnerability functions;
3. include fragility curves for buildings having different construction materials and different numbers of storeys. Although the number of storeys is an important attribute influencing the vulnerability of buildings to tsunamis, no previously published vulnerability function considered it.

The functions developed by Suppasri et al (2012) are probabilistic fragility curves. These describe the probability that a building will reach or exceed a given damage state (for example, collapse) in response to different tsunami flow depths. In order to obtain the mean damage that the building is expected to incur, we adapted Suppasri's probabilistic curves to produce Mean Damage Curves. It should be noted that some purpose-built mean-damage curves are available for tsunamis (Reese et al., 2007; Valencia et al., 2010); however, these were not well-matched to the building types in the COVERMAR inventory.

Numerical calculation and notation

A fragility curve describes the probability (P_i) of reaching or exceeding the i^{th} damage level (D_i) for a given flood depth (x):

$$p_i(x) = p_i(d \geq D_i|x) = \Phi\left[\frac{lnx-\mu'}{\sigma'}\right]$$

where Φ corresponds to the lognormal cumulative distribution function (CDF), which is defined by the constants μ' and σ' – the log-mean and variance of the fragility curves.

Mean damage

From a set of fragility curves containing n damage levels, the mean damage (MD) at a given flood level can be calculated using the following equation:

$$MD(x) = \sum_{i=1}^{n} P_i(d = D_i|x) * i$$

where P_i corresponds to the probability of damage at the i^{th} damage level. The lower case P_i corresponds to the probability of reaching or exceeding the i^{th} damage level fragility curve, as it describes the probability of being in damage state i. P_i is determined from a set of fragility curves with n damage levels as:

$$(d = D_i|x) = p_i - p_{i+1} \quad \text{for } i = 1,2\ldots\text{n-1}$$
$$P_i(d = D_i|x) = p_i \quad \text{for } i = n$$

For the purposes of estimating the economic loss associated with the damage of a building, the mean damage curves were normalised to a value between 0 and 1:

$$\overline{MD(x)} = \frac{1}{n}\sum_{i=1}^{n} P_i(d = D_i|x) * i$$

The normalised mean damage curves represent the proportion of damage (with respect to complete destruction) sustained by a building. Consistent with other studies, we assumed damage to equate to the ratio between the cost of repairing and the cost of replacing a building:

$$\overline{MD(x)} = \frac{Cost\ to\ repair\ (\$)}{Cost\ to\ replace\ (\$)}$$

The fragility curves published in Suppasri et al. (2012) describe the damage response of buildings constructed of timber, brick, steel and reinforced concrete using six different damage levels for each building type (D1 to D6). We transformed these probabilistic fragility curves into deterministic mean damage curves which are more useful for assessing PML. Each damage level corresponds to a descriptive damage state, as shown in Table 6.

Table 6. Tsunami damage scale description, after Suppasri et al. (2012).

Damage level (D_i)	Type	Description
D1	Minor damage	There is no significant structural or non-structural damage, possibly minor flooding. Can be used immediately after minor floor and wall clean-up
D2	Moderate damage	Slight damage to non-structural components. Can be used after moderate repair
D3	Major damage	Heavy damage to some walls but no damage to columns. Can be used after major repair
D4	Complete damage	Heavy damage to several walls and some columns. Can be used after a complete repair and retrofitting.
D5	Collapse	Destructive damage to walls (more than half of wall density) and several columns. Loss of functionality (system collapse). Non-repairable or great cost to retrofit.
D6	Washed away	Washed away, only foundation remains, or totally overturned. Non-repairable, requires replacement.

To account for the variation in damage response related to the number of storeys of a building, Suppasri et al. 2012 provides distinct sets of fragility curves for 1, 2 and >= 3 storey buildings. These are available for wood and RC buildings, while for steel-framed and brick structures only a single average set of curves are available. Figure 11 plots the fragility curves published for single storey wood and RC buildings.

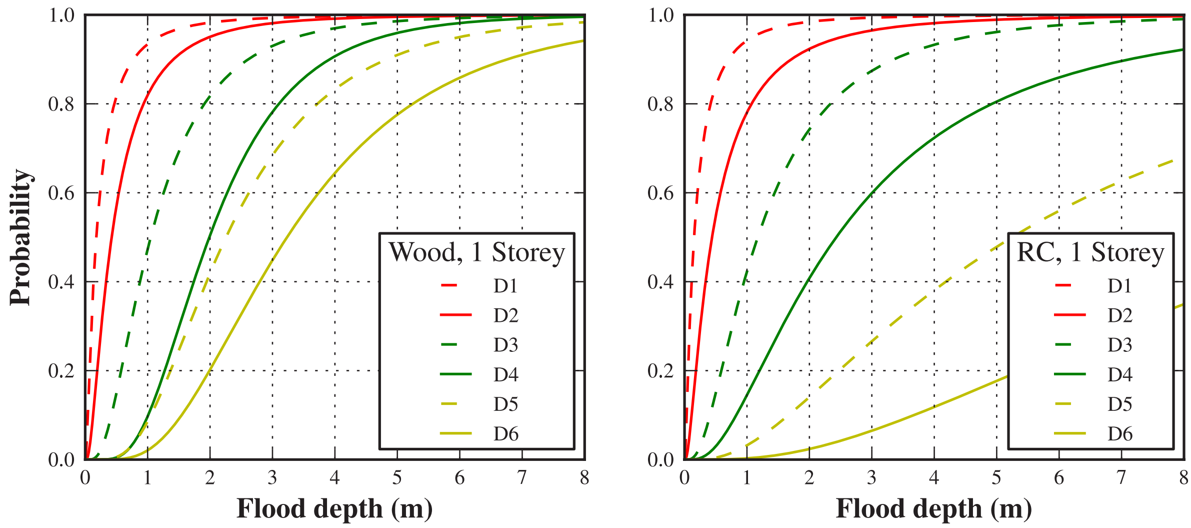


Figure 11. Fragility curves published in Suppasri et al. 2012 for 1 storey Wood and RC buildings

A total of nine distinct mean damage curves were derived from Suppasri et al. (2012), corresponding to 1, 2 and >= 3 storey wood, brick and RC buildings. Figure 12 plots the mean damage curves calculated for a single storey timber building and the underlying fragility curves used to derive them.

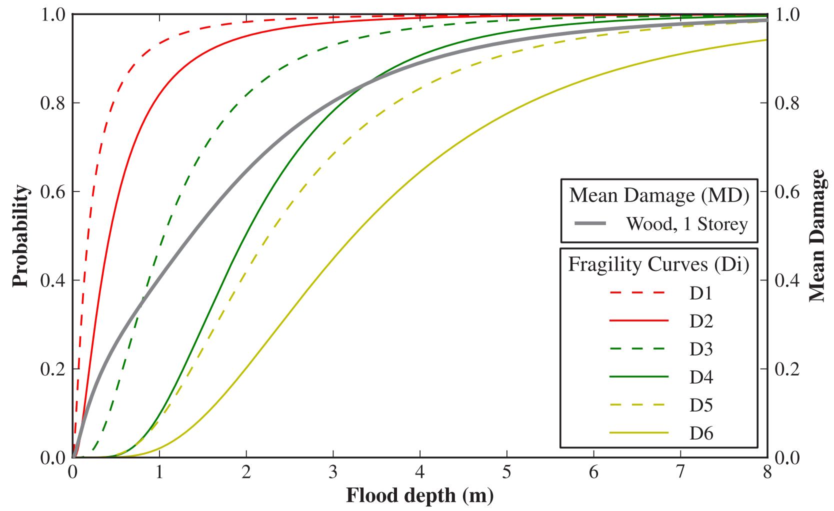


Figure 12. Normalized Mean Damage curve calculated for a single storey timber building and corresponding fragility curves.

Table 7 lists the mean damage curves that were derived along with their corresponding building class. These curves are plotted in Figure 13 and Figure 14. Note that it was not necessary to calculate mean damage curves for steel-framed buildings because no such buildings were identified in the study area.

Table 7. Mean damage curves and their corresponding building class.

MEAN DAMAGE CURVE		COVERMAR BUILDING TYPE
Material	Number of Storeys	
Wood	1	1,2
Wood	2	14,17,
Wood	>=3	-
Brick	1	3,9,21
Brick	2	4,11,15,16,19,22
Brick	>=3	7,10
RC	1	8,23
RC	2	5,6,24
RC	>=3	12,13,18,20

Since fragility curves were unavailable for brick buildings, mean damage curves were estimated by considering the damage response of timber buildings. Brick fragility curves were estimated by scaling and offsetting Average Brick curves. The scaling and offsetting parameters were determined by inspecting the differences observed between the average, 1, 2 and >= 3 storey fragility curves for timber buildings.

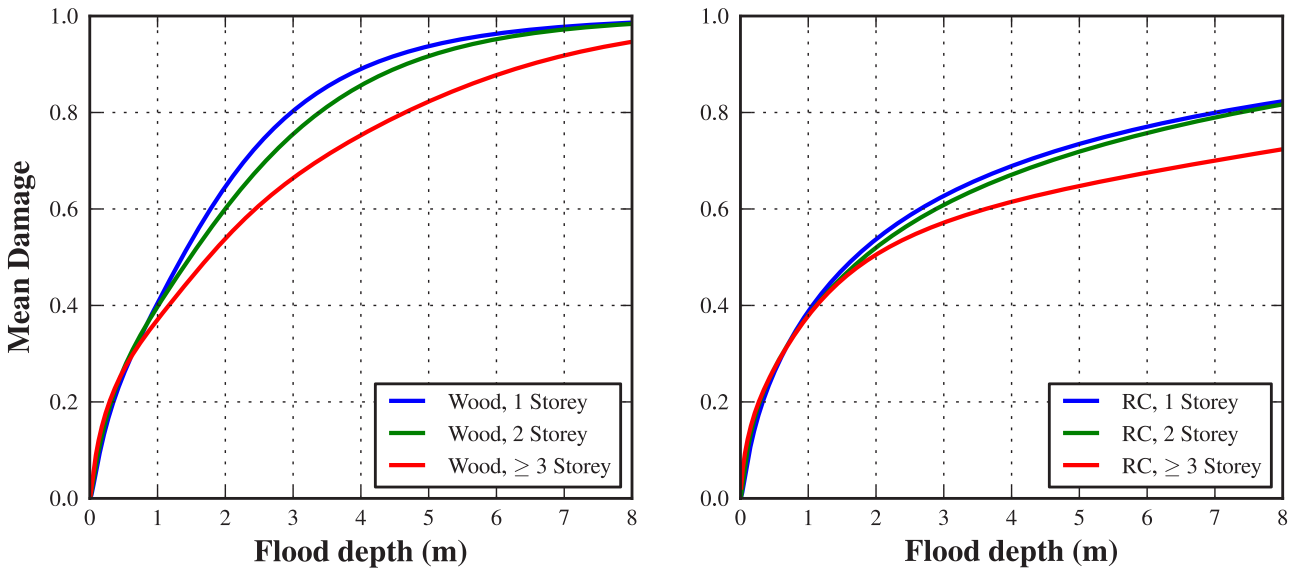


Figure 13. Mean Damage curves for timber and RC buildings obtained from the fragility curves published by Suppasri et al. (2012).

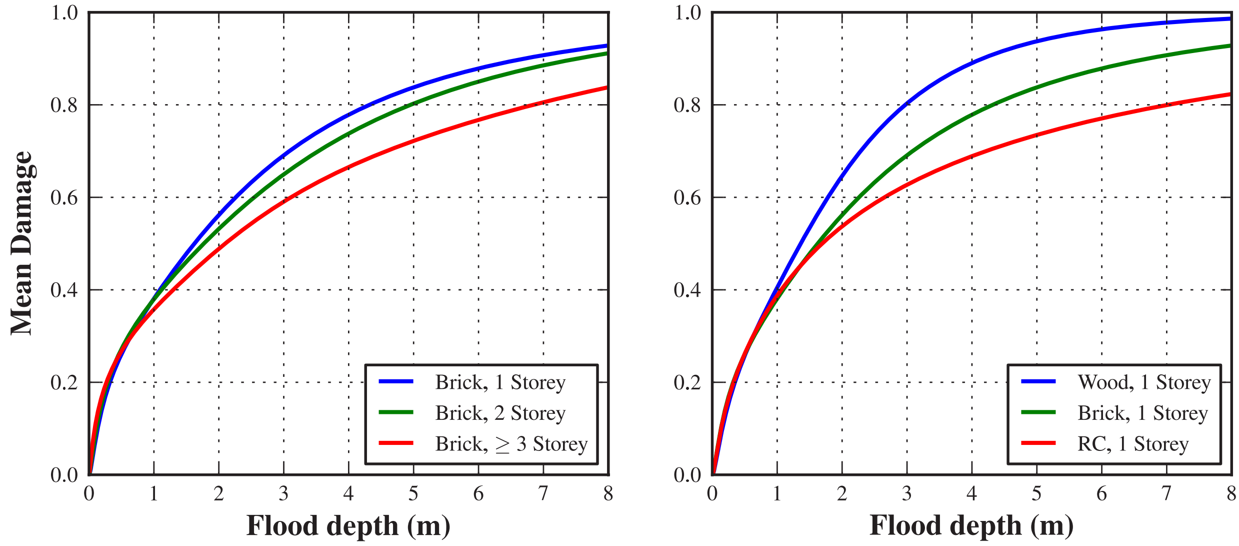


Figure 14. Mean Damage curves for brick buildings obtained from the fragility curves published by Suppasri et al. (2012).

This approach represents the best available option for estimating tsunami damage to typical Australian buildings. However, its limitations must be borne in mind, namely:

1. It does not account for basement levels. When the tsunami flow depth above the ground floor is <= 0 m, the damage is zero. However, flood damage would be expected to occur if a basement exists;
2. The fragility curves by Suppasri et al (2012) are only defined for buildings having 1, 2 or more than 3 levels. Therefore damage estimates for buildings with significantly more than 3 levels (e.g. high-rise buildings) are overestimated.

VULNERABILITY OF CRITICAL INFRASTRUCTURE

We identified and mapped the degree of exposure to the selected storm surge and tsunami inundation scenarios of the infrastructure listed in Table 8.

Table 8. Infrastructure classes whose exposure was identified and mapped

INFRASTRUCTURE CLASS	ELEMENTS WITHIN THE CLASS
Government buildings	Council offices, Police stations, Fire-Brigade stations, Surf-life saving clubs
Utility buildings	Power transmission and distribution, Sydney Water facilities, water treatment plants
Health facilities	Hospitals, ambulance stations, medical centres
Education buildings	Schools, kindergartens
Transport	Airports, harbours, train stations, railways, bus stations, arterial roads, local roads, car parks, bridges
Recreational buildings	Sport facilities, parks, reserves, natural areas, beaches
Coastal structures	Marinas, seawalls, breakwaters, piers

For some infrastructure listed in Table 8, we assessed the degree of damage and economic losses expected to be incurred in response to each inundation scenario. Specifically:

- Damage to buildings was assessed using the building vulnerability models described in the previous sections;
- Damage to streets and carparks was assessed according to the work by Kreibich et al. (2009). Kreibich et al. noted that during the 2002 Elbe Catchment flood in Germany, the degree of damage to streets correlated very well with flow velocity rather than flow depth. Where the flow velocity was higher than 2 m/sec most streets were completely destroyed and required replacement. Since Kreibich et al. provided no data for flow velocities between 0 and 2 m/sec., we adopted a simple linear damage/velocity relationship. Further research can verify this assumption once additional empirical evidence about the relationship between flow velocity and damage to roads becomes available.

Flow velocity	Damage Index (roads and carparks)
0-0.5 m/sec	0-20%
0.5-1 m/sec	20-40%
1-1.5 m/sec	40-60 %
1.5-2 m/sec	60-80%
>2 m/sec	80-100%

PROBABLE MAXIMUM LOSS

The term 'Probable Maximum Loss' or 'PML' refers to an approach widely used in the insurance and re-insurance industry to assess or estimate the expected economic losses associated with a given hazard. Specifically, the PML of a property is defined as that proportion of total value of the property that will equal or exceed, in a stated proportion of all cases, the amount of loss from a specified peril or group of perils (McGuinness, 1969).

The calculation of PML requires comprehensive information about:

- The hazard. A hazard may be described by its intensity, spatial distribution and probability of occurrence. In COVERMAR, hazards are described through a probabilistic hazard assessment, combined with a numerical simulation of the selected inundation scenarios (see the COVEMAR Hazard Assessment Report);
- The degree of expected damage to exposed assets in response to the hazard. This is obtained through specific vulnerability assessment models, described in the 'Vulnerability Assessment' Section of this report. The degree of damage is obtained with a Damage Index, which uses the following ratio:

  cost to repair/cost to replace;

- The economic value of the exposed assets, plus repair and replacement contingencies. The value of buildings and infrastructure within the COVERMAR study area are discussed below.

The PML of buildings was calculated using current building construction costs. Building contents were not considered. For each COVERMAR building type, the construction cost was calculated by using either the total construction cost per building estimated by Geoscience Australia (Maqsood et al., 2013), or the construction costs per square metre currently used for tax depreciation purposes (http://www.bmtqs.com.au/construction-cost-table).

The construction costs applied by Geoscience Australia were used for applicable COVERMAR building types, consistent with the storm surge vulnerability model. The construction cost of the remaining COVERMAR building types used tax depreciation databases. Since these databases provide a construction cost per square metre, the total construction cost was obtained by multiplying the cost by the building surface area.

Depending of the degree of damage incurred by the building, the PML was calculated as follows:

1. For buildings requiring repair:

   PML(repair) = (cost to repair) = (percentage of damage) x (construction cost) x (repair contingency)

2. For buildings requiring replacement:

PML(replace) = (replacement cost) = (construction cost) + (demolition cost)

Geoscience Australia (Maqsood et al., 2013) applied a repair contingency factor of 1.3 to account for demolition and disposal costs. Demolition costs for typical NSW buildings are provided by the NSW Government (http://www.environment.nsw.gov.au/resources/warr/1086CostsOfDecon.pdf). We considered a building to require replacement where repair was uneconomical:

Cost to repair x repair contingency ≥ replacement cost

Table 9 summarises the construction, demolition and replacement costs for each COVERMAR building type.

Table 9. Summary of the construction, demolition and replacement costs for each COVERMAR building type. The construction cost per building unit was provided by Geoscience Australia. For those COVERMAR building types not included in the GA dataset, a construction cost per square metre was used (http://www.bmtqs.com.au/construction-cost-table). 'rf'= raised ground floor, 'g'=garage, 'grf'+garage and raised ground floor, 'ggf'=ground floor entirely used as a garage.

COVERMAR building type		PML			
CLASS	SUBCLASS	Construction cost (per sq.m)	Construction cost (per building)	Demolition cost	TOT Replacement cost
1	-	-	$242,971	$10,376	*$253,347*
	Rf	-	$242,971	$10,376	$253,347
	G	-	$242,971	$10,376	$253,347
	Grf	-	$242,971	$10,376	$253,347
2	-	-	$242,971	$10,376	$253,347
	Rf	-	$242,971	$10,376	$253,347
	G	-	$242,971	$10,376	$253,347
	Grf	-	$242,971	$10,376	$253,347
3	-	-	$304,546	$20,284	$324,830
	Rf	-	$342,401	$20,284	$362,685
	G	-	$339,788	$20,284	$360,072
	Grf	-	$339,788	$20,284	$360,072
4	-	$1,505	*Constr. cost (per m^2) x building surface*	$20,284	*Constr. cost + demolition cost*
	Rf	$1,505	“ “	$20,284	“ “
	G	$1,505	“ “	$20,284	“ “
	Grf	$1,505	“ “	$20,284	“ “
	Ggf	$1,505	“ “	$20,284	“ “
5	-	$2,020	“ “	$27,523	“ “
	rf	$2,020	“ “	$27,523	“ “
	g	$2,020	“ “	$27,523	“ “
	grf	$2,020	“ “	$27,523	“ “
	ggf	$2,020	“ “	$27,523	“ “
6	-	$2,150	“ “	$27,523	“ “
	rf	$2,150	“ “	$27,523	“ “
	g	$2,150	“ “	$27,523	“ “
	grf	$2,150	“ “	$27,523	“ “
	ggf	$2,150	“ “	$27,523	“ “
7	-	$1,985	“ “	$20,284	“ “
	rf	$1,985	“ “	$20,284	“ “
	g	$1,985	“ “	$20,284	“ “
	grf	$1,985	“ “	$20,284	“ “
	ggf	$1,985	“ “	$20,284	“ “
8	-	$1,840	“ “	$27,523	“ “
	rf	$1,840	“ “	$27,523	“ “
	g	$1,840	“ “	$27,523	“ “
	grf	$1,840	“ “	$27,523	“ “
	ggf	$1,840	“ “	$27,523	“ “

9	-	$1,365	“ “	$27,523	“ “
	rf	$1,365	“ “	$27,523	“ “
	g	$1,365	“ “	$27,523	“ “
	grf	$1,365	“ “	$27,523	“ “
	ggf	$1,365	“ “	$27,523	“ “
10	-	$2,167	“ “	$27,523	“ “
	rf	$2,167	“ “	$27,523	“ “
	g	$2,167	“ “	$27,523	“ “
	grf	$2,167	“ “	$27,523	“ “
	ggf	$2,167	“ “	$27,523	“ “
11	-	$1,415	“ “	$27,523	“ “
	rf	$1,415	“ “	$27,523	“ “
	g	$1,415	“ “	$27,523	“ “
	grf	$1,415	“ “	$27,523	“ “
	ggf	$1,415	“ “	$27,523	“ “
12	-	$2,070	“ “	$27,523	“ “
	rf	$2,070	“ “	$27,523	“ “
	g	$2,070	“ “	$27,523	“ “
	grf	$2,070	“ “	$27,523	“ “
	ggf	$2,070	“ “	$27,523	“ “
13	-	$2,050	“ “	$27,523	“ “
	rf	$2,050	“ “	$27,523	“ “
	g	$2,050	“ “	$27,523	“ “
	grf	$2,050	“ “	$27,523	“ “
	ggf	$2,050	“ “	$27,523	“ “
14	-	-	$338,803	$10,376	$349,179
	rf	-	$338,803	$10,376	$349,179
	g	-	$338,803	$10,376	$349,179
	grf	-	$338,803	$10,376	$349,179
	ggf	-	$339,408	$10,376	$349,784
15	-	-	$923,140	$23,695	$946,835
	rf	-	$923,140	$23,695	$946,835
	g	-	$923,140	$23,695	$946,835
	grf	-	$923,140	$23,695	$946,835
	ggf	-	$923,140	$23,695	$946,835
16	-	-	$511,472	$20,284	$531,756
	rf	-	$511,472	$20,284	$531,756
	g	-	$472,513	$20,284	$492,797
	grf	-	$472,513	$20,284	$492,797
	ggf	-	$472,513	$20,284	$492,797
17	-	-	$338,803	$10,376	$349,179
	rf	-	$338,803	$10,376	$349,179
	g	-	$338,803	$10,376	$349,179
	grf	-	$338,803	$10,376	$349,179
	ggf	-	$339,408	$10,376	$349,784
18	-	$2,632	*Constr. cost (per m^2) x building surface*	$27,523	*Constr. cost + demolition cost*
	rf	$2,632	“ “	$27,523	“ “
	g	$2,632	“ “	$27,523	“ “
	grf	$2,632	“ “	$27,523	“ “
	ggf	$2,632	“ “	$27,523	“ “

19	-	-	$511,472	$20,284	$531,756
	rf	-	$511,472	$20,284	$531,756
	g	-	$472,513	$20,284	$492,797
	grf	-	$472,513	$20,284	$492,797
	ggf	-	$472,513	$20,284	$492,797
20	-	$2,370	*Constr. cost (per m^2) x building surface*	$27,523	*Constr. cost + demolition cost*
	rf	$2,370	" "	$27,523	" "
	g	$2,370	" "	$27,523	" "
	grf	$2,370	" "	$27,523	" "
	ggf	$2,370	" "	$27,523	" "
21	-	$1,050	" "	$36,400	" "
	rf	$1,050	" "	$36,400	" "
	g	$1,050	" "	$36,400	" "
	grf	$1,050	" "	$36,400	" "
	ggf	$1,050	" "	$36,400	" "
22	-	$1,110	" "	$36,400	" "
	rf	$1,110	" "	$36,400	" "
	g	$1,110	" "	$36,400	" "
	grf	$1,110	" "	$36,400	" "
	ggf	$1,110	" "	$36,400	" "
23	-	-	$2,753,115	$207,000	$2,960,115
	rf	-	$2,753,115	$207,000	$2,960,115
	g	-	$2,753,115	$207,000	$2,960,115
	grf	-	$2,753,115	$207,000	$2,960,115
	ggf	-	$2,753,115	$207,000	$2,960,115
24	-	-	$2,753,115	$207,000	$2,960,115
	rf	-	$2,753,115	$207,000	$2,960,115
	g	-	$2,753,115	$207,000	$2,960,115
	grf	-	$2,753,115	$207,000	$2,960,115
	ggf	-	$2,753,115	$207,000	$2,960,115

The PML for arterial roads and secondary streets was obtained from construction costs reported by the 2013 Rawlinsons Construction Cost Guide:

Suburban road with in-situ concrete kerbs:

6 m wide – $520–560/m

8 m wide-- $620–660/m

N.B. These prices include minimal cut and fill but exclude lighting and drainage.

City highway/freeway with median strip and emergency lanes:

duplicate two lanes – $1,950–2,250/m

duplicate three lanes – $2,390–2,620/m

For other infrastructure types PML was not calculated due to either a lack of suitable vulnerability assessment models or specific data about the structural characteristics of the infrastructure.

RESULTS

The results of the assessment address the following elements:

Exposure : the quantity of assets that would be inundated by each of the selected storm surge and tsunami scenarios (e.g. the number of buildings, length of roads);

Vulnerability: the susceptibility to damage of each of exposed asset;

Probable Maximum Loss: the economic losses associated with the expected degree of damage experienced by exposed and vulnerable assets.

Each element is discussed separately below:

EXPOSURE

Buildings

The number of buildings inundated by each storm surge and tsunami scenario is presented in Tables 10 and 11 and Figures 15–17. Numbers vary slightly from those reported in the Results section of the Hazard Assessment Report because the vulnerability assessment process examined and ground-truthed individual exposed buildings eliminating sheds and garages, and precisely identifying attached buildings.

Table 10. Number of buildings inundated in each storm surge scenario.

INUNDATED BUILDINGS				
STORM SURGE CODE SCENARIO	BOTANY BAY	ROCKDALE	SUTHERLAND	TOTAL
1 (1/100 yr.)	45	52	151	248
2 (1/100 yr., +34 cm)	138	252	439	829
3 (1/100 yr., +84 cm)	210	1121	1842	3173

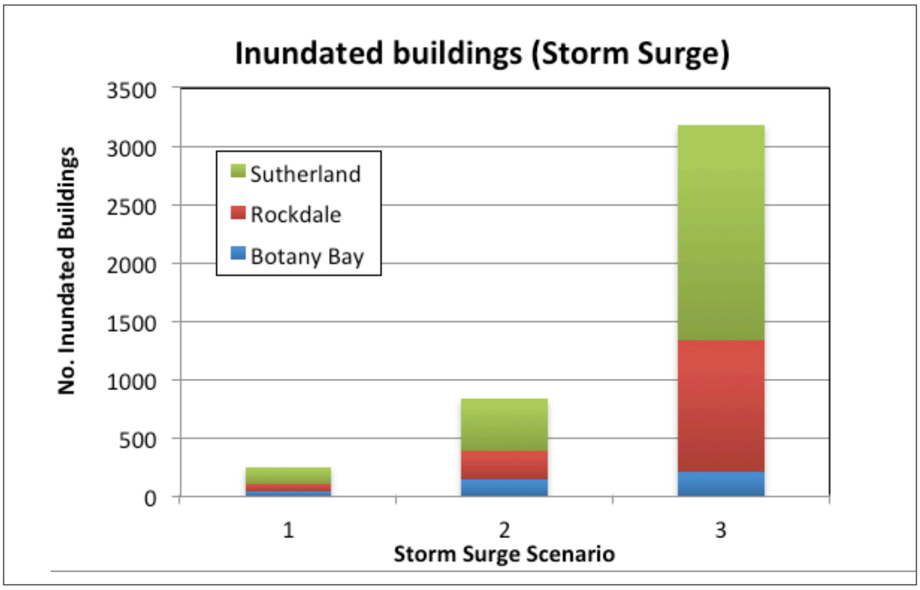


Figure 15. Number of buildings in each LGA inundated in the storm surge scenarios.

Table 11. Number of buildings inundated in each tsunami scenario.

TSUNAMI SCENARIO				INUNDATED BUILDINGS			
Tsunami Source Location	Annual Probability for NSW	Initial Sea Level ***(above the 2010 msl)***	Scenario code	BOTANY BAY	ROCKDALE	SUTHERLAND	TOTAL
New Hebrides	1/100	+0 cm	N1	0	2	15	17
		+34 cm	N2	0	4	32	36
		+84 cm	N3	1	4	112	117
		+97 cm	N4	1	6	125	132
		+131 cm	N5	1	12	171	184
		+181 cm	N6	67	90	754	911
	1/1,000	+0 cm	N7	0	2	32	34
		+34 cm	N8	0	4	60	64
		+84 cm	N9	1	8	175	184
		+97 cm	N10	1	12	199	212
		+131 cm	N11	1	35	289	325
		+181 cm	N12	67	122	1115	1304
	1/10,000	+0 cm	N13	0	2	169	171
		+34 cm	N14	0	8	266	274
		+84 cm	N15	1	29	470	500
		+97 cm	N16	1	42	566	609
		+131 cm	N17	1	107	811	919
		+181 cm	N18	75	306	1937	2318
Puysegur	1/100	+0 cm	S1	0	2	7	9
		+34 cm	S2	0	4	27	31
		+84 cm	S3	1	4	92	97
		+97 cm	S4	1	6	110	117
		+131 cm	S5	1	10	154	165
		+181 cm	S6	67	82	525	674
	1/1,000	+0 cm	S7	0	2	27	29
		+34 cm	S8	0	4	60	64
		+84 cm	S9	1	6	172	179
		+97 cm	S10	1	9	198	208
		+131 cm	S11	1	30	293	324
		+181 cm	S12	67	117	1131	1315
	1/10,000	+0 cm	S13	0	3	155	158
		+34 cm	S14	0	6	255	261
		+84 cm	S15	1	21	488	510
		+97 cm	S16	1	31	575	607
		+131 cm	S17	19	102	731	852
		+181 cm	S18	75	348	2200	2623

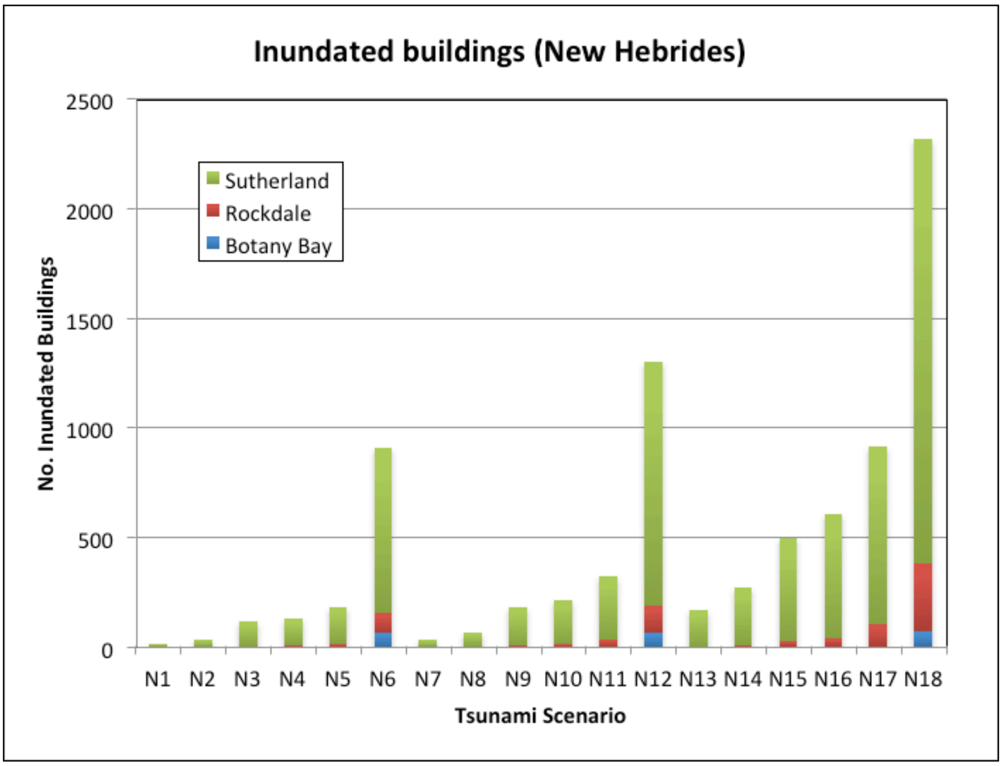


Figure 16. Number of buildings in each LGA inundated in the tsunami scenarios generated by the New Hebrides Trench.

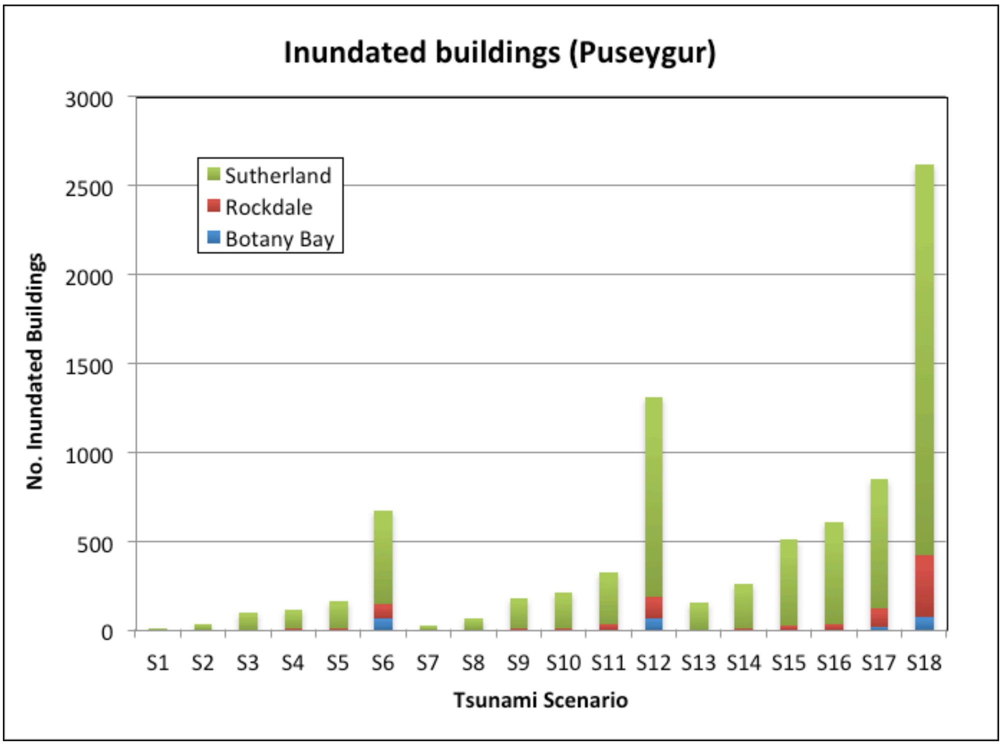


Figure 17. Number of buildings in each LGA inundated in the tsunami scenarios generated by the Puysegur Trench.

Infrastructure

Exposed critical infrastructure is summarised in the following Tables and Figures:

Location	Tables	Figures
Botany Bay	12,13	18–20
Rockdale	14, 15	21–23
Sutherland	16, 17	24–29
Sydney Airport and Port Botany	18, 19	30–33

Table 12. Infrastructure exposed to each of the storm surge scenarios in Botany Bay Council area.

		SCENARIO CODE	Government buildings	Utility buildings	Education buildings	Health buildings	Arterial roads (m)	Local roads (m)	Car parks (Area)	Bridges (Number)	Railway (m)	Train stations	Sydney Airport Buildings	Port Botany (Area, m^2)	Beaches (Area, m^2)	Sport facilities (Number)	Parks and reserves (Area, m^2)	Seawalls or breakwaters (Number)	Marinas (Number)	Other coastal structures (Number)
STORM SURGE	inundation	1	0	0	0	0		1001	0	0	0	0	2	472	0	0	0	1	0	6
	erosion		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	inundation	2	0	0	0	0	422	2117	0	0	0	0	4	745	0	0	0	1	0	7
	erosion		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	inundation	3	0	0	0	0	734	3473	0	0	0	0	7	1940	0	0	0	1	0	7
	erosion		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

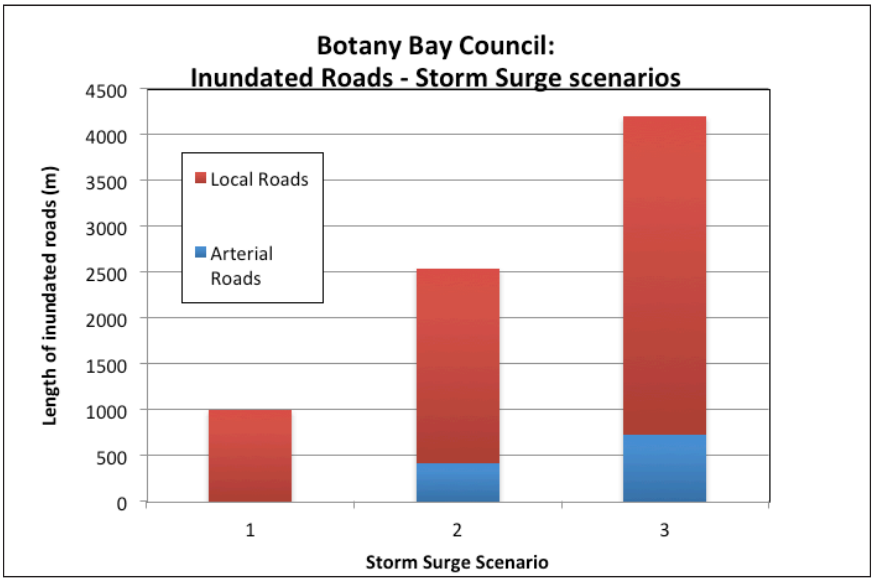


Figure 18. Botany Bay Council area: total length of arterial and local roads exposed to storm surge inundation.

Table 13. Infrastructure exposed to each of the tsunami scenarios in the Botany Bay Council area.

	Return Time	SCENARIO CODE	Government buildings	Utility buildings	Education buildings	Health (buildings	Arterial roads (m)	Local roads (m)	Car parks (Area)	Bridges (Number)	Railway (m)	Train stations	Sydney Airport Buildings	Port Botany (Area, m^2)	Beaches (Area, m^2)	Sport facilities (Number)	Parks and reserves (Area m^2)	Seawalls or breakwaters (Number)	Marinas (Number)	Other coastal structures (Number)
TSUNAMI- New Herbridges	100 yr	N1	0	0	0	0	0	31	0	0	0	0	0	439	0	0	0	0	0	1
		N2	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	0	0	1
		N3	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	0	0	2
		N4	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	1	0	2
		N5	0	0	0	0	12	43	0	0	0	0	0	439	0	0	0	1	0	2
		N6	0	0	0	0	12	804	0	0	0	0	0	439	0	0	0	1	0	3
	1,000 yr	N7	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	0	0	1
		N8	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	0	0	1
		N9	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	1	0	2
		N10	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	1	0	2
		N11	0	0	0	0	12	43	0	0		0	0	439	0	0	0	1	0	2
		N12	0	0	0	0	12	816	0	0	0	0	0	439	0	0	0	1	0	3
	10,000 yr	N13	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	1	0	1
		N14	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	1	0	2
		N15	0	0	0	0	0	107	0	0	0	0	0	454	0	0	0	1	0	2
		N16	0	0	0	0	0	202	0	0	0	0	0	2315	0	0	0	1	0	2
		N17	0	0	0	0	505	978	0	0	0	0	0	48575	0	0	0	1	0	2
		N18	0	0	0	0	3191	2810	0	0	0	0	0	421365	0	0	0	1	0	4
TSUNAMI- Puysegur	100 yr	S1	0	0	0	0	0	31	0	0	0	0	0	439	0	0	0	0	0	1
		S2	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	0	0	1
		S3	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	0	0	2
		S4	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	1	0	2
		S5	0	0	0	0	12	43	0	0	0	0	0	439	0	0	0	1	0	2
		S6	0	0	0	0	12	804	0	0	0	0	0	439	0	0	0	1	0	3
	1,000 yr	S7	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	0	0	1
		S8	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	0	0	1
		S9	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	0	0	2
		S10	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	0	0	2
		S11	0	0	0	0	12	43	0	0	0	0	0	439	0	0	0	1	0	2
		S12	0	0	0	0	12	869	0	0		0	0	547	0	0	0	1	0	3
	10,000 yr	S13	0	0	0	0	0	43	0	0	0	0	0	439	0	0	0	1	0	1
		S14	0	0	0	0	0	54	0	0	0	0	0	439	0	0	0	1	0	1
		S15	0	0	0	0	0	108	0	0	0	0	0	5617	0	0	0	1	0	2
		S16	0	0	0	0	34	219	0	0	0	0	0	97472	0	0	0	1	0	2
		S17	0	0	0	0	1964	1808	0	0	0	0	0	314141	0	0	0	1	0	6
		S18	0	0	0	0	3293	3015	0	0		0	0	439793	0	0	0	1	0	4

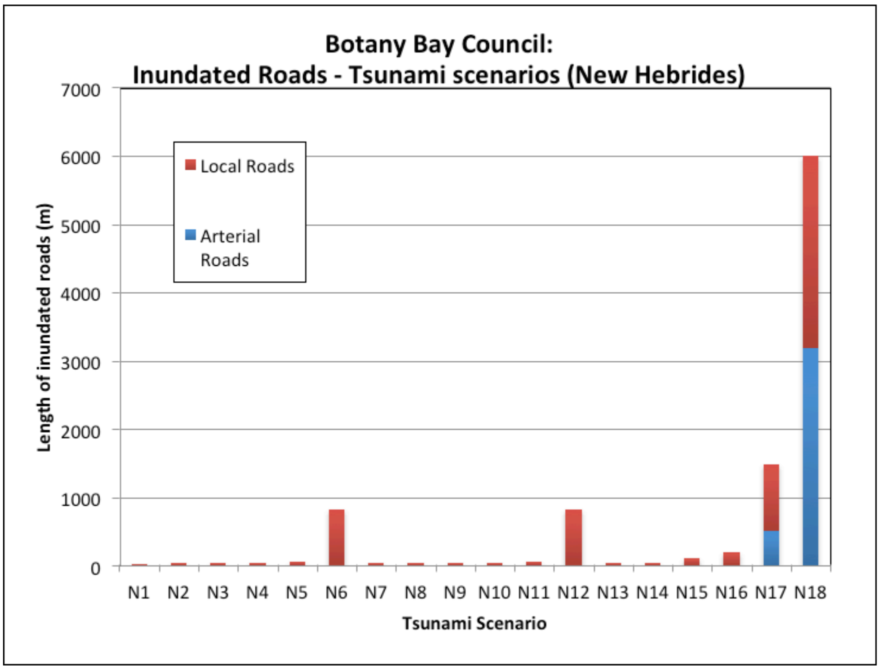


Figure 19. Botany Bay Council area: total length of arterial and local roads exposed to tsunami inundation (originating: New Hebrides).

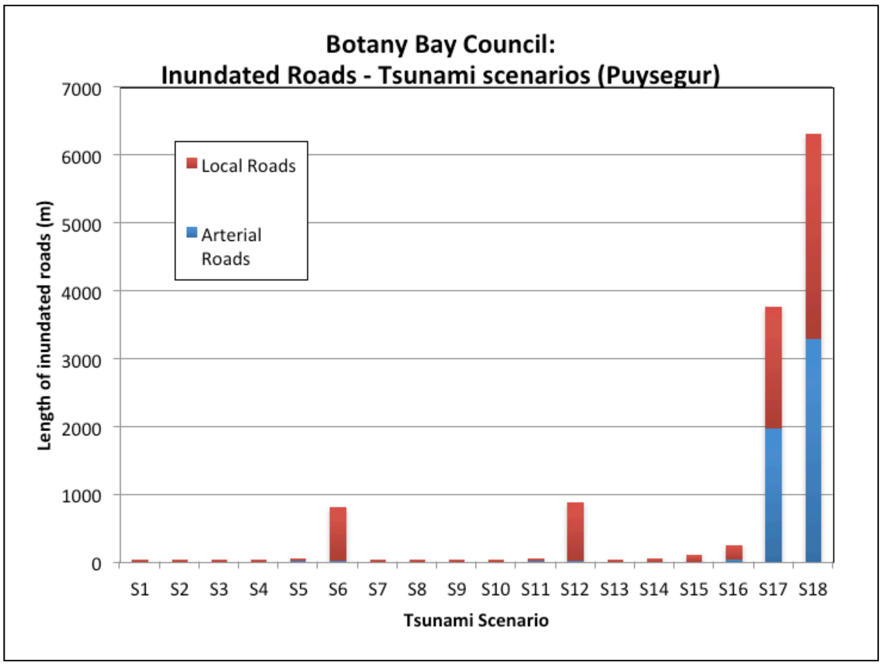


Figure 20. Botany Bay Council area: total length of arterial and local roads exposed to tsunami inundation (originating: Puysegur).

Table 14. Infrastructure exposed to each of the storm surge scenarios in the Rockdale Council area.

		SCENARIO CODE	Government buildings	Utility buildings	Education buildings	Health buildings	Arterial roads (m)	Local roads (m)	Car parks (Area)	Bridges (Number)	Railway (m)	Train stations	Sydney Airport Buildings	Beaches (Area, m^2)	Sport facilities (Number)	Parks and reserves (Area, m^2)	Seawalls or breakwaters (Number)	Marinas (Number)	Other Coastal structures (Number)
STORM SURGE	inundation	1	0	0	0	0	557	1494	107	9	55	1	2	94448	2	323253	20	0	24
	erosion		0	0	0	0	0	0	172	0	0	0	0	258434	0	10400	16	0	0
	inundation	2	0	0	0	0	1414	4669	777	9	62	1	3	130584	3	729857	22	0	27
	erosion		0	0	0	0	0	0	168	0	0	0	0	257938	0	10198	15	0	0
	inundation	3	0	0	4	1	3697	17086	13402	10	128	1	5	160548	3	984682	22	0	27
	erosion		0	0	0	0	0	0	181	0	0	0	0	256114	0	8467	15	0	0

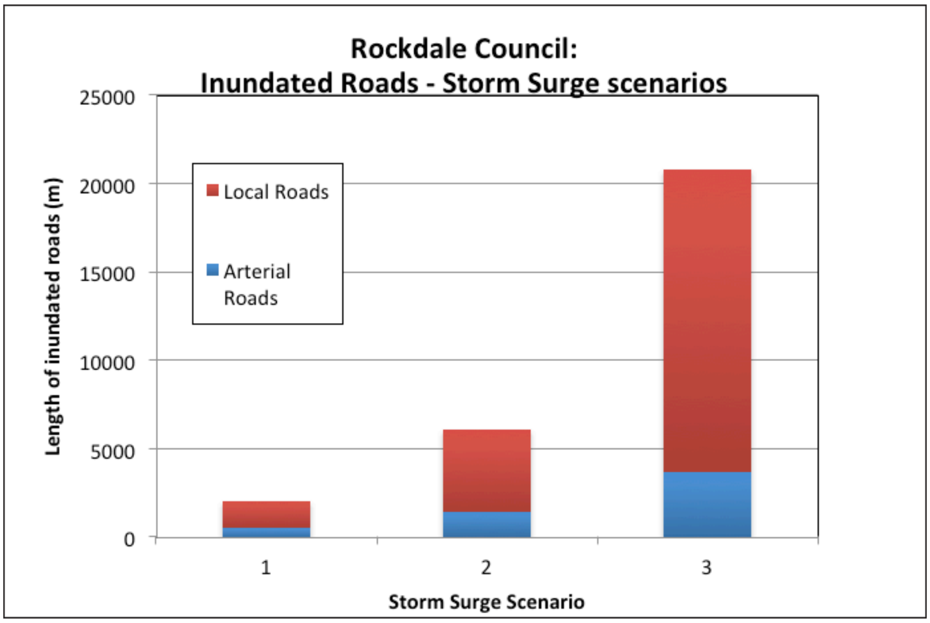


Figure 21. Rockdale Council area: total length of arterial and local roads exposed to storm surge inundation.

Table 15. Infrastructure exposed to each of the tsunami scenarios in the Rockdale Council area.

	Return Time	SCENARIO CODE	Government buildings	Utility buildings	Education buildings	Health buildings	Arterial roads (m)	Local roads (m)	Car parks (Area)	Bridges (Number)	Railway (m)	Train stations	Sydney Airport Buildings	Beaches (Area, m^2)	Sport facilities (Number)	Parks and reserves (Area, m^2)	Seawalls or breakwaters (Number)	Marinas (Number)	Other Coastal structures (Number)
TSUNAMI - New Hebrides	100 yr	N1	0	0	0	0	811	129	0	3	0	0	0	20311	1	454	14	0	7
		0	0	0	0	0	844	129	0	4	0	0	0	34556	2	522	18	0	9
		N3	0	0	0	0	944	196	0	7	0	0	0	63113	2	17387	19	0	16
		N4	0	0	0	0	976	196	3	7	0	0	0	75396	2	24986	21	0	16
		N5	0	0	0	0	1048	785	123	7	0	0	0	115536	2	93419	22	0	22
		N6	0	0	0	0	560	2193	525	9	0	0	0	157170	3	221231	22	0	24
	1,000 yr	N7	0	0	0	0	844	129	0	3	0	0	0	35493	1	522	18	0	8
		N8	0	0	0	0	915	129	0	4	0	0	0	54568	2	1431	18	0	14
		N9	0	0	0	0	1029	737	3	7	0	0	0	102518	2	55004	20	0	17
		N10	0	0	0	0	1048	921	123	7	0	0	0	119894	2	88754	22	0	17
		N11	0	0	0	0	1319	1549	345	7	0	0	0	54649	3	133504	23	0	23
		N12	0	0	0	0	2148	2994	932	9	0	0	0	178354	3	236637	22	0	24
	10,000 yr	N13	0	0	0	0	954	129	0	3	0	0	0	79524	1	1551	19	0	12
		N14	0	0	0	0	1000	571	3	4	0	0	0	119550	2	28378	20	0	14
		N15	0	0	0	0	1279	1752	348	7	0	0	0	167344	3	116177	21	0	18
		N16	0	0	0	0	1351	2067	528	7	0	0	0	174302	3	123215	22	0	19
		N17	0	0	0	0	1907	3105	1277	7	0	0	0	189649	3	157386	23	0	23
		N18	0	0	0	1	2931	5954	8755	9	0	0	1	213504	3	304103	23	0	24
TSUNAMI - Puysegur	100 yr	S1	0	0	0	0	799	29	0	3	0	0	0	18743	1	454	14	0	7
		S2	0	0	0	0	844	129	0	4	0	0	0	34019	2	522	18	0	9
		S3	0	0	0	0	944	196	0	7	0	0	0	64616	2	15686	19	0	16
		S4	0	0	0	0	976	205	3	7	0	0	0	79462	2	24457	21	0	16
		S5	0	0	0	0	1042	580	221	7	0	0	0	118538	2	70950	23	0	22
		S6	0	0	0	0	1477	2022	525	9	0	0	0	155916	3	215354	22	0	24
	1,000 yr	S7	0	0	0	0	844	129	0	3	0	0	0	36647	1	454	18	0	7
		S8	0	0	0	0	892	129	0	4	0	0	0	57388	2	1282	18	0	12
		S9	0	0	0	0	1023	390	123	7	0	0	0	111251	2	42445	20	0	17
		S10	0	0	0	0	1048	823	333	7	0	0	0	126586	2	80770	22	0	17
		S11	0	0	0	0	1094	1393	525	7	0	0	0	153323	3	124967	22	0	23
		S12	0	0	0	0	2060	3061	1560	9	0	0	0	179716	3	241171	22	0	24
	10,000 yr	S13	0	0	0	0	1060	129	3	3	0	0	0	93225	1	1617	18	0	11
		S14	0	0	0	0	977	189	333	4	0	0	0	129621	2	19520	20	0	14
		S15	0	0	0	0	1466	1176	578	7	0	0	0	169925	3	105315	20	0	18
		S16	0	0	0	0	1220	1859	1062	7	0	0	0	176576	3	123943	23	0	19
		S17	0	0	0	0	2166	3043	4245	6	0	0	0	178379	3	176138	23	0	23
		S18	0	0	0	1	3322	5731	11236	9	0	0	1	214961	3	308794	23	0	24

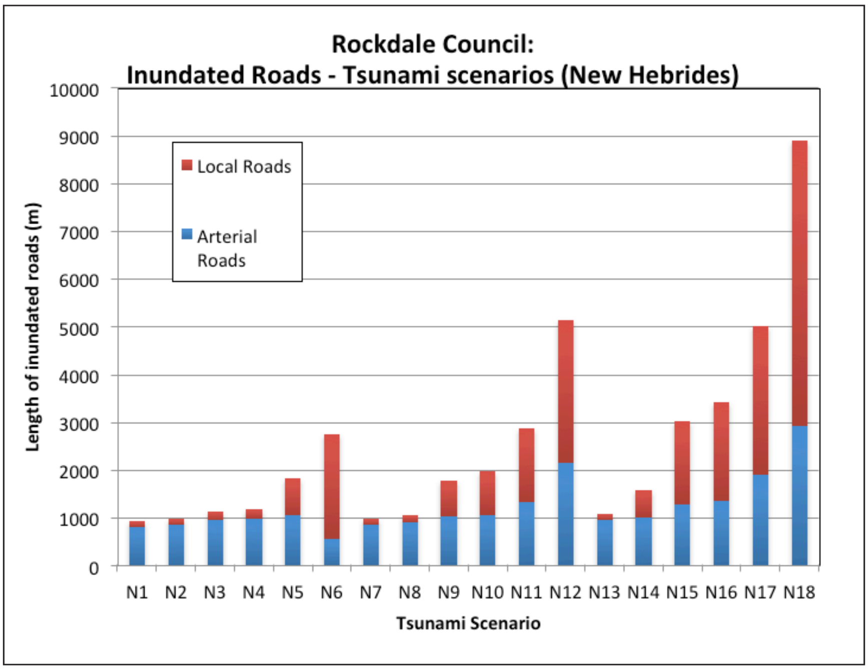


Figure 22. Rockdale Council area: total length of arterial and local roads exposed to tsunami inundation (originating: New Hebrides).

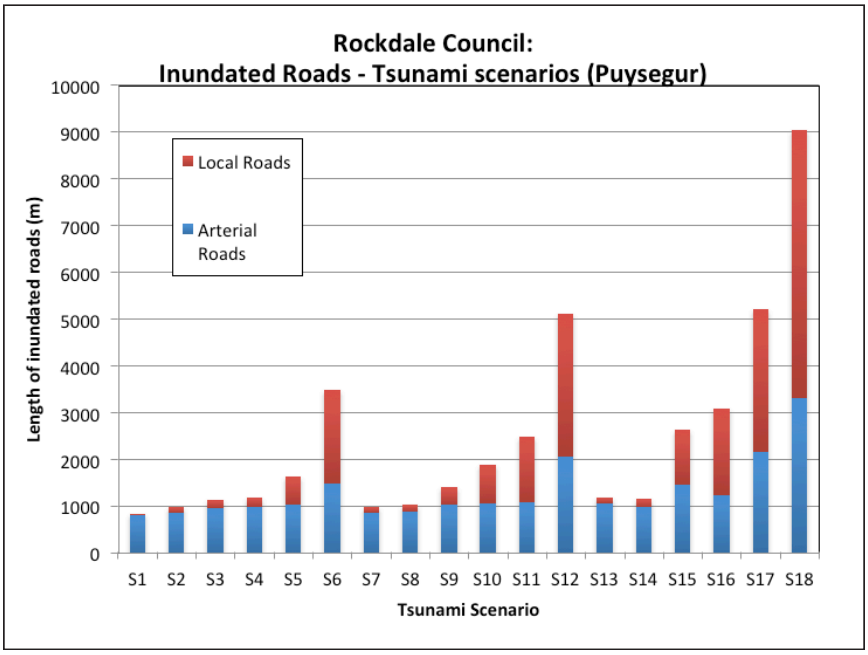


Figure 23. Rockdale Council area: total length of arterial and local roads exposed to tsunami inundation (originating: Puysegur).

Table 16. Infrastructure exposed in each of the storm surge scenarios in the Sutherland Council area.

		SCENARIO CODE	Government buildings	Utility buildings	Education buildings	Health buildings	Arterial roads (m)	Local roads (m)	Car parks (Area)	Bridges (Number)	Railway (m)	Train stations	Beaches (Area, m^2)	Sport facilities (Number)	Parks and reserves (Area, m^2)	Seawalls or breakwaters (Number)	Marinas (Number)	Other Coastal structures (Number)
STORM SURGE	inundation	1	1	0	0	0	351	2060	199	6	9	0	236347	7	3244405	8	7	8
	erosion		0	0	0	0	0	38	145	0	0	0	347276	0	235898	2	0	0
	inundation	2	2	0	3	0	1117	7563	3892	6	11	0	292328	11	4075443	9	7	21
	erosion		0	0	0	0	0	59	209	0	0	0	375098	0	292757	2	0	0
	inundation	3	3	1	12	1	2862	25686	18593	6	9	0	357932	13	4849666	11	7	16
	erosion		0	0	0	0	0	161	716	0	0	0	376663	0	354575	2	0	0

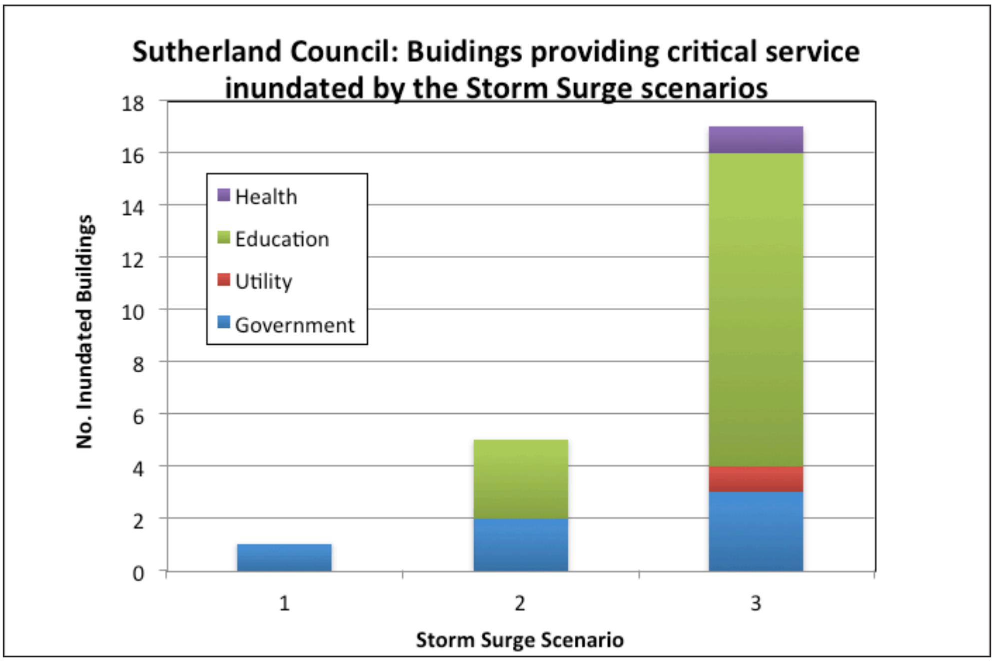


Figure 24. Sutherland Council area: number of buildings providing critical services exposed to storm surge inundation.

Table 17. Infrastructure exposed to each of the tsunami scenarios in the Sutherland Council area.

	Return Time	SCENARIO CODE	Government buildings	Utility buildings	Education buildings	Health buildings	Arterial roads (m)	Local roads (m)	Car parks (Area)	Bridges (Number)	Railway (m)	Train stations	Beaches (Area, m^2)	Sport facilities (Number)	Parks and reserves (Area, s m^2)	Seawalls or breakwaters (Number)	Marinas (Number)	Other Coastal structures (Number)
TSUNAMI - New Hebrides	100 yr	N1	0	0	0	0	740	896	121	5	47	0	142878	1	3897606	12	7	8
		N2	0	0	0	0	762	1118	121	6	67	0	196118	1	4322140	13	7	10
		N3	1	0	0	0	815	2092	121	6	94	0	289288	4	5960377	16	7	11
		N4	1	0	0	0	832	2263	121	6	94	0	313875	4	6459666	16	7	11
		N5	1	0	0	0	1117	2325	121	6	97	0	382355	6	7578021	17	7	11
		N6	2	0	4	0	1918	8720	2636	6	109	0	469618	9	8734841	17	7	15
	1,000 yr	N7	0	0	0	0	740	1155	121	5	47	0	279840	2	4246630	14	7	10
		N8	1	0	0	0	258	1306	131	6	67	0	353116	2	4971481	15	7	11
		N9	1	0	0	0	842	2577	386	6	94	0	430410	4	6937167	16	7	11
		N10	1	0	0	0	896	2697	654	6	96	0	445974	4	7368130	16	7	12
		N11	1	0	0	0	1326	3346	708	6	114	0	485822	6	8307090	17	7	13
		N12	2	0	5	0	2154	11882	6104	6	117	0	534540	9	9248701	18	7	17
	10,000 yr	N13	1	0	0	0	758	2733	762	5	60	0	492263	2	5428689	16	7	12
		N14	1	0	0	0	821	3607	762	6	72	0	519339	3	6575073	16	7	12
		N15	1	0	2	0	962	6009	762	6	108	0	565581	7	8226907	17	7	12
		N16	3	0	2	0	1168	7033	762	6	110	0	572221	7	8510974	17	7	12
		N17	3	1	6	0	1706	9629	973	6	124	0	600051	8	9207438	18	7	14
		N18	3	3	11	0	4080	22426	17694	6	126	0	633693	10	9850694	18	7	17
TSUNAMI - Puysegur	100 yr	S1	0	0	0	0	740	943	121	5	47	0	124485	1	3841510	12	7	8
		S2	0	0	0	0	762	1143	121	6	67	0	168963	1	4250589	13	7	8
		S3	0	0	0	0	815	1931	121	6	94	0	261074	4	5715407	16	7	11
		S4	0	0	0	0	832	2200	121	6	94	0	287926	4	6314552	16	7	11
		S5	1	0	0	0	1126	2406	121	6	97	0	360997	6	7509665	17	7	11
		S6	2	0	3	0	1675	5395	2636	6	109	0	457366	9	8676243	17	7	15
	1,000 yr	S7	0	0	0	0	740	1235	121	5	47	0	327016	2	4278103	14	7	10
		S8	1	0	0	0	774	1418	177	6	67	0	385067	2	4924686	15	7	18
		S9	1	0	0	0	854	2402	654	6	94	0	455408	4	6835621	17	7	12
		S10	1	0	0	0	877	2751	695	6	94	0	471828	4	7321389	17	7	12
		S11	1	0	0	0	1276	3674	708	6	101	0	511945	6	8319104	18	7	13
		S12	2	1	5	0	2043	11881	5843	6	117	0	554974	9	9262917	18	7	17
	10,000 yr	S13	1	0	0	0	774	2581	762	6	67	0	517706	2	5355931	16	7	11
		S14	1	0	0	0	850	3503	762	6	72	0	548484	2	6615307	16	7	12
		S15	2	0	1	0	1328	5952	762	6	110	0	593492	6	8370542	17	7	12
		S16	2	0	2	0	1447	7468	762	6	110	0	605353	7	8687463	18	7	12
		S17	2	1	2	0	1845	10891	1365	6	242	0	642487	8	9295046	18	7	13
		S18	4	3	11	0	3933	26199	15640	6	128	0	657980	10	9971374	18	7	17

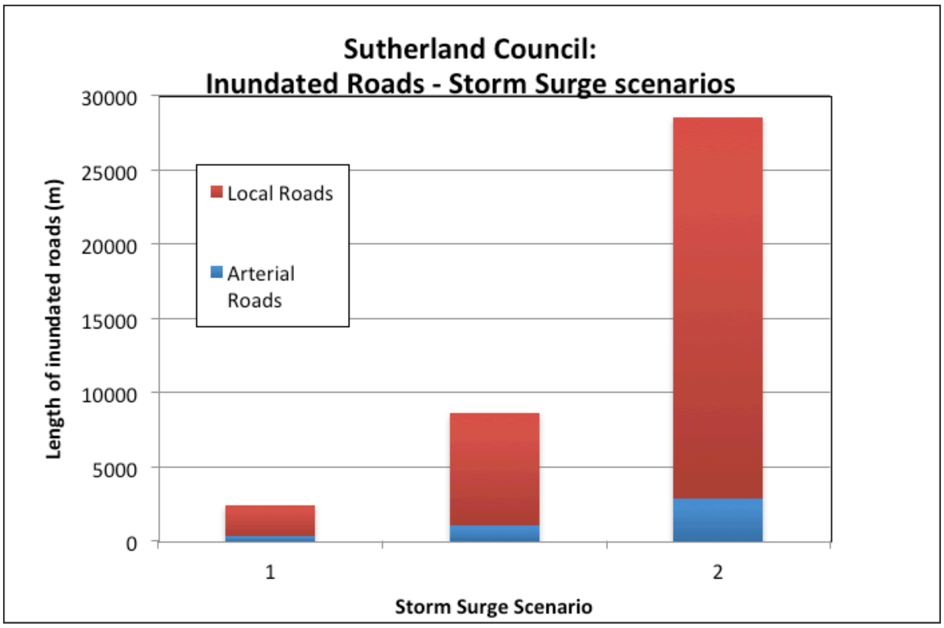


Figure 25. Sutherland Council area: total length of arterial and local roads exposed to storm surge inundation.

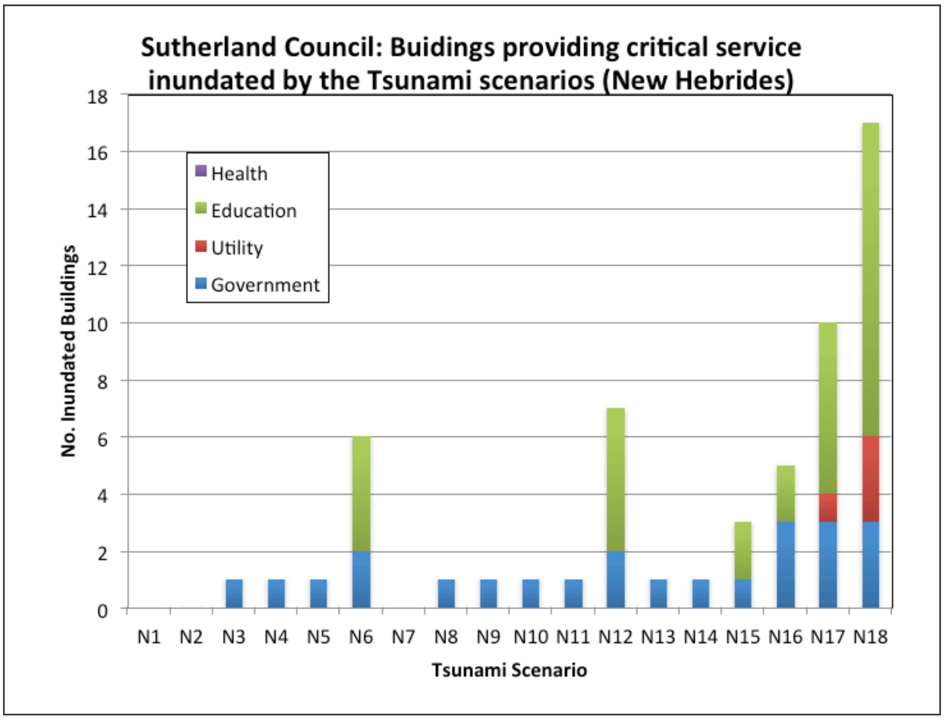


Figure 26. Sutherland Council area: buildings providing critical services exposed to tsunami inundation (originating: New Hebrides).

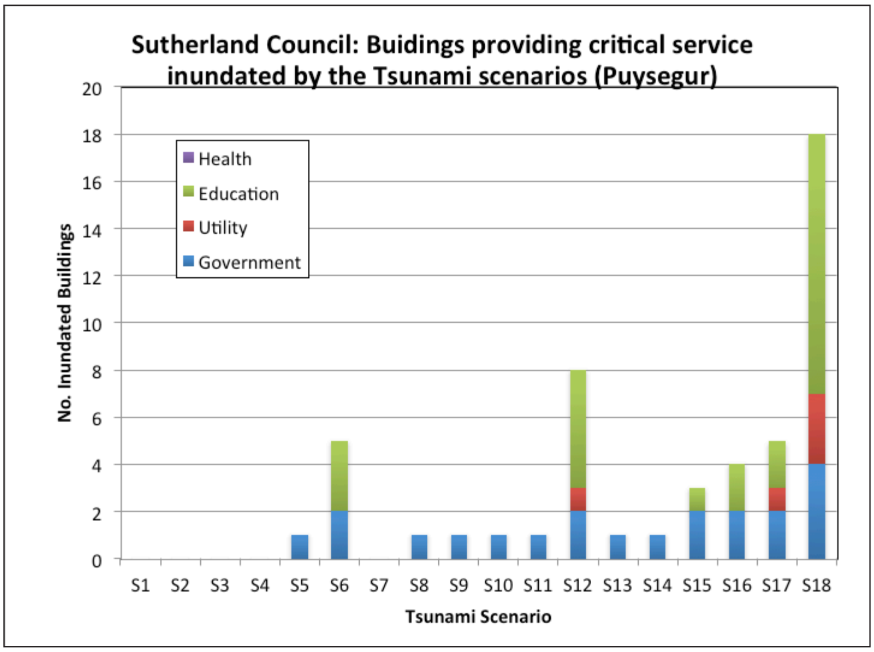


Figure 27. Sutherland Council area: buildings providing critical service exposed to tsunami inundation (originating: Puysegur).

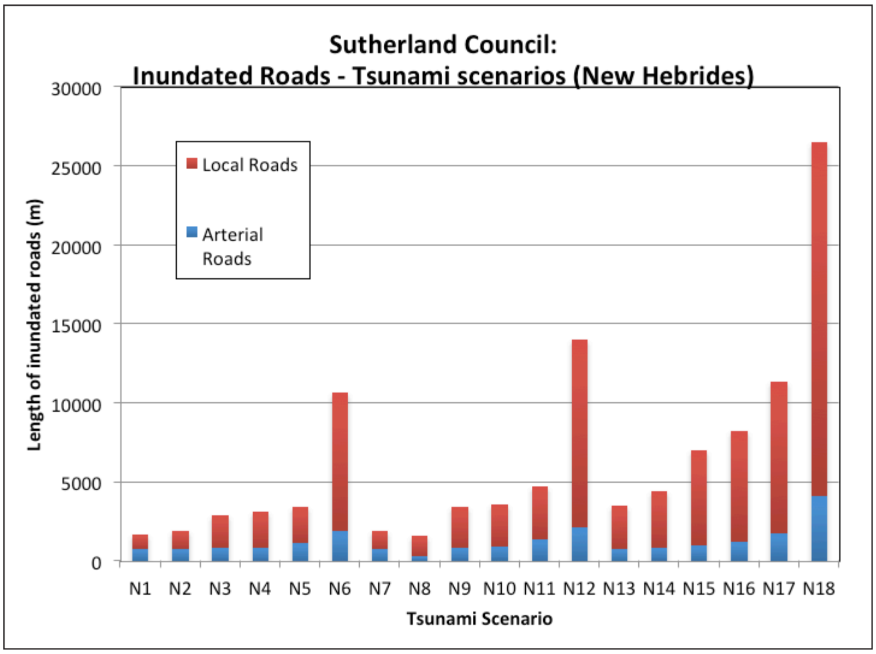


Figure 28. Sutherland Council area: length of arterial and local roads exposed to tsunami inundation (originating: New Hebrides).

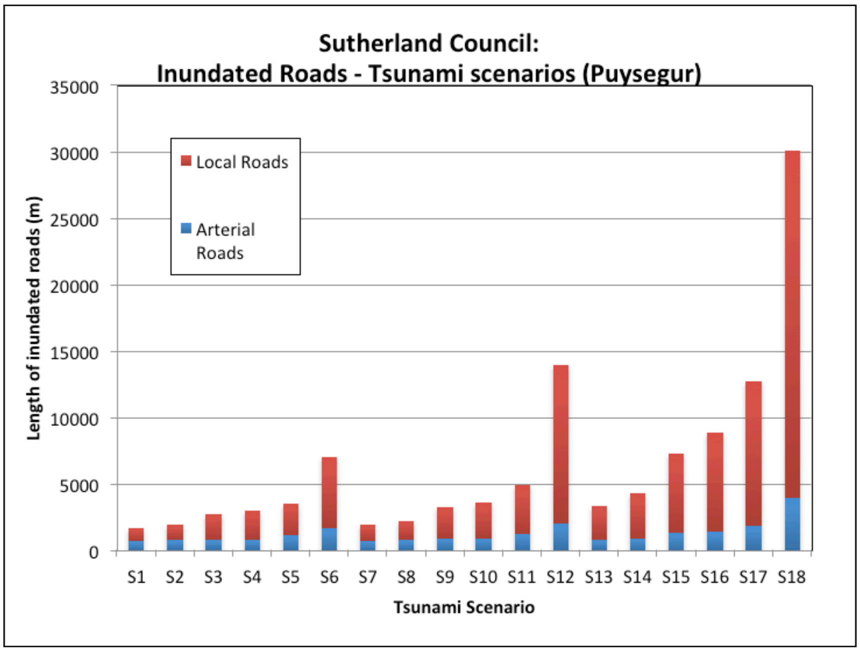


Figure 29 Sutherland Council area: length of arterial and local roads exposed to tsunami inundation (originating: Puysegur).

Table 18. Area of Sydney Airport and Port Botany (within Botany Bay LGA only) inundated by the Storm Surge scenarios.

		SCENARIO CODE	SYDNEY AIRPORT (area, m^2)	PORT BOTANY (area, m^2)
STORM SURGE	inundation	1	283049.5	472
	erosion		0	NA
	inundation	2	804541.6	745
	erosion		0	NA
	inundation	3	1627392	1940
	erosion		0	NA

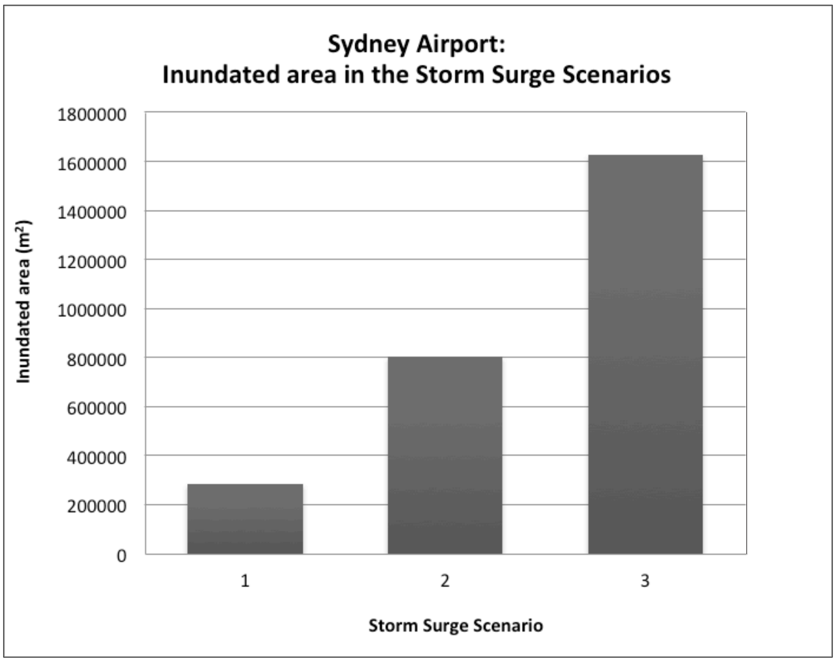


Figure 30. Sydney Airport: area exposed to storm surge inundation.

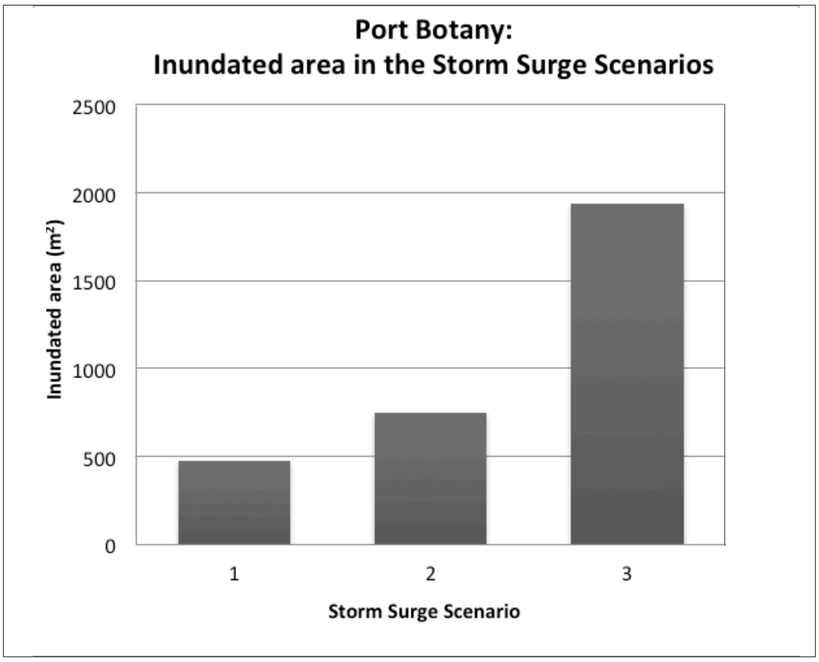


Figure 31. Port Botany: area exposed to storm surge inundation.

Table 19. Area of Sydney Airport and Port Botany (within Botany Bay LGA only) inundated by the tsunami scenarios.

		SCENARIO CODE	Sydney Airport (area, m^2)	Port Botany (area, m^2)				SCENARIO CODE	Sydney Airport (area, m^2)	Port Botany (area m^2)
TSUNAMI - New Hebrides	100 yr	N1	6200	439		TSUNAMI - Puysegur	100 yr	S1	6088	439
		N2	7162	439				S2	7099	439
		N3	8491	439				S3	8459	439
		N4	9152	439				S4	8950	439
		N5	12942	439				S5	12079	439
		N6	30461	439				S6	25238	439
	1,000 yr	N7	7222	439			1,000 yr	S7	7210	439
		N8	8386	439				S8	8522	439
		N9	13174	439				S9	16033	439
		N10	16000	439				S10	20657	439
		N11	31493	439				S11	42423	439
		N12	194176	439				S12	176493	547
	10,000 yr	N13	20660	439			10,000 yr	S13	29603	439
		N14	44703	439				S14	57032	439
		N15	109383	454				S15	125408	5617
		N16	145829	2315				S16	152314	97472
		N17	320785	48575				S17	406534	314141
		N18	785224	421365				S18	940826	439793

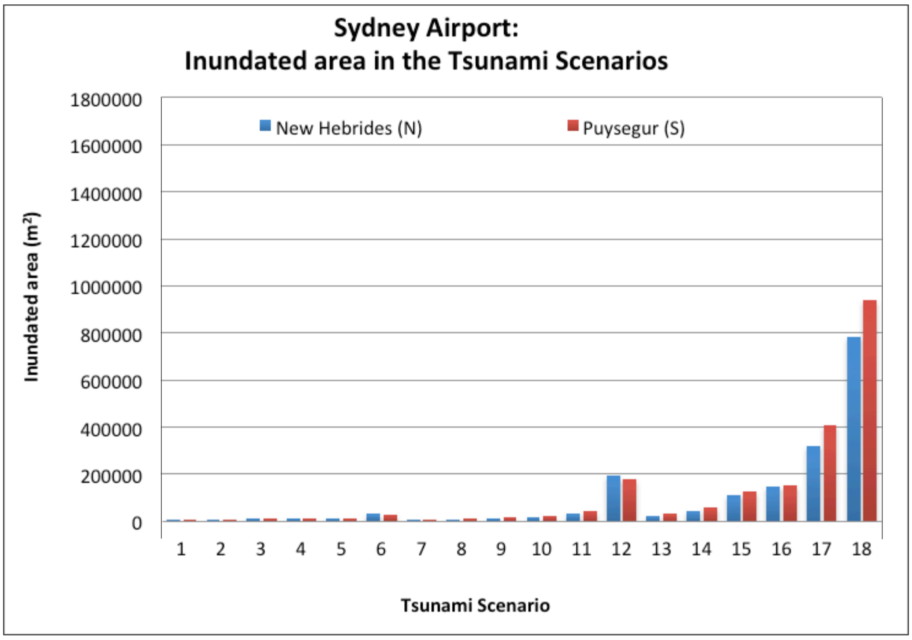


Figure 32. Sydney Airport: area exposed to tsunami inundation.

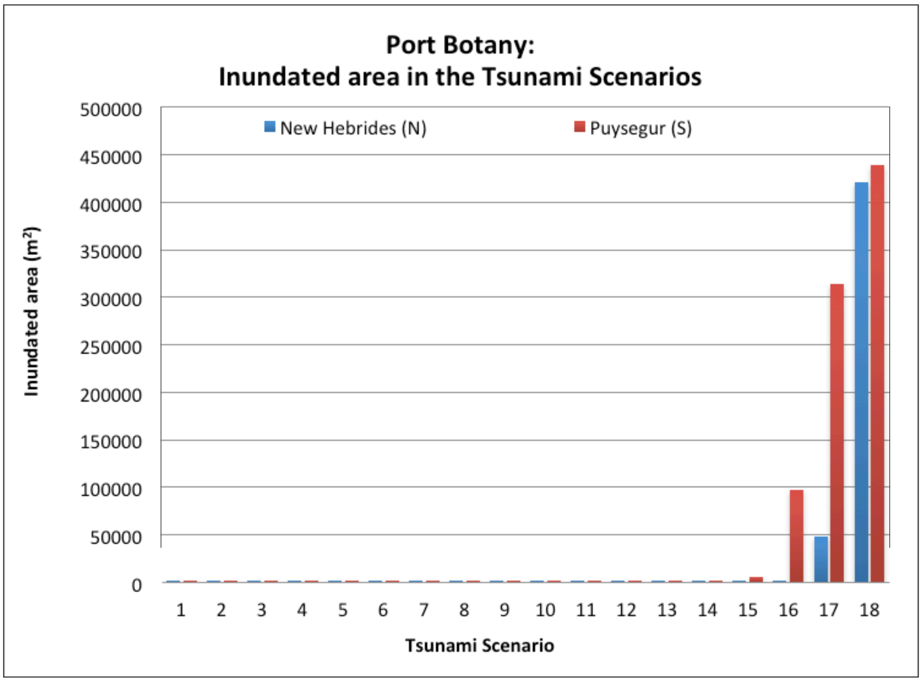


Figure 33. Port Botany: area exposed to tsunami inundation.

VULNERABILITY

The vulnerability of individual buildings and selected infrastructure was calculated within the COVERMAR GIS and used to generate thematic vulnerability maps. In these maps, vulnerability is represented using a colour-coded scale ranging from green (low vulnerability) to red (high vulnerability). The maps also show the 'use' of each building (e.g. residential, commercial, health and education) following Dall'Osso and Dominey-Howes (2009). The approach by Dall'Osso and Dominey-Howes (2009) was positively evaluated by Sydney stakeholders and residents in a subsequent study, namely Dall'Osso and Dominey-Howes (2010).

Given the extent of the study area and the benefits of a geographic scale that allows a view of single building units, we created five maps per inundation scenario. These maps have scales ranging between 1:5,000 and 1:10,000. They have been printed in A0 size and are also available in a digital form with the pdf version of this report. We also generated six detailed maps as examples (Appendix II). The areas covered by the maps included in this report are shown in Figure 34.

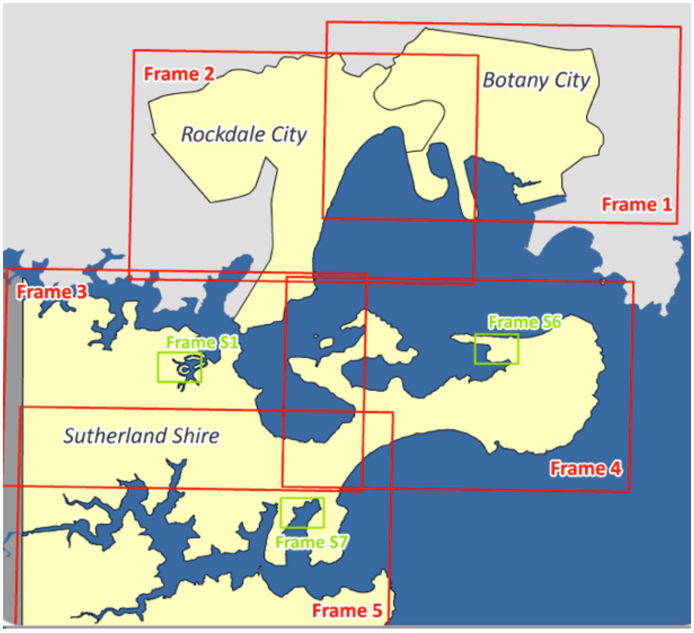


Figure 34. Coverage of the COVERMAR vulnerability maps. Frames 1 to 5 were printed in an A0 format, with scales ranging between 1:5,000 and 1:10,000. Frames S1, S6 and S7 are detail maps (Appendix II).

PROBABLE MAXIMUM LOSS

The Probable Maximum Loss (PML) caused by each inundation scenario was calculated for buildings and roads. Since the physical and engineering characteristics of 555 buildings were unavailable because they were inaccessible during the survey, their vulnerability could not be directly assessed. Therefore, in order to have comprehensive estimates of the expected economic losses associated with each inundation scenario, we calculated two different PML values:

1. Values for all the accessible buildings, whose characteristics were identified during the survey and stored in the GIS (Table 20 and Table 21, Figure 35 and Figure 37).
2. Values which included both accessible and inaccessible buildings (Table 22 and Table 23, Figure 36 and Figure 38). In order to estimate the expected damage to inaccessible buildings, we assumed that they were the most common building type found in the study area: COVERMAR type 3RF (one storey brick veneer buildings, with a raised ground-floor):
    - For storm surges, this approximation means that the storm surge building vulnerability model used to assess the expected damage is the FCM9 vulnerability function;
    - For tsunamis, this approximation uses the vulnerability function (i.e. the Mean Damage Curve) obtained for one Storey Brick Buildings.

Table 20. PML of buildings caused by each storm surge scenario. The number of buildings used for PML calculations is smaller than the total number of inundated buildings – those inaccessible are not considered.

		SCENARIO CODE	No. Inundated buildings	No. buildings used in PML Calculation	PML ($ Millions)
STORM SURGE	100 yr	1	248	108	17.5
		2	829	556	47.5
		3	3173	2717	212.7

Table 21. PML of buildings caused by each tsunami scenario. The number of buildings used for PML calculation is smaller than the total number of inundated buildings as those inaccessible are not considered.

	Return Time	SCENARIO CODE	No. Inundated buildings	No. buildings used in PML Calculation	PML ($ Millions)		Return Time	SCENARIO CODE	No. Inundated buildings	No. buildings used in PML Calculation	PML ($ Millions)
TSUNAMI - New Hebrides	100 yr	N1	17	10	4.8	TSUNAMI - Puysegur	100 yr	S1	9	6	3.1
		N2	36	17	9.9			S2	31	14	7.1
		N3	117	56	18.9			S3	97	46	16.1
		N4	132	58	23.3			S4	117	54	20.3
		N5	184	62	34.0			S5	165	57	29.3
		N6	911	694	145.3			S6	674	466	114.2
	1,000 yr	N7	34	16	11.3		1,000 yr	S7	29	15	10.2
		N8	64	25	16.2			S8	64	27	17.3
		N9	184	81	36.0			S9	179	80	37.3
		N10	212	92	44.8			S10	208	90	44.1
		N11	325	168	72.2			S11	324	172	68.6
		N12	1304	1025	263.5			S12	1315	1034	257.4
	10,000 yr	N13	171	108	44.8		10,000 yr	S13	158	85	42.5
		N14	274	157	64.5			S14	261	143	66.1
		N15	500	302	114.0			S15	510	306	123.2
		N16	609	391	137.0			S16	607	385	144.0
		N17	919	655	219.7			S17	852	649	198.8
		N18	2318	1923	577.1			S18	2623	2212	668.6

Table 22. PML of all buildings caused by each storm surge scenario. The number of buildings used for PML calculation is equal to the total number of inundated buildings – those inaccessible were included in the PML estimate.

		SCENARIO CODE	No. Inundated buildings	No. buildings used in PML Calculation	PML including inaccessible buildings ($ Millions)
STORM SURGE	100 yr	1	248	248	26.2
		2	829	829	64.4
		3	3173	3173	263.3

Table 23. PML of all buildings caused by each tsunami scenario. The number of buildings used for PML calculation is equal to the total number of inundated buildings – those inaccessible were included in the PML estimate.

	Return time	SCENARIO CODE	No. Inundated buildings	No. buildings used in PML Calculation	PML including inaccessible buildings ($ Millions)		Return time	SCENARIO CODE	No. Inundated buildings	No. buildings used in PML Calculation	PML including inaccessible buildings ($ Millions)
TSUNAMI - New Hebrides	100 yr	N1	17	17	4.8	TSUNAMI - Puysegur	100 yr	S1	9	9	3.1
		N2	36	36	10.6			S2	31	31	7.3
		N3	117	117	23.1			S3	97	97	19.6
		N4	132	132	29.1			S4	117	117	25.1
		N5	184	184	44.9			S5	165	165	38.7
		N6	911	911	168.5			S6	674	674	135.1
	1,000 yr	N7	34	34	11.8		1,000 yr	S7	29	29	10.7
		N8	64	64	18.1			S8	64	64	19.0
		N9	184	184	44.0			S9	179	179	44.4
		N10	212	212	55.2			S10	208	208	53.9
		N11	325	325	89.7			S11	324	324	85.5
		N12	1304	1304	294.5			S12	1315	1315	287.4
	10,000 yr	N13	171	171	49.9		10,000 yr	S13	158	158	47.6
		N14	274	274	73.8			S14	261	261	76.4
		N15	500	500	136.5			S15	510	510	146.4
		N16	609	609	163.6			S16	607	607	171.4
		N17	919	919	256.9			S17	852	852	227.6
		N18	2318	2318	635.8			S18	2623	2623	728.1

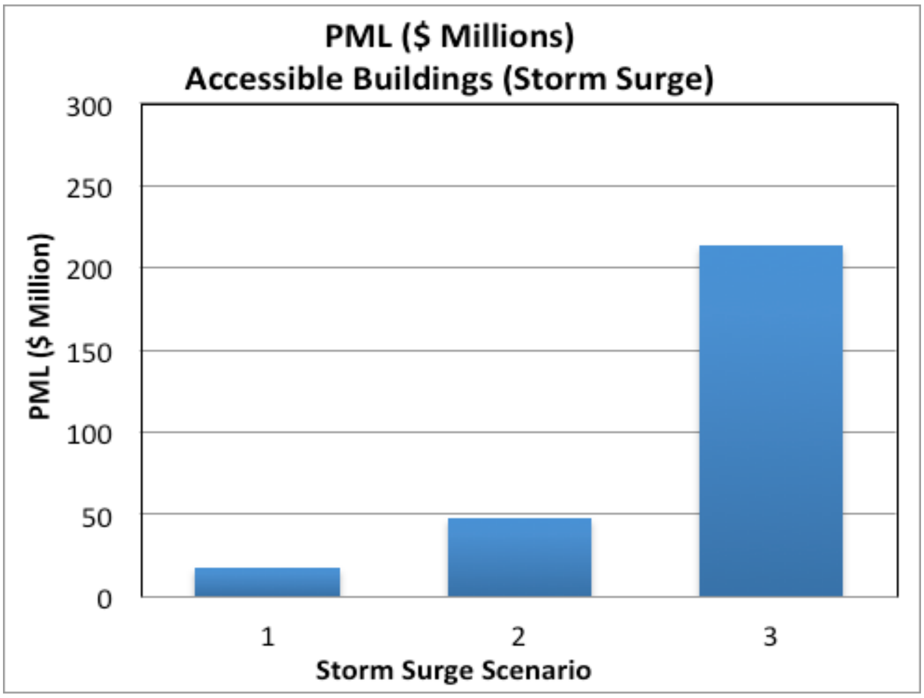


Figure 35. PML of buildings for each storm surge scenario (inaccessible buildings are not considered).

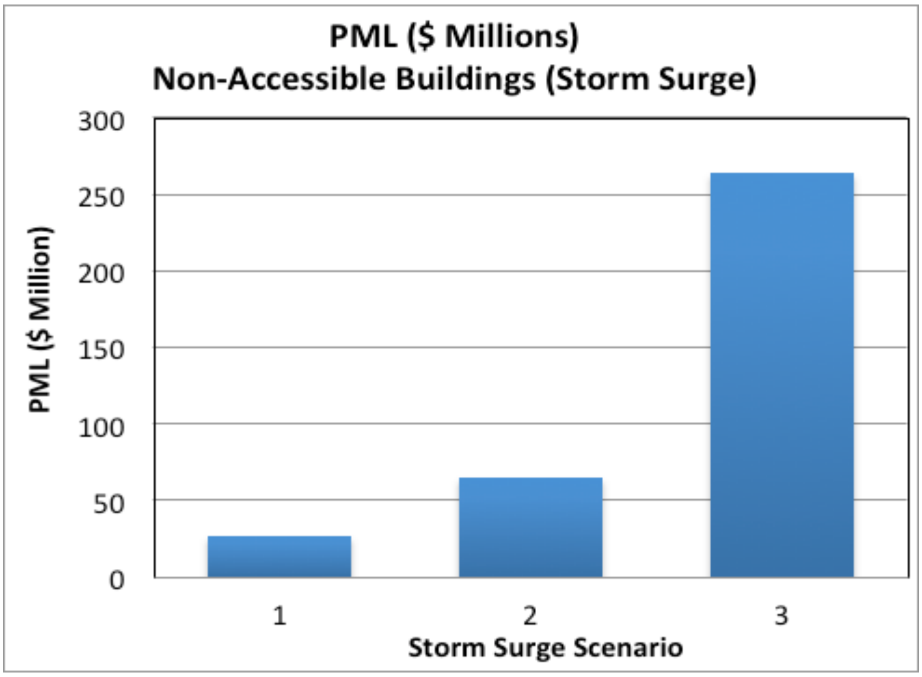


Figure 36. PML of buildings for each storm surge scenario (including inaccessible buildings)

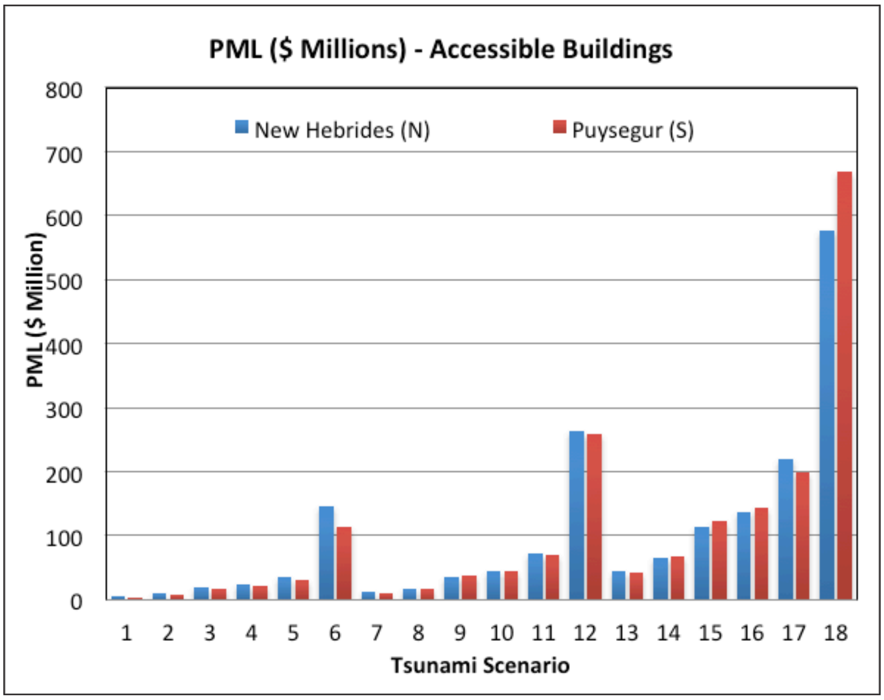


Figure 37. PML of buildings for each tsunami scenario (excluding inaccessible buildings)

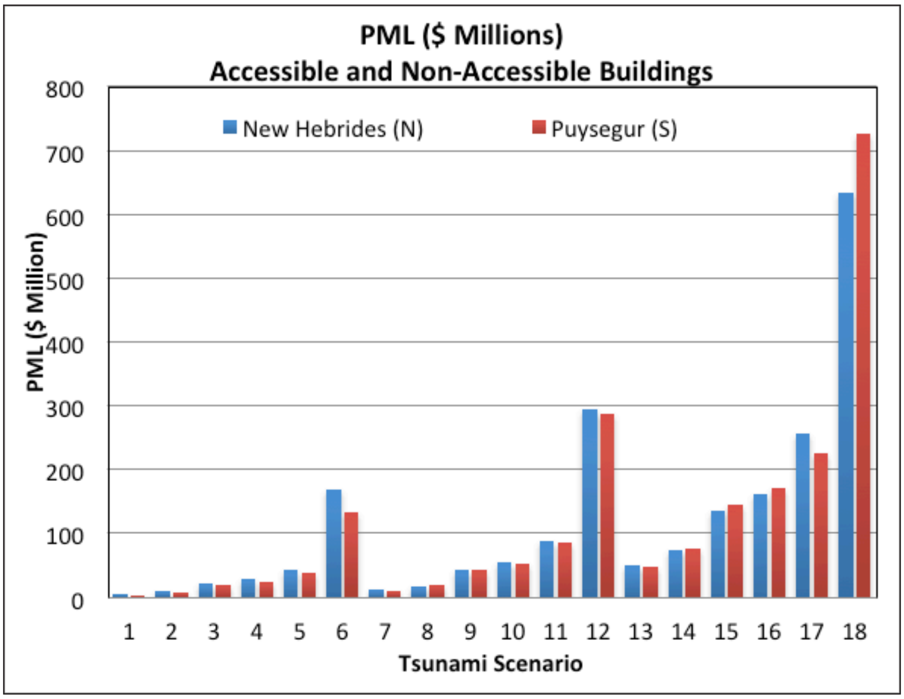


Figure 38. PML of buildings for each tsunami scenario (including inaccessible buildings)

Table 24. PML estimates ($ thousands) for damage to arterial and local roads for each tsunami scenario.

			BOTANY BAY			ROCKDALE			SUTHERLAND		
		SCENARIO CODE	Arterial Roads	Local Roads	Total PML for Roads	Arterial Roads	Local Roads	Total PML for Roads	Arterial Roads	Local Roads	Total PML for Roads
TSUNAMI - New Hebrides	100 yr	N1	0	4	4	536	17	553	502	129	631
		N2	0	9	9	560	17	577	528	41	570
		N3	0	10	10	662	30	691	518	345	863
		N4	0	6	6	641	30	671	502	374	876
		N5	6	6	11	624	164	788	659	44	703
		N6	6	106	112	891	394	1284	1444	1776	3220
	1,000 yr	N7	0	11	11	689	18	707	650	211	861
		N8	0	11	11	731	21	752	709	243	952
		N9	0	12	12	919	157	1075	761	490	1252
		N10	0	6	6	934	200	1134	790	524	1313
		N11	6	6	11	1175	365	1540	1189	642	1830
		N12	6	108	113	1799	658	2457	2065	2869	4934
	10,000 yr	N13	0	14	14	1045	27	1071	830	823	1653
		N14	0	15	15	1043	120	1164	886	1156	2042
		N15	0	24	24	1338	425	1763	1027	1918	2946
		N16	0	48	48	1413	516	1929	1163	2207	3370
		N17	383	255	638	1973	824	2797	1733	3101	4834
		N18	2818	713	3531	2843	1670	4513	4076	7037	11113
TSUNAMI - Puysegur	100 yr	S1	0	4	4	490	17	507	428	141	569
		S2	0	9	9	565	17	582	459	165	623
		S3	0	6	6	625	31	657	511	318	830
		S4	0	6	6	649	35	684	502	355	857
		S5	6	6	11	609	109	717	663	348	1011
		S6	6	106	112	769	356	1125	1117	901	2018
	1,000 yr	S7	0	8	8	728	20	747	630	279	909
		S8	0	14	14	802	24	827	679	290	969
		S9	0	12	12	974	74	1048	749	532	1281
		S10	0	10	10	1000	185	1185	772	614	1386
		S11	6	6	11	1007	319	1326	1101	839	1940
		S12	6	116	122	1719	665	2384	1939	3010	4949
	10,000 yr	S13	0	20	20	1052	27	1080	809	940	1750
		S14	0	19	19	1160	40	1200	910	1302	2212
		S15	0	31	31	1337	359	1696	1299	2119	3418
		S16	28	65	92	1341	487	1829	1482	2662	4144
		S17	1897	544	2441	2197	783	2980	2261	3927	6188
		S18	3400	939	4339	3200	1626	4826	4267	8860	13127

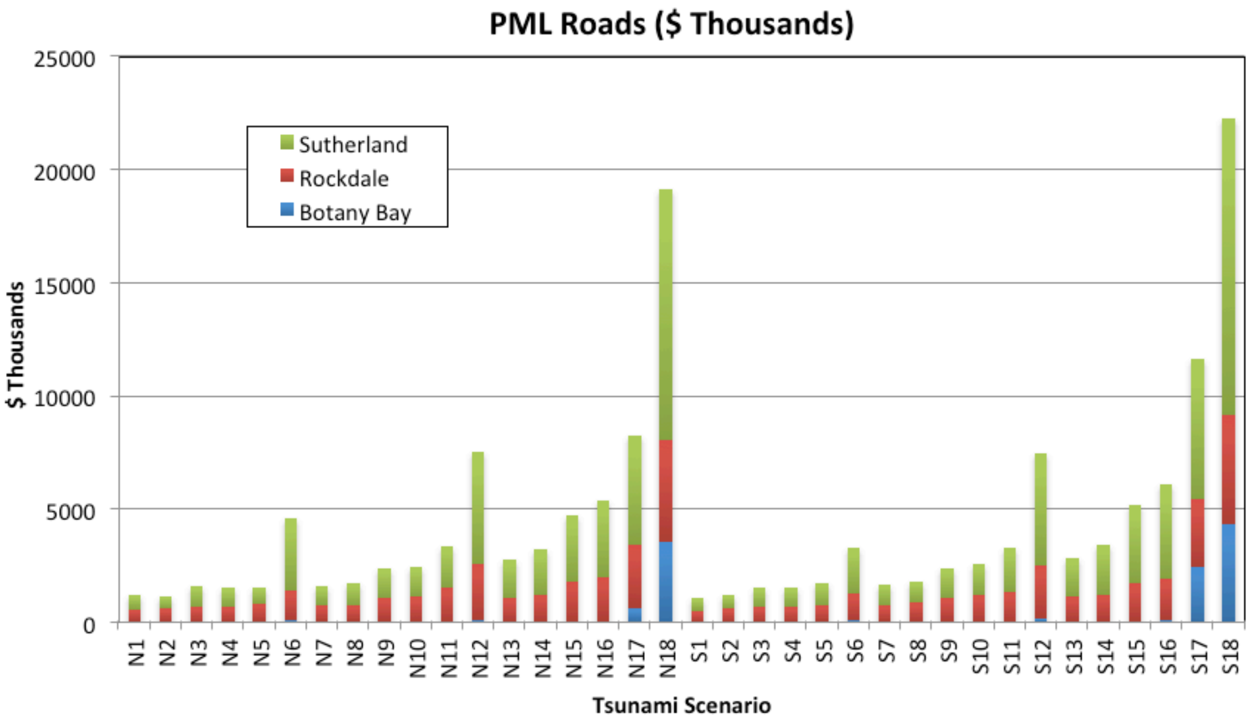


Figure 39. Per-Council PML estimates for damage to roads.

DISCUSSION

EXPOSURE

The results for building and infrastructure exposure are detailed in Table 25.

Table 25. Building and infrastructure exposure assessment results.

EXPOSURE	STORM SURGE	TSUNAMI
Buildings	1. A relatively low number of buildings (i.e. 248) are inundated in scenario 1 (2010 sea level conditions, 1/100 yr storm). 2. The number of exposed buildings increases exponentially across the three storm surge scenarios, with the largest differential being between scenarios 2 and 3. This shows that the initial sea level conditions play a key role in defining the extent of inundation. 3. In each storm surge scenario, the most exposed Council LGA is Sutherland, followed by Rockdale and Botany Bay. In Botany Bay City Council exposure remains relatively low, with only 210 buildings exposed in scenario 3, as opposed to 1121 buildings in Rockdale and 1842 buildings in Sutherland.	1. In each tsunami scenario, building exposure is lower than that for storm surges. For instance, the worst tsunami scenario (i.e. S18, a 1 in 10,000 yr event generated in Puysegur and occurring during high sea level conditions) would affect 2623 buildings, which is less than those exposed to a storm surge with a much higher probability of occurrence (i.e. 1/100 yr), with the same initial sea level conditions (storm surge scenario 3). This may in part be explained by the approach of McInnes et al. (2012) to create storm surge inundation layers (see the Hazard Assessment Report for more details). However, in spite of the lower exposure, the total damage caused by tsunamis would be significantly higher (see the PML section for further details). 2. As for storm surge, exposure increases exponentially with initial sea level conditions. 3. Tsunamis triggered in Puysegur would inundate more buildings than those generated in the New Hebrides. Note that Puysegur tsunamis would reach the study area in about 2.5 hours, whereas those originating in the New Hebrides would take over 4 hours.
Infrastructure and buildings providing critical services	1. In the LGAs of Botany Bay and Rockdale City Councils, the exposure of buildings providing critical services during emergencies (e.g. police stations, fire brigades, surf life savers, schools, hospitals, power transmission) is zero to very low. In Rockdale, the NSW Health Service offices in Primrose House, Dolls Point would be flooded by the third storm surge scenario. 2. Kingsford Smith Airport and Port Botany would be inundated under all storm surge scenarios. 3. In Sutherland the exposure of critical buildings is higher, particularly for government and education buildings. Specifically, the Woolooware School, Cronulla Beach Surf Life Saving clubhouse (in Gunnamatta bay) and the Coast Guard Radio base (in Kurnell) would be flooded by storm surge scenarios 2 and 3. The Kurnell Public School and the Fire Brigades base in Bundeena are exposed only in the worst storm surge scenario (no.3). 4. The road network in the Botany Bay City Council LGA would be marginally affected by tidal inundation, with Foreshore Road being virtually untouched by the water. However, no storm erosion data was available from Botany Bay City Council, therefore Foreshore Road cannot be considered risk free until erosion hazard lines are considered.	1. In the Botany Bay City Council LGA, tsunami exposure of buildings and infrastructure is relatively low with high exposure only in the worst tsunami scenarios (i.e. 1 in 10,000 yr events occurring during high sea level conditions – N17, N18 and S17, S18). 2. Inundation of Kingsford Smith Airport and Port Botany would be significant only for the worst tsunami scenarios (i.e. 1 in 10,000 yr events occurring in high sea level conditions – N17, N18 and S17, S18). 3. In Rockdale, the exposure of roads to tsunamis is significantly lower than that to storm surges. In the worst tsunami scenarios (N18 and S18), the total length of inundated roads would be about half of that affected by the worst case storm surge scenario (no.3). However, beachfront roads, critical buildings and infrastructure would be heavily affected. In the worst case scenarios (N18 and S18), the M1–M5 freeways would be flooded at the entrance of the airport tunnel, and most likely the whole tunnel would be unusable. In the southern part of the LGA, Dolls Point and Sandringham are the most exposed zones. 4. None of the bridges on Cooks River or Georges River would be completely submerged, but damage may occur as a result of high flow velocities and impact from debris or boats.

EXPOSURE	STORM SURGE	TSUNAMI
Infrastructure and buildings providing critical services	5. Road exposure is significantly higher in Rockdale and Sutherland councils. In Rockdale, no damage would occur to Grand Parade, but water would penetrate inland through Cooks River (to the north) and Baldo-Berong Creek (to the south) causing significant inundation of inner streets. Erosion would be an issue only in the southern part of the council (Carruthers Drive, Vanston Parade). 6. In Sutherland road exposure is very high, with local roads being much more affected than arterial roads. The road network in the areas of Gwawley Bay, Taren Point and Woolooware Bay would be heavily inundated. Importantly, Captain Cook Drive, which is the only connection to Kurnell, would be flooded (mainly along the section which passes through Woolooware Bay) and would be impassable.	5. Critical buildings in Rockdale have a low to very low exposure to tsunamis. The only building that would be flooded under scenarios N18 and S18 is the Primrose House at Dolls Point, which is currently used for health care administration. 6. In Sutherland, the pattern of critical buildings exposed to tsunamis is similar to that for storm surges (i.e. dominated by government and education buildings). Woolooware High School is exposed under all tsunami scenarios occurring in high sea level conditions (i.e. N6, S6, N12, S12, N16, N17, N18, S16, S17, S18). The Kurnell Public School is exposed under tsunami scenarios N18, S18. The Cronulla Beach Surf Life Saving clubhouse (in Gunnamatta Bay) and the Coast Guard Radio base (in Kurnell) are highly exposed under most tsunami scenarios. 7. As with storm surges, Sutherland streets are highly exposed to tsunamis. Special attention should be given to Captain Cook Drive, which is the only connection to the Kurnell residential area. 8. In Kurnell, the pier supporting the oil pipeline connecting the Kurnell Refinery to the ship access point would experience water levels in excess of 3 m and flow velocities up to 2 m/sec, which may result in damage to the structure and potential oil spills. This risk is further exacerbated by the possible impact of debris and large boats/ships.

VULNERABILITY AND PROBABLE MAXIMUM LOSS

The outcomes of the vulnerability assessment and PML estimates are discussed below:

1. For each of the study LGAs, the COVERMAR vulnerability maps show that the most critical built areas across the selected storm surge and tsunami scenarios are:

   Botany Bay City Council

   Port Botany and the industrial-residential area nearby Hale Street.

   Rockdale City Council

   The built-up areas along Cooks River, Muddy Creek and Wolli Creek and the residential units in Dolls point and Sandringham.

   Sutherland Shire Council

   - The residential area in Kurnell (this includes several one- and two-storey timber houses, the most vulnerable to inundation). The Kurnell refinery pipeline may be an additional hazard.

- Kurnell peninsula is connected to the mainland by Captain Cook Drive which would be flooded in most storm surge and tsunamis scenarios.
- The residential area of Gwawley bay, where most houses have direct access to the water.
- The industrial-residential areas of Taren Point; Woolooware Bay; Bundeena Bay and Simpsons Bay.

2. The PML in relation to buildings for both storm surges (scenarios 1 to 3) and tsunamis (scenarios S1 to S6, S7 to S12 and S13 to S18) follows the same trend observed for exposure (Table 25), which is an exponential increase through the three storm surge scenarios. This emphasises the critical influence of the initial sea level condition.
3. The PML for tsunamis generated in Puysegur is typically higher than that for those triggered in the New Hebrides, reflecting the same pattern observed for exposure.
4. The damage to buildings caused by tsunamis is substantially higher than that caused by storm surges. Specifically, the average 1/100yr. tsunami PML per building is $237,000, whereas for storm surge it is about one-third less at $88,000.
5. For similar exposure values, the PML estimates for tsunamis are much higher than those for storm surges. This is the case for tsunamis and storm surges having the same probability of occurrence and, in some cases, when the storm surge exposure is significantly higher. For instance, tsunami scenario N4 (i.e. 1/100 yr. event, occurring in 2010 sea level conditions, high tide) would inundate only 132 buildings, and the PML would be $29.077 million; storm surge scenario no.1 (i.e. 1/100 yr. event, 2010 sea level conditions) would affect 248 buildings, but the associated PML would be less at $26.193 million.
6. The vulnerability of buildings is dependent upon their structural and engineering attributes. Even simple construction options may significantly contribute to a reduction in damage and associated PML. Thus, if all the buildings of the study area had a raised ground-floor (+30 cm above the ground level), the total PML estimates would decrease by 44.6% (storm surge scenarios, Figure 40) and 29.6% (tsunami scenarios, Figure 41 and Figure 42).

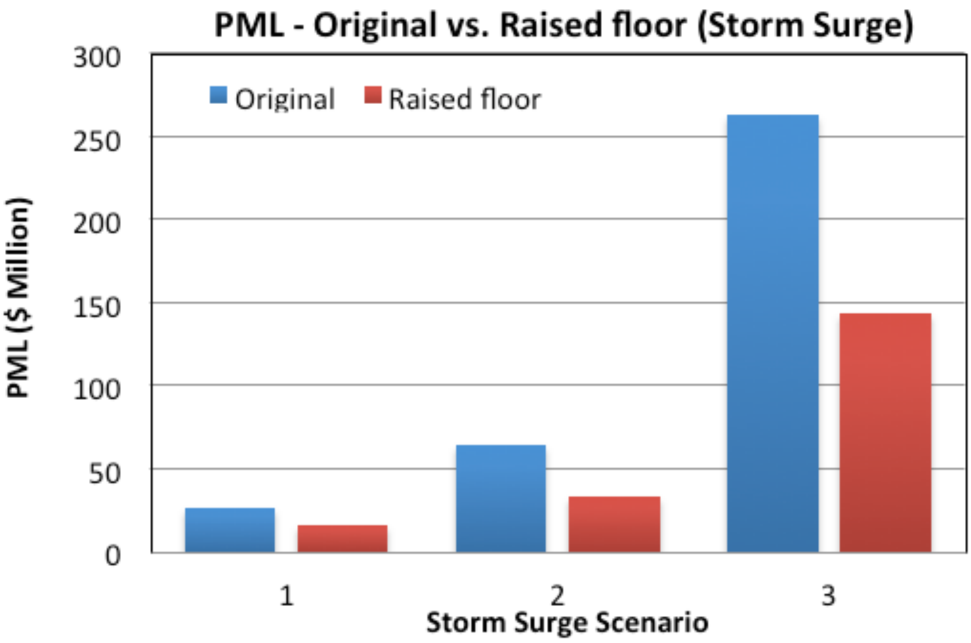


Figure 40. PML estimates for the storm surges scenarios. Blue columns represent the existing stock of buildings; red columns represent an imaginary stock in which all buildings have a raised ground floor.

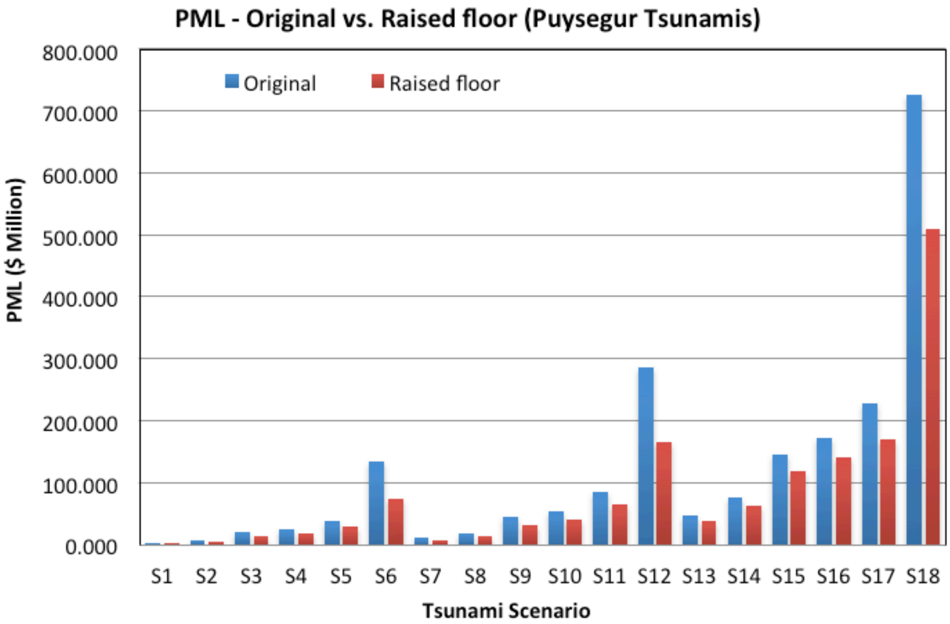


Figure 41. PML estimates for the tsunami scenarios triggered in Puysegur. Blue columns represent the existing stock of buildings; red columns represent an imaginary stock in which all buildings have a raised ground floor.

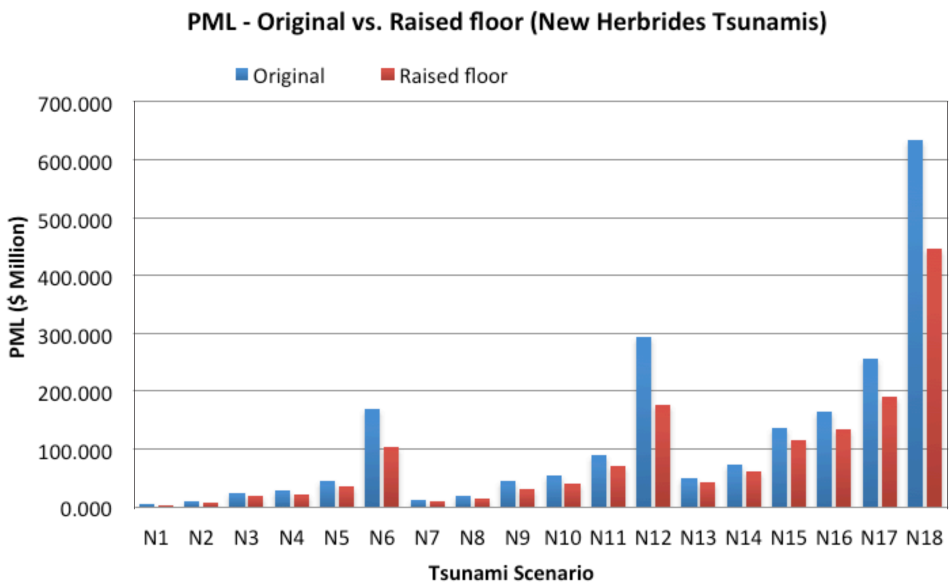


Figure 42. PML estimates for the tsunami scenarios triggered in New Hebrides. Blue columns represent the existing stock of buildings; red columns represent imaginary buildings with a raised ground floor.

7. In the case of extreme inundations, the risk to coastal assets and people is further exacerbated by cascading effects. A cascading effect occurs when a secondary hazard is triggered by the inundation (e.g. a chemical spill from a damaged industrial site).

   Vulnerability models currently available to the scientific community do not allow an accurate simulation of cascading effects. However, risk is generally higher for areas in close proximity to secondary hazards. Within the COVERMAR case study locations, these include:

   - The oil pipeline on the Kurnell pier (Figure 43). The pier could easily be damaged during a tsunami, both by waves and by the impact of large objects mobilised by the waves such as cars, containers, boats and oil tankers. A potential oil spill within Botany Bay could lead to explosions, fires and contamination to the surrounding built and natural environment (e.g. the protected wetland areas of Towra Point and Carters Island).
   - The industrial-residential areas in Taren Point (Sutherland), Wolli Creek (Rockdale) and Hale Street (Botany Bay) from potential contamination.
   - The container deposit facility in Port Botany. Cascading effects may include potential chemical spills or the impact of containers mobilised by the water flow.

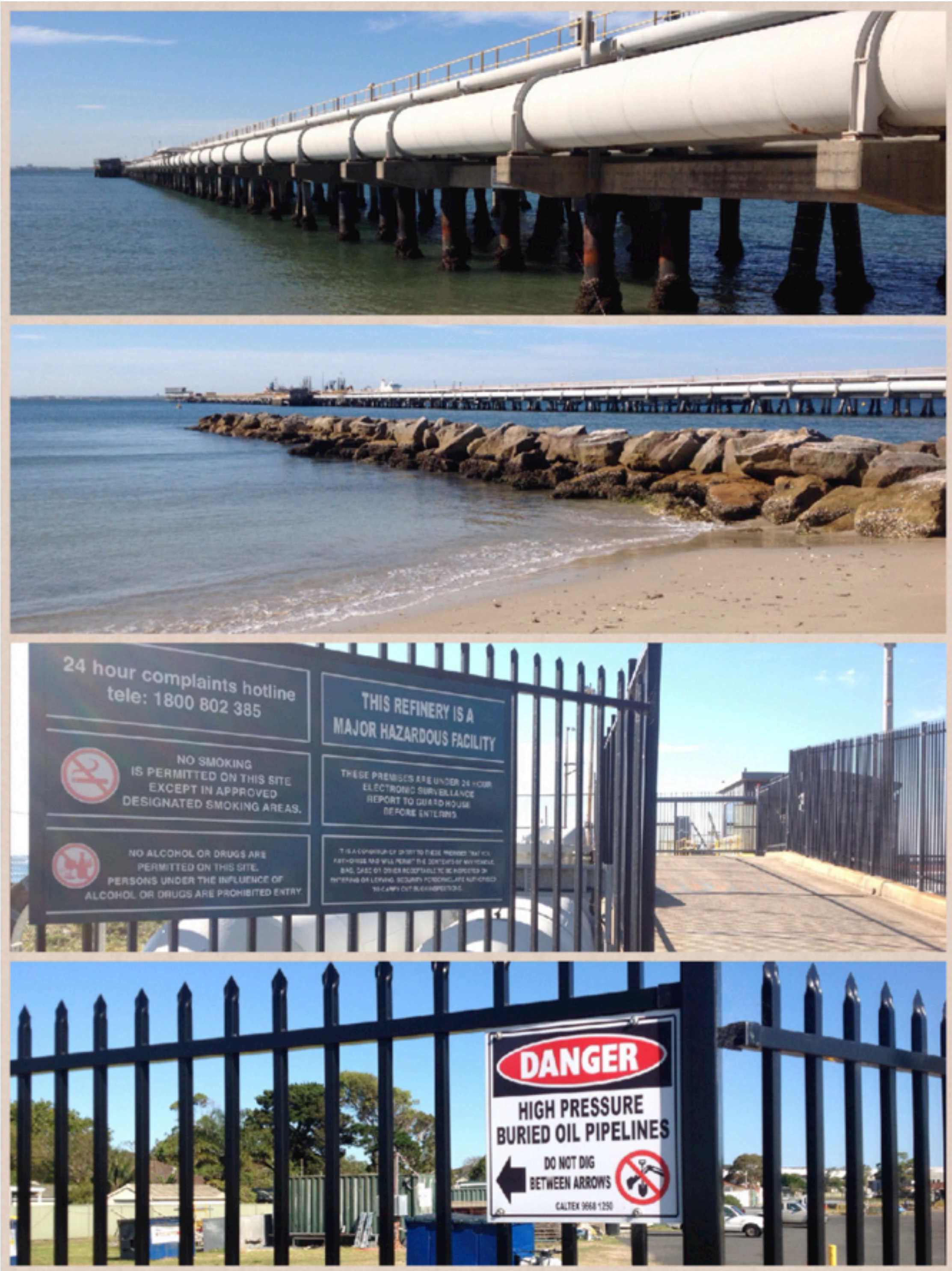


Figure 43. The oil pipeline along the pier in Kurnell (Sutherland).

RECOMMENDATIONS

RECOMMENDATIONS IN RELATION TO HAZARD ASSESSMENT AND BUILDING VULNERABILITY

We make the following recommendations:

1. Compare the COVERMAR tsunami hazard assessment with that undertaken by NSW SES (Hanslow et al., 2013) using a different numerical model (i.e. DELFT 3D);
2. Expand the range of flood building fragility models currently available for Australia (Maqsood et al., 2013) to include more building classes (e.g. multi-storey buildings);
3. Generate a set of Australia-specific building vulnerability functions for tsunamis based on synthetic or judgmental methods;
4. Until the functions in Item 3. are available, use the approach adopted in COVERMAR, that is a combination of:
   a. The PTVA model, for comparing the vulnerability of different building types; and
   b. The use of the building vulnerability functions developed in Japan (Suppasri et al., 2012), for a first-order estimate of economic losses.

GENERAL RECOMMENDATIONS

Recommendation	Reasoning
Undertake multi-risk assessments for all LGAs along the NSW coastal fringe using the COVERMAR methodology.	Built assets along the NSW coastal zone are at risk of extreme inundation. The risk caused by storm surges and tsunamis is dependent on local coastal zone characteristics, such as near-shore bathymetry and topography. Whilst the COVERMAR methodology and modelling have general application and utility, the results of this study cannot be extended or extrapolated to locations beyond the study area.
Conduct further research to expand the number of hazards considered in the COVERMAR methodology. We suggest the inclusion of hazards such as extreme rain, catchment runoff, landslide and bushfire.	The utility of an assessment can be expanded to include different hazard types. This would increase the capability for risk and emergency managers to compare different risks and adopt more effective and balanced mitigation measures.
Amend the Guidelines for preparing CZMPs to include a requirement that councils consider low frequency, high consequence hazards.	The current NSW legislation on coastal risk does not require Councils to undertake risk assessment studies for hazards having a likelihood of occurrence beyond 100 years. Tsunami risks can be addressed under Section 3.3 of the NSW Guidelines for Preparing Coastal Zone Management Plans, (OEH 2013) which provides: 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 rock fishing, beach safety, sand drift, stormwater outlets onto beaches and tsunami impacts. COVERMAR demonstrated that low frequency hazards such as tsunamis can cause significant damage to coastal assets on timescales longer than 100 years.

Recommendation	Reasoning
Establish sea level rise planning benchmarks.	The hazard assessment demonstrated that the urban inundation extent is strongly dependent on initial sea level conditions. The 2012 NSW Government's Coastal Reforms revoked the 2009 NSW Sea Level Rise Policy Statement and transferred to local councils, responsibility in relation to sea level rise projections. The provision of benchmarks by State government will allow consistent assessment of exposure and vulnerability to marine hazards across LGAs.
The State Emergency Service and councils facilitate workshops with owners of critical infrastructure to review their specific storm and tsunami risk management approaches and strategies to ensure they are up to date and relevant.	Ensure integration of risk management across the built environment.
Facilitate workshops among relevant stakeholders in relation to the generation of Australian tsunami building fragility curves, design standards and building code regulations for tsunami flooding.	Provide capacity to construction authorities, building regulators, councils, insurance companies and other stakeholders.
Develop building codes in areas exposed to storm surges or tsunamis stipulating appropriate construction standards. The Codes should consider the following:	No building codes for storm surges or tsunamis have been developed in NSW (or elsewhere in Australia).
a) A raised ground floor height.	Buildings with raised ground floors are significantly less exposed to inundation.
b) Raised, rigid foundations, such as reinforced concrete piles or brick columns.	Reduce exposure to flood and increase the overall building resilience to wave impact and scouring.
c) Construction of buildings with greater mass.	Heavier buildings are more likely to resist hydrodynamic forces such as buoyancy and drag. In highly exposed areas, full brick and reinforced concrete buildings provide greater protection than timber and brick veneer buildings.
Restrict residential units on the ground floor of multi-storey buildings that are not raised over pile foundations or columns.	Ground floors are by far the most exposed to inundation and should not be used for residential purposes.
Planning strategies consider open ground-floors (i.e. columns, many windows).	Open ground floors would allow a tsunami to flow-through the building, imposing a smaller hydrodynamic pressure onto the load-bearing structure. Closed ground-floors (e.g. no windows or columns) would be inundated as a tsunami would destroy walls, causing a greater risk of structural failure or collapse. This is particularly important for multi-storey buildings, or for one-storey buildings with raised ground floors.
Planning strategies prefer two-storey buildings with garages and car spaces on the ground floor over single-storey buildings with basements.	Multi-storey buildings are more resilient than single-storey buildings, as they weigh more and generally have stronger foundations. They may also afford vertical evacuation. Basements would be completely inundated.

SPECIFIC RECOMMENDATIONS

<table>
<tr><th>Category</th><th>#</th><th>Recommendation</th></tr>
<tr><td rowspan="6">Coastal Risk Management</td><td>1</td><td>Coastal Zone Management Plans incorporate a COVERMAR multi-risk hazard assessment. COVERMAR is consistent with NSW coastal risk management policies and regulations.</td></tr>
<tr><td>2</td><td>Undertaken hazard and vulnerability assessments where sea level rise benchmarks are adopted which differ from the former NSW SLR policy (because inundation extent and the number of exposed buildings can change significantly).</td></tr>
<tr><td>3</td><td>Councils and emergency service organisations develop regional workshops to communicate current best practice for storm surge and tsunami risk. Workshops should identify, rank and explain alternative local risk management strategies practised by local government around the world.</td></tr>
<tr><td>4</td><td>Stakeholders address risk management needs and strategies for areas affected by the forecast scenarios. Stakeholders include the general public (residents), tourists and other temporary visitors, business, companies operating infrastructure, and buildings providing critical services.</td></tr>
<tr><td>5</td><td>Engage directly with coastal communities to understand and assess their knowledge and interest in tsunami and storm surge risk management information.</td></tr>
<tr><td>6</td><td>Establish a regional extreme events policy officer in a key coastal representative organisation with responsibility in relation to coastal risk management processes. Alternatively, the Regional Emergency Manager Officer could assume this responsibility.</td></tr>
<tr><td rowspan="4">Planning and Development</td><td>7</td><td>Integrate COVERMAR hazard maps into Local Environmental Plans, as indicated in SEPP 71 – Coastal Protection.</td></tr>
<tr><td>8</td><td>Consider all potential cascading effects. For example, industrial facilities and critical infrastructure within Botany Bay can produce ‘cascading effects’ when subject to extreme inundations (particularly tsunamis). Councils and stakeholders must consider these additional risks in long term planning strategies. Potential sources of cascading effects include:
<table>
<tr><th>Botany Bay</th><th>Rockdale</th><th>Sutherland</th></tr>
<tr><td>Port Botany
Adjoining industrial areas
All marinas and boating facilities.</td><td>St George Motor Boat Club
Other marinas
Boating facilities.</td><td>Kurnell Oil Refinery
Kurnell Pier
Boating facilities.</td></tr>
</table></td></tr>
<tr><td>9</td><td>Preserve coastal dunes and vegetation from future development and protected from other human pressures such as pollution and ecosystem degradation. These zones provide significant protection against extreme inundation by slowing water flow and trapping debris. In the study area, the majority of beaches and green zones along the shoreline would be flooded in most storm and tsunami scenarios, acting as a ‘freeboard’ between the sea and the built environment. These zones exist in the following locations:
<table>
<tr><th>Botany Bay</th><th>Rockdale</th><th>Sutherland</th></tr>
<tr><td>• Sir Joseph Banks Park
• Engine Pond
• Mill Ponds
• Dransfield Avenue Reserve
• Todd Reserve.</td><td>• Barton Park
• Muddy Creek Reserve
• Lance Stoddert Reserve
• Barton Park Driving Range
• Banksia Field
• Kogarah Golf Club, Wooli Creek
• Cook Park
• Peter Depena Reserve
• Scott Park
• Sans Souci Park
• Badu-Brong Creek
• Coastal dunes along the Grand Parade.</td><td>• Towra Point Nature Reserve
• Bonna Point Reserve
• Captain Cook’s Landing Place
• Endeavour Field
• Green Hills Cronulla
• Luca’s Reserve
• Dunningham Park
• Solander Playing Fields
• Bundeena Reserve
• Horderns Beach Reserve
• Maianbar Reserve
• Tonkin Park
• Burraneer Park
• Kareena Park.</td></tr>
</table></td></tr>
<tr><td>10</td><td>Protection or relocation of buildings providing critical services during emergencies. Relevant buildings in the study area include:
<table>
<tr><th>Botany Bay</th><th>Rockdale</th><th>Sutherland</th></tr>
<tr><td>na</td><td>The Primrose House
(health system) (average exposure)</td><td>• Cronulla Lifesaver Building (high exposure)
• Sutherland Coastguard Radio-Base (average exposure)
• Sutherland Fire Brigades in Bundeena (low exposure)</td></tr>
</table></td></tr>
</table>

Category	#	Recommendation		
Emergency Management	11	Use of the COVERMAR GIS inundation and vulnerability maps in education and awareness activities, as indicated in the NSW Tsunami and Storm Emergency Sub Plans. These maps are readily interpretable by non-experts. Activities should emphasise that tsunamis are a series of many waves, and that the first one may not necessarily be the most dangerous. Identify specific tsunami evacuation locations using the inundation maps generated in COVERMAR, especially in areas where there is limited warning time, or along estuaries (where tsunamis can propagate for over 1 Km from the coast). The NSW Tsunami Emergency Sub-Plan indicates that tsunami evacuation centres should be located at a distance of 1Km form the shore, or 10 m above sea level. Suggested locations for each Council LGA are listed below:		
	12	Botany Bay Garnet Jackson Reserve area	Rockdale • Wolli Creek and Arncliffe: to Arncliffe Park • Muddy Creek: to Rockdale Park or Rockdale Public School • Area east of the A.S. Tanner Reserve: to James Cook and Moorefield high schools • Area west of the AS Tanner Reserve: to Burton St. and Jones Ave. • Dolls Point and Sandringham: to Ramsgate Rd. and Rocky Point Rd.	Sutherland • Kurnell: to Solanders Drive • Woolooware Bay: to North Caringbah Oval area • Taren Point: to Endeavour Sports High School • Gwawley Bay: to Sylvania Heights Reserve • Bundeena: to the Bundeena RSL Memorial Club
	13	Integrate the COVERMAR GIS outputs into the existing Tsunami and Flood Intelligence Systems.		
	14	Use the buildings identified by COVERMAR as safe refuges for vertical evacuation (e.g. the Kurnell area) for areas that cannot be evacuated in a timely fashion.		
	15	NSW SES work in partnership with Councils to draft inundation emergency plans for vulnerable areas. Plans may include evacuation to higher ground or vertical evacuation in rigid multi-storey buildings. Tsunamis generated in New Zealand (Puysegur Trench) would reach the study area in about 2h30m. This would allow a very limited time to evacuate certain areas, such as the peninsula of Kurnell (Sutherland). The only road to Kurnell (i.e. Captain Cook drive) would be inundated by each storm surge scenario and by most tsunami scenarios. Kurnell would be isolated with access by emergency services difficult.		
	16	Identify evacuation routes. During extreme inundations, conventional transport lines may be damaged or inundated and should not be considered as an option for evacuation or the transportation of aid. The most significant examples are: Botany Bay • Kingsford-Smith Airport • Botany Bay Harbour • M1 and M5 tunnels under the Airport • Bridges over Cooks River (A1, Marsh Street, Princes Highway).	Rockdale • Bridges over Cooks River (A1, Marsh Street, Princes Highway); • Bridges over Georges River (Taren Point Rd., Princes Highway East, Princes Highway West, Como Bridge); • Wooli Creek Train Station and railway; • The Grand Parade.	Sutherland • Bridges over Georges River (Taren Point Rd., Princes Highway East, Princes Highway West, Como Bridge); • Captain Cook's Drive, the only road connecting Kurnell's Peninsula to the mainland.

Category	#	Recommendation
Emergency Management	**17**	Emergency managers consider the additional risk caused by potential 'cascading effects'. Common effects include the impact of large movable objects on people and assets and the spill of chemicals and pollutants into the environment. Although movable objects and chemicals can be transported widely, the most exposed zones are those nearby the source such as: • Buildings adjacent to marinas and the first rows of buildings along the shore and estuaries; • Buildings adjoining large car parks Botany Bay Buildings near Port Botany Rockdale Sutherland Buildings in Kurnell, nearby the oil pipeline.
	18	Emergency response plans address buildings providing critical services during emergencies (e.g. police stations) and buildings particularly vulnerable such as education and health facilities. These buildings include (in addition to the buildings listed at recommendation 10): Botany Bay na Rockdale • Bambino's kindergarten (low exposure) • Green Gables kindergarten (low exposure) • The Primrose House (average exposure) Sutherland • Woolooware High School (high exposure) • Kurnell Public School (average exposure) • 12 other schools and kindergartens (low exposure)
	19	Relevant Emergency Management Authorities organise engaging public awareness days for the community to participate in evacuation drills to test and prepare community response to evacuation orders.
	20	Erect inundation zone signage in low lying at-risk zones.
	21	Erect evacuation route signs along transport corridors.
	22	Approach the owners of buildings which are suitable for vertical evacuation for consent to public access during an emergency.
	23	Explore opportunities for 'citizen science' during emergencies – the use of data submitted by community members to inform emergency responses.
	24	Update any existing disaster emergency plan for Port Botany and the Kingsford Smith Airport to include the risk of tsunamis and storm surges. In the worst storm surge and tsunami scenarios, these critical assets would be heavily inundated.
	25	Local government authorities collaborate with relevant State and Federal government agencies to enhance the quality, accuracy and coverage of their building inventory databases. High quality datasets aid accurate inundation risk assessment, development and planning, and natural hazard risk assessment.

FURTHER RESEARCH OPPORTUNITIES

1. Undertake social vulnerability assessments of local communities to complement and extend engineering focused work.
2. Conduct additional numerical modelling to refine the storm surge inundation assessment by McInnes et al. (2012). This modelling should:
    a. Consider the contribution of wave run-up to coastal inundation;
    b. Simulate the inundation process using a hydrodynamic approach, accounting for the hydraulics of the inundation (storage, connectivity, resistance);
    c. Assess the erosion caused by the storm scenarios and how erosion may affect the inundation extent;
    d. For future sea level conditions, analyse long-term shoreline recession to determine the initial conditions for the simulation;
    e. Merge storm inundation and river catchment run-off data to comprehensively identify the inundation extent.
3. Conduct hazard assessment of submarine slides and their tsunami potential. The risk of tsunamis arising from underwater submarine slides off the continental shelf is unknown but potentially high.
4. Test the sensitivity of the tsunami model MOST against different spatial resolutions of the Digital Elevation Model depicting the topography and bathymetry of the study area.
5. Compare the COVERMAR tsunami hazard assessment against that undertaken by NSW SES (Hanslow et al., 2013) which uses a different numerical model (i.e. DELFT 3D).
6. Expand the range of flood building fragility models currently available for Australia (Maqsood et al., 2012) to include additional building classes (e.g. multi-storey buildings).
7. Generate a set of Australia-specific building vulnerability functions for tsunamis based on synthetic or judgment methods. Until this model is available, we recommend using the same approach adopted in COVERMAR, that is a combination of:
    a. The PTVA model, for comparing the vulnerability of different building types; and
    b. The use of the building vulnerability functions developed in Japan (Suppasri et al., 2012), for a first-order estimate of economic loss.

LIMITATIONS OF THE STUDY

COVERMAR end-users should bear in mind the following assumptions and limitations:

- The hazard assessment did not extend upstream of the Como Bridge, i.e. beyond the case study area.
- The storm surge inundation layers of McInnes et al. (2012) were simulated using a dynamic model to the shoreline. For landward inundation a modified bathtub filling approach was used, which can overestimate the storm surge inundation extent because it is not able to consider hydraulic processes such as discharge, connectivity, storage and resistance.
- Of the 4083 buildings exposed to inundation, 555 could not be surveyed because they were inaccessible, or not visible from public areas. Most of these building are villas in close proximity to the water along Georges River or Port Hacking.
- The vulnerability models used to estimate damage and PML were not specifically designed for the buildings in the COVERMAR study area, but adapted from a storm surge vulnerability model for typical NSW and Queensland building classes (Geoscience Australia), and a tsunami vulnerability model for typical Japanese buildings (Suppasri et al., 2012).
- Vulnerability and PML were only calculated for buildings and infrastructure whose structural characteristics could be surveyed.

CONCLUSION

COVERMAR is the first multi-hazard probabilistic vulnerability study undertaken in Australia. In a key Sydney location spanning three LGAs, results quantitatively compared risks to buildings and critical infrastructure posed by two different natural hazards, namely storm surges and tsunamis, which can produce similar consequences. Project outputs can be applied to other case study locations to value add local risk reduction strategies and activities. The methodology developed is consistent with NSW coastal management legislation and informs strategic planning and development assessment and emergency management.

This report describes in detail the vulnerability assessment of the Coastal Vulnerability to Multiple Inundation Sources (COVERMAR) project and summarises earlier outputs, namely the Literature Review Report and Hazard Assessment Report.

An assessment was undertaken of the exposure and vulnerability of all buildings and critical infrastructure within Botany Bay, Port Hacking and Bate Bay to selected storm surge and tsunami scenarios. The scenarios considered events with annual probabilities of 1/100, 1/1000 and 1/10,000, occurring under 2010 and potential future sea level conditions. The physical and engineering attributes of each building were surveyed using a combined approach: Google Street View database (updated to November 2009) and high-resolution satellite images taken in 2011. Field surveys demonstrated the building dataset was accurate to approximately 94%. All data obtained was stored and organised into a Geographic Information System (GIS).

Following the 2010 NSW Coastal Risk Management Guide recommendations, the vulnerability of buildings to **storm surge** was assessed, considering two principal processes:

- Damage caused by the erosion of the soil substrate, which may undermine building foundations causing complete collapse. The relevant storm erosion lines were provided by the SCCG.
- Damage caused by inundation along tidal waterways, or water access point along the shoreline. The vulnerability to tidal inundation was assessed using flood vulnerability functions for typical Australian buildings, provided by Geoscience Australia. The functions were adapted to match the COVERMAR building database.

The vulnerability of buildings to **tsunamis** was assessed using a bipartite approach:

- Utilising the PTVA Model which is the best method for assessing the relative vulnerability of buildings in areas where no validated tsunami vulnerability functions have been developed, such as in Australia.

  COVERMAR updated the PTVA Model Version 3. A new version 4 was developed by introducing weights applicable to building attributes influencing vulnerability.
- Utilising a set of building vulnerability functions for tsunamis developed by Supparsi et al (2012) (modified and adapted for the study area) to estimate the actual level of damage that each building would incur in response to the tsunami inundation scenarios.

The outputs of the PTVA-4 Model were used to generate GIS vulnerability maps, showing the relative vulnerability level of individual buildings using a colour-coded scale.

Across the study areas, Sutherland Shire LGA had the highest number of exposed and vulnerable buildings and infrastructure, followed Rockdale and Botany Bay City Councils. Kurnell (Sutherland) is particularly problematic because most tsunami and storm surge scenarios would flood the road connecting it to the mainland. In addition, the oil pipeline located on the Kurnell pier may be a source of serious cascading effects.

Results also showed that the exposure of buildings and infrastructure to 1/100 yr. storm surges would be significantly higher than the exposure to all the simulated tsunami events (1/100 yr, 1/1,000 yr, 1/10,000 yr), under the same initial sea level conditions. However, in terms of economic loss, the effect on buildings by tsunamis and storm surges (with the same annual probability of occurrence, i.e. 1/100 yr.) is comparable. The PML of 1/1,000 and 1/10,000 yr. tsunamis is significantly higher than 1/100 yr. storm surges. However, if all buildings in the study area had a raised ground-floor (+30 cm above the ground level), it is likely that the total PML would decrease by 44.6% for storm surge scenarios and by 29.6% for tsunami scenarios. Further, results highlighted the influence of sea level rise on the final inundation extent and thus the damage to buildings and infrastructure. A series of recommendations addressing coastal risk management, planning and development and emergency management are presented to assist guide NSW State and local governments.

REFERENCES

Bryant, E. and Nott, J.: Geological indicators of large tsunami in Australia, Nat. Hazards, 24, 231–249, 2001.

Burbidge, D., Mleczko, R., Thomas, C., Cumminis, P., Nielsen, O., Dhu, T.: A probabilistic tsunami hazard assessment for Australia. Geoscience Australia Professional Opinion. No.2008/04, 2008.

Chen, K. and McAneney, J.: High-resolution estimates of Australia's coastal population, Geophys. Res. Lett., 33, L16601, doi:10.1029/2006GL026981, 2006.

Coburn

, A. W., Sspence, R. J. S., Pomonis, A.: Vulnerability and Risk Assessment, 2nd edition, UNDP Disaster Management Training Programme, 1994.

Dale, K., Edwards, M., Middelmann M. and Zoppou C. Structural flood vulnerability and the Australianisation of Black's curves. Risk 2004 conference proceedings. Risk Engineering Society, 8–10 November 2004, Melbourne, 2004.

Dall'Osso, F., Gonella, M., Gabbianelli, G., Withycombe, G., and Dominey-Howes, D.: A revised (PTVA) model for assessing the vulnerability of buildings to tsunami damage, Nat. Hazards Earth Syst. Sci., 9, 1557-1565, 2009a.

Dall'Osso, F. and Dominey-Howes, D.: A method for assessing the vulnerability of buildings to catastrophic (tsunami) marine flooding, Report prepared for the Sydney Coastal Councils Group Inc., pp. 138, 2009.

Dall'Osso, F. and Dominey-Howes, D.: Coastal vulnerability to multiple inundation sources – COVERMAR project – Literature Review (Second Edition). Report prepared for the Sydney Coastal Councils Group Inc. pp. 87, 2012.

Dall'Osso, F. and Dominey-Howes, D.: Public assessment of the usefulness of 'draft' tsunami evacuation maps from Sydney, Australia – implications for the establishment of formal evacuation plans, Natural Hazards and Earth System Sciences (NHESS),10, 1729-1750, 2010.

Dall'Osso, F., Gonella, M., Gabbianelli, G., Withycombe, G. and Dominey-Howes, D.: Assessing the vulnerability of buildings to tsunami in Sydney. Natural Hazards and Earth System Sciences, 9, 2015 – 2026, 2009b.

Dall'Osso, F., Summerhayes, S. and Dominey-Howes, D.: Coastal vulnerability to multiple inundation sources – COVERMAR project – Hazard Assessment Report. Report prepared for the Sydney Coastal Councils Group Inc. pp. 123, 2013.

Dall'Osso, F., Summerhayes, S., Withycombe, G., Moore, C. and Dominey-Howes, D.: Sydney's first probabilistic multi-hazard assessment of extreme coastal inundation, NSW Coastal Conference, 2013.

Department of Environment, Climate Change and Water (DECCW) NSW: Derivation of the NSW Government's sea level rise planning benchmarks – Technical note, ISBN 978 1 74232 465 4 DECCW 2009/709, October 2009.

Dias, W., Yapa, H. and Peiris, L.: Tsunami vulnerability functions from field surveys and Monte Carlo simulation, Civil Engineering and Environmental Systems, 26, 181-194, 2009.

Dominey-Howes, D.: Geological and historical records of Australian tsunami, Mar. Geol., 239, 99–123, 2007.

Engineers Australia: Climate change adaptation guidelines in coastal management and planning, Engineers Media, 2012.

Forman, E. and Peniwati, K.: Aggregating individual judgments and priorities with the Analytic Hierarchy Process. European Journal of Operational Research 108, 165-169, 1998.

Gardi, A., Valencia, R., Guillande and Andre. C.: Inventory of uncertainties associated with the process of tsunami damage assessment on buildings (SCHEMA FP6 EC co-funded project), Nat. Hazards Earth Syst. Sci., 11, 883–893, 2011.

Hanslow, D., Andrews, F., Beadle, C., Davies, B., Fraser, A., Garber, S., Greenslade, D., Horspool, N., Kuster, N., Opper, S. and Treloar, D. progressing towards an understanding of tsunami risk in NSW, NSW Coastal Conference, 2013.

Helman, P., Thomalla, F. and Metusela, C.: Storm tides, coastal erosion and inundation, report for the National Climate Change Adaptation Research Facility, Gold Coast, Australia, 2010.

IOC (Intergovernmental Oceanographic Commission of UNESCO): Manual on Sea-level Measurements and Interpretation, Volume IV: An update to 2006. Paris,. 78 pp. (IOC Manuals and Guides No.14, vol. IV ; JCOMM Technical Report No.31; WMO/TD. No. 1339) (English), 2006.

IOC UNESCO (Intergovernmental Oceanographic Commission of UNESCO): Reducing and managing the risk of tsunamis, IOC Manuals and Guides, 57 - 74 pp. (IOC/2011/MG/57Rev.2), 2011.

IPCC (Intergovernmental Panel for Climate Change): Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (Field, C.B., V. Barros, T.F. Stocker,

D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)). Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp., 2012.

Koshimura, S., Oie, T., Yanagisawa, H. and Imamura, F.: Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia, Coastal Engineering Journal, 51, 243-273, 2009.

Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., Merz, B. and Thieken, A. H.: Is flow velocity a significant parameter in flood damage modelling? Nat. Hazards Earth Syst. Sci., 9, 1679–1692, 2009.

Maqsood, T., Senthilvasan, M., Corby, N., Wehner, M., Edwards, M.: Improved assessment of flood impact: an urban stormwater case study of a city of Sydney catchment, FMA Conference, 2013.

McGuinness, John S., "Is 'Probable Maximum Loss' (PML) A Useful Concept?" Proceedings of the Casualty Actuarial Society, Vol. LVI, 1969, p. 31.

McInnes, K. L., Lipkin, F., O'Grady, J., Inman, M.: Mapping and responding to coastal inundation, Sydney Coastal Councils and CSIRO, 2012.

Nadal, N. C., Zapata, R.E., Pagan, I., Lopez, R., Agudelo, J.: Building Damage due to Riverine and Coastal Floods, J. Water Resour. Plann. Manage. 2010.136:327-336, 2010.

NOAA (National Oceanic and Atmospheric Administration): Tsunami Terminology, available at http://www.tsunami.noaa.gov/, last accessed in May 2012.

NSW Government: NSW Coastline Management Manual, available at: http://www.environment.gov.au/archive/coasts/publications/nswmanual/index.html, 1990.

NSW OEH (NSW Office of Environment and Heritage): Guidelines for preparing coastal zone management plans, 2013.

Oey, L. Y. and Wang, D. P.: Modeling Waves and Currents Produced by Hurricanes Katrina, Rita, and Wilma, U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, 2009.

Omira, R., Baptista, M., Miranda, J., Toto, E., Catita, C. and Catalao, J.: Tsunami vulnerability assessment of Casablanca-Morocco using numerical modelling and GIS tools, Natural Hazards, 1-21, 2009.

Papathoma, M.: Assessing Tsunami Vulnerability Using GIS with Special Reference to Greece. PhD thesis, Coventry University, 2003.

Papathoma, M., Dominey-Howes, D.: Tsunami vulnerability assessment and its implications for coastal hazard analysis and disaster management planning, Gulf Of Corinth, Greece, Nat. Hazards Earth Syst. Sci., 3, 733–747, 2003.

Reese, S., Bradley, B.A., Bind, J. et al.: Empirical building fragilities from observed damage in the 2009 South Pacific tsunami. Earth-Science Reviews 107: 156–173, 2011.

Reese, S., Cousins, W. J., Power, W. L., Palmer, N. G., Tejakusuma, I. G., and Nugrahadi, S.: Tsunami vulnerability of buildings and people in South Java: field observations after the July 2006 Java tsunami. Nat. Hazards Earth Syst. Sci., 7(5):573;589, 2007.

Schultz, M. T., Gouldby, B. P., Simm, J. D. and Wibowo, J. L.: Beyond the factor of safety: developing fragility curves to characterize system reliability, report prepared for Headquarters, U.S. Army Corps of Engineers Washington, DC 20314-1000, 2010.

Suppasri, A., Koshimura, S., and Imamura, F.: Developing tsunami fragility curves based on the satellite remote sensing and the numerical modeling of the 2004 Indian Ocean tsunami in Thailand. Nat. Hazards Earth Syst. Sci., 11(1):173;189, 2011.

Suppasri, A., Mas, E., Charvet, I., Gunasekera, R., Imai, K., Fukutani, Y., Abe, Y., Imamura, F.: Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami, Nat Hazards, DOI 10.1007/s11069-012-0487-8, 2012.

Tarbotton, C., Dominey-Howes, D., Goff, J.R., Papathoma-Kohle, M., Dall'Osso, F., Turner, I.: GIS-based techniques for assessing the vulnerability of buildings to tsunami: current approaches and future steps, Geological Society, London, Special Publications; v. 361; p. 115-125 doi: 10.1144/SP361.10, 2012.

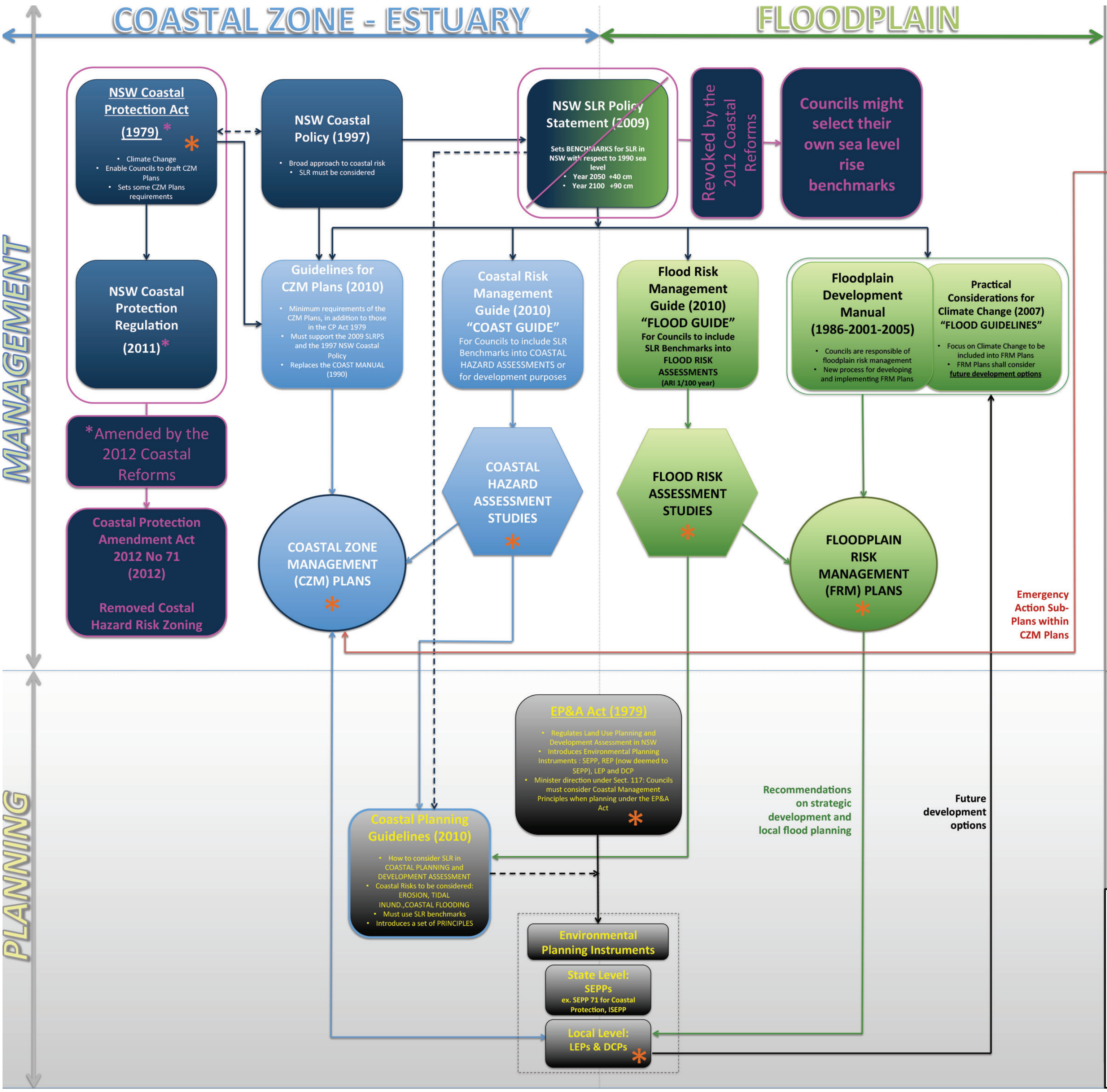
Titov, V.V., Moore, C.W., Greenslade, D.J.M., Pattiaratchi, C., Badal, R., Synolakis, C.E.: A new tool for inundation modeling: Community Model Interface for Tsunamis (ComMIT), Pure Appl. Geophys, 168, 2121-2131, 2011.

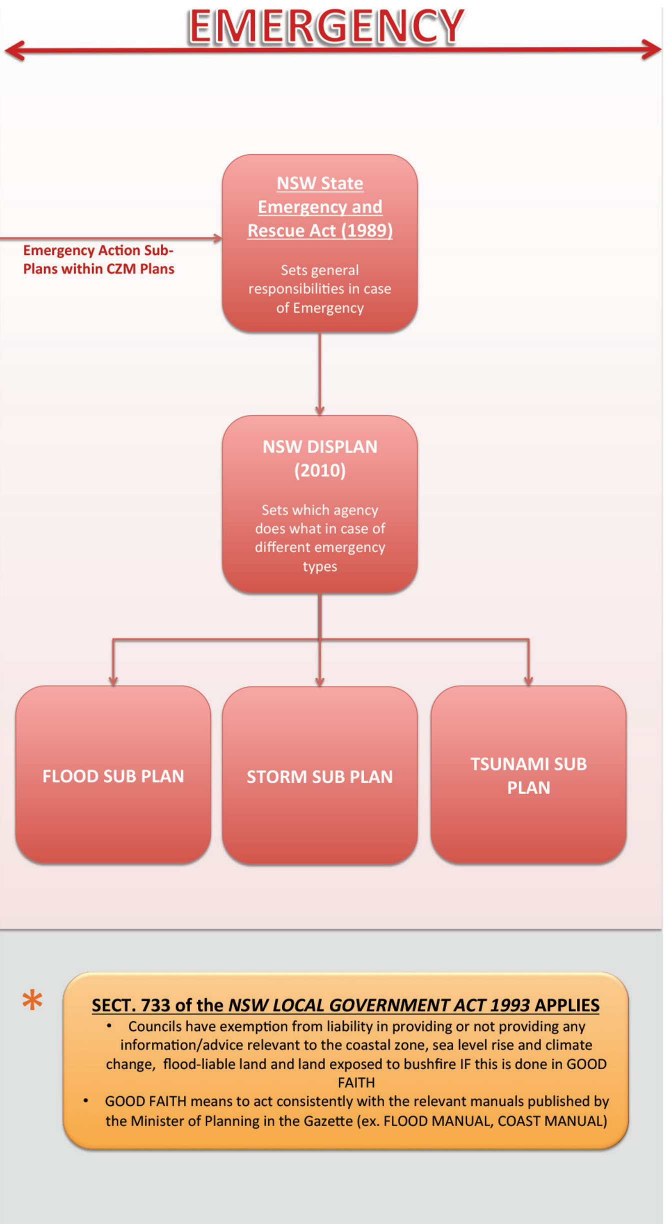
UN ISDR (United Nations International Strategy for Disaster Reduction): 2009 UNISDR Terminology on Disaster Reduction, Geneva, May 2009.

Valencia, N., Gardi, A., Gauraz, A. L., Leone, F., and Guillande, R.: New tsunami damage functions developed in the framework of SCHEMA project: application to Euro-Mediterranean coasts. Nat. Hazards Earth Syst. Sci., 2011.

USBR (U.S Department of the Interior Bureau of Reclamation): Downstream hazard classification guidelines, ACER technical memorandum No. 11, Colorado, Denver, 1988

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

December 2013

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

APPENDIX II- Vulnerability Maps

The coverage of the following maps is represented by the green frames in Figure 44.

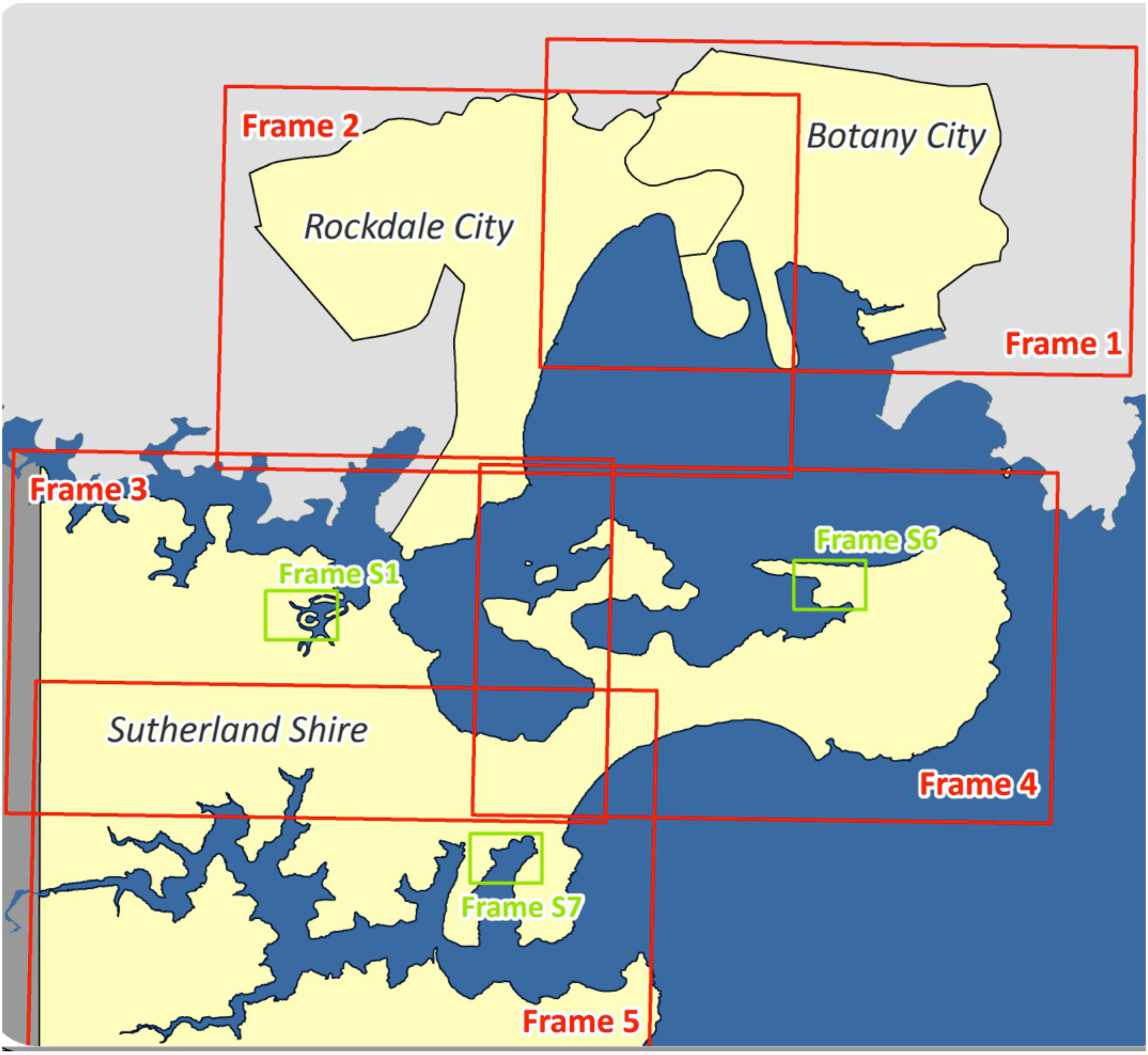


Figure 44. Coverage of the COVERMAR vulnerability maps. Red frames represent A0 maps (attached to the present report in a digital format), while green frames show the location of the vulnerability maps included in this section (Appendix II).

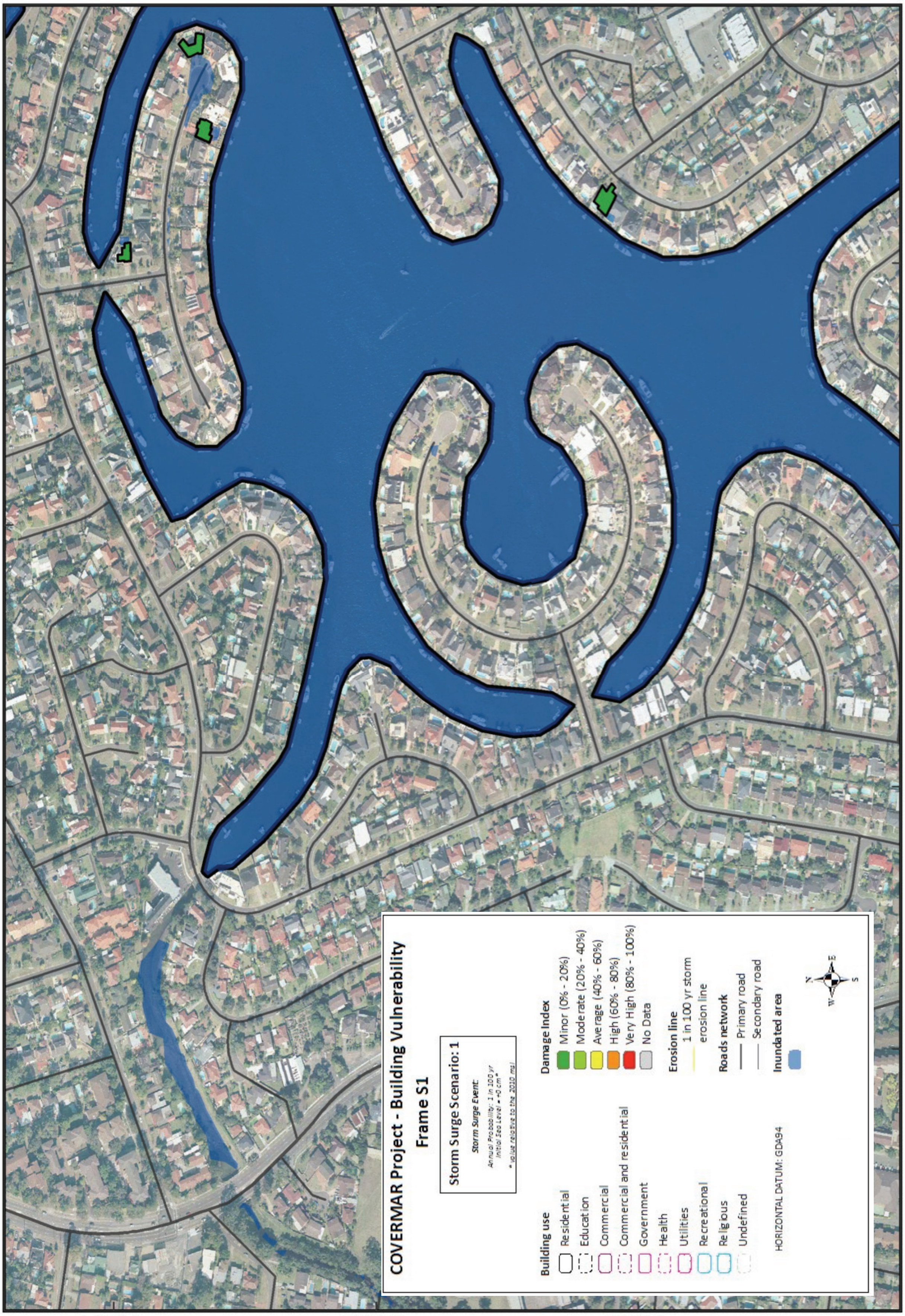


Figure 45. Storm Surge vulnerability map of frame S1 (Sutherland Council), storm inundation scenario n.1.

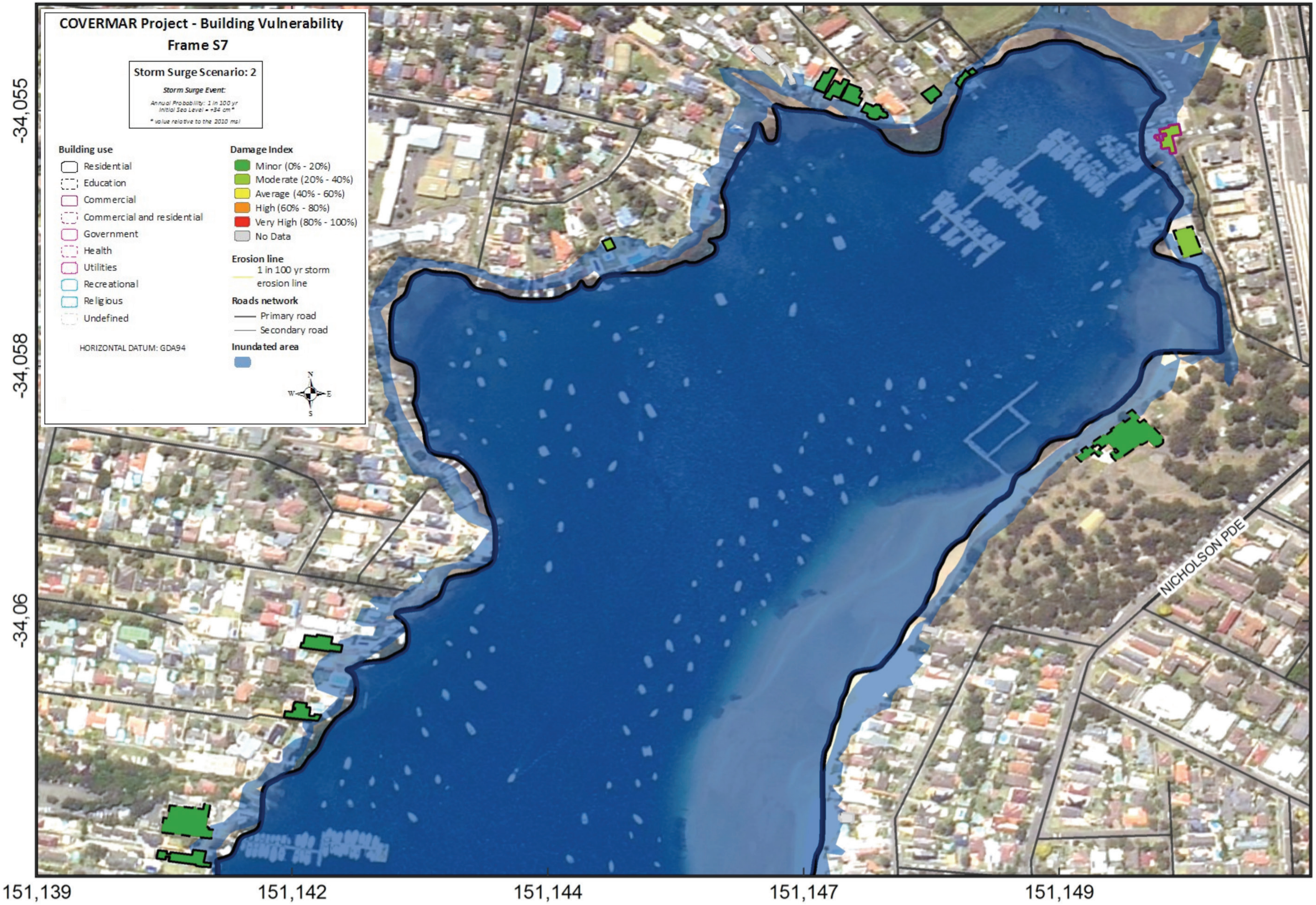


Figure 46. Storm Surge vulnerability map of frame S7 (Sutherland Council), storm inundation scenario n.2.

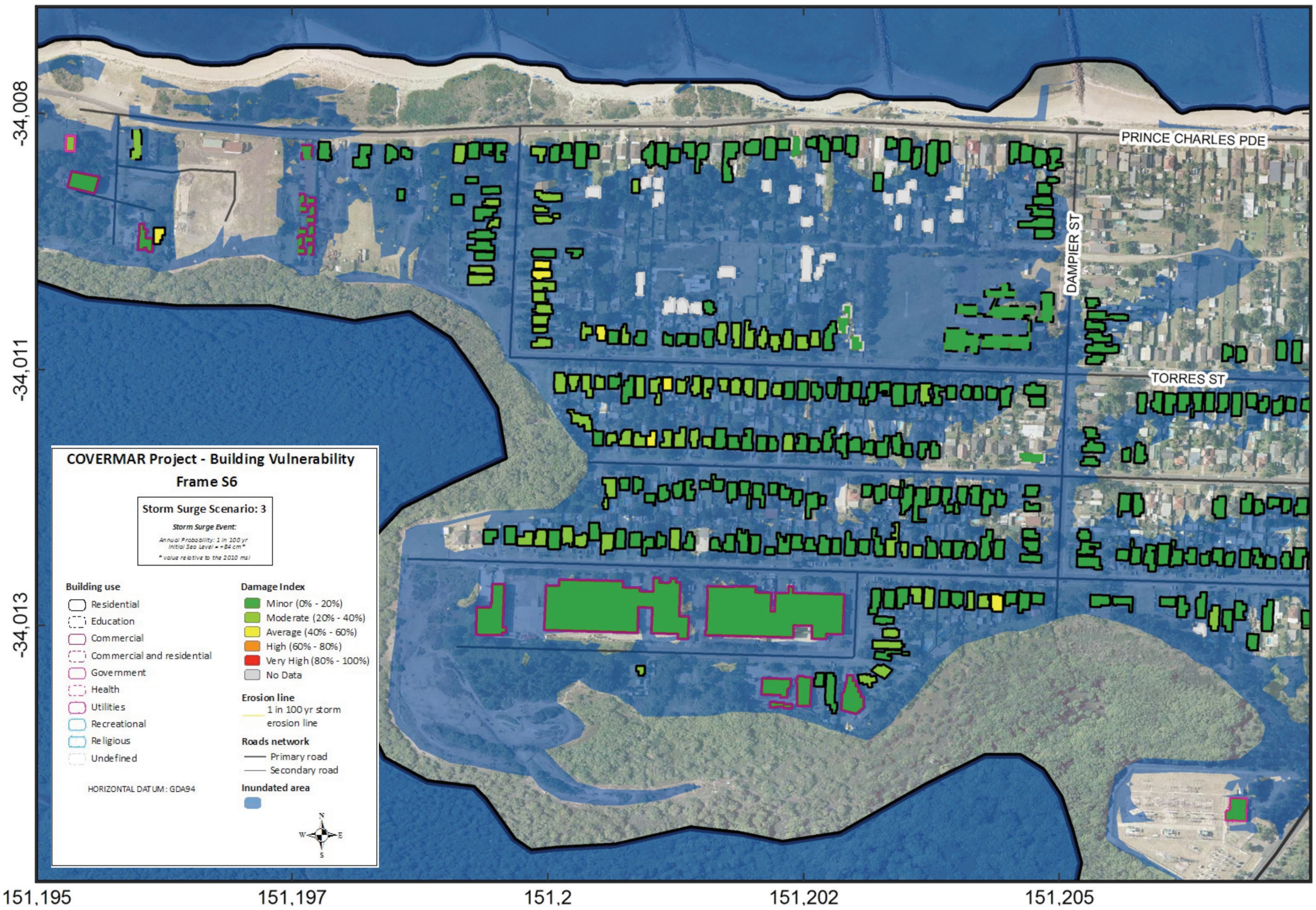


Figure 47. Storm Surge vulnerability map of frame S6 (Sutherland Council), storm inundation scenario n.3.

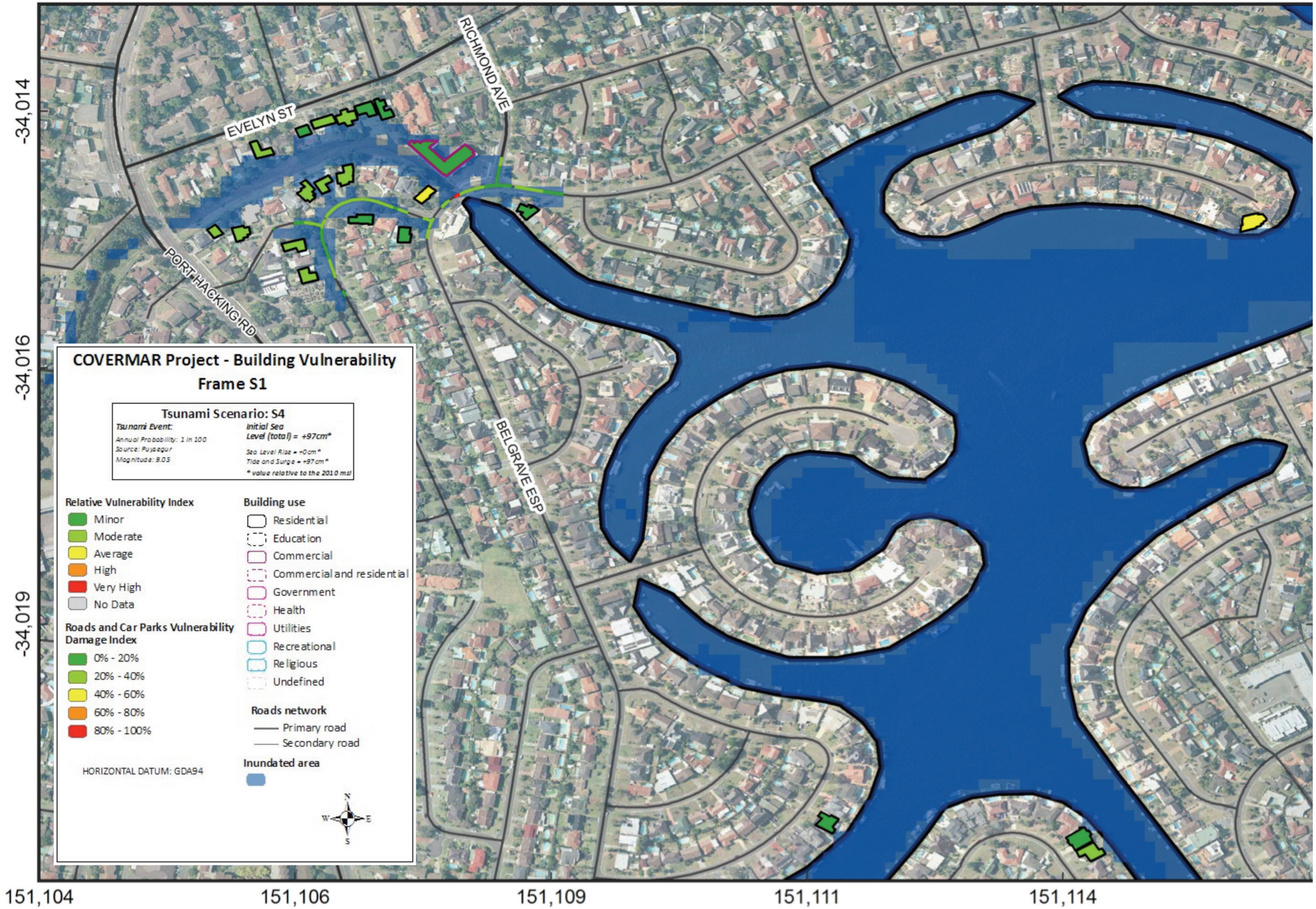


Figure 48. Tsunami vulnerability map of frame s1 (Sutherland Council), inundation scenario S4.

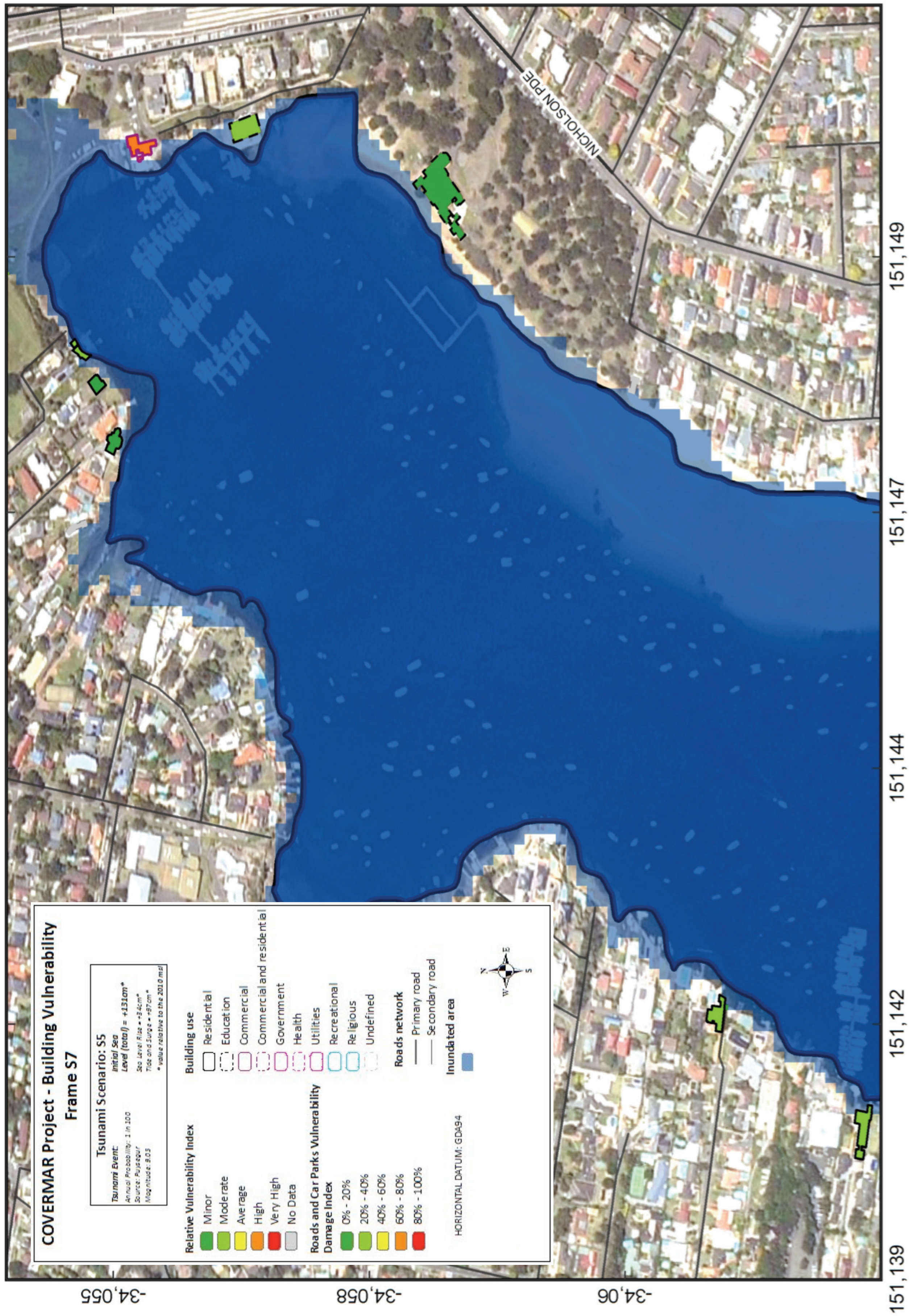


Figure 49. Tsunami vulnerability map of frame s7 (Sutherland Council), inundation scenario S5

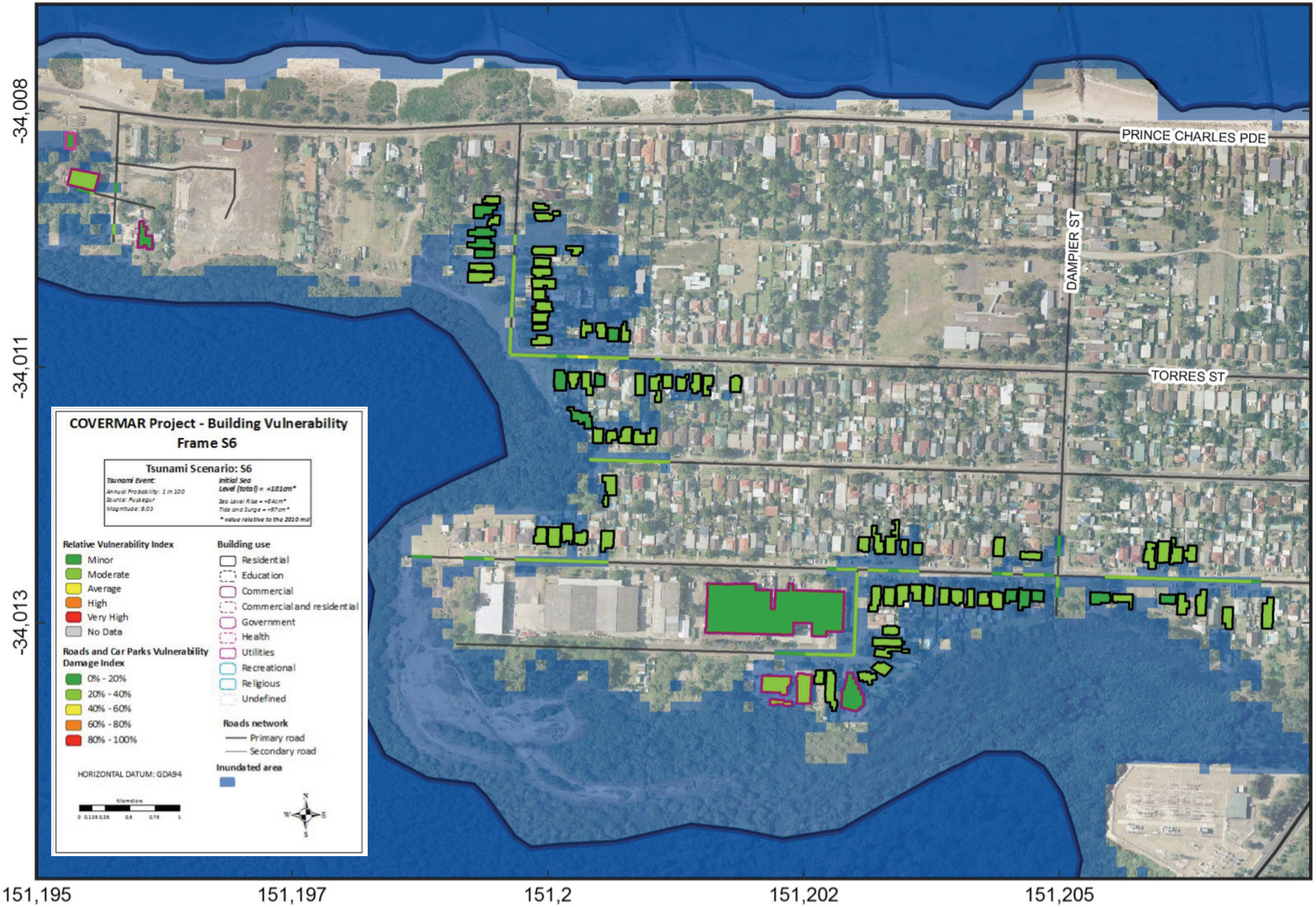


Figure 50. Tsunami vulnerability map of frame s6 (Sutherland Council), inundation scenario

Appendix III- List of project outcomes

REPORTS, MAPS, GIS

1. Literature Review Report

a) Dall'Osso, F. and Dominey-Howes, D.: Coastal Vulnerability to Multiple Inundation Sources – COVERMAR project – Literature Review (Second Edition). Report prepared for the Sydney Coastal Councils Group Inc. pp. 87, 2013.

b) Dall'Osso, F.: Flow-chart of NSW Regulation, Policy and Guidelines on Coastal and Flood Risk, prepared for the COVERMAR Project, December 2013.

2. Hazard Assessment Report

Dall'Osso, F., Summerhayes, S. and Dominey-Howes, D.: Coastal Vulnerability to Multiple Inundation Sources – COVERMAR project –Hazard Assessment Report. Report prepared for the Sydney Coastal Councils Group Inc. pp. 123, 2013.

3. Final Report (Vulnerability Assessment)

a) Dall'Osso, F., Summerhayes, S., Withycombe, G. and Dominey-Howes, D.: Coastal Vulnerability to Multiple Inundation Sources (COVERMAR) Project – Vulnerability Assessment Report. Report prepared for the Sydney Coastal Councils Group Inc. pp. 114, 2013.

b) 60 vulnerability maps, printed-out in a pdf format, A0 size.

4. COVERMAR GIS (Geographic Information System)

GIS database containing all the COVERMAR inputs and outputs including 75 inundation maps and 195 interactive vulnerability maps.

5. COVERMAR ArcGIS User's Manual

A step by step manual for non-expert GIS users describing how to apply the COVERMAR approach to different case study locations.

CONFERENCE PRESENTATIONS AND POSTERS

6. ***Dall'Osso, F., Summerhayes, S., Withycombe, G., Moore, C., Dominey-Howes, D.***: Sydney's First Probabilistic Multi-hazard Assessment of Extreme Coastal Inundation, NSW Coastal Conference, 2013.

7. ***Dall'Osso, F., Withycombe, G., Summerhayes, S., Dominey-Howes, D.***: "Coastal VulnERability to Multiple inundAtion souRces (COVER MAR)", Coast to Coast, Living on the Edge, Brisbane, 17-21 September 2012.AWARDED PEOPLE'S CHOICE AWARD

8. ***Dall'Osso, F., Withycombe, G., Summerhayes, S., Dominey-Howes, D.***: "Coastal VulnERability to Multiple inundAtion souRces (COVER MAR)", 6th Australasian Natural Hazards Management Conference, Christchurch, 21-22 August, 2012.

9. ***Ellis, M., Dall'Osso, F., Withycombe, G., Summerhayes, S., Dominey-Howes, D.***: "An approach to assess the "Coastal VulnERability to Multiple inundAtion souRces (COVER MAR)", Institute of Australian Geographers Conference, Sydney, 2-4 July, 2012.

SCIENTIFIC PUBLICATIONS (in preparation)

10. ***Dall'Osso, F., Tarbotton, C., Goff. J., Dominey-Howes, D.***: The use of vulnerability functions to assess the response of buildings to tsunami impact: comparative review and best practice, Natural Hazards and Earth System Sciences.

11. ***Dall'Osso, F., Moore, C., Burbidge, D., Dominey-Howes, D.***: A probabilistic tsunami hazard assessment in Sydney, Geophysical Research Letters.

12. ***Dall'Osso, F., Summerhayes, S., Withycombe, G., and Dominey-Howes, D.***: The PTVA-4: Assessing the vulnerability of buildings to tsunamis using an index-based model, Natural Hazards and Earth System Sciences.

13. ***Dall'Osso, F., Summerhayes, S., Withycombe, G., and Dominey-Howes, D.***: Assessing the risk to storm surges and tsunamis in Sydney: a probabilistic multi-hazard approach.

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