University of Southern Queensland
Faculty of Health, Engineering and Sciences

Key Infrastructure Review (Newcastle, NSW) Vulnerability to a Tsunami

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Abstract

The project aim was to undertake a key infrastructure review of the Newcastle (NSW) area in relation to vulnerability to tsunami damage. Previous research by Xing, Ding, Yuen (2014), and Hayes & Furlong (2010) found there is significant risk of a major tsunami event on the south east coast of Australia as a result of movement and earthquakes along the tectonic plate boundary in the Puysegur Trench south of New Zealand. On completion of the Newcastle inundation model the second part of the project was to identify the location of and impact to key infrastructure as a result of the wave inundation throughout the Newcastle Local Government Area (LGA).

Using the hydrodynamic modelling software ANUGA a tsunami inundation model for the Newcastle LGA was created. This model was conservative with the tsunami event to coincide with the Newcastle Probable Maximum Flood (PMF). For the tsunami modelling the deep water wave data from Xing et al (2014) was adopted. The model was created and used for data extraction such as inundation depths, flow velocity, inundation height and VxD values for all impacted areas.

The inundation results found that over 60%, 115km^2 of the Newcastle LGA was inundated by the tsunami. Over 55km^2 was located within regions where the flow characteristics were greater than the critical values and placed all buildings at risk of failure. It was identified through analysis of data and cross referencing to maps of the Newcastle LGA that major infrastructure had a significant risk of catastrophic impacted by the modelled tsunami including:

- Arterial Roadways,
- Rail Networks,
- Emergency Services,
- Schools,
- Electricity,
- Sewer and Water, and
- General buildings.

The project was able to identify the inundation zone and estimate the impact of inundation on the infrastructure. This information was used to make various suggestions relating to the relocation of certain infrastructure and the improvement in network redundancies.

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1. Introduction

“Its awesome fury cannot be diminished, but lessons learned from a rash of disasters this decade – and a new way to track these killer waves – will help save lives” (Gonzalez, 1999, p.56)

Outline of the Project

The impact and devastation caused by tsunamis has been experience around the world. This project will review the potential risk of a major tsunami event impacting the Australian East Coast and develop a model to determine the susceptibility of the Newcastle LGA and its key infrastructure to a potential tsunami event.

Introduction

Newcastle is a coastal city which contains one of the major industrial ports within Australia. The city has a high coastal population density and generates a significant portion of it economy within the CBD and port area. As a result there is significant infrastructure development in these areas which has little protection from a possible tsunami event. There is potential for significant damage to this infrastructure which would also result in extensive delays to emergency response times and significant loss of life.

The Problem

Despite the potential risks associated with tsunami damage to the key infrastructure no previous detailed modelling has been undertaken to review Newcastle’s susceptibility to such an environmental event. The Literature Review and tsunami modelling will consider:

- Historical tsunami events and damage,
- Major causes of tsunamis,
- Is the Australian East Coast at risk and from where?
- The Australian tsunami monitoring & warning system,
- The vulnerability of the Newcastle LGA,
- Potential structural damage, and
- Modelling options (software) for potential inundation tsunami.

Research Objectives

The research objectives are divided into a number of key research and modelling based tasks:

- Undertake background research into the likely causes and sources of tsunamis impacting the east coast of Australia;
- Prepare an inundation model of the Newcastle coastline to determine the full extent of a major tsunami impact;
- Locate and document key infrastructure within the inundation zone;
- Detail and discuss potential damage to key infrastructure; and
- Draw conclusions on Newcastle's susceptibility to tsunami damage and list potential mitigating actions or areas of required ongoing research.

Conclusion

This dissertation aims to determine if the key infrastructure in the Newcastle LGA is at risk of major damage and impact from a tsunami event. If found to be at significant risk a review for the potential relocation of infrastructure, and a review of existing systems and improvements to network redundancies will be undertaken.

2. Literature Review

Introduction

This literature review will look to establish relevant historical precedents where significant key infrastructure has been damaged during tsunami events. The review will identify significant tsunami events and review the levels of infrastructure damage and the resulting flow on effects.

The main causes of tsunamis will then be identified with respect to their relevance to the Australian East Coast. The literature review will establish the location of the major tsunami risks generators for the east coast and identify the level and potential size of the tsunami risk. A review of the current warning systems in relation to the identified potential tsunami generators will be undertaken.

An assessment of the Newcastle Local Government Area (LGA) and its susceptibility to tsunami inundation will be undertaken including a detailed literature review into Newcastle's flood history and susceptibility to ocean serge. A community profile will also be developed looking at the population spread and industrial / commercial development in coastal and river areas.

Historical building and structural damage records and studies will be examined to determine threshold inundation values for significant structural damage. The development of these threshold values will allow for a high level review of the potential structural impacts within the areas impacted by tsunami inundation.

Finally an appraisal of the available modelling software options for the tsunami event and their suitability to the research project will be undertaken. A software selection will be made allowing for the identification and resourcing of all required data.

Historical Perspective – Key Infrastructure Damaged by Tsunamis

Indonesian Tsunami - Boxing Day (26th Dec) 2004

On the 26th of December 2004 an earthquake on the west coast of the Indonesian island of Sumatra resulted in a major tsunami event felt around the globe (Titov, Rabinovich, Mofjeld, Thomson, & Gonza´lez, 2005).

> The uplift of the ocean floor created a tsunami that affected 19 countries, causing death and destruction in 12 countries including Indonesia, Sri Lanka, India, Thailand, Somalia, Maldives, Malaysia, Myanmar, Tanzania, Seychelles, Bangladesh, and Kenya. The impact of the earthquake and tsunami event was catastrophic. Damage from the event is staggering and loss of life exceeded 300,000 with an estimated 1.5 million made homeless.(Ghobaraha, Saatcioglub, & Nistorb 2005, p.312).

The earthquake of magnitude 9.3 was the largest seismic event on Earth in more than 40 years and resulted in the most devastating tsunami event on record (Lay, Kanamori, Ammon, Nettles, Ward, Aster, Beck, Bilek, Brudzinski, Butler, DeShon Ekström, Satake, Sipkin, 2005). The first of three waves hit the Indonesian coastline approximately 25 minutes after the earthquake, followed by two further waves which hit the coastline at 25 minute intervals (Ghobaraha et al, 2005). The second and third waves proved to be the most devastating (Ghobaraha et al, 2005).

Wave inundation reached up to 4.5km inland along the coast of Sumatra and Banda Aceh (Ghobaraha et al, 2005). The average run-up height experienced throughout the impact area varied between 6-12 metres (Ghobaraha et al, 2005). Impact on infrastructure was significant with damage to the harbours, docks, roads and bridges (Ghobaraha et al, 2005). Detailed research undertaken by Ghobaraha et al, 2005, found that the damage to buildings and other structures varied greatly based on the methods of construction; at one end of the scale timber structures suffered total destruction whereas engineered and well-constructed structures remained intact. All structures within the inundation zone that where not destroyed suffered severe water and contents damage (Ghobaraha et al, 2005).

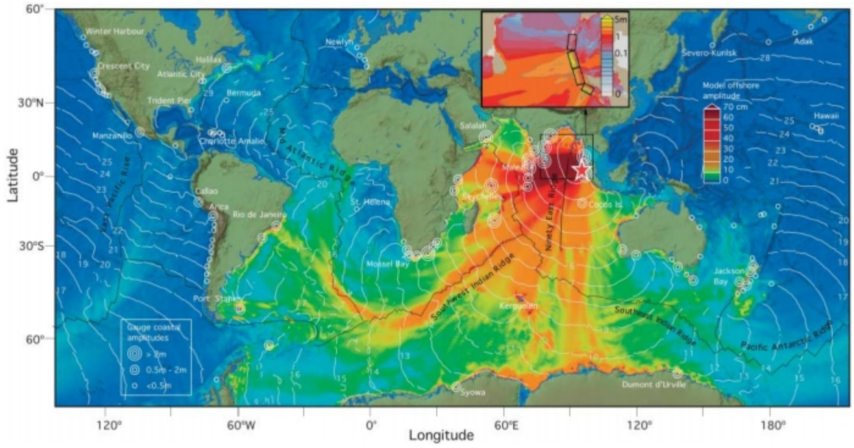

Figure 1: Global chart showing energy propagation of the 2004 Tsunami (Source Titov et al. 2005)

Roadways were significantly damaged and in many cases heavily covered in debris (Ghobaraha et al, 2005). This impeded search and rescue efforts for months in some regions (Ghobaraha et al, 2005). The death toll in the Sumatra and Banda Aceh region reached over 100,000 including up to 60% of Bana Aceh public servants (Ghobaraha et al, 2005). Failure of telecommunications and local hospitals further impacted the rescue and treatment of impacted survivors (Ghobaraha et al, 2005). It was estimated that the damage bill of the earthquake and resulting tsunami ran into billions of dollars (Titov et al. 2005)

Japanese Tsunami – 11th May, 2011

In May of 2011 the Northeast coast of Japan was subject to a 9.0 magnitude earthquake which occurred off the Japanese coastline (Mimura, Yasuhara, Kawagoe, Yokoki & Kazama, 2011). This was the largest recorded earthquake event Japan had ever experienced (Mimura et al, 2011). "Consequently, the tsunami associated with the Great East Japan Earthquake attached a long coastline of over 800 km in the northeast Japan, representing a major external force that imposed devastating damages on the coastal areas" (Mimura et al, 2011, p.811).

As much as 70% of Japans landmass is classed as mountainous terrain and as a result its population, assets, industrial areas, and infrastructure is located in the low level coastal areas (Mimura et al, 2011). Japan has been proactive in its investment in tsunami mitigation systems and technologies and is considered a world leader in this area (Mimura et al, 2011). The systems currently installed in the higher risk locations are considered the most advanced in the world (Mimura et al, 2011).

Japan has a history of major tsunami events. A number of key tsunami events reordered over the past century including;

- 1886 - Meiji Snriku Tsunami
- 1933 - Showa Sanriku Tsunami
- 1960 – Chilean Earthquake Tsunami
- 1968 – Off Tokachi Tsunami (Mimura et al, 2011).

Based on these historical events both the local and national Japanese Governments undertook construction of major tsunami protection infrastructure such as breakwaters and large coastal dykes (Mimura et al, 2011). The breakwaters constructed extend up to 8m and in parts are as deep as 63m below the above average tide levels (Mimura et al, 2011). These are the largest breakwaters constructed in the world. The coastal dykes where constructed extend to 10m in height and were built in response to the 1933 Showa Sanriku Tsunami which reached up to 10m in these locations (Mimura et al, 2011).

The 2011 tsunami which hit the Japanese northeast coastline as a result of a major offshore earthquake was of unprecedented size (Miyajima & Murata, 2013). Tide measuring devices recorded maximum wave heights of up to 13m above the tide level and a low of minus 6m below the tide giving an appreciation of the wave surge (Mimura et al, 2011). The maximum recorded run-up elevation reached over 38m with approximately 535km2 of land being inundated as a result (Miyajima & Murata, 2013).

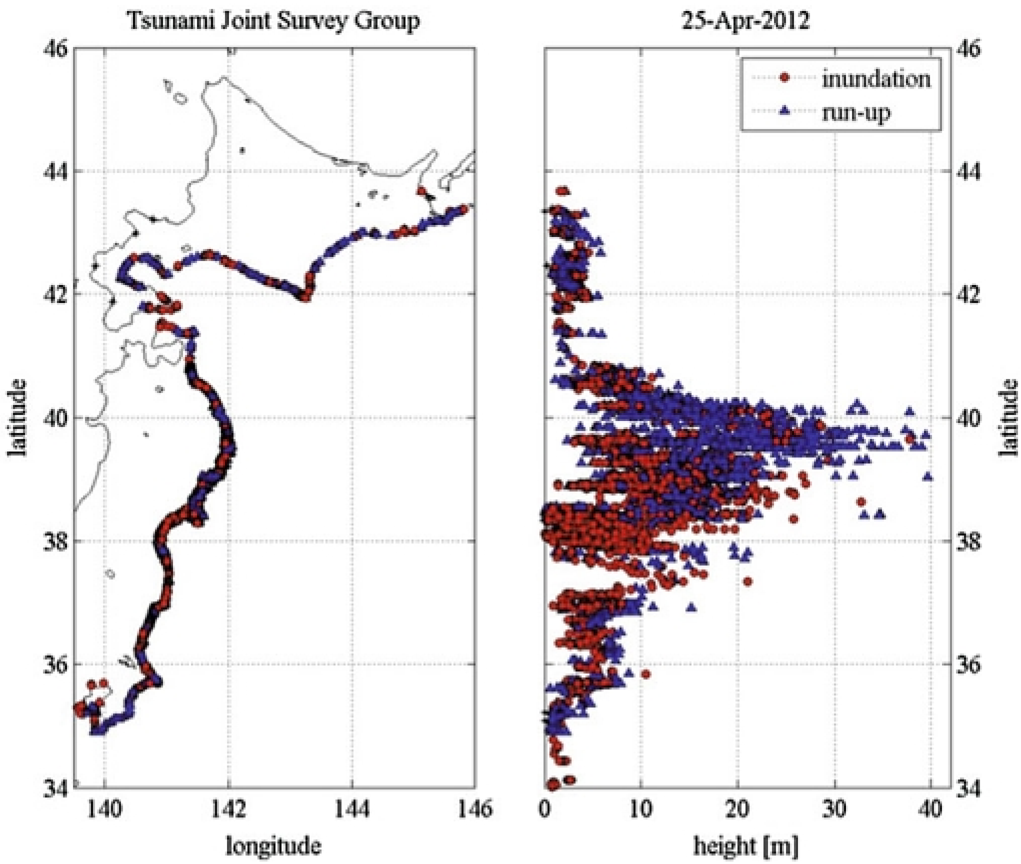

Figure 2: The distribution of inundation and run-up heights (Source Miyajima & Murata, 2013)

Due to the size of the tsunami none of the specifically designed mitigation infrastructure was effective in preventing or even reducing the tsunamis wide spread impact and damage (Mimura et al, 2011). The breakwaters and coastal dykes were simply not of sufficient height to prevent the wave surge from passing directly over the top (Mimura et al, 2011). According to Mimura et al, 2011 and Miyajima & Murata, 2013, some of the key damage and impact statistics from the tsunami event are as follows:

- First wave surge struck 30-40 minutes after the initial earthquake:
- In May 2011 over 24,000 people were reported dead or missing:
- Temporary refugees exceeded 350,000:
- Inundation area of 535km2:
- 3,918 specific locations of roadway damage:
- 16,000 people were isolated due to damaged roadways:
- 28 rail stations damaged:
- 1100 power poles damaged:
- Significant damage to water supply infrastructure and;
- 2 nuclear power plants damaged.

The impact and damage to the Fukushima Nuclear Power Plant No.1 received major worldwide attention and criticism (Martin Fackler, 2012). According to Mimura et al, 2011, the design of the Fukushima power plant had accounted for a design tsunami event with a run-up height of 5.7m with the buildings being placed at a height of 10m. The plant experienced a run-up height of 14-15m during the 2011 event (Mimura et al, 2011). It was reported by Martin Fackler of the New York Times (2012, p.A4) that "Tepco and regulators had for years ignored warnings of the possibility of a larger-than-expected tsunami in north eastern Japan, and thus failed to take adequate countermeasures, such as raising wave walls or placing backup generators on higher ground".

The plants standard power supply was damaged by the initial earthquake and the backup generators were providing power to the cooling systems of each reactor (Mimura et al, 2011). The tsunami damaged and flooded the buildings containing the backup generators leading to failure in the cooling system, partial meltdown and leaking of radioactive matter. (Mimura et al, 2011)

What are the major causes of tsunamis?

Tsunamis are a result of a sudden movement within the ocean (typically the ocean floor) that causes large scale displacement of water (Geoscience Australia (GA), 2007). The displacement of water causes large wave masses to propagate through oceans typically until they reach landfall and dissipate their energy (Bryant, 2008). They can be caused by a number of different environmental actions including;

- earthquakes,
- sudden changes to the ocean bed such as landslides,
- volcanic eruptions,
- oceanic impact of meteorites (Ryan & Davidson, 1999).

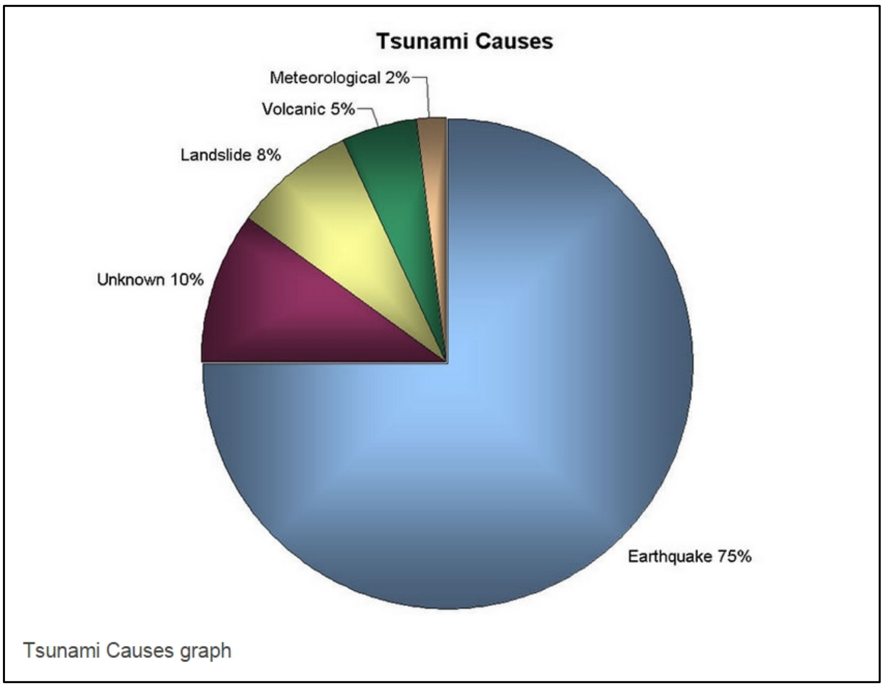

Figure 3: Tsunami Causes Graph (Source GA, 2015)

Tsunamis caused by landslides are the second most common type of Tsunami (GA, 2015). Geoscience Australia (2015) lists the percentage of landslide tsunamis as only eight percent of the total recorded number of tsunamis. This is an extremely small percentage for it to be seen as a calculated threat. Bryant (2008) discussed the difficulty in identifying and proving landslides as the cause of tsunamis due to the limited detailed bathymetric data available, thus making landslides hard to locate or confirm. Earthquakes are also a primary cause of submarine landslides which in tsunami events will see landslides defined as a result of the earthquake not the cause of the tsunami event (Bryant, 2008). This makes landslide tsunamis unpredictable and near impossible to correctly quantify (Bryant, 2008).

Ryan & Davidson (1999) identified five key locations as potential tsunami causing submarine volcanoes. Of these only three locations pose a serious threat to the east coast of New South Wales due to their geographic location:

- The Tonga-Samoa volcanic arc,
- The South Fiji Basin
- The Kermedec Island region located to the north of New Zealand along the Kermedec Trench (Ryan & Davidson, 1999).

These locations, although highly active are not believed to pose a threat of a mega-tsunami to the Australian East Coast (Xing et al, 2014). Xing et al. (2014) states that the Solomon Trench, Tonga Trench, Kermedec Trench and the southern extent of the New Hebrides Trench which include the above volcanic locations are within heavy collision zones of the Australian and Pacific tectonic plates (Figure 4) (Xing et al, 2014). As a result the locations contain many islands and a heavily undulating ocean floor. This negatively impacts tsunami propagation and also results in these locations having interrupted deep ocean access to the Australian coastline (Xing et al, 2014).

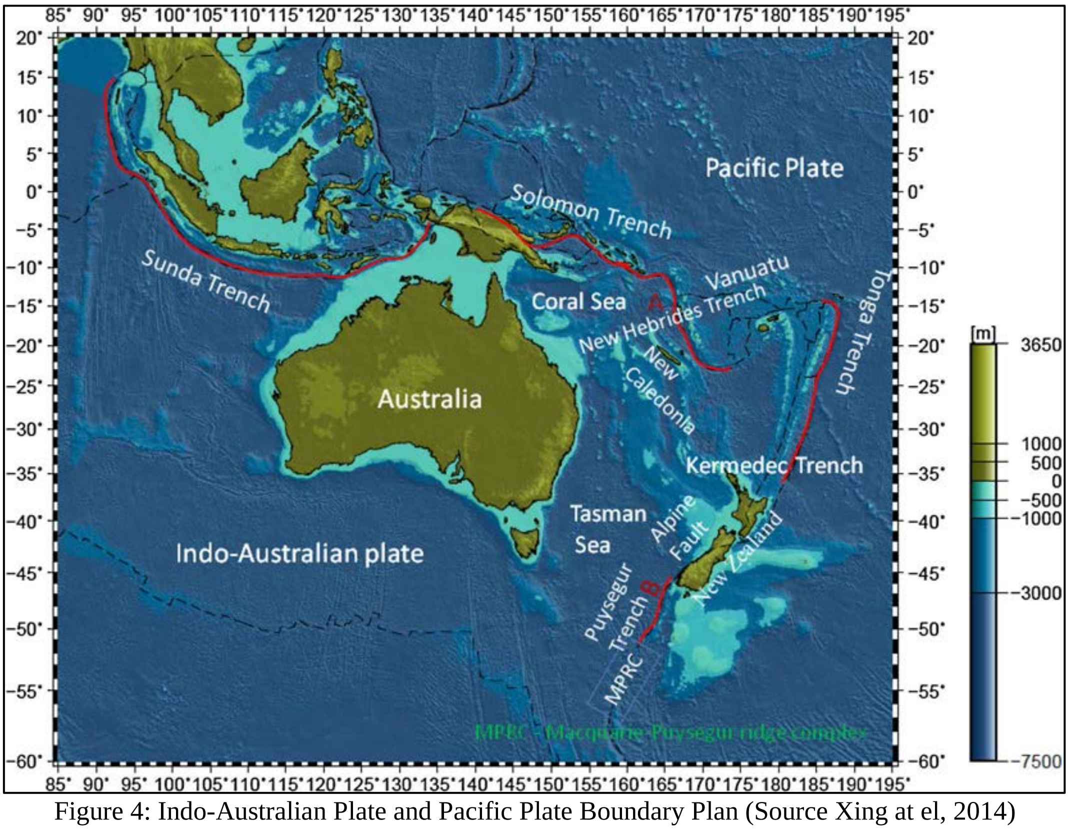

Figure 4: Indo-Australian Plate and Pacific Plate Boundary Plan (Source Xing at el, 2014)

Meteorological impact tsunamis make up a minor number of the recorded Tsunamis (GA, 2015). Geoscience Australia (2015) places this at around two percent of all tsunamis. The Prime Minister's Science, Engineering and Innovation Council (PMSEIC) (2005) suggest that objects up to a diameter of 100 metres are not large enough to cause damaging tsunamis. Objects in the range of 100m to 1km in diameter are of far more concern in relation to tsunami generation (PMSEIC, 2005). Ryan and

Davidson (1999) discuss that the major issue with this type of tsunami generation is lack of historical evidence and unpredictability of extra-terrestrial impacts. They have the potential to produce mega-tsunamis that have been linked to species extinction but are near impossible to predict (GA, 2007).

According to Geoscience Australia (2015) up to 75% of tsunamis are caused by earthquakes (Figure 3). “The most frequent sources of tsunamis are large earthquakes that occur in subduction zones” (PMSEIC, 2005, p.31). The high ratio of earthquake produced tsunamis is also confirmed by Bryant (2014) who states that the most common cause of tsunami related events is seismic activity. He expands further to say up to 83% of all tsunamis on record, caused within the Pacific Ocean have been the result of earthquakes (Bryant, 2014). Subduction zones are located at the interface between tectonic plates (GA, 2007). Subduction zone earthquakes are the result of large rock formations trying to move past each other as the plates shift, as the plates move past each other one is forced below the other creating an immense amount of stress (GA, 2007). When this stress surpasses the frictional strength the upper plate shifts violently upward quickly displacing the water above causing a tsunami to propagate outwards from the location (Figure 5) (GA, 2015). Since the beginning of the 1900’s eleven of the twelve largest recorded earthquakes have occurred in subduction zones all of which produced large tsunamis (PMSEIC, 2005).

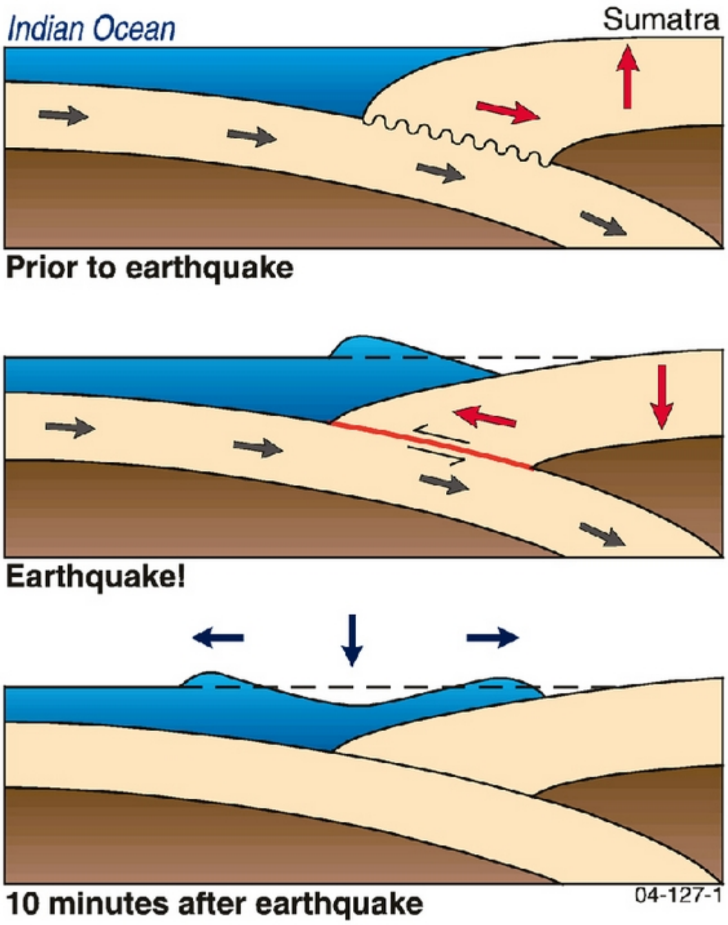

Figure 5: Tsunami Earthquake Generation (Source GA, 2007)

Is Australia (Southern East Coast) at risk & from where?

On average Australia is struck by a tsunami every two years (BOM, 2015). Australia is located within a particularly volatile area in relation to earthquakes (Xing at el. 2014). Located off the eastern Australian coastline is the boundary between the Australian and Pacific tectonic plates (Xing at el. 2014). This boundary is a zone of high earthquake activity due to clashing and movement of the two plates which form part of the "Ring of Fire" where approximately 90% of all earthquakes occur (Figure 6) (National Geographic, 2015). The tectonic boundaries that directly surround Australia account for over 30% of the world's annual seismic activity (PMSEIC, 2005).

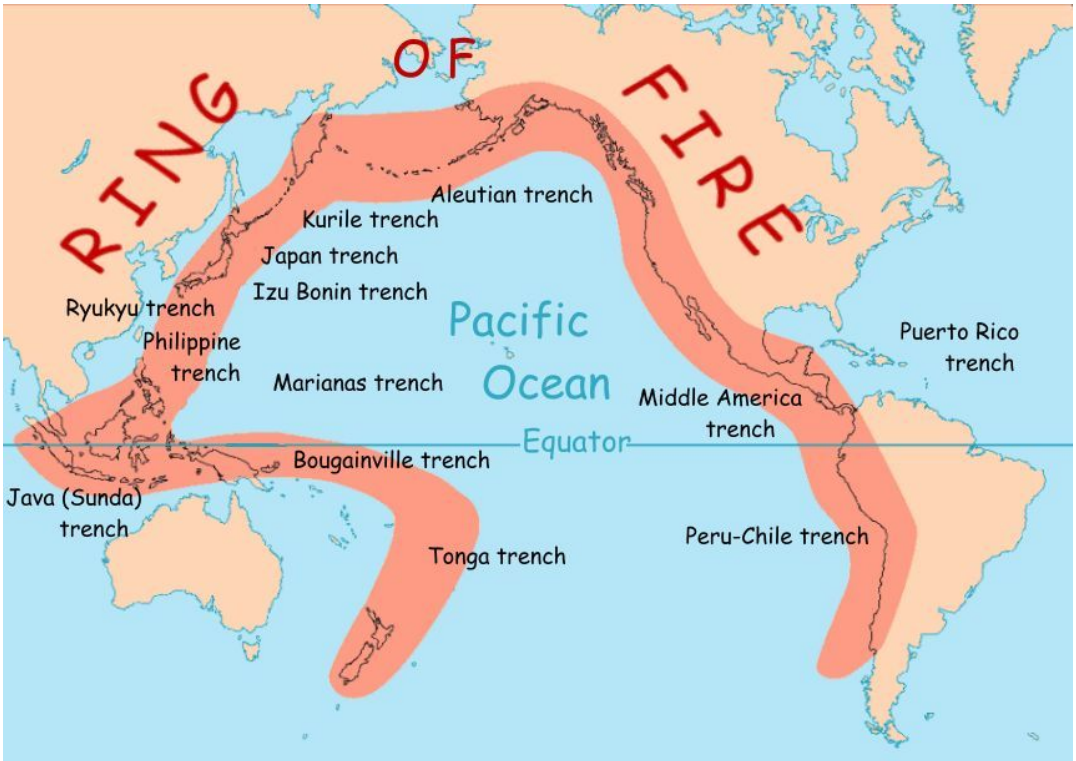

Figure 6: Ring of Fire (Source National Geographic, 2015)

According to PMSEIC (2005) the information we now have regarding tsunamis illustrates a serious threat to Australia. The highly active plate boundaries that surround Australia are capable of causing major tsunami events that would strike the coastline in as little as two hours (Hayes & Furlong, 2010).

> The lack of major historical events along these boundaries is no reason for complacency and is not an indication of the absence of tsunami danger. The Indian Ocean tsunami should be regarded as a warning that strain energy is accumulating in preparation for one or more massive earthquakes producing large tsunamis that would impact the coast of Australia. Australia's coastal communities and infrastructure are particularly vulnerable to inundation from large tsunamis due to our narrow continental shelf and lack of protective islands. (PMSEIC 2005, p.6)

Data compiled by Ryan & Davison (1999) suggest that between 1788 and 1995 there were 65 recorded tsunami events around the Australian coastline. Further research by

Goff and Chaugé-Goff (2014) has discovered using modern detection techniques and data review that this number is closer to 145 tsunami events on record. Their findings also suggest that there have been up to 11 possible tsunami related deaths in Australia all of which occurred in the eastern states (Goff & Chaugé-Goff, 2014). This number is higher than the number of Australia's tsunami prone neighbouring countries suggesting that we are under prepared for such events (Goff & Chaugé-Goff, 2014).

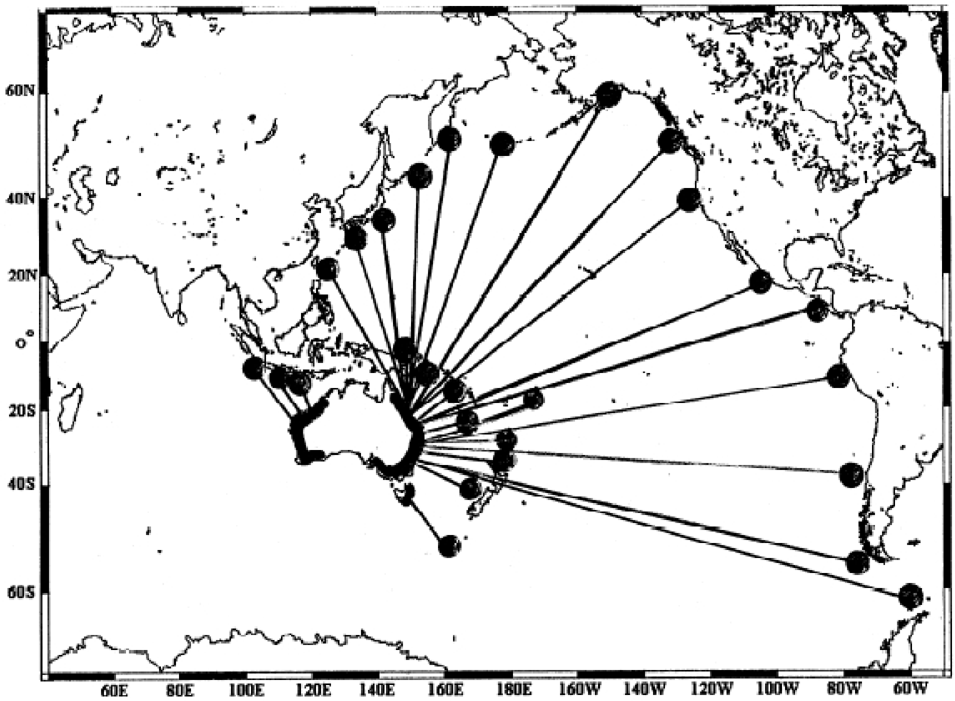

Figure 7: Earthquake Sources for Known Tsunamis Impacting the Coastline of Australia and its Island Territories (Source Ryan & Davidson, 1999)

When we look more specifically at the area of the east coast near Newcastle some of the research suggests that although the area is at a high risk of tsunami it is actually protected from many of the potential tsunami producing locations to the east of the country (Ryan & Davidson, 1999). According to Xing et al. (2014) along the boundary between the Australian and Pacific plates there are two subduction zones that pose the most significant Tsunami threat to the Australian east coast. The two subduction zones are the Puysegur Trench and the northern end New Hebrides Trench (Figure 4) (Xing et al. 2014). These are seen as the most likely to produce tsunamis that will significantly impact the east coast due to their substantial depth and their unobstructed ocean connection to the coastline (Xing et al. 2014).

There are also concerns from within the scientific community that our knowledge regarding the relationship between high risk geological settings such as subduction zones and giant earthquakes (magnitude >8.5) is insufficient and our predictions on the potential earthquake locations imperfect (Cummins & Goldberg 2007). Cummins and Goldberg (2007) express concern that with the number of studies that have been undertaken on high risk subduction areas there are still major tsunami causing geological events occurring outside of these locations. No studies prior to the 2004

Boxing Day tsunami predicted that there was the potential for such a large event to occur in this location (Cummins & Goldberg, 2007).

The potential for tsunamis along the Australian east coast varies (Xing et al. 2014). One of the major factors that impacts the potential for a large tsunami is the ocean topography adjacent to the coastline (Xing et al. 2014). The propagation of tsunamis is more efficient over deeper water bodies (GA, 2015). The south eastern coast has a deep body of water in the Tasman Sea, with minimal protection from the open ocean and the Puysegur Trench (Xing et al. 2014). The north eastern coast has a mush shallower body of water in the Coral Sea and has far greater protection from its main tsunami hazard, the New Hebrides Trench; as a result the southern section of the east coast is more susceptible to large tsunami events (Xing et al. 2014).

The Puysegur Trench is located directly on the tectonic plate boundary and at its deepest point is approximately 6,300m deep (Xing et al. 2014). It is a highly active subduction zone in which a number of large earthquakes have been recorded (National Geophysical Data Center, 2015). Xing et al. (2014) and Hayes (2010) both use large earthquakes from the Trench as part of their detailed tsunami modelling and see the Trench as having high potential to cause a seismic event resulting in a large tsunami. Figure 8 details the location of three particular earthquakes; the 2004 (M7.1) and the 1979 (M7.4) that Xing et al. (2014) and Hayes (2010) used in their Tsunami models respectively and the 2004 (M7.4) which resulted in a small tsunami event on the Australian east coast (National Geophysical Data Center, 2015).

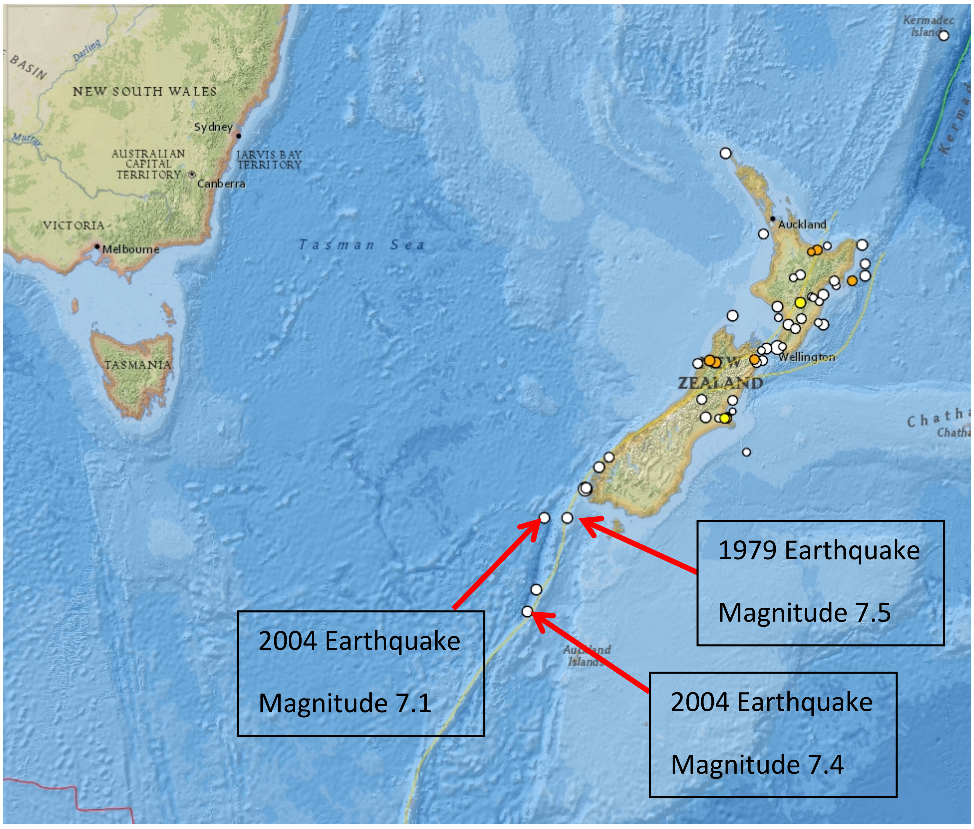

Figure 8: Puysegur Trench - Major Earthquake Events (Source National Geophysical Data Center, 2015)

The numerical modelling of Xing et al. (2014) using a theoretical earthquake event of similar magnitude and properties to the historical events shown in Figure 8 found the potential for a wave height of up to 2.0m to reach the east coast. The same model calculated offshore wave heights of up to 1.5m reaching the coastline near Sydney and Newcastle (Xing et al. 2014).

The New Hebrides Trench is also an area of high seismic activity (National Geophysical Data Center, 2015). It is located between New Caledonia and Vanuatu and is the main reason why only the northern end of the Trench is considered a tsunami risk to the east coast of Australia (Xing et al. 2014). The Trench itself is a very deep subduction zone with recorded depths in the order of 7,600m (Xing et al. 2014). Two key seismic events have been highlighted on Figure 9 (National Geophysical Data Center, 2015). These earthquakes occurred on the same day and both caused Tsunamis (National Geophysical Data Center, 2015). The earthquakes were the basis of the New Hebrides Trench tsunami modelling by Xing et al. (2014) in relation to their potential impact on the Australian coastline. The numerical modelling of Xing et al. (2014), used a theoretical earthquake event based on historical earthquake events found the potential for an offshore wave height of up to 0.6m to reach the east coast (Refer to Figure 9). The calculated offshore wave height of up to 0.13m reached the coastline around Sydney (Xing et al. 2014).

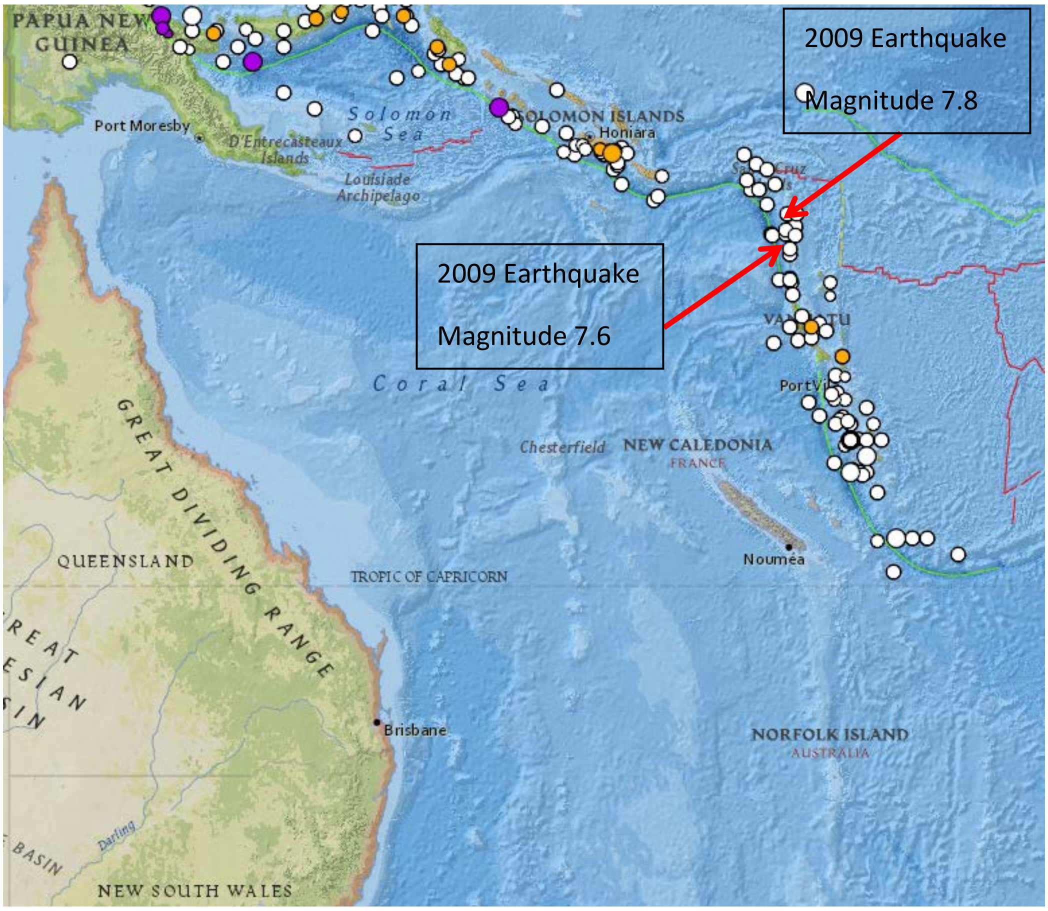

Figure 9: New Hebrides Trench - Earthquake Events (Source National Geophysical Data Center, 2015)

The issue with Xing et al.'s (2014) research is the lack of coastal damage and inundation modelling. The research is solely aimed at offshore tsunami analysis. To use this data for inundation modelling would require an extension of the analysis into shallow water wave propagation and tsunami run-up analysis as the wave will increase significantly in height as is approaches land (GA, 2007). As a tsunami approaches land from the open ocean the depth of water and wave velocity decrease (González, 1999). The wave period remains relatively unchanged which forces the wave to increase in height to contain the same volume of water (González, 1999).

Understanding the evolution of a tsunami and its reaction as it approaches the coastline is key to more accurate modelling and prediction of potential inundation and damage (González, 1999). González (1999), steps through the three stages of tsunami evolution, generation, propagation and inundation (refer to Figure 10. The inundation modelling is the most contentious area of modern tsunami models as the interaction between the shoreline and a potential breaking wave, wall of water, or a major tidal like surge is extremely difficult to model (González, 1999). González (1999) explains that due to the complex nature of such modelling it is common for post disaster models to underestimate a tsunami inundation by between 5 -10 times.

The difficulty in modelling the tsunami's shore interaction and inundation is evident in the tsunami modelling studies undertaken by Xing et al. (2014) and Hayes & Furlong (2010). Xing et al. (2014) undertook detailed research of the tsunami threat along the Australian east coast and didn't include any inundation modelling. Xing et al. (2014) even state that further modelling is required to determine actual onshore wave propagation and inundation. A similar approach is undertaken by Hayes & Furlong (2010) where detailed deep ocean tsunami generation and propagation simulations were undertaken as part of the research into the potential tsunami threat posed to the New Zealand south coast but no further inundation models have been completed.

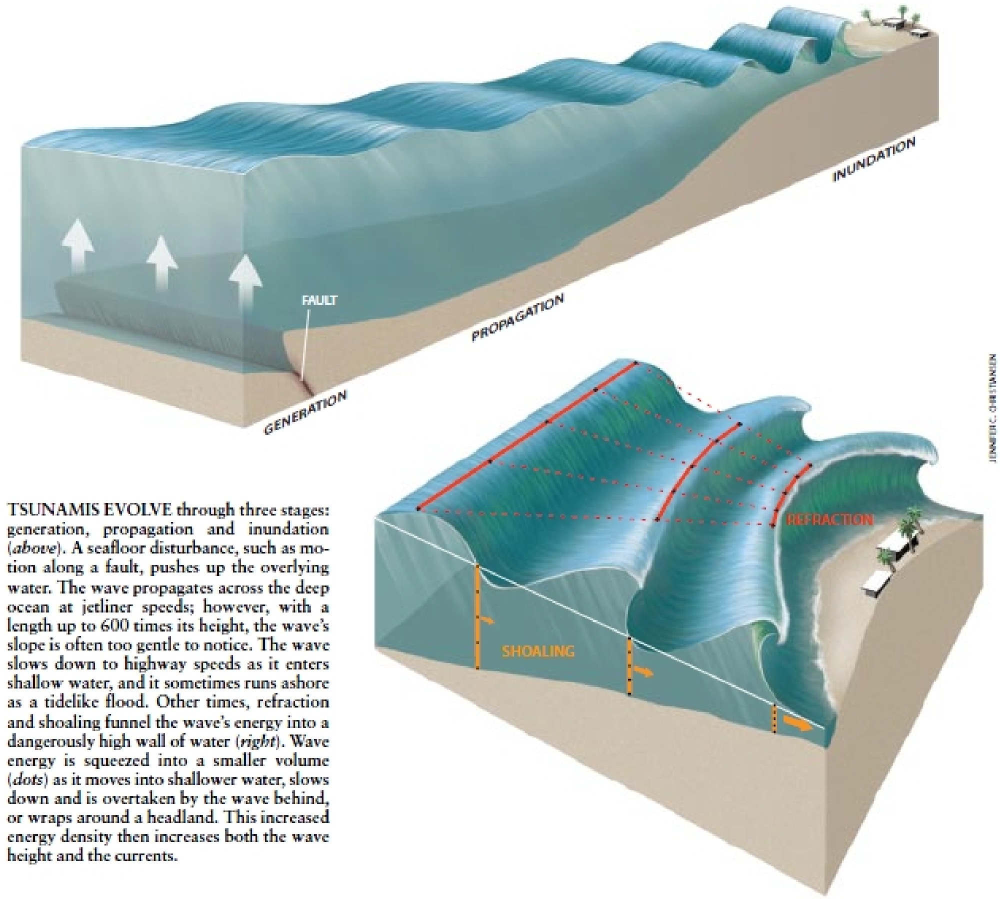

Figure 10: Tsunami Evolution (Source. González 1999)

Australian Tsunami Monitoring & Warning System.

The Joint Australian Tsunami Warning Centre (JATWC) detects, monitors and warns the Australian public of potential tsunami strikes using the Australian Tsunami Warning System (ATWS) (GA, 2015). The JATWC is a joint operation between Geoscience Australia out of Canberra and the Australian Bureau of Meteorology (BOM) out of Melbourne. The ATWS is monitored 24hrs a day by experts within the government agencies (GA, 2015).

The ATWS was developed over a number of years from Geoscience Australia's existing Australian National Seismic Network (ANSN) (GA, 2015). The ANSN originally contained 33 seismic monitoring stations but by October 2009 major upgrades and additions had been made to create the current ATWS (GA, 2015). The current ATWS contains;

- 19 of the existing ANSN stations
- 28 ANSN stations that have been substantially upgraded
- 9 new ANSN stations within Australia
- 3 new overseas stations built by Geoscience Australia (one in Niue and two in Papa New Guinea) and;
- 133 stations from shared international seismic networks (GA, 2015)

The BOM (2015) details the steps undertaken in the event of a potential tsunami:

- Stage 1 is the issuing of a 'tsunami watch' by the BOM. This occurs when the experts monitoring the ATWS determine there is tsunami potential resulting from recorded seismic activity.
- Stage 2: If a threat is confirmed a 'National Tsunami Watch' will be issued or if no threat is confirmed a 'National No Threat Bulletin' will be issued.
- Stage 3: If through the sea level buoys or other data an actual threat is confirmed the BOM on behalf of the JATWC will issue a detailed tsunami warning through its severe weather warning system to the locations under threat.
- Stage 4: Cancelation of tsunami threat.

All of the above stages will be delivered to the public via the BOM's severe weather warning system and the JATWC website (BOM, 2015). The minimum time criterion for a tsunami warning via the BOM or JATWC is 90 minutes between the warning and the potential tsunami impact time (BOM, 2015).

One of the most important pieces of equipment used in the ATWS is the deep ocean detection buoys (BOM, 2015). These buoys are equipped with multiple sensors to assist in early warning and tsunami detection (BOM, 2015). The buoys monitor and record seismic activity in the sea floor (moves faster than a potential tsunami) and also water level (BOM, 2015). These buoys have been placed in strategic locations around Australia (NOAA 2015). These locations confirm previous research about the potential risk of the Puysegur Trench to the south of New Zealand and the New Hebrides Trench to the north of New Zealand as the JATWC and the BOM have placed ocean detection buoys in these locations (Figure 11) (NOAA, 2015).

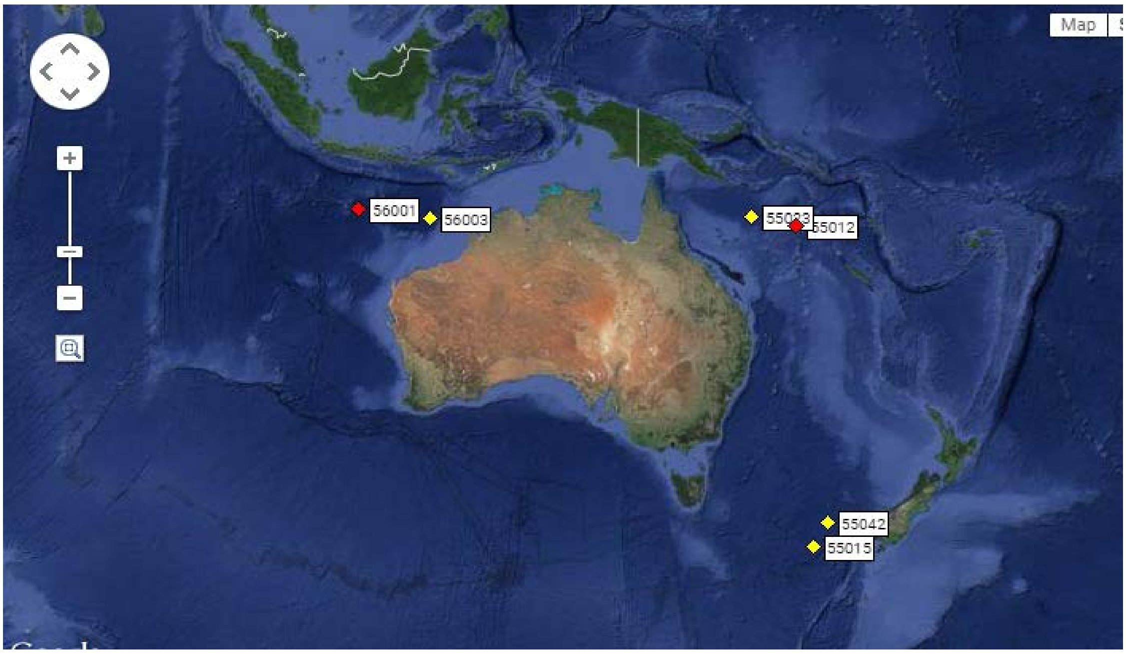

Figure 11: Location of Australian Detection Buoys (Source, NOAA 2015)

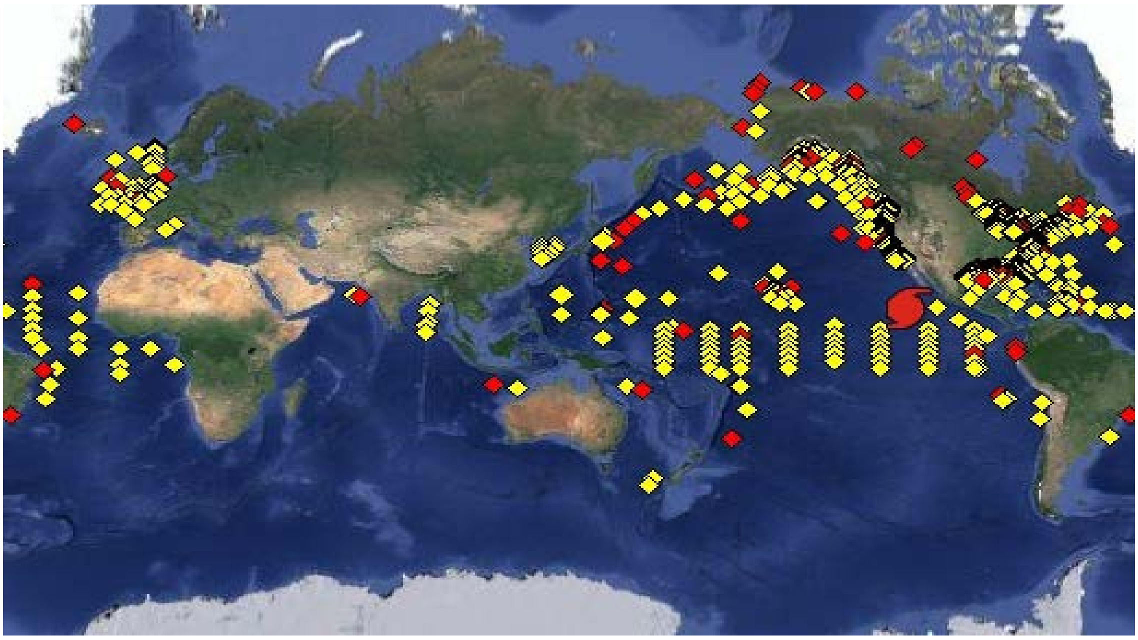

Figure 12: World Tsunami Detection Locations (Source, NOAA 2015)

Is the Newcastle LGA vulnerable to such an event?

The City of Newcastle

Newcastle is a coastal city located approximately 160km north of Sydney (Economic Profile, 2014). It is one of New South Wales' largest cities with a population base of approximately 160,000 within its local government area (Economic Profile, 2014). Historically Newcastle has a high population density around its coastal zones and inland river area (Department of Infrastructure and Regional Development, 2012). Figure 13 details the high density of Newcastle's population around these locations.

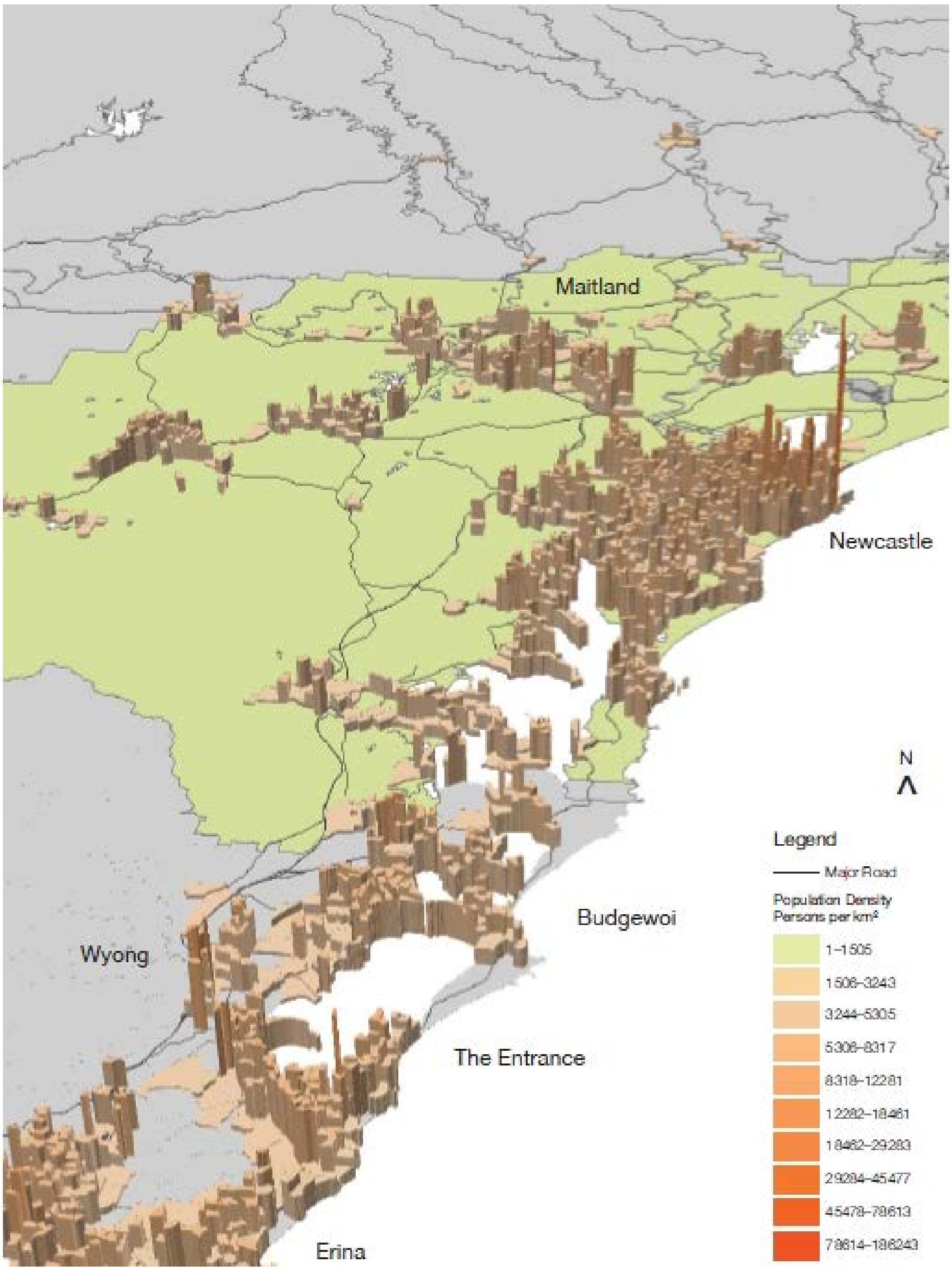

Figure 13: Newcastle Population Density (Source, Department of Infrastructure and Regional Development, 2012)

Newcastle is the main economic hub for the Hunter Region with the generated output exceeding $29 billion in 2014 (Economic Profile, 2014). This is only a small part of the overall Hunter economy which outputs almost $100 billion dollars annually (Economic Profile, 2014). The size of the economy and the potential threat of major tsunami damage are linked through geographical location. High percentages of this economy are generated through local industry or facilities, such as resources mined in the Hunter that are processed and shipped through the Port of Newcastle (Newcastle Port Corporation, 2015). Figure 14 details the areas of high economic output which are typically located on Newcastle Port and coastline. Refer to Figure 15 which gives further examples of the high levels of development and infrastructure within these locations.

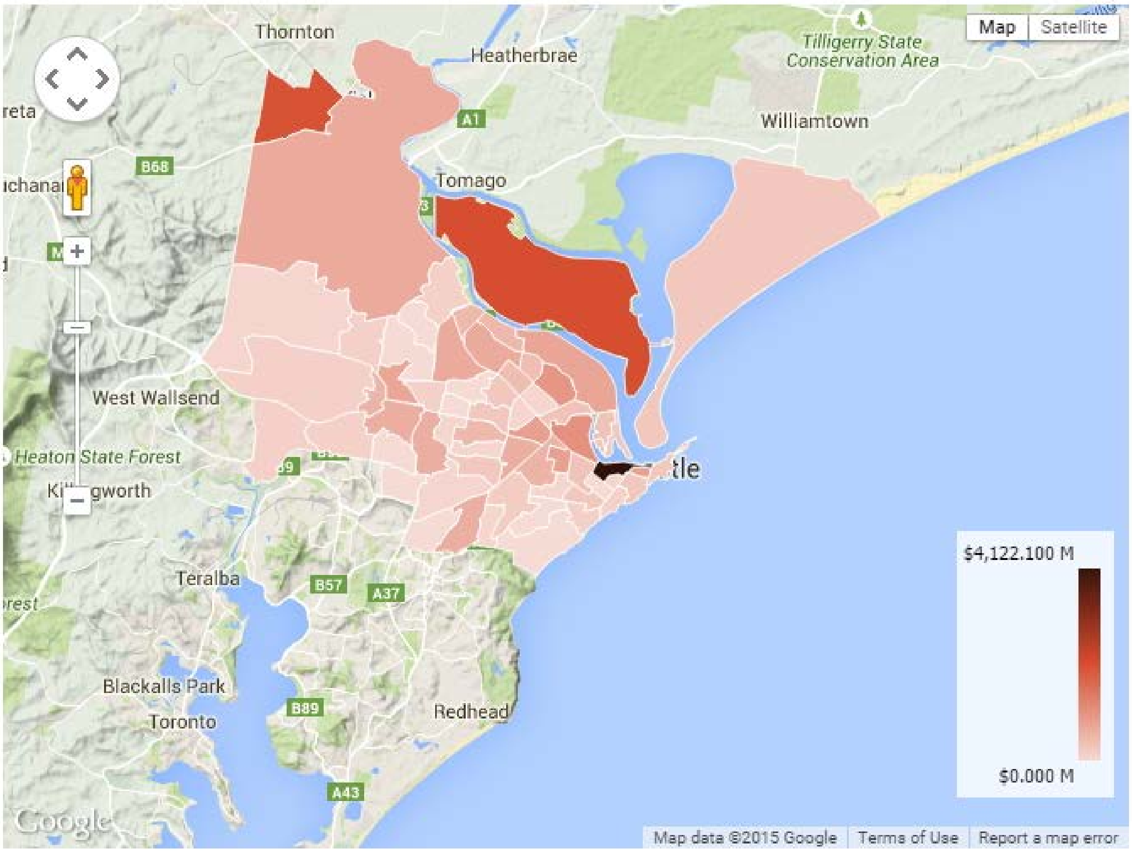

Figure 14: Output by Industry - Location Map (Source Economic Profile, 2014)

The Port of Newcastle

For many years Newcastle has been highly industrialised with key industries surrounding the City's port and river system (Economic Profile, 2014) The Port of Newcastle is the economic trade centre for both the city and the Hunter Valley which is flush with natural resources (Newcastle Port Corporation, 2015). It is the world's largest coal export port and the largest bulk shipping port on Australia's east coast (Port of Newcastle, 2014).

The Port of Newcastle incorporates a high level of infrastructure for Port related industries and services, and has potential for future development due to the direct deep water access (Port of Newcastle, 2014). Features of the Port of Newcastle include:

- Handles more than 25 different cargoes and 4,600 ship movements per annum;
- Total land holdings of 792 hectares;
- 200 hectares of vacant port side land available for development, with significant deep water access;
- Connectivity to national road and rail networks;
- 20 operational berths;
- Cruise Ship Terminal and;
- Main channel depth of 15.2 metres (constantly monitored and maintained) (Port of Newcastle, 2014).

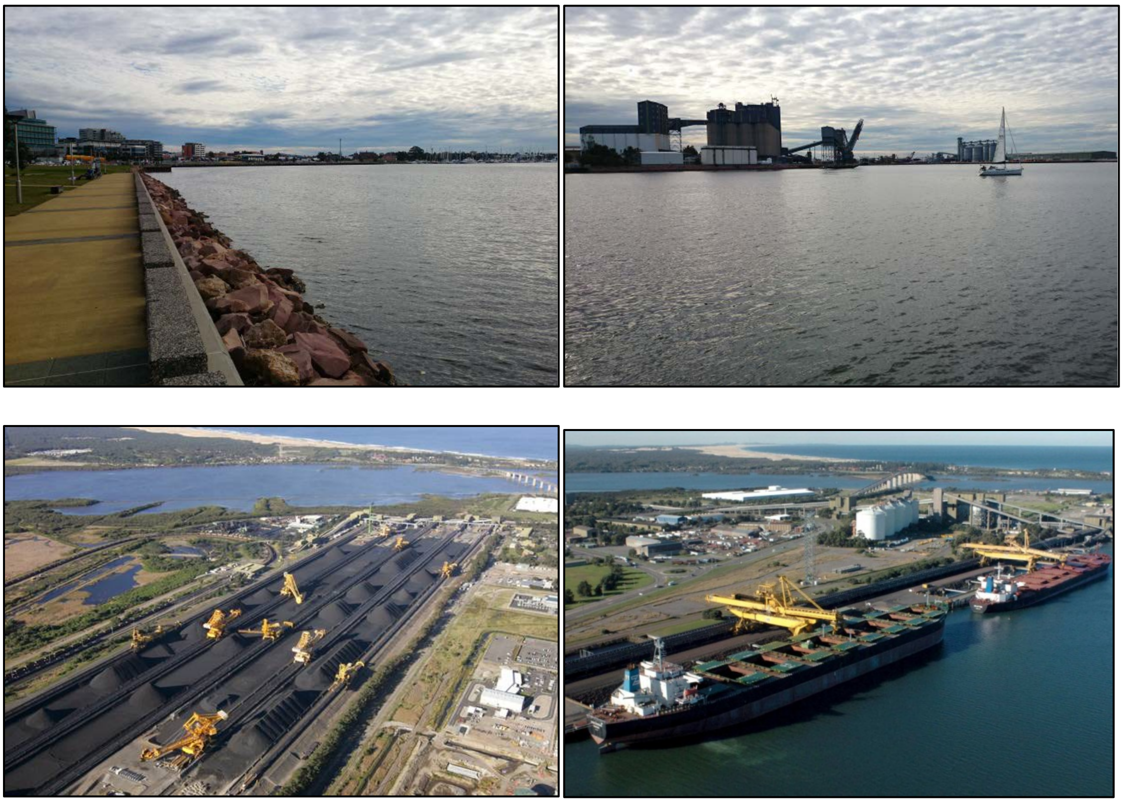

Figure 15: Port of Newcastle (Photos Clockwise Direction 1) Newcastle Harbour - Taken 20/5/15, 2) Newcastle Harbour - Taken 20/5/15, 3) Kooragang Island (Source ABC, 2014), 4) Kooragang Island (Source The Herald, 2012)

Newcastle – Flood Prone?

In locations of high tsunami potential low lying coastal areas are particularly vulnerable to inundation and subsequent damage (GA, 2015). One of the main risk mitigation strategies for tsunamis is to relocate to higher ground (GA, 2015). In the Newcastle LGA 1 in 3 housing lots are potentially subject to flooding in a major storm event (BMT WBM, 2009). In 2009 Newcastle City Council engaged BMT WBM to undertake Stage 1, of a multi stage flood risk management study (Newcastle City Council, 2015). It is Council's plan to use the Stage 1 report for future planning and flood mitigation strategies, but this information can also be adapted to identify key areas potentially susceptible to tsunami inundation (BMT WBM, 2009).

Flood Planning Process	Suburban Flash Flooding			River and Sea	
	THROSBY/STYX COTTAGE CBD	DARK CREEK	WALLSEND	HUNTER RIVER	SEA LEVEL FLOODING
1 DATA COLLECTION **Collect scientific data**	Completed	Completed	Completed	Completed	Completed
2 FLOOD STUDY - **Build computer flood models**	Completed	Completed	Completed	Completed	Completed
3 FLOOD MANAGEMENT STUDY - **Investigate options with Stakeholders (including community)**	Stage 1 (Concept planning) Completed	Stage 1 (Concept planning) Completed	Draft Completed 2007 Stage 1	Stage 1 (Concept planning) Completed	Stage 1 (Concept planning) Completed
	Stage 2 (Testing Options) 2010*	Stage 2 (Testing Options) 2010*	Stage 2 (Remaining Testing Options) 2010*	Stage 2 (Testing Options) 2010*	Stage 2 (Testing Options) 2010*
4 FLOOD MANAGEMENT PLAN - **Works and actions prioritised across LGA.**	2011*	2011*	Wallsend Commercial Centre Plan 2009	2011*	2011*
			Remainder 2011*		

** subject to funding and specialist consultant availability*

Figure 16: Status of Floodplain Management in Newcastle (Source BMT WBM, 2009)

The BMT WBM (2009) report prioritises a number of areas from Newcastle's existing flood plans into different priority categories. "High Priority Flood Risk" have high probability of major structural damage and collapse to buildings and infrastructure (BMT WBM, 2009). "Medium Priority Flood Risk" are the locations likely to experience significant flooding where existing buildings and infrastructure would need modifications to withstand the flood inundation (BMT WBM, 2009). The following six suburbs according to the report are located almost entirely within the high or medium risk zone;

- Hamilton,
- Hamilton North,
- New Lambton,
- Wickham,
- Maryville,
- Hexham (BMT WBM, 2009).

The following fifteen suburbs have large portions located with the high and medium risk flood zones;

- Merewether,
- The Junction,
- Bar Beach,
- Cooks Hill,
- Hamilton South,
- Islington,
- Carrington,
- Kotara,
- Adamstown,
- Georgetown,
- Mayfield,
- Jesmond,
- Birmingham Gardens,
- Wallsend,
- Elermore Vale (BMT WBM, 2009).

Recent flood data confirms the reports outline of flood prone areas (Haines, 2013). In 2007, Newcastle was hit by a succession of low pressure systems which are locally known as the “Pasha Bulker Storm” due to the large coal ship which grounded on Newcastle’s Nobby’s Beach (Haines, 2013). During the weather event, approximately 10,000 to 15,000 properties where inundated within the Newcastle LGA (Haines, 2013). This storm has been approximated over the entire Newcastle LGA to have been a 100 year ARI storm event (Haines, 2013).

The Port of Newcastle is another key area that appears to be susceptible to tsunami inundation. The Port, with its direct ocean connection and flood susceptibility appears to make it a soft target for a potential tsunami event (BMT WBM, 2009). The Port has a variety of surrounding developments ranging from high level industry such as coal and chemical manufacturing plants (Kooragang Island) through to business centres and residential apartments and housing (Economic Profile, 2014). Flood modelling by BMT WBM (2009) for the probable maximum flood, (PMF), shows extensive flooding throughout the Newcastle LGA. The modelled ocean flood level for the PMF is 3.4m AHD which is shown in Appendix B - Probable Maximum Flood – Ocean Flood Depths. This map details the vast extent of the potential flooding issues (BMT WBM, 2009).

Potential Structural Damage

Tsunamis apply a wide range of extreme forces to inundated structures in the form of hydrodynamic pressures, buoyancy and uplift, scour and debris carried by the water striking the structures (Ghobaraha et al, 2005). Studies undertaken on the 2004 Boxing Day Tsunami by Ghobaraha et al, (2005), and 2011 Japanese Tsunami by Suppasri et al, (2013), found relationships between structural damage and construction types, environmental conditions and wave properties. This kind of relationship is critical in planning and future proofing vulnerable areas (Suppasri et al, 2013).

The data collected from the Boxing Day Tsunami research of Ghobaraha et al, (2005), was used to make general damage assessments based on a structures construction material. The following construction material and damage summaries are based on the Sumatra and Banda Aceh regions:

- Residential hosing of mainly timber construction was completely destroyed;
- Non-engineered concrete construction suffered significant damage;
- Engineered reinforced concrete construction although suffering water damage remained generally structurally intact. Areas of impact damage caused by debris were clearly visible (Ghobaraha et al, 2005).

Figure 17: Construction Types (Clockwise) Timber, Non-engineered Concrete, Engineered Reinforced Concrete (Source Ghobaraha et al, 2005).

In the 2011 Japanese Tsunami over 400,000 buildings were damaged (Suppasri et al, 2013). Damage characteristics for over 250,000 buildings were collected as part of a survey (Suppasri et al, 2013). The survey data included damage levels, building location, building size (number of storeys) and the buildings main structural material (Suppasri et al, 2013). The combined results as detailed in Figure 18 shows the inundation depth against damage probability with no other characteristics considered (Suppasri et al, 2013). It is obvious from the figure that small increases in inundation depth result in a large increase in damage probability and severity.

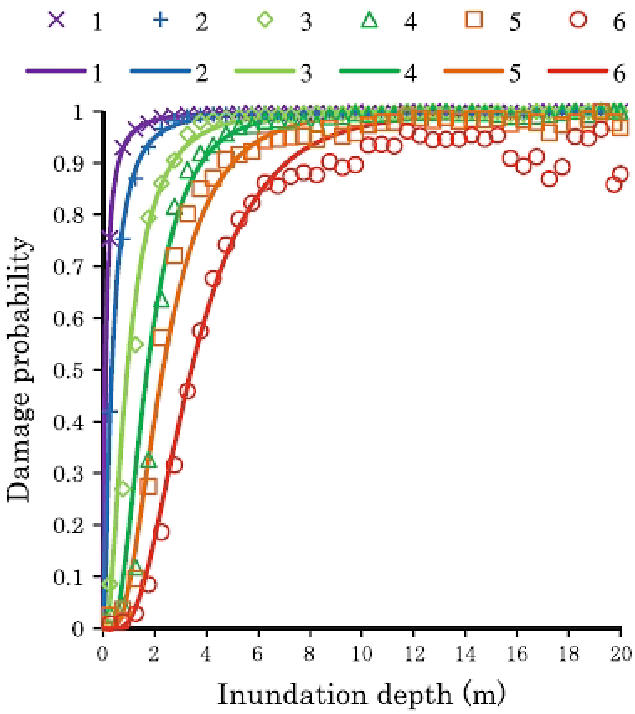

Figure 18: Tsunami fragility curves for the whole area (Chiba to Aomori) with mixed structural material in different damage levels (1 = Minor damage, 2 = Moderate damage, 3 = Major damage, 4 = Complete damage, 5 = Collapse and 6 = Washed away) (Source Suppasri et al, 2013)

Separating the buildings into the four major construction material categories means direct relationships can be formed between damage probability and material type (Suppasri et al, 2013). An inundation depth of 2m was found to be a critical threshold as from this depth all structure types were vulnerable to catastrophic damage (Suppasri et al, 2013). Figure 19 illustrates that wooden structures were the worst performing structure and that reinforced concrete structures were the best performing during tsunami inundation (Suppasri et al, 2013). Even at inundation depths up to 10m more than half of the reinforced concrete structures survived the Japanese Tsunami event. (Suppasri et al, 2013).

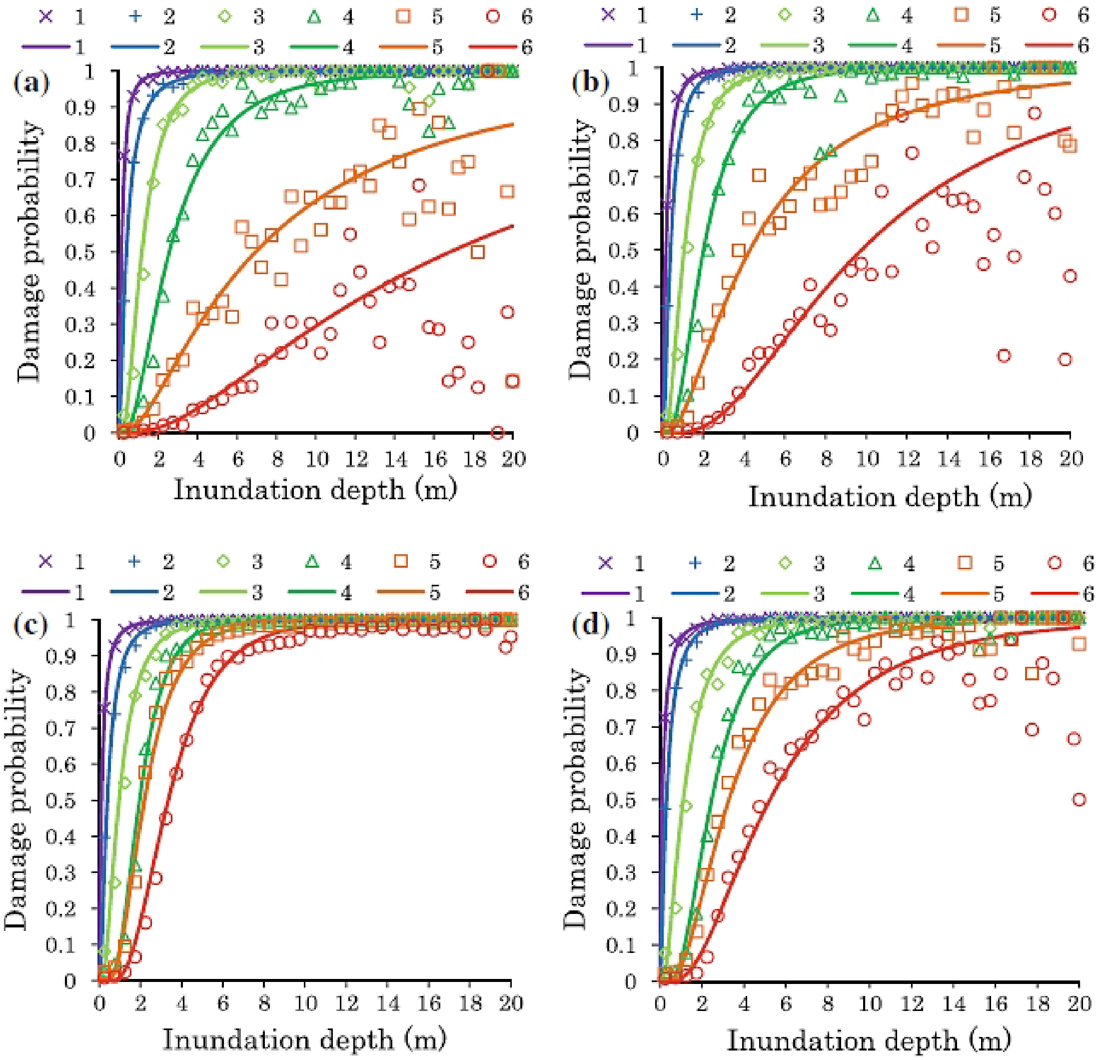

Figure 19: Tsunami fragility curves for the whole area (Chiba to Aomori) with separated structural material (a) RC, (b) Steel,(c) Wood and (d) Masonry (Source Suppasri et al, 2013)

Construction materials were not the only physical building property to affect the damage probability (Suppasri et al, 2013). The buildings height or number of storeys had a major impact on the resulting inundation damage (Suppasri et al, 2013). A minimal difference in the damage to buildings up to two storeys was recorded, however for buildings of three storeys or greater there was a significant reduction in the damage probability (Suppasri et al, 2013). The report recommends from these findings that any buildings that are to be used as future tsunami evacuation centres “should be at least three storeys high” (Suppasri et al, 2013, p.337).

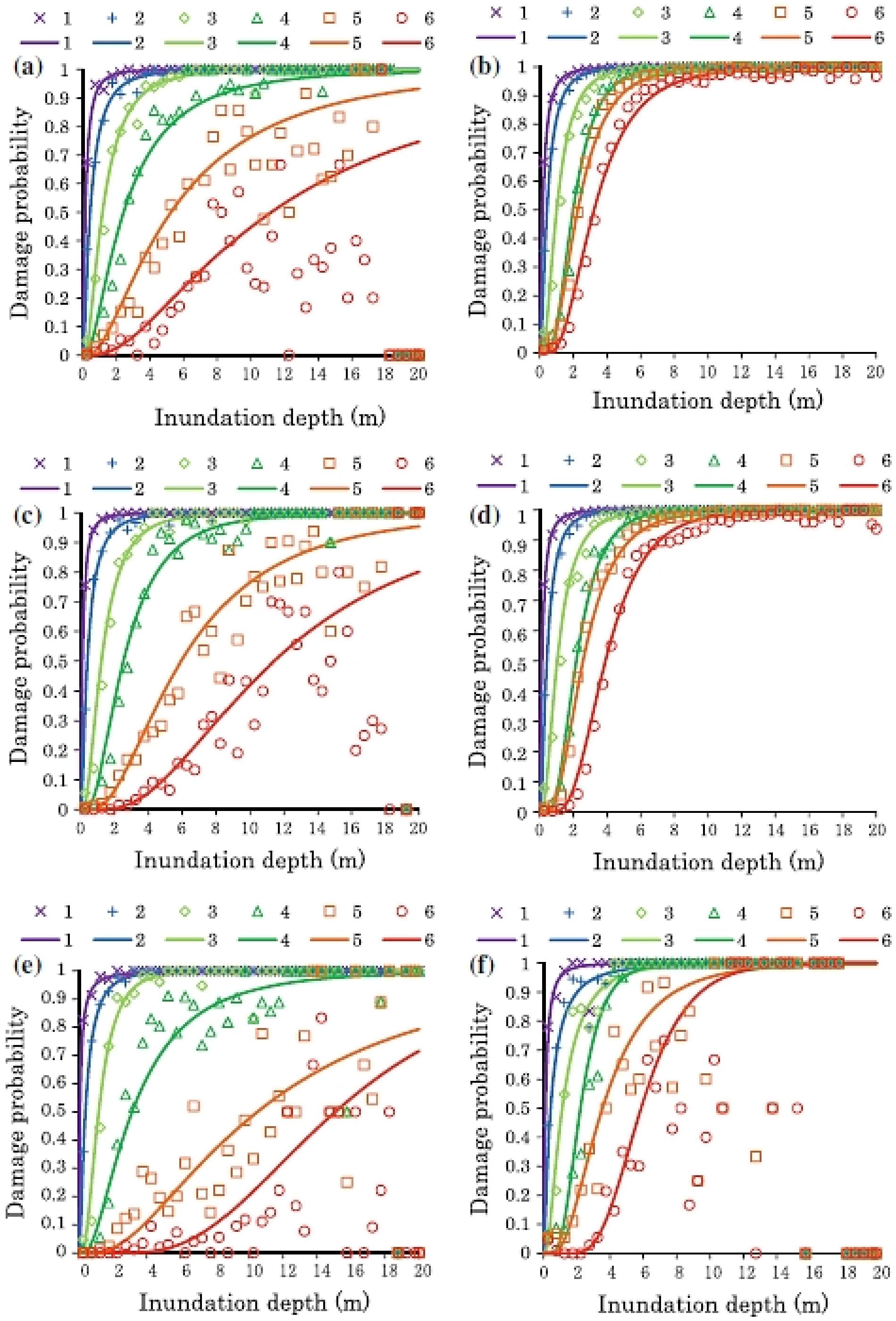

Figure 20: Tsunami fragility curves for the whole area (Chiba to Aomori) with separated structural material and number of stories (a) RC—1 story, (b) Wood—1 story, (c) RC—2 stories, (d), Wood—2 stories, (e) RC—3 stories or more and (f) Wood—3 stories or more

The location of buildings along the Japanese coast was also found to be a factor in their extent of their damage (Suppasri et al, 2013). It was found that variance in site topography and location had a direct impact on the wave velocity during inundation (Suppasri et al, 2013). The study found that locations along the coastline that faced directly to the open ocean had a higher damage probability than the locations that were indirectly connected to the open ocean (Suppasri et al, 2013). The key finding in the damage data collected from these locations was that lower inundation levels caused more damage in direct coastal locations than that in the indirect coastal locations (Suppasri et al, 2013). This was explained by the potentially higher wave and flow velocities experienced by the direct coastal locations (Suppasri et al, 2013).

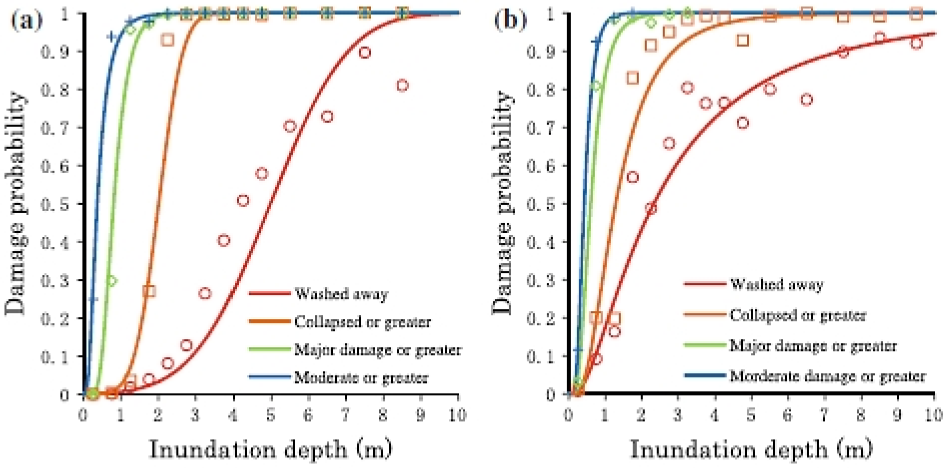

Figure 21: Tsunami fragility curves using data from Ishinomaki City only (mixed materials) for a comparison between (a) Indirect Coastline (b) direct Coastline

The 2009 Newcastle Flood Planning Report (BMT WBM, 2009) defined specific flood risks and hydraulic behaviour thresholds relating to "Risk to Life" and "Risk to Property". The thresholds are used to review flood data and flood modelling and assign risk values to flooded areas (BMT WBM, 2009). During the PMF (Probable Maximum Flood) there are up to 5,000 properties in the Newcastle area that would be impacted (BMT WBM, 2009). The report has modelled the entire flood area and assigned risk threshold values to specific locations (BMT WBM, 2009). There are five specific flood hydraulic behaviour thresholds as detailed in Figure 22 (BMT WBM, 2009).

Table 5-1 Flood Hydraulic Behaviour Thresholds

H1	v < 0.5m/s & d < 0.3m	Hydraulically suitable for parked or moving cars.
H2	v < 2m/s, d < 0.8m & v < 3.2-4*d	Hydraulically suitable for parked or moving heavy vehicles only, and for wading by able-bodied adults
H3	v < 2m/s, d < 2m, v*d < 1	Hydraulically suitable for light construction (eg timber frame and brick veneer), but not for vehicles or for wading.
H4	v < 2.5m/s, d < 2.5m, v*d < 2.5	Hydraulically suitable for heavy construction (eg steel frame and reinforced concrete) only.
H5	remainder	Generally unsuitable for any construction type.

Figure 22: Flood Hydraulic Behaviour Thresholds (Source, BMT WBM, 2009)

The thresholds are based on the key value of flow velocity multiplied by depth (VxD) (BMT WBM, 2009). This value is used in drainage design to analyse flows through open drains and swales and determine their safety and potential erosion issues (NCC, 2013). Many local Councils set maximum values for VxD as part of their engineering design requirements. Newcastle City Council has a maximum allowable VxD value for its open drains and storm water overflow routes of $0.36m^2/s$ (NCC, 2013). The threshold value for flood VxD at which all structures become significantly vulnerable to catastrophic damage is $2.5m^2/s$ (BMT WBM, 2009). This is greater than stated development design flows.

Software Options – Tsunami Inundation Model

Option 1 – ANUGA

ANUGA is a hydrodynamic modelling program that was first developed by the Australian National University in the nineties and in more recent times Geoscience Australia (GA) (Van Drie, Simon, & Schymitzek, 2008). The program, which is available for free, is under constant refinement and development to further improve its modelling capabilities (ANUGA, 2015).

> "GA identified that there where gaps in capacity to model the impact of tsunami striking the coast, even though there were models available to propagate the wave across the Ocean. ANUGA was specifically written to fill that gap in capacity" (Van Drie, Simon, & Schymitzek, 2008, p.2).

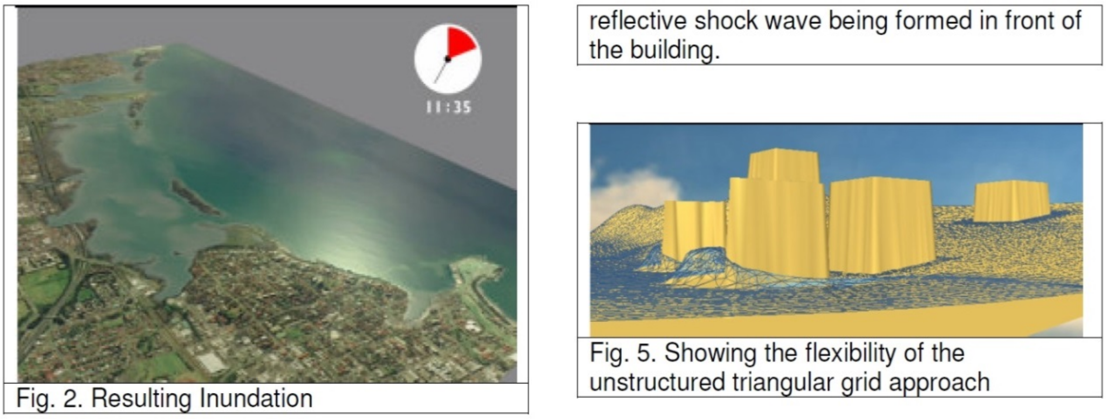

Figure 23: ANUGA Modelling Examples (Source Van Drie et al. 2008)

ANUGA solves the shallow water wave equation using a finite volume method (ANUGA, 2015). This method is applied across a detailed 3D surface/mesh of the proposed subject area which makes it easy to calculate both depth and momentum of the water inundation or flow at any and all locations over time within the 3D model (ANUGA, 2015). The complex modelling system of ANUGA allows for the model to easily cope with flow transition between wet (rivers and coastlines) and dry land (ANUGA, 2015). It also has the capability to simulate flow around structures such as buildings, roadways, bridges etc. (ANUGA, 2015). The main limiting factor in the quality of the results produced by the ANUGA model is the level of input data available, this includes topographic and bathymetric data, tsunami and surge data, and existing conditions data such as tidal information (ANUGA, 2015).

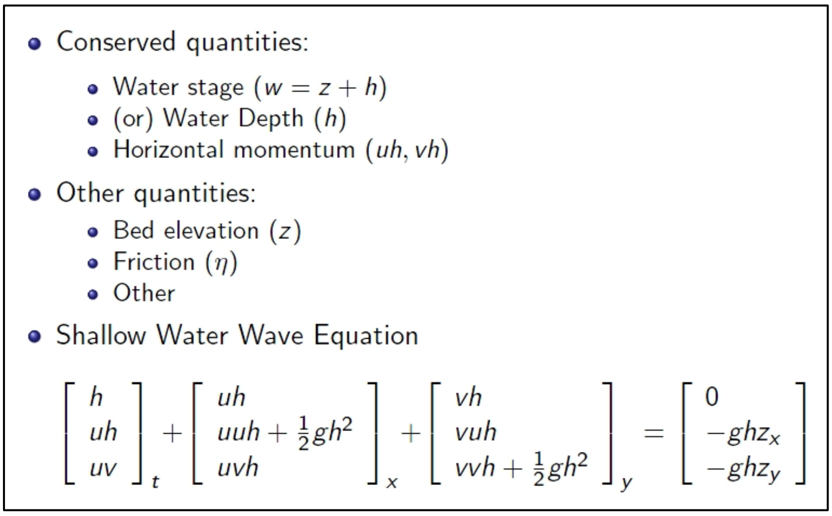

Figure 24: ANUGA algorithm (Roberts, 2008)

ANUGA has the capability to be used for a number of water modelling projects such as:

- Tsunami surge and inundation,
- Storm surges,
- Urban and rural flood modelling,
- Dam breaks
- Bridge hydraulics (Van Drie et al, 2008) and,
- Validations for many of these are provided with the program download (ANUGA 2015).

The ANUGA user manual (2015) lists restrictions and limitations of the program.

- "The mathematical model is the 2D shallow water wave equation. As such it cannot resolve vertical convection and consequently not breaking waves or 3D turbulence (e.g. vorticity).
- All spatial coordinates are assumed to be UTM (meters). As such, ANUGA is unsuitable for modelling flows in areas larger than one UTM zone (6 degrees wide), though we have run over 2 zones by projecting onto one zone and living with the distortion.
- Fluid is assumed to be inviscid – i.e. no kinematic viscosity included.
- The finite volume is a very robust and flexible numerical technique, but it is not the fastest method around. If the geometry is sufficiently simple and if there is no need for wetting or drying, a finite-difference method may be able to solve the problem faster than ANUGA.

- Frictional resistance is implemented using Manning's formula." (ANUGA User Manual, 2015, p.2)

These limitations don't negatively impact the modelling undertaken within this report.

Option 2 - RiCOM (River and Coastal Ocean Model).

RiCOM is an alternate modelling option for tsunami propagation and inundation. RiCOM uses a finite element approximation in space with an unstructured grid and is capable of calculations in two or three dimensions (Cascadia Coast Research Ltd, 2013). It has been extensively used for tsunami modelling and has also been verified through modelling of historic Tsunamis (Lane, Gillibrand, Arnold & Walters, 2011). RiCOM is also heavily reliant on available topographic and bathymetric data (Cascadia Coast Research Ltd, 2013). A perceived advantage of RiCOM to traditional inundation modelling software is the use of a continuous model for both propagation and inundation which is claimed to provide smoother transitions within the model (Cascadia Coast Research Ltd, 2013).

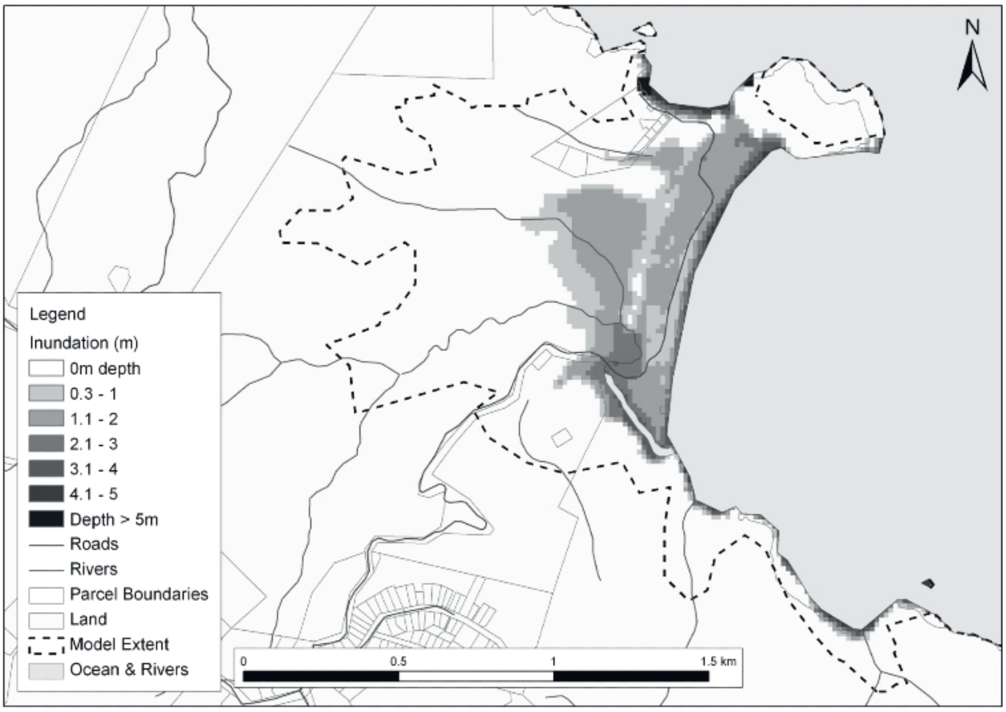

Figure 25: Example RiCOM Inundation Model - New Zealand (Source Lane et al. 2011)

Conclusion

The literature review determined that the East Coast of Australia is at significant risk of a tsunami resulting from a subduction zone earthquake event (Xing et al. 2014). The earthquake is the most common cause of tsunamis and Australia has a number of high risk earthquake locations off the east coast (GA, 2007). The Puysegur Trench is located of the south coast of New Zealand and due to its high earthquake history and uninterrupted deep water connection to the Australian Coastline was found to be the most likely source for such an event (Xing et al. 2014). The deep water wave model developed by Xing et al. (2014) from the Puysegur Trench was adopted as the basis for the tsunami modelling.

The Australian Tsunami Monitoring & Warning System has a number of detection buoys located between Australia and the Puysegur Trench meaning that the current system will provide a warning from any events within the trench. The current warning requirements are 90 minutes between receipt of the warning and potential impact.

Large sections of the Newcastle LGA were found to be vulnerable to tsunami inundation. Newcastle has significant flooding issues and is also susceptible to ocean level serge as shown by the PMF modelling (BMT WBM, 2009). The review found there is significant risk of structural damage resulting from a major tsunami event. The findings from the literature review of previous tsunami and flood damage studies varied with different threshold values being provided for when all types of building construction are at risk. The values used for the modelling and infrastructure review are:

- An inundation depth of 2m (Suppasri et al, 2013).
- A flow velocity of 2.5m/s (BMT WBM, 2009)
- A VxD of 2.5m^2/s (BMT WBM, 2009)

ANUGA was selected as the modelling software for the Newcastle tsunami inundation model. The program is well supported by Geoscience Australia with detailed user manuals and many additional resources available. It is also free which provided further incentive for its use.

3. Methodology

Key Project Tasks

- **Background Research and literature review**

Background research was broken into a number of key areas.

Environmental Conditions - Tsunamis are caused by a number of specific environmental conditions. Detailed research into these environmental conditions was undertaken to identify patterns in tsunami creation such a major causes, inhibiting factors, tsunami hotspots, etc. A review into the current environmental conditions specific to the Newcastle coastline was undertaken for the purpose of determining its potential risk of tsunami strike.

Physical Tsunami Properties - Is Newcastle located within a high tsunami risk area? What are the physical properties of the potential tsunami? Research into the potential risk, size, speed (timing from tsunami creation to inundation), number of potential waves, etc, was undertaken. This information is critical in the proposed inundation modelling.

Impact of inundation on affected infrastructure - On completion of the inundation modelling a list of affected infrastructure was compiled. Further research was undertaken to confirm this list and to determine the impact of salt water inundation. The research determined how long infrastructure that sustains little damage in the initial tsunami impact takes to be operational again once inundation levels recede.

Physical impact of a tsunami on affected infrastructure - On completion of the inundation modelling a list of affected infrastructure was compiled. Further research was undertaken into the potential impact of the initial tsunami strike on the inundated infrastructure, such as roadways, bridges, rail lines, buildings, emergency services, the electrical network, water and sewer supply, and other key infrastructure.

- **Tsunami Inundation Modelling**

The detailed tsunami inundation modelling was undertaken using the Geoscience Australia backed program ANUGA. ANUGA is a hydrodynamic modelling program that was first developed by the Australian National University in the nineties currently by Geoscience Australia (Van Drie, Simon, & Schymitzek, 2008). ANUGA and its components are run using the programing platform Python (ANUGA 2015)..

The first step in the modelling process was to create a 3D terrain model for the Newcastle LGA. The data required for the 3D terrain model was collected from a number of sources then converted and combined into a singular 3D terrain model using the civil design software 12d. This software is able to smoothly combine data from different sources into 3D terrain models. The data acquired for the 3D terrain model included;

- Full LIDAR topographic survey for the extent of the Newcastle LGA. The data provided contained aerial survey of the entire land base within the Newcastle LGA with a grid spacing of 1m. This was provided by Newcastle City Council for the purpose of the research.

- Bathymetric survey data for the Port of Newcastle and Hunter River. The data contained a previous survey of the Newcastle Port and Hunter River system that was undertaken by the Newcastle Port Corporation in 2011. It contained a 2.5m survey grid. It was provided by the Port Authority of New South Wales for the purpose of the research.

- Bathymetric survey data for a large section of the ocean bed adjacent to the Newcastle coastline. This was extracted from available survey data on the Geoscience Australia website.

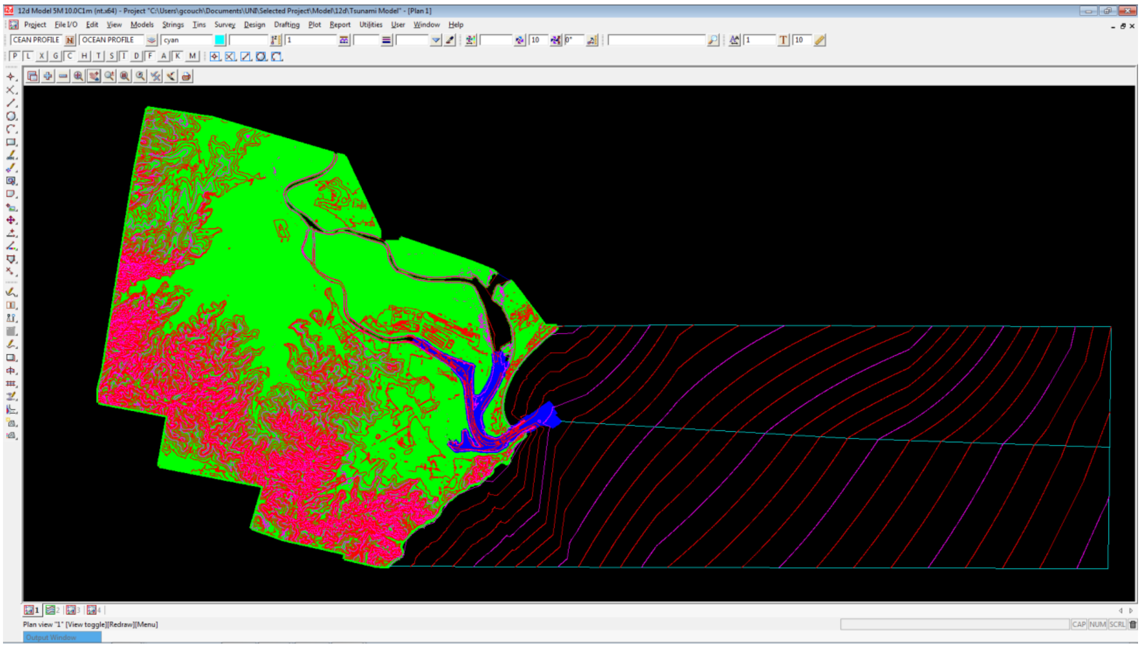

Figure 26: 3D Terrain Model - 12d

ANUGA Modelling Code

A detailed program script was created for the ANUGA inundation modelling. The ANUGA software operates using the programing tool Python as a platform to run and create modelling scripts. All of the models inputs, critical values and calculations are combined and initiated using the project specific Python script. The script created and used for the Newcastle tsunami modelling is contained below. It has been divided into its key sections with outlines on the operational objectives of each.

Initial setup within the script file involves importing the required project models and initialising the ANUGA software. This is an example of the Python platform linking the models and software components to run from a single script file. Figure 27 details the initial setup component of the tsunami modelling script.

```
"""Tsunami inundation script for Newcastle LGA coastline, NSW Australia.
Script compiled using example data provided with the ANUGA program files and
the ANUGA User Manual. Script is to produce an inundation model of the
Newcastle Local Government Area which will be adapted to undertake a key
infrastructure review relating to tsunami damage. Refer to project report for
further details.
"""

#------------------------------------------------------------------------------
# Import Required Project Modules
#------------------------------------------------------------------------------
# Operating System Model
import os

# Time Model
import time

# System - specific parameters and functions Model
import sys

# Import Anuga - Modeling Software
import anuga
```

Figure 27: Tsunami Modelling Script – Part 1

Following the initial project setup the script moves into setting a number of model base values. This includes the file name profile, the modelling boundary, mesh resolution, and the export for the resultant data grid. Setting the file name profile using the “name_stem” command allowed for a standard naming approach to be followed throughout the script. With this a direct script reference was carried throughout the model meaning any future adjustment to the naming convention can be implemented by adjusting this single name. The naming profile set also controls the naming convention of the modelling 3D mesh file and the result output files.

The extent of modelling is specified in this section of code (refer Figure 28). This is done by referencing a .csv file which contains model boundary coordinates. No surface triangulation will be undertaken outside of the specified boundary. The desired modelling resolution is set and applied at this point for the area within the modelling boundary. Internal boundaries for areas requiring further detailed modelling would be specified in this part of the script file if required. As the proposed modelling was investigating the entire Newcastle LGA a global resolution was applied and no increased detail for internal polygons was specified.

The project asci grid specified for export is a simple rectangular area that covers the full extent of modelling. This rectangular boundary is used to define the extremities of the modelling area where results are to be extracted.

```
#------------------------------------------------------------------------------
# The following code sets files names, domain definitions, project polygons
# and export extent.
#------------------------------------------------------------------------------

# Runtime parameters

cache = False
verbose = True

# Set Project Filenames

name_stem = 'newcastle'
meshname = name_stem + '.msh'

#  Filename for locations where timeseries are to be produced

gauge_filename = 'newcastle_gauges.csv'

#------------------------------------------------------------------------------
# Define extent of project modeling boundary and simulation resolution.
#------------------------------------------------------------------------------
#  bounding polygon for study area
bounding_polygon =  anuga.read_polygon('newcastle_extent.csv')

A =  anuga.polygon_area(bounding_polygon) / 1000000.0
print  'Area of bounding polygon  =  %.2f km^2' %   A

# No Interior regions setup. No interior polygons required.
# Define resolution. Only 1 area so only 1 resolution requied.
default_res = 10000

#------------------------------------------------------------------------------
# Define extent of project asci grid - for export
#------------------------------------------------------------------------------
eastingmin = 368000
eastingmax = 390000
northingmin = 6350990
northingmax = 6372160

#------------------------------------------------------------------------------
# Setting on time measurement method, time() sets
#------------------------------------------------------------------------------
time00 = time.time()
```

Figure 28: Tsunami Modelling Script – Part 2

The next section of the project script finalises the setup preparation for the tsunami model (refer Figure 29). Here each section of the boundary polygon is tagged with a number. The boundary tagging is undertaken to allow for specific boundary conditions to be applied along each section of the polygon as required. Using the Newcastle model as an example the boundaries to the north and south of the extent polygon require the model to calculate the potential wave inundation as flowing straight through with no restriction. This is because the extent polygon for the project is a theoretical boundary and not a physical barrier that will impact a tsunami event and needs to be modelled accordingly.

A number of key modelling and calculation limits and settings are specified within this section of script. These include:

- The reference / importation of the 3D elevation file for the modelling area;

The 3D elevation file is a simple text file containing easting, northing and elevation data for points spread throughout the entire modelling area. A reference to the elevation file is made allowing for alterations to the file without requiring adjustments to the modelling script.

- Minimum water depths constituting inundation (the inundation extent);

The minimum water depth applied for the modelling calculations is 1cm. Inundation below this minimum value is not recorded as part of the results.

- The tsunami flow algorithm (as specified by the ANUGA user manual);

ANUGA contains a number of specific flow algorithms which are to be used for different types of hydraulic modelling. The algorithm DE1 was specifically developed by the ANUGA programmers for tsunami modelling.

- The initial water / flood level;

An ocean flood level of 3.4m was applied as a base level prior to the tsunami impact. This setup models as worst case scenario for the Newcastle LGA where the tsunami event coincides with the ocean PMF event. To test the impact of the coinciding events an identical tsunami model was run with an average high tide level of 1m AHD. This allowed for a direct comparison of the tsunami inundation results. Refer to Results for details.

- Applied friction value;

ANUGA uses Manning's friction values in its hydraulic modelling. Due to the size and varying land types within the Newcastle LGA a nominal friction value of zero was applied to the tsunami model. This provided conservative inundation results and removes the requirement for a detailed friction analysis which is seen to be outside of the scope of the project.

- Result output names;

This allows for the resulting model files to follow a naming convention. This allows for the results files to be found and separated from the raft of files used for the modelling.

```
#--------------------------------------------------------------------------------
# Setup 3d surface mesh and domain details using extent polygon. Boundary tags
# set on extent poly for future boundary condition specification.
#--------------------------------------------------------------------------------
domain = anuga.create_domain_from_regions(bounding_polygon,
                                    boundary_tags={'north_one': [0],
                                                   'north_two': [1],
                                                   'north_three': [2],
                                                   'north_four': [3],
                                                   'north_five': [4],
                                                   'east_one': [5],
                                                   'south_one': [6],
                                                   'south_two': [7],
                                                   'south_three': [8],
                                                   'south_four': [9],
                                                   'south_five': [10],
                                                   'south_six': [11],
                                                   'west_one': [12]},
                                    maximum_triangle_area=default_res,
                                    mesh_filename=meshname,
# interior_regions=interior_regions,
                                    use_cache=cache,
                                    verbose=verbose)

# Print detials reltating to mesh and domain
print 'Number of triangles = ', len(domain)
print 'The extent is ', domain.get_extent()
print domain.statistics()

#--------------------------------------------------------------------------------
# Setup initial parameters of computational model
#--------------------------------------------------------------------------------
domain.set_name('newcastle') # Name of sww file
domain.set_datadir('.')                    # Store sww output here
domain.set_minimum_storable_height(0.01)   # Store only depth > 1cm
domain.set_flow_algorithm('DE1')           # Refer to report for details


#--------------------------------------------------------------------------------
# Setup initial conditions for tsunami impact
#--------------------------------------------------------------------------------

#Tide RL based of BMT WBM flood report for PMF ocean flood event.|
#Refer to project report for detials

tide = 3.4
domain.set_quantity('stage', tide)

# For details on friction value refer to project report,

domain.set_quantity('friction', 0.0)


domain.set_quantity('elevation',
                    filename=name_stem + '.txt',
                    use_cache=cache,
                    verbose=verbose,
                    alpha=0.1)


time01 = time.time()
print 'That took %.2f seconds to fit data' %(time01-time00)
```

Figure 29: Tsunami Modelling Script – Part 3

With the initial environmental and mathematical conditions set the script now applies tsunami wave data to the model and undertakes the inundation modelling. The wave data for this project model is referenced into the script using a simple .csv spreadsheet containing the tsunami profile. The spreadsheet contains the full profile on the tsunami event including multiple wave crests and sumps and the related time scale. The tsunami wave data is based on the previous research undertaken by Xing et al. 2014. Refer to the Literature Review for further details.

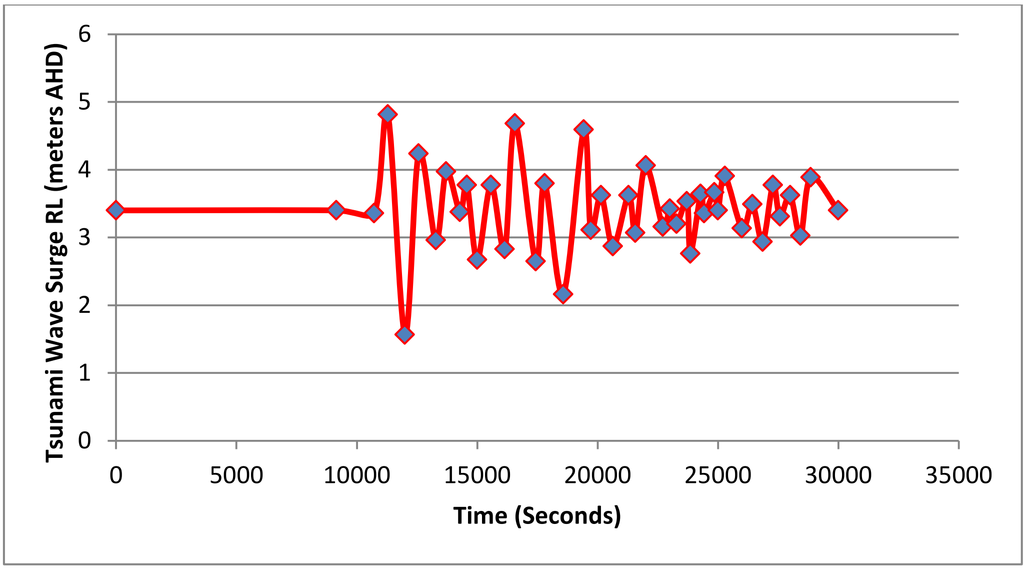

Figure 30: Tsunami Wave Profile - Based on Modelling Import Data

```
#-------------------------------------------------------------------------------
# Setup for time-varying wave simulation - Tsunami!!
#-------------------------------------------------------------------------------
print 'Available boundary tags', domain.get_boundary_tags()

Bd = anuga.Dirichlet_boundary([tide, 0, 0]) # Mean water level
Bs = anuga.Transmissive_stage_zero_momentum_boundary(domain) # Neutral boundary

#------------------------------------

# Here we read a timeseries, and then pass
# that function as a set stage transmissive boundary

#import scipy
from scipy import interpolate,genfromtxt
import anuga.shallow_water.boundaries as asb

# The wave data file also known as the boundary_data_file should be a csv with
# 2 columns: time in seconds, stage in m.In this model the data file has a
# single header row which is skipped (see 'skip_header' below). |
boundary_data_file = 'wave_time.csv'


# Read data
boundary_data = genfromtxt(
    boundary_data_file,
    delimiter=',',
    skip_header=1)

# Make interpolation function
#stage_time_fun = scipy.interpolate.interp1d(

stage_time_fun = interpolate.interp1d(
    boundary_data[:, 0],
    boundary_data[:, 1])

# Make boundary condition
Bw = asb.Transmissive_n_momentum_zero_t_momentum_set_stage_boundary(domain, stage_time_fun)

#------------------------------------

domain.set_boundary({'north_one': Bs,
                     'north_two': Bs,
                     'north_three': Bs,
                     'north_four': Bs,
                     'north_five': Bs,
                     'east_one': Bw,
                     'south_one': Bs,
                     'south_two': Bs,
                     'south_three': Bs,
                     'south_four': Bs,
                     'south_five': Bs,
                     'south_six': Bs,
                     'west_one': Bd})
```

Figure 31: Tsunami Modelling Script – Part 4

The final section of modelling script specifies the detail and timing of the model calculations. The Model for this project was set to record results every two minutes prior to the tsunami event and then every thirty seconds following the initial tsunami strike. The level of detail can be easily increased by reducing the time increments, however this increases the modelling calculation time and produces extremely large result files. The level of timing chosen provides more than sufficient details for this project.

```
#------------------------------------------------------------------------------
# Development of model and calculation time specs.
#------------------------------------------------------------------------------
import time
t0 = time.time()

from numpy import allclose

    # Save every two mins leading up to wave approaching land
for t in domain.evolve(yieldstep=2*60, finaltime=9000):
    print domain.timestepping_statistics()
    print domain.boundary_statistics(tags='east_one')

    # Save every 30 secs as wave starts inundating ashore
for t in domain.evolve(yieldstep=60*0.5, finaltime=30000,
                       skip_initial_step=True):
    print domain.timestepping_statistics()
    print domain.boundary_statistics(tags='east_one')

print 'That took %.2f seconds' %(time.time()-t0)
```

Figure 32: Tsunami Modelling Script – Part 5

Tsunami Inundation Results & Mapping Extraction

A single results file was produced by the modelling script. The following data was extracted from the results file (refer to Results for full details);

- Inundation extent,
- Inundation depths,
- Flow velocity within inundation area;

The following script file is used to extract individual results from the ANUGA produced results file. A single script was setup for each of the result variables being extracted. The results were extracted into an asci file format containing an easting, northing and result value. These files were easily manipulated and used for results mapping.

```
import os
import sys
import anuga

name = 'newcastle'

print 'output dir:', name
which_var = 2

if which_var == 0:    # Stage
    outname = name + '_stage'
    quantityname = 'stage'

if which_var == 1:    # Absolute Momentum
    outname = name + '_momentum'
    quantityname = '(xmomentum**2 + ymomentum**2)**0.5'    #Absolute momentum

if which_var == 2:    # Depth
    outname = name + '_depth'
    quantityname = 'stage-elevation'  #Depth

if which_var == 3:    # Speed
    outname = name + '_speed'
    quantityname = '(xmomentum**2 + ymomentum**2)**0.5/(stage-elevation+1.e-3)'  #Speed

if which_var == 4:    # Elevation
    outname = name + '_elevation'
    quantityname = 'elevation'  #Elevation

print 'start sww2dem'

anuga.sww2dem(name+'.sww',
        outname+'.asc',
        quantity=quantityname,
        cellsize=10,
        #easting_min=eastingmin,
        #easting_max=eastingmax,
        #northing_min=northingmin,
        #northing_max=northingmax,
        reduction=max,
        verbose=False)
```

Figure 33: Results extraction script file – Inundation Depth

The main results file can also be run as an annotation using the ANUGA Viewer. This allows for visual simulation of the tsunami inundation. The below screen shot shows the approaching tsunami crest wave towards the Newcastle coastline.

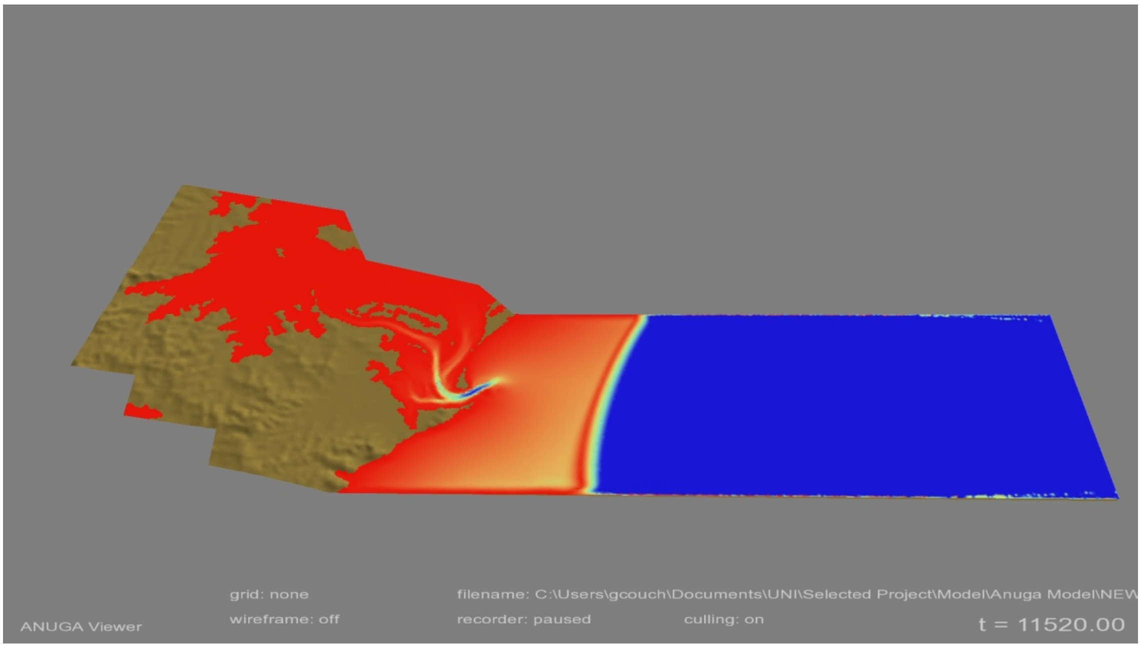

Figure 34: Screen shot from ANUGA Viewer results similuation

Infrastructure Research/Location Review

Detailed lists and locations of key infrastructure within and adjacent to the inundation zone were created. These lists form the extent of the infrastructure review. The infrastructure included in the preliminary lists which were used to undertake the detailed damage review includes:

- Major roadways including the Pacific Hwy, the New England Hwy and a number of bridges,
- Rail network and associated infrastructure such as lines and bridges
- Major electrical infrastructure including substations, and high electricity dependant consumers,
- Major water reticulation and sewer supply systems,
- Structures within the inundation zone;
- Communication networks and systems.

Refer to Results for mapping and further details on affected infrastructure.

Inundated Infrastructure damage review and assessment

A detailed review of the potential impact and damage was undertaken on the infrastructure within and directly adjacent to the inundation zone. This review was based on;

- Historical damage data from previous tsunami events. Refer to Historical Perspective – Key Infrastructure Damaged by Tsunamis for details,
- Historical flood damage data. Refer to Literature Review for details,
- Inundation Results and extent. Refer to Results for details,

A comparison of the potential damage was also made between design tsunami event coinciding with the ocean PMF and the same tsunami event coinciding with an average high tide. This is to provide a balanced perspective to the levels of potential infrastructure damage and impact of the tsunami event.

4. Results – Tsunami Inundation

Tsunami Results & Data (PMF)

Tsunami Strike and Run-up

The tsunami event simulated was directly based on the Puysegur Trench subduction zone research by Xing et al. 2014 which modelled the potential deep ocean wave caused by an earthquake event in the Trench (refer to the Literature Review for further details). The deep ocean was applied to the eastern boundary of the model at a location which coincides with the commencement of the tsunami deep ocean wave shoaling and peaking (ocean depth < 100m).

The first impact of the approaching wave occurs approximately 175 minutes after the initial earthquake. Figure 35 shows the commencement of the water recession/runout which can be identified by the slight adjustment in depth shading at the mouth of the Port of Newcastle. The water runout continues rapidly for more than 20 minutes before the first wave peak hits the coastline.

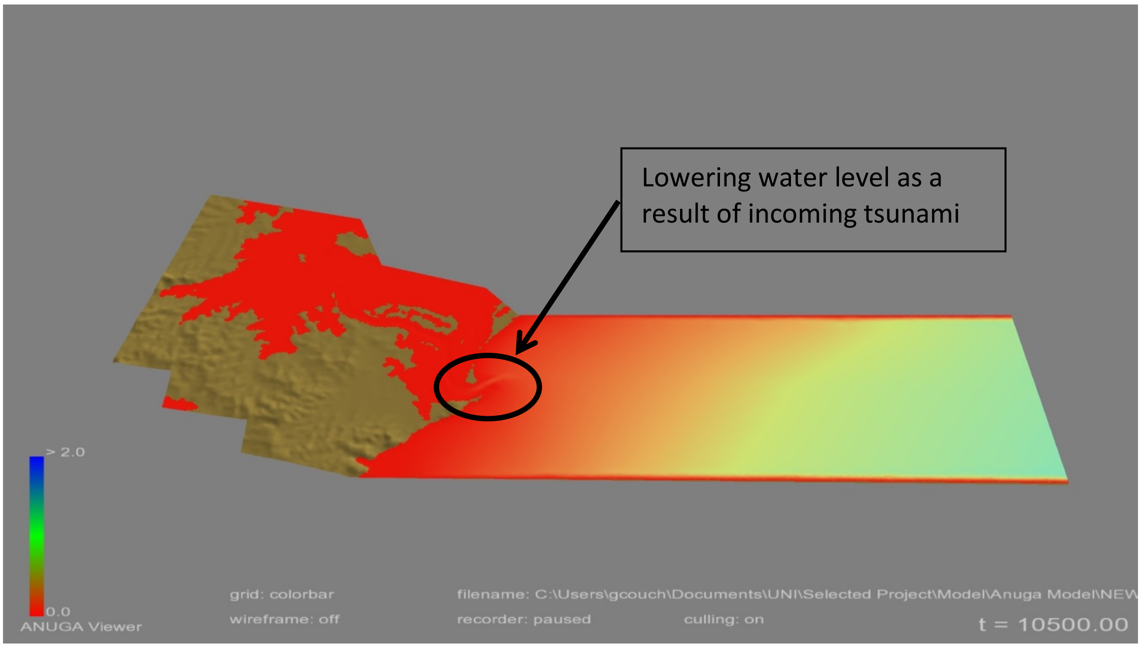

Figure 35: Initial water runout - 175 minutes – (PMF)

The first wave hits the Newcastle coastline 197 minutes after the earthquake. The average crest height of the wave is around 9.5-10.5m AHD. This is reflected along most of the Newcastle LGA coastline. At the southern end of the Newcastle LGA there is an isolated section of coastline where the wave crest rises to over 13m. With the PMF ocean level being 3.4m AHD the average wave crest is over 7m in height when it reaches the coastline. When the crest heights are compared to the 1.41m wave height while traveling across the Tasman Sea as a deep ocean wave the shoaling effect on the wave as it approaches the coastline is evident.

The initial wave is followed by twenty additional wave peaks over a five hour period. Only two of these wave peaks are comparable in size to the initial wave peak and these are highlighted in Table 1.

TIME (S)	WAVE HEIGHT (m)	WAVE No.
11286	1.41	1
12571	0.84	2
13714	0.57	3
14571	0.38	4
15571	0.38	5
16571	1.28	6
17800	0.40	7
19429	1.19	8
20143	0.22	9
21286	0.22	10
22000	0.66	11
23000	0.02	12
23714	0.13	13
24286	0.24	14
24857	0.26	15
25000	0.00	16
25286	0.51	17
26429	0.09	18
27286	0.38	19
28000	0.22	20
28857	0.49	21

Table 1: Tsunami wave peaks - Ocean wave heights

The tsunami run-up height is the maximum elevation at which inundation took place. The maximum run-up height of the Newcastle tsunami event was over 60m. This occurred immediately adjacent to the coastline near Strezelecki Lookout in the Newcastle suburb of The Hill. The topography is such that progression of the wave inland was violently stopped forcing a high localised run-up height. This was a common occurrence along the Newcastle LGA coastline, particularly to the south of the entrance to the port. The steep cliffs along this section of coastline provide some protection from the tsunami but results in exaggerated run-up heights that didn't necessarily translate into significant inundation or damage.

The run-up heights in the lower lying areas surrounding the port and Hunter River system are far more critical in relation to inundation and damage predictions. The run-up heights within the CBD area were as high as 33m but are on average between 5-7m. There are also pockets where the run-up heights rise to over 10m due to the topography in the city suburbs of Hamilton, Mayfield, Carrington, Wickham, Cooks Hill and Merewether. With the PMF level being 3.4m these run-up heights result significant levels of additional inundation.

The large flood plain which borders the suburbs of Sandgate, Warabrook, Jesmond, Birmingham Gardens, Maryland, Fletcher, Hexham, Tomago and Beresfield is also significantly impacted by the tsunami run-up. Around the flood plain run-up heights of over 15m AHD are common with most locations only reaching a maximum of 10m AHD. This run-up height places all infrastructure located at the boundaries of these suburbs and the flood plain at risk.

Tsunami Inundation Area

The Newcastle LGA has an overall area of approximately 187km^2. The tsunami modelling results suggest that up to 115km^2 or 60% will be inundated as a result of the event. Not all of the inundation area contains major infrastructure with over 55km^2 forming part of either existing national parks or swamp areas. Refer to Inundation Map 1 in Appendix C for details of the full extent of the tsunami inundation.

Tsunami Inundation Depth Modelling

The depth of inundation was found to be directly related to the extent and type of damage caused by either tsunami or flood inundation. The research found that in historical tsunami and flood events water depth of 2m was the critical point at which all structure types became venerable to catastrophic damage (Suppasri et al, 2013). Map 2 in Appendix C details the water depth across the entire inundation zone. From this map it can be seen that of the 115km^2 inundation zone approximately 103km^2 is impacted by water inundation of greater than or equal to 2m. Negating the National Park and swamp areas this leaves an area of over 50km^2 where all structures are vulnerable to catastrophic damage.

Maximum Inundation Depth (m) Excluding River System	Location:
4.8m	Maryville

Table 2: Maximum Inundation (PMF)

Tsunami Inundation Velocity Modelling

The velocity of the flowing water is also a critical factor in determining potential damage and identifying areas at significant risk. The 2009 Newcastle Flood Planning report (BMT WBM, 2009) identified that above a flow velocity of 2.5m/s all structure types are at risk. Map 3 in Appendix C details the water velocity across the entire inundation zone. From this map it can be seen that of the 115km^2 inundation zone approximately 25km^2 is impacted by flow velocities of greater than 2.5m/s with maximum velocities of over 20m/s experienced.

Maximum Flow Velocity (m/s)	Location:
>20m/s	Stockton

Table 3: Maximum Flow Velocity (PMF)

Tsunami Inundation Depth x Velocity Modelling

It can be misleading to singularly use the inundation depths or flow velocities to identify critical impact areas. In areas subjected to inundation the critical depth required to pose threat of significant damage reduces as the flow velocity increases. The same is true for critical flow velocities which reduce as the inundation depths increase. The 2009 Newcastle Flood Planning Report (BMT WBM, 2009) lists a Velocity x Depth (VxD) value of 2.5m^2/s as the damage threshold for all structure types. Map 4 in Appendix C details the critical VxD value across the entire inundation zone and identifies that an area of 55km^2 exceeds the critical value of 2.5m^2/s.

The locations impacted by the critical VxD of 2.5m^2/s or greater are low laying areas located adjacent to the coastline or the Hunter River. These areas offer very little protection from the wave surge and as a result are subject to such significant inundation. The key areas and suburbs subjected to the critical inundation VxD include:

- Newcastle West,
- Newcastle,
- Cooks Hill,
- Stockton,
- Wickham,
- Carrington,
- Maryville,
- Mayfield East,
- Mayfield North,
- Kooragang Island & Wetlands, and
- Bar Beach and Merewether (Coastal Areas),

The area subject to the greatest average VxD as part of the modelling was Stockton. Stockton is one of only two suburbs to be completely inundated by critical flow. The second suburb is Carrington. These suburbs have large residential populations with

Carrington also being home to a number of large industries (MDRE, 2015). The impacts on these two suburbs is likely to be significant is terms of the severity of damage.

Inundation Area (km^2)	115km^2
Maximum Inundation Depth (m)	4.8m (excluding river area)
Maximum Flow Velocity (m/s)	>20m/s
Critical VxD (>2.5m^2/s) Area (km^2)	55km^2

Table 4: Tsunami Summary (PMF)

Tsunami Results & Data – Sensitivity Check (Standard High Tide)

As a sensitivity and logic check an alternate tsunami model was created to determine the extent of the tsunami impact if the event occurred during a standard ocean high tide. Based on the 2015 and 2016 tide predictions for Newcastle (BOM, 2015) a high tide of 1m Australian Height Datum (AHD) was selected. This relates to a high tide of approximately 1.97m Lowest Astronomical Tide (LAT) which is at the larger end of the high tide predictions. The tide height of 1m AHD is significantly lower than the PMF level of 3.4m AHD and is probably more representative of the likely worst case environmental conditions for the potential tsunami event in terms of actual risk.

Tsunami Strike and Run-up

The timing of the first noticeable impact of the approaching wave is unchanged from the PMF model at approximately 175 minutes after the initial earthquake. Figure 36 shows the commencement of the water recession/runout which can be identified by the slight adjustment in depth shading at the mouth of the Port of Newcastle. The water runout continues at the same rate as the PMF model with the first wave peak striking the coastline approximately 197minutes after the earthquake.

There is no adjustment to the following wave peaks. Table 1 details the 21 total wave peaks that occur during the event. The heights are unchanged across the two models as they are heights above the relative ocean level for each model.

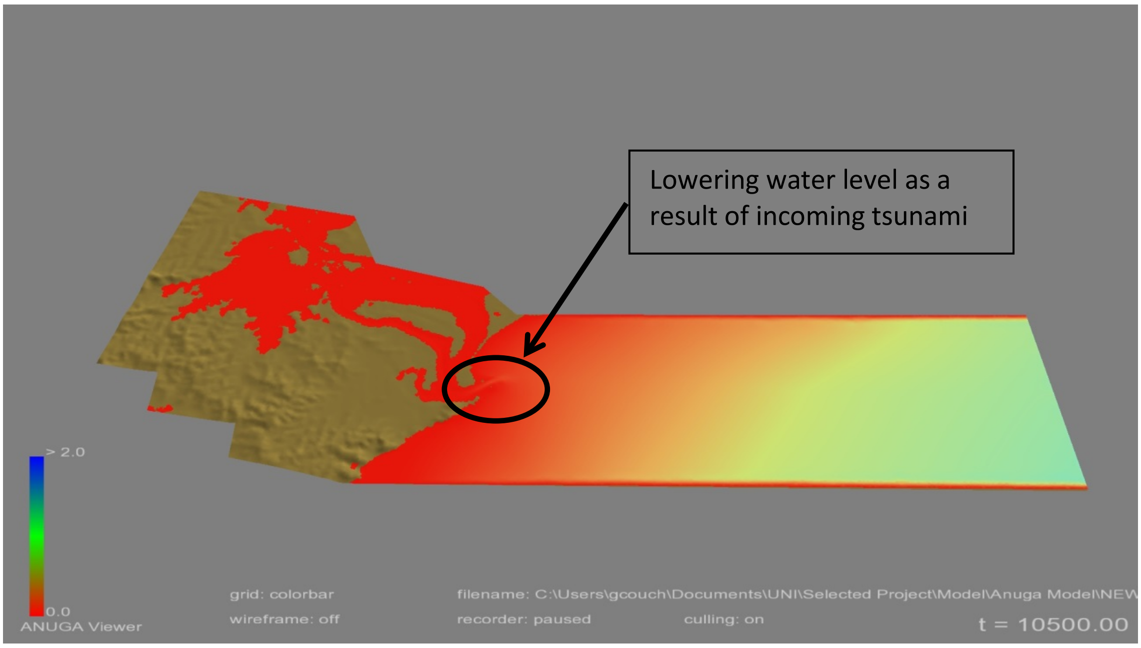

Figure 36: Initial water runout - 175 minutes – (HT)

The maximum run-up height of the wave surge remained significant at over 56m. This again occurred immediately adjacent to the coastline near Strezelecki Lookout in the Newcastle suburb of The Hill. This reinforces the impact of the localised topography in this area on the tsunami surge. High run-up heights continued along most of the coastline south of the entrance to the Port of Newcastle.

The lower lying areas surrounding the Port of Newcastle and Hunter River system were identified as locations potentially sensitive to the adjustment in ocean and river water levels. The run-up heights within the CBD area were as high as10m but are on average between 3-5m. The pockets of high run-up heights within the inner city suburbs remained but with the maximum heights reducing. Previous run-up heights of over 10m reduced to around 5-6m. This has a direct impact of the overall area of inundation.

A reduction in the run-up heights was also found across the large flood plain which borders the suburbs of Sandgate, Warabrook, Jesmond, Birmingham Gardens, Maryland, Fletcher, Hexham, Tomago and Beresfield. Around the flood plain the extent of run-up heights over 9-10m are less common with most locations only reaching a maximum of 7m. Even with the reduced run-up heights there is still significant risk to the infrastructure located at the boundaries of these suburbs and the flood plain.

Tsunami Inundation Area

Surprisingly there was only a minor reduction in the overall inundation area in comparison to the PMF tsunami model. The inundation area is reduced by only 2% from the PMF model to 109km^2. Refer to Inundation Map 5 in Appendix C for details of the full extent of the high tide tsunami inundation. The minimal reduction in inundation area along with the consistent impact to the inner city suburbs of across both models justified the conservative selection of the PMF model for the basis of the infrastructure review.

5. Impact on Key Infrastructure

Arterial / Major Road Networks

The arterial road network within the Newcastle LGA will be heavily impacted during the Tsunami (PMF) event. 10 key locations were identified where the arterial road network is inundated. Inundation of any roadway can lead to significant damage to the road infrastructure including;

- Pavement material damage and subsidence such as potholes and washouts,
- Erosion and siltation of roadway drainage network,
- Rapid inundation poses serious threat to current road users,
- Roadway electrical systems such a signals and lighting,
- Resulting economic damage caused by closed roadways.

The potential levels of inundation and impact vary across each of the 10 identified locations. The following table provides details on the tsunami impact for each location. Refer to Appendix D for roadway inundation locality map.

Location	Inundation Depth (m)	Flow Velocity (m/s)	VxD (m^2/s)
1 – New England Highway (A43)	2	0.5	1.0
2 – Pacific Highway (A1)	2.9	0.8	2.3
3 - Pacific Highway (A43)	5	1	5.0
4 - Newcastle Inner City Bypass (A37)	2.5	0.4	1.0
5 - Industrial Drive (A43)	3.8	2.8	10.6
6 - Pacific Highway (A43)	2.8	5.0	14.0
7 Maitland Road / Pacific Highway	3.3	5.0	16.5
8 - Newcastle / Griffith Road (A15)	1.1	4.0	4.4
9 Tudor Street	1.0	4.4	4.4
10 Pacific Motorway (M1)	1.5	0.5	0.75

Table 5: Artirial Roadway Inundation Summary

1. New England Highway (A43)

The New England Highway between Beresfield and Hexham is inundated by over 2m of water where it runs adjacent to the Hunter River. This section of highway connects the Pacific Highway through to the Pacific Motorway which is the major traffic route along the Australian East Coast (RMS, 2015). It is also one of the major roadways connecting Newcastle to western NSW. The average annual daily traffic (AADT) passing through this section of roadway is over 50,000 vehicles (Parsons Brinckerhoff, 2012) meaning there will be significant traffic and transport impacts during its inundation.

The maximum flow velocity in this location is approximately 0.5m/s. This calculates into a localised VxD of $1m^2/s$ which apart from the inundation and potential debris collection is less likely to cause major structural damage to the roadway. Longer term pavement damage may appear as a result on the inundation of the pavement materials. This VxD is unsuitable for all vehicular traffic and any vehicles caught within the inundation zone will likely be submerged and washed from the roadway.

2. Pacific Highway (A1)

This section of the Pacific Highway is located to the east of the Hexham Bridge over the Hunter River and will be inundated by up to 2.9m.The AADT of this section of the highway is over 40,000 vehicles (RMS, 2012). This location forms a critical link in the Pacific Highway from the end of the Pacific Motorway (M1) and the dual carriageway to the north east of Heatherbrae. The bridge crossing the Hunter River in this location will not be overtopped but the road approaches will be severely inundated.

The maximum flow velocity in this location is approximately 0.8m/s producing a localised $VxDm^2/s$ of $2.3m^2/s$. This VxD is unsuitable for all vehicles and will likely cause damage to a number of the roadways ancillary structures and signage. There is the potential for erosion and washout of roadway sections. The large inundation depth will likely also lead to debris and road pavement issues post inundation.

3. Pacific Highway (A43)

The Pacific Highway is inundated between Hexham and Sandgate. This section of the highway runs parallel to the Hunter River with little protection from tsunami inundation. The maximum inundation depth along the 6.1km section of the highway is over 5m with a flow velocity of 1m/s. The resulting VxD value of $5m^2/s$ is very large and results in significant threat to all of the roadways associated structures. This location is likely to be impacted by significant erosion and pavement damage such as washouts. The large inundation depth is also likely to lead to debris and road pavement issues post inundation.

4. Newcastle Inner City Bypass (A37)

This roadway has recently been extended to intersect with the Pacific Highway to the north of Sandgate. The RMS is currently undertaking concept design and development for its extension south from Jesmond to Rankin Park formalising it as one of the major vehicular traveling routes within Newcastle (RMS, 2014). On completion it will have an estimated AADT of over 40,000 vehicles (RMS, 2014). Most of the inundation along the current bypass is minor with depths approximately 0.5m. There is an isolated section at the northern end of the bypass where the inundation depth exceeds 2.5m. This section of the bypass is located to the west of Sandgate and runs across previously identified flood prone land (BMT WBM, 2009). The maximum flow velocity through this location is only 0.4m/s producing a minor VxD of $1m^2/s$. Apart from standard debris clean-up and potential long term pavement issues the damage to the roadway is anticipated to be minor.

5. Industrial Drive (A43)

A 5km section of Industrial Drive which runs from Mayfield through to the Newcastle CBD is impacted by the tsunami inundation. This roadway is one of the major routes into Newcastle and allows traffic to bypass a number of inner city suburbs to gain access to the CBD. It also forms part of the Pacific Highway route A43 which runs through Newcastle. In terms of impacted traffic, the roadway has a current AADT of approximately 30,000 vehicles (RMS, 2012) which is only 25% lower than the Pacific Highway at Hexham.

The depth of inundation varies significantly along the 5km length of Industrial Drive. A large portion of the impacted roadway is located near the extent of inundation and is only subject to minor inundation up 0.5m. The maximum inundation occurs near the Throsby Creek Bridge crossing where the depth reaches 3.8m. This location is not only close to the coastline but also adjacent to a main arm of the Hunter River. As a result the maximum velocity at this location is 2.8m/s. The VxD for this location is over $10.6m^2/s$ which has the potential to be extremely destructive. It would be expected in this location that all ancillary road structures such as signals, barriers, and signage would be damaged during the inundation. Erosion and road washouts become increasing likely particular around the Throsby Creek location. Standard debris and road pavement issues associated with inundation would also be prevalent. This has a major impact on traffic movements and would likely have a major economic impact on the city if a prolonged closure resulted.

6. Pacific Highway (A43)

This section of roadway provides access to the CBD from the southern suburbs. It runs through the Newcastle CBD and connects to Industrial Drive / Hannell Street. The location of inundation is through both Hamilton East and Hamilton South and is approximately 1.4km in length. There are two major intersections within the inundated area. The maximum of inundation depth is 2.8m and this is located as the intersection of Industrial Drive / Hannell Street. The depth reduces quickly moving in a southern direction with the majority inundation being below 1m in depth. Major intersections with Maitland Road and Newcastle Road have inundation depths of 2.5m and 1.1m respectively.

The flow velocity through this location peaks at 5m/s resulting in VxD values over $14m^2/s$. It would be expected that all ancillary road structures such as signals, barriers, and signage would be damaged during the inundation. The low profile and urban setting of the roadway makes erosion and washouts unlikely. Significant damage and siltation of the drainage network would be expected along with debris and road pavement issues associated with inundation would also be prevalent.

7. Maitland Road / Pacific Highway

Maitland Rd is inundated for approximately 4.5km through the suburbs of Mayfield and Hamilton. The roadway has a high daily traffic volume with an AADT of over 25,000 vehicles (RMS, 2012). The maximum inundation depth along this section of roadway is 3.3m. The flow velocities in this location peak at 5m/s resulting is a localised VxD over $16.5m^2/s$. Again due to the roadways urban profile erosion and washouts are not likely. Ancillary road structures such as signals, barriers, and signage would be damaged during the inundation. Significant damage and siltation of the drainage network would be expected along with debris and road pavement issues associated with major inundation.

8. Newcastle / Griffith Road (A15)

This is another major roadway providing access to the Newcastle CBD. The AADT is over 30,000 vehicles (RMS, 2012). The majority of the inundation is minor with levels being below 0.5m. The maximum inundation depth of 1.1m occurs at the intersection with the Pacific Highway. Minimal damage would be expected along this roadway outside of the initial road closure and potential longer term pavement issues.

9. Tudor Street

Tudor Street in Newcastle links a number of major roadways and suburbs and provides access to and from the CBD. The traffic volumes towards the CBD end of Tudor Street are significant with an AADT of 20,000 vehicles (RMS, 2012). There is only minimal depth of inundation of this roadway, until it reaches the CBD where a maximum inundation depth of 1m occurs. Minimal impact would be expected along this roadway outside of the initial road closure and potential longer term pavement issues.

10. Pacific Motorway (M1)

The results show a short section of the Pacific Motorway adjacent to Pambalong Nature Reserve is inundated during the tsunami event. The surrounding area is subject to flooding during the PMF event and the tsunami surge adds significant depth to the inundation level. An inundation depth of 1.5m over the motorway is found based on the available survey data and tsunami modelling. A maximum velocity of only 0.5m/s was calculated resulting is low VxD value of 0.75m^2/s. Outside of the road closure impacts minimal damage would be expected along this roadway apart from debris and potential longer term pavement issues

Figure 37: Road Inundation Newcastle CBD (Source: The Herald, 2015).

Rail Network

The majority of the rail network within the Newcastle LGA is controlled and maintained by the Australian Rail Track Corporation Ltd. (ARTC). They lease and are responsible for the majority of the coastal rail network from Newcastle to the Queensland border (ARTC, 2015). ARTC also control the Hunter Valley coal network including the rail infrastructure to the Port of Newcastle (ARTC, 2015).

The rail network within the Newcastle LGA is significantly impacted by the tsunami inundation. Inundation and flooding of the network has the potential to cause significant damage and delays. The Hunter network has shown its vulnerability to inundation in recent times where large sections of the rail line were cut when drainage culverts and bridges were destroyed during the 2015 flood (The Herald, 2015). Any damage to the network will have a significant flow on effect with an average of 300 trains accessing the Hunter network daily (ARTC, 2014)

Figure 38: Damaged rail culvert - Newcastle 2015 flood (Source The Herald, 2015)

Location	Length of Impact (km)	Inundation Depth (m)	Flow Velocity (m/s)	VxD (m^2/s)
1 – Beresfield to Warabrook	11	3	0.9	2.9
2 – Waratah to Newcastle	6	4	10	40
3 – Kooragang Island	13.3	3	2.2	6.6
4 - Carrington	9.7	3.6	3.5	12.6

Table 6: Hunter Rail Network - Inundation Summary

The inundation areas can be broken into four major zones. Refer to Appendix D for the Rail Inundation Map. The first zone is an 11km section from Beresfield Station through to Warabrook Station. Between these stations there are three additional stations that will also be inundated:

- Tarro Station,
- Hexham Station and,
- Sandgate Station,

This section of rail line is shared (across a number of tracks) by both heavy freight and passenger services. Of the 300 hundred trains that access the Hunter network on a daily basis, the majority will access this section of the track due to its connection of the Hunter Valley to Newcastle. Of the rail traffic that uses this section of the network:

- Approximately half are coal trains (ARTC, 2014).
- Sydney Trains provides 48 services in each direction (Sydney Trains, 2015),
- NSW TrainLink provides 3 services in both directions (NSW TrainLink, 2015) and,
- The remainder are freight services.

This section of rail is subject to a maximum inundation depth of 3m approximately 1.6kms south of Hexham. The maximum flow velocity in this location is just over 0.9m/s. This produces a VxD of $2.9m^2/s$ which falls into the high risk category in terms of potential damage. The types of damage that could be expected along this section of rail line would include major washouts and track erosions along with significant damage to signalling and control equipment. Debris being located on the track would also cause issues with service reinstatement.

The second section of rail line to be subject to inundation as a result of the tsunami event is a 6km section from Waratah Station through to Newcastle Station. There are currently parts of this particular section of rail that are nonoperational. The Newcastle rail network is currently in the process of being revitalised and long terms adjustments to the network are likely. For the purposes of this research the existing rail network was included. Therefore between the Waratah and Newcastle Stations there a three additional stations that will be subject to inundation:

- Hamilton Station,
- Wickham Station and,
- Civic Station

This section of rail turns primarily into a passenger network to the east of Hamilton Station. The coal and freight trains have already diverted across the Hunter River to Kooragang Island or into the Carrington industrial zone. Any additional rail traffic not traveling through to Newcastle Station is diverted to the Broadmeadow station and Sydney line prior to reaching Hamilton Station. The maximum inundation depth along this section of rail is 4m which occurs near the end of the line at Newcastle Station. The flow velocities in this location reach a maximum value of 10m/s. This results in a significant VxD of around $40m^2/s$ which has the potential to cause significant damage to the infrastructure. This section of rail is located adjacent to the Port of Newcastle and is likely to suffer significant damage, erosion and debris to the tracks as well as major structural damage to the stations and signalling network.

The remaining sections of rail network identified as being located with the inundation area are the heavy rail networks that supply the highly industrialised areas of Kooragang Island and Carrington. These locations are known for the coal industry and export system located at the Port of Newcastle but there are also a large number of industries that use the Port to import and export goods and materials here. The combined length of rail impacted by inundation in these areas is over 23km.

The Kooragang Island rail network accesses the island via a rail bridge located between Sandgate and Warabrook Stations. Modelling suggests that this rail bridge is also inundated during the tsunami event but without detailed survey levels of the bridge this cannot be confirmed. However both rail approaches are subject to inundation. A maximum inundation depth of 3m occurs on the north western corner of Kooragang Island. This is due to a lower level of the rail line at this end of the island. The flow velocities through this location peak at 2.2m/s producing a localised VxD of $6.6m^2/s$. As a result this section of the rail network will likely be impacted by washouts or major erosion, and significant damage to network power and signalling systems. There is also the potential issue of major debris obstruction on the rail line post inundation.

The Carrington industrial rail network is accessed via a rail interchange located between Waratah and Hamilton Stations. The rail line travels through Tighes Hill and into the Carrington industrial area. The majority of the rail lead-in line and rail network within Carrington is inundated during the tsunami event. Maximum inundation occurs at the northern end of Carrington with the depth reaching 3.6m. The flow velocities through this location peak at 3.5m/s producing a localised VxD of $12.6m^2/s$. The same potential impact and damage apply with washouts and erosion to the rail formation the most critical along with signalling and electrical damage. The potential for significant debris obstruction post inundation remains.

Electrical Network

The electrical distribution network in the Newcastle LGA is operated and maintained by the energy company Ausgrid. Ausgrid's distribution network supplies power to approximately 1.64 million customers which is around half of the NSW supply (Ausgrid, 2014). Ausgrid were provided with the tsunami inundation model and they identified five key assets located within the inundation zone. There are also a large number of minor assets located within the inundation zone such as power poles and kiosk substations. These were not included as part of the research project which only covers major infrastructure items.

Overall the major electrical assets identified within the inundation zone are impacted to varying degrees. Two of the substations are located within major inundation zones, two will be subject to minor inundation and a further substation is speared due to its location in a higher section of the CBD. The below table provides a summary of the inundation levels of the identified major assets. At Ausgrid's request the actual names and locations of the assets discussed below have been removed from the report. This was requested by Ausgrid on security grounds.

Location	Type	Inundation Depth (m)	Flow Velocity (m/s)	VxD (m^2/s)
Substation 1	Zone Substation	0.5	0.3	0.15
Substation 2	Zone Substation	3.3	6	19.8
Substation 3	Zone Substation	0	0	0
Substation 4	Zone Substation	3.5	2.5	8.75
Substation 5	Sub-Transmission Substation	0.6	3	1.8

Table 7: Ausgrid Distribution Newtork - Inundation Summary

Substation 1 is located at the north western extent of the inundation zone. As a result it is not subjected to major flow depths or velocities. Substation 1 supplies mainly residential services and if damaged as a result of the tsunami inundation power could be restored through temporary measures such as network rerouting or the setting up of portable zones (Ausgrid, 2015); meaning power supply could be available relatively quickly while repairs are made to the network.

The depth of inundation in the location of Substation 1 is only 0.5m with a flow velocity of 0.3m/s. This produces a VxD of 0.15m^2/s. These low values are due to the location being close to the extent of inundation. Based on the current modelling Substation 1 is unlikely to suffer major structural damage with any potential damage being from equipment failure issues due to minor inundation.

Substation 2 is located within a coastal zone that is severely impacted by tsunami inundation. The location of Substation 2 is a narrow land area that is bounded by the ocean to its east and the Port of Newcastle to its west. At its narrowest point this area is approximately 300m in width (Google Maps, 2015). The substation mainly supplies residential services and if damaged as a result of tsunami inundation alternate supply could be provided to the area being serviced by Substation 2 through network rerouting or the setting up of temporary zones (Ausgrid, 2015).

The maximum inundation depth at the substation site is 3.3m. The area is subjected to relatively high flow velocities due to its location, with the maximum velocity at the substation reaching over 6m/s. The results in a localised VxD of 19.8m^2/s which based on previous flooding and tsunami research is likely to cause significant damage to the substation. The immediate rerouting of power supply to the Substation 2 area may not be undertaken by Ausgrid due to safety concerns based on the likely hood of significant damage to the area.

Substation 3 was identified by Ausgrid as a key asset within the modelled inundation zone. This zone is significantly larger in area than those supplied by Substation 1 and Substation 2 and was of major concern to Ausgrid (Ausgrid, 2015). Through further development of my initial inundation modelling and with the exact location of the substation being provided by Ausgrid it was found to be located outside of the inundation area. The substation is located in an elevated area within the CBD which is protected from the inundation due to its height.

The first of three coal loaders in the Port of Newcastle and the surrounding suburb is served by Substation 4 (Ausgrid, 2015). This substation is located within a major inundation area. Substation 4 is located adjacent to Throsby creek which is a major source of the tsunami inundation. The maximum depth at the substation location is approximately 3.5m and a maximum flow velocity of 2.5m/s. The produces a localised VxD of 8.75m^2/s which will likely result in significant damage to the substation and subsequent power supply issues for the areas supplied by Substation 4.

The final key asset identified by Ausgrid within the inundation zone was Substation 5. This substation supplies all of the heavy industry located on Kooragang Island. It is a high voltage substation running 132kv to 33kv where most zone substations reduce the voltage to 11kv (Ausgrid, 2014). The Kooragang Island district is home to many of Newcastle's major heavy industries including two of the three coal loading terminals.

Interruptions to the power supply would result in major economic impact and potentially significant safety concerns. If damaged the power supply to Kooragang Island cannot be restored through network rerouting and the repair of significant damage could take months (Ausgrid, 2015). A number of industries serviced by this substation require constant power supply to specific storage facilities. With the potential for the tsunami inundation to also damage emergency redundancies such a backup generators as occurred at the Fukushima Nuclear Power Plant (refer Literature Review). Any damage to the substation would be treated as a critical incident (Ausgrid, 2015).

Fortunately the tsunami modelling shows that the substation location is only subjected to minor levels of inundation and average flow velocities. The maximum inundation depth and flow velocity recorded are 0.6m and 3m/s respectively. This produces a localised VxD of $1.8m^2/s$.

According to Ausgrid this level of damage would be state significant in terms of loss of load and could cause the state grid to wobble. To counteract this a number of power stations would be required to initiate emergency ramp offs to stabilise the grid frequency. There is an additional risk to the overall health of the state grid and this is the Tomago Aluminium plant. The plant straddles the extent of the inundation zone, and at full operation this plant draws approximately three times the power from the grid as the above mentioned electrical infrastructure. If the tsunami were to damage or impact the supply of power to this plant the following impact to the network grid would require significant offset from the available power stations to negate the potential wobble and protect the NSW grid, including Sydney from collapse.

Water Supply & Sewer Networks

Hunter Water is the water and sewer authority in the Newcastle LGA and the Lower Hunter area. It is a State Owned Corporation providing services to, approximately 575,000 people and managing more than $2.7 billion infrastructure across its network (Hunter Water, 2015). Hunter Water did not wish to provide network specific details for review as part of the research project despite numerous approaches. As such the following results are based on data and information already publically available on their website and the internet. Refer to Water & Sewer Supply Inundation Map – Appendix D for further details.

Water Network

Over 230,000 people are connected to the water supply network (Hunter Water 2015). There are six main water sources that supply the network of which only the Tomago Sandbeds are located within close proximity to the Newcastle LGA (Hunter Water 2011). The Sandbeds are located within the adjacent Local Government Area of Port Stephens Council (PSC) and due to their location close to the surrounding river systems are at risk of partial inundation (Hunter Water 2011). The Sandbeds currently supply only 20% of the Hunter Water supply but provide significant backup water supply and storage should the other supplies be compromised (Hunter Water 2011). Any research into impact of a tsunami on the Port Stephens Council area should include the potential impact of saltwater and potentially polluted water inundation of these Sandbeds.

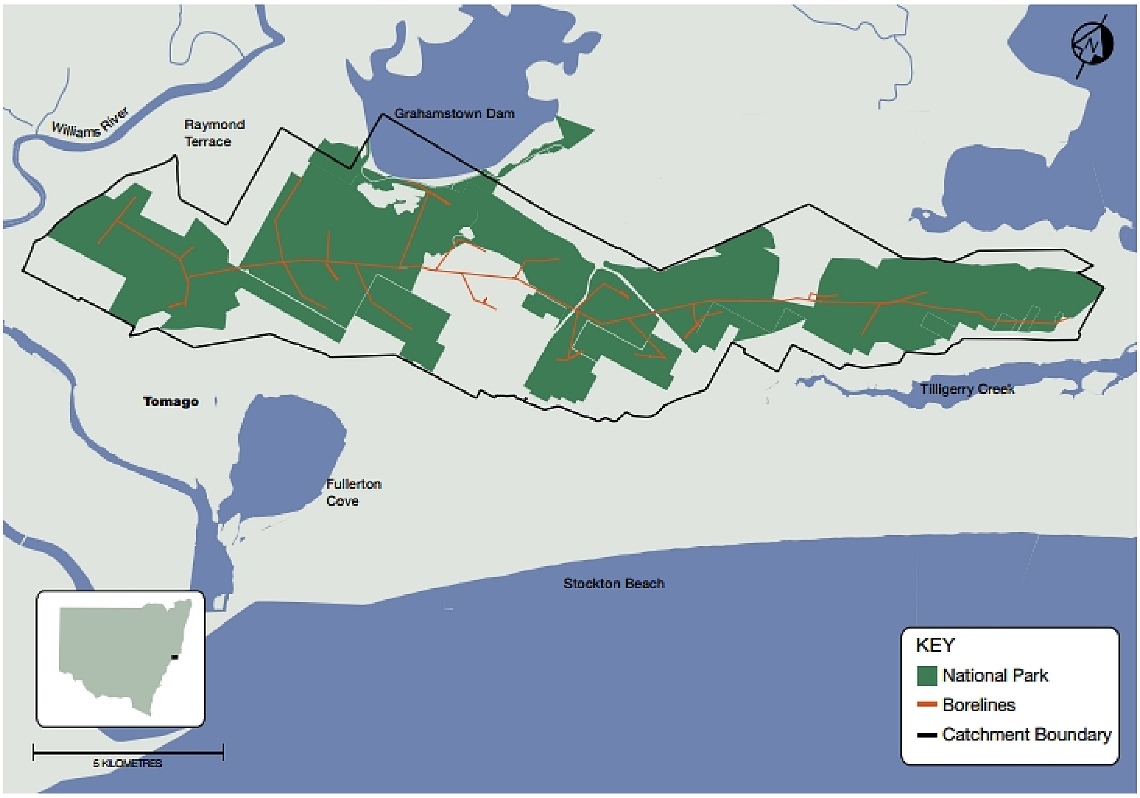

Figure 39: Tomago Sandbeds (Source Hunter, 2011)

Hunter Water has invested $20 million dollars into the upgrade and relocation of the existing 900mm diameter above ground main between Tarro and Shortland to below ground (Hunter Water, 2015). This is the Chichester Trunk Gravity Main and provides water access to Chichester Dam which is one of the networks major water supplies (Hunter Water, 2015). It also allows for water transfer between different Hunter Water catchments (Hunter Water, 2015). Until recently this section of above ground water main would have been at significant risk of damage during the tsunami inundation due to its limited protection from large external water forces and potential debris strikes. The relocation of the main below ground provides an increased level of protection from potential tsunami inundation. Refer to the Water & Sewer Supply Inundation Map – Appendix D for further details.

The Fletcher Trunkmain is another above ground water supply asset. This main currently supplies up to 4,500 connections across a number of suburbs (Hunter Water, 2015) and runs across the Hexham Swamp Wetland which is heavily impacted by potential tsunami inundation. This section of main is subjected to a maximum inundation depth of 3.2m with a flow velocity of 0.4m/s This produces a localised VxD of 1.3m^2/s. Due to the nature of high pressure watermains this inundation will not pose significant risk of damage. The most likely cause of major damage to the main is being struck by debris during the inundation period. Refer to the Water & Sewer Supply Inundation Map – Appendix D for further details.

Another potential area of damage to the major watermains is alongside any significant road washouts or areas of erosion. It is common for watermains to be located within specific service allocations along roadways or attached to bridges and drainage structures. The damage to this infrastructure has to potential to greatly impact all of the adjacent services including water supply mains.

Sewer Network

The Hunter Water wastewater system contains over 4,850km of sewer main, 435 pumping stations and 19 wastewater treatment plants (Hunter Water, 2015). Within the inundation area there a two major waste water treatment plants servicing approximately 200,000 people. Refer to Water & Sewer Supply Inundation Map – Appendix D for further details.

The Shortland Wastewater Treatment Works (WWTW) is located near the extent of the inundation zone. The Shortland WWTW has the capacity to serve up to 32,000 people and treat 9.6 megalitres of waste water daily (Hunter Water, 2011). The Shortland WWTW receives industrial waste from a number of key industrial sites including Kooragang Island and redirected residential waste from two decommissioned WWTW. The inundation results show that the area of the Shortland WWTW experiences inundation depths up to 3m with a maximum flow velocity of 0.33.m/s resulting in a localised VxD of 1m^2/s. The significant inundation depth is likely to greatly impact the operational activities and result in damage to the WWTW infrastructure.

The Shortland WWTW is the smaller of the two WWTW located within the inundation zone. The Burwood Beach WWTW is the largest treatment facility in the Newcastle LGA. It currently services up to 190,000 people by treating 48 megalitres of waste water daily (Hunter Water, 2011). Hunter Water are currently in the community consultation and planning process for future development and upgrades to the farcicality to increase its capacity to allow for projected property growth over the next 30 years (Hunter Water, 2014).

The Burwood Beach WWTW are located approximately 350m from the coastline and the modelling results show that its location suffers a direct impact from the coastal tsunami inundation. The maximum inundation depth recorded across the site is 2m and due to the close proximity to the coastline the maximum flow velocity is up to 10m/s. This produces a localised VxD of 20m^2/s which is well above the previously discussed threshold of significant structural damage.

Figure 40: Burwood Beach WWTW (Source: Hunter Water, 2010)

The location of other wastewater infrastructure was not made available by Hunter Water for the research project. However through the inundation results of the Shortland and Burwood Beach WWTW it is evident that there is potential for significant impact and damage to the wastewater system within the Newcastle LGA.

Emergency Services

In times of disaster societies reliance on the large network of emergency service providers increases exponentially. The emergency services provide a response and service that is critical in the saving of lives and in mitigating further damage and impact to critical infrastructure. If these services were to be significantly impacted or destroyed during a disaster and were unable to provide their normal responses it could result in a significant rise in casualties and secondary damage to infrastructure.

Within the Newcastle LGA the locations of the following emergency services were mapped and compared against the tsunami inundation model (Refer to the Emergency Services Inundation Map - Appendix D).

- Ambulance Stations,
- Fire Stations,
- Police Stations,
- State Emergency Service Depots (SES),
- Newcastle Council Chambers and Depots.

The modelling showed that during the tsunami event two ambulance stations, two police stations, four fire stations, the SES depot and the Newcastle Council chambers were directly impacted by water inundation. Refer to Table 8 for further details. A further impact on the emergency services was found during the modelling. The significant inundation of roadways throughout the Newcastle LGA would provide major access issues for many of the services that are not damaged by the tsunami inundation.

Service	Location	Inundation Depth (m)	Flow Velocity (m/s)	VxD (m^2/s)
Ambulance Station	Hamilton	0.18	3.5	0.63
Ambulance Station	Birmingham Gardens	1.2	0.25	0.3
Police Station	Newcastle	1.0	4.0	4
Police Station	Stockton	1.25	7.5	9.38
Police Station	Broadmeadow	n/a		
Police Station	Waratah	n/a		
Fire Station	Stockton	1.7	33	56.1
Fire Station	Carrington	3.5	3.2	11.2
Fire Station	Newcastle	0.3	1.5	0.45
Fire Station	Merewether	n/a		
Fire Station	Hamilton	n/a		
Fire Station	New Lambton	n/a		
Fire Station	Lambton	n/a		
Fire Station	Mayfield West	n/a		
Fire Station	Wallsend	n/a		

Fire Station	Minmi	n/a		
Fire Station	Tarro	0.3	0.1	0.03
State Emergency Service (SES)	Wickham	4.5	2.8	12.6
Newcastle Council Chambers		1.8	3.5	6.3
Newcastle Council Depot		n/a	n/a	

Table 8: Emergency Services - Inundation Summary

Ambulance Service of NSW

The primary role of the Ambulance Service of New South Wales is to respond to requests for assistance and to provide emergency medical treatment (Ambulance Service NSW, 2015). They also provide the services of a number of specialised units to large scale disasters (Ambulance Service NSW, 2015). As part of the Newcastle Local Disaster Plan (DISPLAN) the NSW Ambulance Service has a number of additional roles and responsibilities during times of emergency and disaster including:

- “Provide and/or assume responsibility for transport of Health Service teams and their equipment to the site of incidents or emergencies, receiving hospitals or emergency medical facilities when so requested by the Health Services Functional Area Coordinator”;
- Setup and maintain communication networks for all health systems involved in emergency responses;
- “As determined by the State Rescue Board, provide accredited rescue units”;
- “Provide specialist Special Casualty Access Team (SCAT), Special Operations Team (SOT) and Urban Search and Rescue (USAR) paramedics as required”;
- Provide rescue aircraft retrieval services across New South Wales;
- Provide a Liaison Officer with communications to the Local Emergency Operations Centre (LEOC) and;
- Provide a Liaison Officer to the Police Site Controller (Newcastle DISPLAN, 2012, p.7).

The Ambulance Service has two stations located within the Newcastle LGA (Ambulance Service of New South Wales, 2015). Both of these stations are impacted by tsunami inundation. The major ambulance station is located in the suburb of Hamilton close the CBD. The station is subject to a maximum inundation depth of 0.18m with a flow velocity of 3.5m/s. This produces a localised VxD of 0.63m^2/s. These flow characteristics are unlikely to cause any significant damage to the Hamilton station. The major issue faced by the Hamilton station will be access to the impacted locations within Newcastle due to extensive inundation across the road network.

Located in the suburb of Birmingham Gardens the second ambulance station is impacted by a significantly greater level of inundation. With a maximum depth of 1.2m and a flow velocity of 0.25m/s the localised VxD of 0.3m^2/s is unlikely to cause significant structural damage to the station. There is however a high risk of damage to vehicles and inventory. Compounding these issues will be the significantly reduced roadway access to and from its location due to roadway inundation.

NSW Police Force

The NSW Police Force will be required to play a significant role before, during and after the tsunami event. The Police Force aim to protect the community during such an event by:

- Preventing, detecting and investigating crime,
- Monitoring and promoting road safety,
- Maintaining social order and,
- Performing and coordinating emergency and rescue operations (NSW Police Force, 2015).

As part of the Newcastle DISPLAN (2012) the NSW Police have a number of additional roles relating to emergency and disaster situations including:

- Setup and maintain a disaster victim register and provide information to families of victims regarding the victim status and location;
- Rolling the NSW disaster victim register into the national register;
- Provide a liaison officer to the LEOC; and
- "Marine Area Command – The following units have now been incorporated under the Marine Area Command controlled & coordinated by Police Marine Command. Royal Volunteer Coastal Patrol, Australian Volunteer Coast Guard and Waterways Authority of NSW" (Newcastle DISPLAN, 201, p.10).

If the Police were restricted or unable to perform the above duties it would have a significant detrimental effect on those impacted by the tsunami. The NSW Police Force has four stations within the Newcastle LGA (NSW Police Force, 2015). Two of these, the Newcastle and Stockton Police stations, are located within the tsunami inundation zone. Refer to Appendix D for the Emergency Services Inundation Map.

The Newcastle Police Station is subject to a maximum inundation depth of 1.0m with a flow velocity of 4.0. The resulting VxD of 4.0m^2/s does pose a risk of significant damage to the station however the relatively low inundation depth and the size of the station make this unlikely. The station will be impacted by water damage and will also be isolated during the tsunami inundation. The likely impact of this is the station being inoperable for a period time.

As previously discussed the suburb of Stockton is particularly vulnerable to the modelling tsunami event. The Stockton Police Station is no exception. The station is subject to a maximum inundation depth of 1.25m with a flow velocity of 7.5m/s. The resulting VxD of 9.38m^2/s is above the threshold for risk of significant structural damage. With Stockton being one of the worst affect areas the impact to the Police Station will further hamper any type of emergency response.

Fire & Rescue NSW

Fire & Rescue NSW "is one of the world's largest urban fire and rescue services" (Fire & Rescue NSW, 2015). They work in coordination with the other emergency service providers to respond to emergency incidents and minimise impact (Fire & Rescue NSW, 2015). As part of the Newcastle DISPLAN (2012), Fire and Rescue NSW have a number of additional roles which fall outside of their daily services including:

- Provide Land Rescue Units as determined by the State Rescue Board,
- "In accordance with Major Structure Collapse Sub Plan provide, control and deploy USAR Task Force(s)",
- Provision of assistance anywhere skill set of Fire & Rescue NSW is suitable,
- Provide assistance to the NSW State Emergency Service during emergencies,
- Provide a liaison officer to the (LEOC), and
- Inform the Local Emergency Operations Controller (LEOCON) of the existence of incidents (Newcastle DISPLAN, 2012, p.8).

There are eleven fire stations within the Newcastle LGA (Fire & Rescue NSW, 2015). Of these four are located within the tsunami inundation zone with Stockton and Carrington stations being the worst affected. The suburbs of Stockton and Carrington are heavily inundated during the tsunami event. The topographical profile of these suburbs offers very little protection from the wave surge.

The Stockton Fire Station is subject to a maximum inundation depth of 1.7m with a large flow velocity 33m/s. This produces a localised VxD of 56.1m^2/s which will result in a significant risk of complete destruction of the station and its surrounding infrastructure. The Carrington Fire Station is subject to a maximum inundation depth of over 3.5m with a flow velocity of 3.2m/s. This also produces a localised VxD of 11.2m^2/s which is more than four times the threshold for significant risk of catastrophic structural damage to the building.

The Newcastle and Tarro Fire Stations are located on the inundation boundary and as such are not subjected to major inundation or flow velocities (Refer Table 8). This will result in minimal risk of damage to these stations. The Newcastle Fire Station will be isolated as a result of the inundation. This will result in significant access issues for the Fire Station and may result in the station being inoperable for a significant period post tsunami.

NSW State Emergency Service (SES)

The NSW State Emergency Service (SES) primary role is to provide emergency and rescue assistance to the community 24 hours a day (SES, 2015). It is an organisation heavily reliant on volunteer members. Trained rescuers within the SES provide valuable assistance and support to the other emergency services during major disasters (SES, 2015). Under the requirements of the Newcastle DISPLAN one of the key tasks assigned to the SES is the planning for and response to a tsunami event specifically warnings and evacuations (Newcastle DISPLAN, 2012). The SES will also provide a liaison officer to the LEOC to improve the interaction between services (Newcastle DISPLAN, 2012). All of the remaining roles would be considered standard practice for the SES during times of emergency (Newcastle DISPLAN, 2012).

The Newcastle SES headquarters are located within a heavily affected area of the tsunami inundation zone, adjacent to Throsby Creek in Tighes Hill (Refer to Appendix D for the Emergency Services Inundation Map). The headquarters are subject to a maximum inundation depth of 4.5m with a flow velocity of 2.8m/s. This produces a significant VxD of 12.6m^2/s which is five times the risk threshold for catastrophic damage to all types of building construction. There is a high risk of total damage to the headquarters and its inventory. The loss of any emergency equipment stored within the headquarters will provide the greatest hindrance to the local SES volunteers and their ability to provide the required levels of emergency assistance.

Newcastle City Council

Newcastle City Council (NCC) was formed through the amalgamation of eleven surrounding Councils in 1938 (NCC, 2015). The Council provides over seventy services to the community on a daily basis. Some of the major services include:

- Town planning,
- Construction and maintenance of local roads, streets and bridges,
- Preservation of historic places,
- Food and public health services,
- Waste management and recycling,
- Supervision of building and development control,
- Maintenance of parks, golf courses, sporting fields, pools and beach facilities, and
- Fire prevention enforcement (NCC, 2015).

As part of the Newcastle DISPLAN (2012) NCC hold a number of vita roles and responsibilities outside of its daily operations. The major roles include under the DISPLAN include:

- To establish and maintain a LEOC for the (LEOCON) and provide additional support staff,
- "To investigate impacted areas and provide post emergency damage assessments",
- "The provision of all available services, including staff, equipment etc. as required during such emergencies",
- Provide any assistance requested by the emergency service providers,
- "Provide engineering resources required for response and recovery operations including:
  - Damage assessment,
  - Clear and re-establish roads and bridges,
  - Demolish and shore-up buildings,
  - Remove debris,
  - Construct and maintain temporary levees and evacuation routes, where appropriate,
  - Erection of barricades and fences for public protection" (Newcastle DISPLAN, 2012, p.6).

As a result of the increased roles and responsibilities during times of disaster and emergency any potential damage to NCC facilities will result in an increased impact to the community and may delay the implementation of the Newcastle DISPLAN. The two major NCC facilities reviewed as part of the research project were the NCC Administration Centre and the Works Depot.

The Administration Centre is located in the Newcastle CBD. The tsunami modelling results show the building is subject to inundation as a result of the wave surge. The maximum inundation depth reaches 1.8m with a flow velocity of 3.5m/s. This results in a localised VxD of $6.3m^2/s$ which is sufficient to produce significant damage to NCC's major operations building. Damage to this building is likely to impact current plans in the operation of the LEOC during emergencies and a large number of daily services.

The works depot is located in the suburb of Waratah and is NCC's major location for equipment maintenance and storage. With the facilities and equipment located at the works depot it will provide major assistance in NCC's ability to fulfil is requirements under the proposed DISPLAN. The good news for NCC is that the results of the tsunami modelling found that the Works Depot is outside the inundation zone and as a result the facility is not impacted.

Schools

Schools within the Newcastle LGA are not spared from the tsunami impact. Within the Newcastle LGA eleven schools are subject to varying levels of inundation while a further five are isolated or located directly adjacent to the inundation boundary. Table 9 contains a summary of the affected schools and details regarding the inundation results. The impact is wide spread with over 8,700 students and staff impacted (My Schools, 2015). Refer to Appendix D for a School Inundation Map.

School	Location	Inundation Depth (m)	Flow Velocity (m/s)	VxD (m^2/s)
Newcastle High	Hamilton South	1.1	7.7	8.5
Newcastle Grammar	Cooks Hill	2.5	2.0	5.0
Newcastle Grammar	Newcastle	Isolated		
The Junction Public	Merewether	<0.1	0.4	0.04
Hunter Christian	Mayfield	Outside - Just		
San Clemente High	Mayfield	Outside - Just		
St Francis Xavier's College	Hamilton	0.3	5.0	1.5
St Philips Christian College	Waratah	Outside		
Callaghan College	Wallsend	0.4	0.1	0.04
Callaghan College	Waratah	<0.1	0.3	0.03
Stockton Public	Stockton	2.9	20.2	58.6
St Peters	Stockton	1.3	19.3	25.1
Carrington Public	Carrington	3.5	3.3	11.6
Newcastle East Public	The Hill	Isolated		
St Joseph's Primary	Merewether	<0.1	1.1	0.11
Mayfield East Public	Mayfield	<0.1	0.2	0.02

Table 9: Newcastle Schools - Inundation Summary

Newcastle High School is a government school located close to the CBD. With a student enrolment of 1,029 students and 66 teaching staff in the 2014 school year it is one of the larger schools within the inundation zone (My Schools, 2015). The tsunami model results show Newcastle High to be located within the inundation zone and subject to significant potential impact. The school's location is subject to a maximum inundation depth of 1.1m with a high flow velocity of 7.7m/s. This produces a localised VxD of 8.5m^2/s which based on previous research provides a major risk of catastrophic structural damage to the schools numerous buildings and infrastructure.

Newcastle Grammar School is divided into two campuses. The Park St campus in Cooks Hill, and the Newcomen St campus in Newcastle. Across the two campuses in the 2014 school year there were a total of 722 student enrolments and 72 teaching staff (My Schools, 2015). The Cooks Hill campus is located well within the tsunami impact zone and according to the modelling is subject to significant inundation. The maximum inundation depth and flow velocity at the Cooks Hill campus is 2.5m and 2.0m/s respectively. This produces a localised VxD of 5.0m^2/s which puts all school infrastructure at major risk of significant damage or destruction. The Newcastle campus although located outside of the inundation zone it's completely isolated by the tsunami event. There are risks of long term isolation through damage to surrounding infrastructure such as roads and the rail network. Further research into the potential duration of such isolation would be required to determine the full impact to the Newcastle campus.

Newcastle East Public School is located only 250m from the Newcastle campus of Newcastle Grammar. It is also outside of the inundation zone but isolated during the tsunami event. The school has 217 students and 14 staff members who will be unable to travel to or from the school during the inundation period. As previously stated further research into the potential duration of such isolation would be required to determine the full impact to the school.

The Junction Public is located in the Newcastle suburb of Merewether. It is a government run primary school and in the 2014 school year had 586 student enrolments and 25 staff members (My Schools, 2015). The school is located marginally inside of the modelled inundation area and as a result it is only subjected to minor inundation. With a maximum inundation depth of 0.1m and flow velocity of 0.4m/s there is little risk of damage to any of the school's infrastructure.

Two schools within the suburb of Mayfield are located just outside of the tsunami inundation zone. San Clemente High School had 722 student and 59 staff while Hunter Christian School had 422 students and 41 teaching staff in 2014 (My Schools, 2015). Although these schools are not subject to inundation there may be significant issues with school access and evacuation due to damage from surrounding tsunami impacts. Around these schools there is significant inundation of the major roadways which will at a minimum cause short term access issues. Refer to Impact on Key Infrastructure

Arterial / Major Road Networks for details on potential inundation and damage.

St Francis Xavier's College is a non-government school located close to the Newcastle CBD in the suburb of Hamilton. With 987 students and 95 staff it is one of the larger schools within the Newcastle area (My Schools, 2015). Located within the tsunami inundation zone St Francis Xavier's College according to the modelling results is subject to a maximum depth of 0.3m and a flow velocity of 5m/s. This produces a localised VxD of 1.5m^2/s. This VxD does pose a risk to the minor structures and infrastructure of the campus, however it will only pose a very minor risk of serious damage.

During initial tsunami modelling St Philip's Christians College fell within the inundation zone. St Philip's is a large school for the area catering for 1,102 student of all schools years from kindergarten to year 12 (My Schools, 2015). There are also 94 staff members working within the school (My Schools, 2015). During refinement of the tsunami model St Philip's was removed from the inundation list due to a more accurate inundation zone being produced. The current risks to the school are impacts and restrictions on access during the tsunami event. A number of major roads around the school are inundated during the event and may be significantly damaged. Refer to Impact on Key Infrastructure

Arterial / Major Road Networks for further details on roadway impact and damage.

Callaghan College has three major campuses across Newcastle. Two of these campuses, Wallsend and Waratah suffer minor impact from the tsunami inundation. The Wallsend campus had 1,059 students and 69 staff during the 2014 school year (My Schools, 2015). The Waratah campus is smaller with 551 students and 46 staff (My Schools, 2015). Based on the tsunami model the Wallsend campus is subject to a maximum inundation depth of 0.4m with a very minor flow velocity of 0.1. The Waratah campus is subjected to only minor inundation depth and velocity of 0.1m and 0.3m/s respectively. These minor inundation values are due to the schools being located close to the extent of inundation. Damage to either of these campuses is unlikely with the major potential impact being access to and from the schools due to roadway inundation.

Stockton Public School is located in the worst location of all the schools in terms of the levels of inundation and flow velocity. Stockton Public is a small government primary school with 262 students and 15 staff members (My Schools, 2015). Stockton is one of the worst hit suburbs in the Newcastle LGA due to its coastal location and flat topographical profile. The school is subjected to a maximum inundation depth of 2.9m and flow velocity of 20.2m/s. The VxD produced by this combination is an immense 58.6m^2/s. These results show that the school and its infrastructure will likely be destroyed during the tsunami event and highlights the requirement for total evacuation prior to impact.

There is a second school located within the suburb of Stockton; St Peter's Primary is a small school of 86 students and 7 staff (My Schools, 2015). The inundation results for the school are slightly improved on Stockton Public but still lie well beyond reasonable structural limits. The maximum inundation depth is 1.3m with a high flow velocity of 19.3m/s resulting in a VxD of 25.1m^2/s. As a result the school and its entire infrastructure are likely to suffer catastrophic damage during such a tsunami event.

Carrington is another suburb which is extensively impacted by the tsunami inundation. The primary school located in Carrington is a small government primary school of 84 students and 4 staff (My Schools, 2015). The school is subject to a maximum inundation depth of 3.5m with a maximum flow velocity of 3.3m/s. The resulting VxD of 11.6m^2/s shows that the schools is under significant threat of major damage and would most likely be destroyed during the tsunami event.

St Joseph's Primary School Merewether is located at the inundation boundary. As a result the school is only subject to minor levels of inundation. The inundation depths are only 0.1m with flow velocities reaching 1.1m/s. Based on these results it is highly unlikely that any damage will be inflicted to the school or its infrastructure. The school has 349 students and 24 staff (My Schools, 2015). During the tsunami event students and staff will be able to evacuate the school as suitable roadway access is maintained.

Mayfield East Public School is a government school with 266 students and 12 staff members (My Schools, 2014). The school is located on the inundation boundary and as a result only suffers minor inundation to its grounds. Damage to the school is unlikely. The major impact to the school will be inundation of major roadways accessing it. However the location of the school provides a number of alternate access routes from the surrounding suburbs that are not impacted by the tsunami inundation.

General Structural Impacts - Buildings

Post tsunami research undertaken for the 2003 Boxing Day tsunami and the 2011 Japanese Tsunami looked at the types of buildings that were destroyed or damaged and determined the conditions at which this occurred. Flood research has also been undertaken within the Newcastle LGA catchment to determine potential structural impacts from varying flow conditions (refer to the Literature Review - Potential Structural Damage).

As discussed in the Literature Review there are a number of key factors that impact the structural risk of a building suffering catastrophic damage. This included building construction type, the depth of flow exceeding 2m or the flow VxD exceeding $2.5m^2/s$. In Appendix C, Map 2 provides details on the extent of the 2m flow depth and Map 4 provides details of the extent of critical flow VxD of $2.5m^2/s$. These maps highlight the large area where all structures are subject to risk of major damage or destruction

- Area of flow depth > 2m = 103km
- Area of VxD > $2.5m^2/s$ =. $55km^2$

In 2002 Geoscience Australia commissioned the Earthquake Risk in Newcastle and Lake Macquarie research report. As part of this report a building inventory survey was compiled for the area (GA, 2002). The survey recorded a number of key characteristics of each building including the wall and building construction types (GA, 2002). Figure 41 and Figure 42 show the distribution of building types in relation to the type of wall construction. A number of survey trends are immediately obvious with regards to the distribution of building wall and construction types.

Figure 41: Building Wall Construction Type (Source: GA, 2002) clearly shows that the majority of the surveyed buildings were of brick or timber construction. With brick wall construction being denser around the Newcastle CBD and timber rapidly increasing in volume as you move away from the CBD into the suburban areas.

Figure 42: Building Wall Construction Type (Source: GA, 2002) shows an almost identical pattern with respect to the building construction type. Around the CBD unreinforced masonry construction is the most prevalent. Again as you move from the CBD into the outer suburbs timber frame construction becomes the dominant construction type.

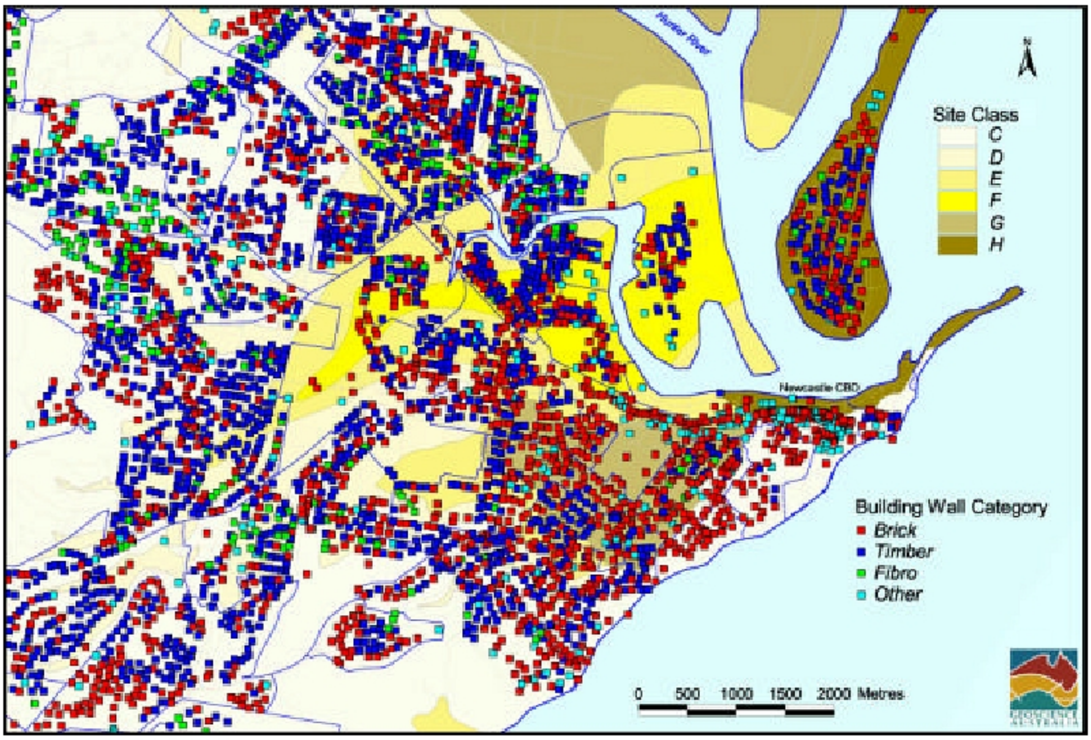

Figure 41: Building Wall Construction Type (Source: GA, 2002)

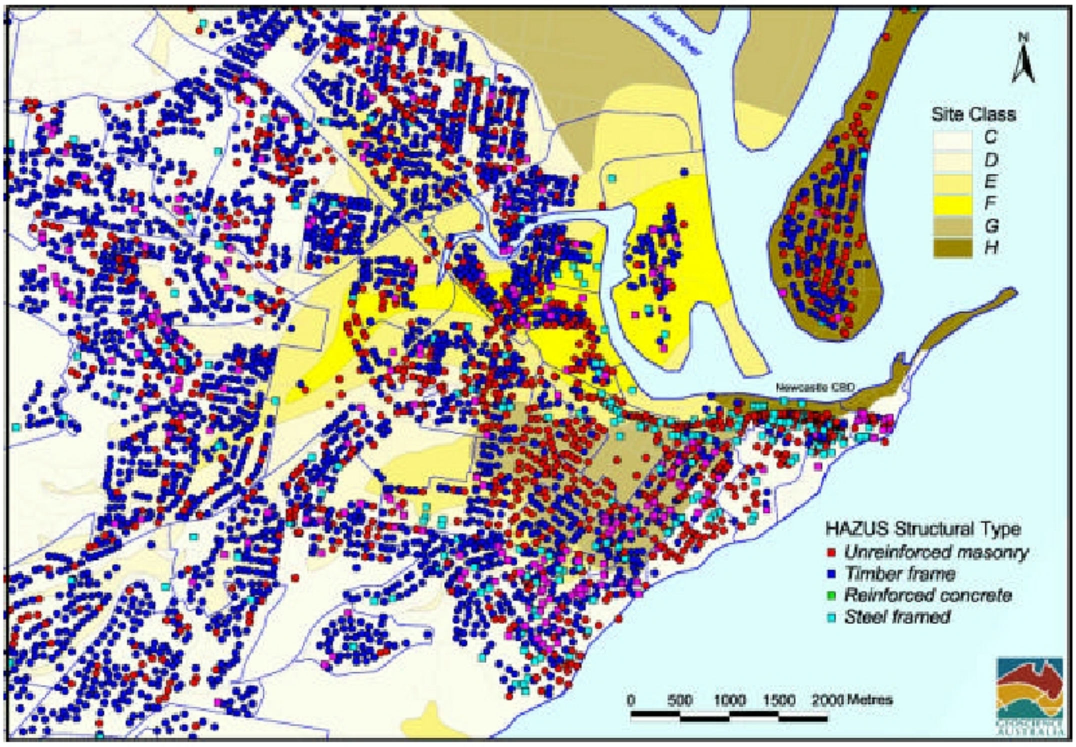

Figure 42: Building Wall Construction Type (Source: GA, 2002)

The building survey covered approximately 6,300 sites across the two Council areas (GA, 2002). The sampling rates varied for different locations with the density of survey being maximised in the Newcastle CBD and Newcastle's outer suburbs (GA, 2002). Figure 43 details the survey sample rates adopted throughout the study area. A sampling rate of less than 1 in 10 buildings was adopted within the inner Newcastle CBD with 1 in 10 being used for surrounding suburbs (GA, 2002). The sample density reduced further to 1 in 20 buildings for the outer suburbs (GA, 2002).

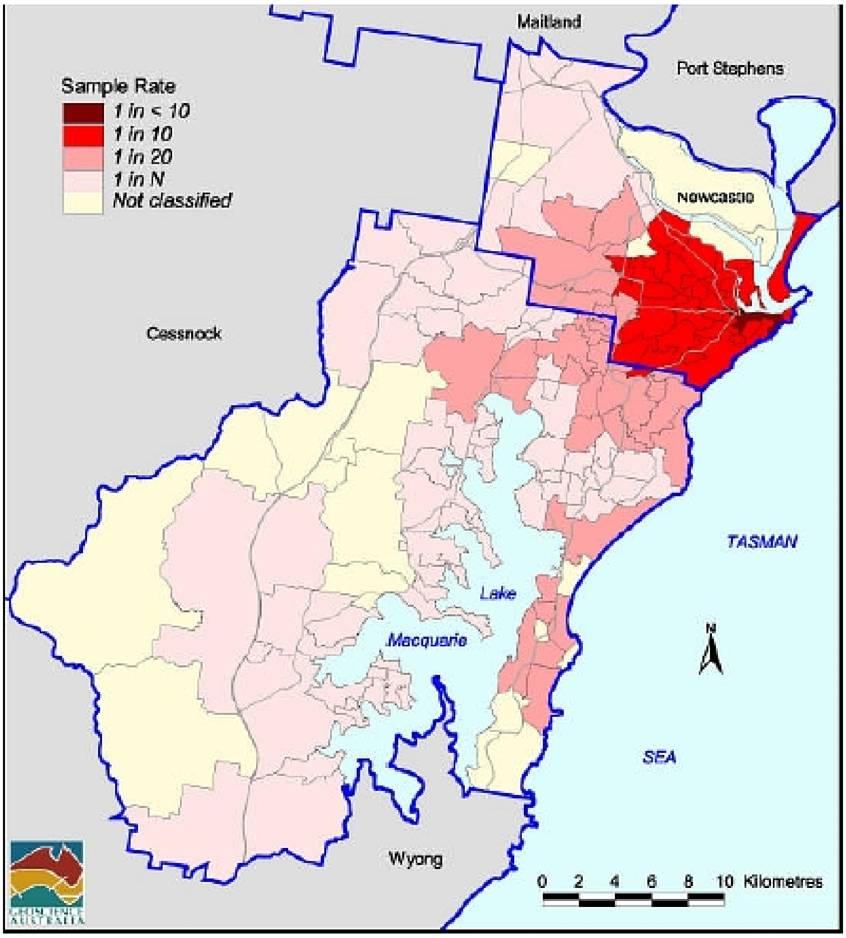

Figure 43: Building Inventory Survey Sampling Rate (Source: GA, 2002)

The results of the building inventory survey when paired with the tsunami modelling, highlight a significant risk of wide spread structural damage to building infrastructure during the tsunami event. Appendix C, Maps 2 and 4 detail the extent of the inundation thresholds where all structural types are at risk of total failure. The Building Inundation Map in Appendix D overlays the results from the building inventory survey with the critical inundation thresholds. This map clearly shows the potential tsunami impacts where all structure types are vulnerable to catastrophic failure. It should be noted that many buildings outside of these threshold areas are still at high risk of significant damage with both timber and unreinforced masonry buildings vulnerable to catastrophic damage at much lower inundation values.

Infrastructure & Services Unobtainable For Review

The following data sets where unable to be obtained for the purposes of the research project. Unfortunately the following services providers or owner of the data were unwilling to provide details network and infrastructure data. This was mainly due to security concerns and financial concerns. .

- **Telstra**

Available in small segments through the Dial Before You Dig (DBYD) service. This could be utilised for more targets research projects and was not a viable options for a project of this size.

- **Gas**

Also available through DBYD in small sections. Two supply companies unsuccessful were contacted for information regarding the network

- **Hunter Water**

Hunter Water did not wish to provide detailed infrastructure data for use in the research project. Fortunately the Hunter Water website contains a large volume of network information and major project construction data. All of the Hunter Water data used within the project was sourced from the website. Hunter Water infrastructure is also included in DBYD requests.

- **Building & Structural Data**

A private company was approached to gain access to their 3D building model of Newcastle. This data would have been included in the 3d inundation modelling base. The company did not respond to numerous approaches.

6. Conclusions / Recommendations

The research and modelling suggest that Newcastle is at significant risk of a major tsunami and the most likely source of such a wave event is the highly active subduction zone, the Puysegur Trench. Located to the south of New Zealand the Puysegur Trench is at the junction of the Indo-Australian and Pacific tectonic plates (Xing et al. 2014). The southern east coast of Australia provides the right deep water ocean conditions for unobstructed wave propagation which further compounds the tsunami risk (Xing et al. 2014).

The topography and layout of the Newcastle LGA does little to reduce the potential impact of such a tsunami event. Large portions of the LGA are flood prone and susceptible to tsunami inundation. The size of Newcastle's port and river system is also detrimental to the risk of tsunami inundation. The port and river system play major roles in Newcastle's economic production and as a result are heavily developed and utilised by significant infrastructure investment.

The detailed tsunami inundation modelling has found that significant key infrastructure in the Newcastle LGA is at risk of major damage and impact from such an event. A worst case inundation model was used as the case study where the tsunami event coincided with the Newcastle Probable Maximum Flood (PFM). This resulted in over 60% of the Newcastle LGA being inundated. While a conservative option this event produces only a 2% increase in inundation area compared to if the same tsunami event occurred during a typical high tide. An extensive list of key infrastructure was found to be impacted by the modelled event including:

- The arterial road network being inundated in ten locations including the Pacific and New England Highways and the Pacific Motorway. The level of inundation in these locations is up to 3.8m in depth and 6km in length. This level of inundation has significant potential to result in major damage, washouts and erosion to the road network. The potential impact of this cannot be understated. These road networks are the major travel routes within the Newcastle area and the impact of their inundation and damage will have a far greater reach than simply to the daily road user. The inundation and damage will restrict movement of the emergency services to impacted and inaccessible areas requiring assistance or repairs. It will also effectively cut the supply and delivery chain effecting thousands of businesses and resulting in additional economic impact.

- The impact to the rail network is significant with inundation and potential damage occurring at 9 railway stations, to 17kms of public rail network and to 23kms of heavy industry rail network. These distances take no account for multiple tracks and as a result the actual length of track impacted is thought to be far more significant. The inundation and damage to the network will also effectively stop all rail movements including freight, coal and passenger services.

- Major assets were identified by energy company Ausgrid within the inundation area. These were four zone substations and a sub-transmission substation (Ausgrid, 2015). The impact on these substations varies with two subject to significant inundation, two subject to minor inundation and the final substation escaping inundation due to its elevation. The resulting power loss will impact large residential and industrial areas. There will also likely be an impact to a number of industrial customers who require constant power supply for safety reasons.

- Two waste water treatment plants are key assets impacted as part of the sewer and water supply network. There is risk of additional damage to the pipe infrastructure of both networks but these were not quantified as part of the research project.

- Eleven schools are located within the inundation zone. Four additional schools are isolated as a result of the inundation. The total number of students and staff impacted exceeds 8,700. At least six of the schools within the inundation area are at risk of significant structural damage to their buildings and surrounding infrastructure.

- The network of emergency service providers are also impacted by the inundation. The inundation of these emergency services will impact the networks ability to respond and cope with the tsunami event. This will likely result in greater casualties and damage throughout the impacted area. The services impacted are:
    - Two ambulance stations,
    - Two police stations,
    - Four fire stations,
    - State Emergency Service (SES) headquarters, and
    - Newcastle Council Administration and Chambers building.

- General structural impacts on the buildings in Newcastle LGA are likely to be extensive. A building survey of the city undertaken by Geoscience Australia (2002) found that a significant number of the buildings within Newcastle are of construction types that would be severely impacted by the modelled tsunami inundation.

A review into the possible relocation of affected infrastructure should be undertaken as part of further research into Newcastle’s susceptibility to a tsunami. Much of the infrastructure included in this research project would be impractical or cost prohibitive to relocate, however relocation of some of the impacted infrastructure has the potential to significantly reduce the level of direct inundation and damage.

- The following emergency services providers are located marginally located within the inundation zone.
  - Two fire stations - Newcastle and Tarro,
  - Two ambulance stations – Hamilton and Birmingham Gardens,
  - One police station – Newcastle,
  - The SES headquarters, and
  - The Newcastle Council Administration and Chambers building.

  To relocate these services outside of the inundation zone would only entail moving them a few hundred metres which would have minimal impact, if any, on their response times. The exceptions to this are the Stockton Police and Fire Station, and the Carrington Fire Station. These are located centrally within suburbs that are completely inundated as a result on the tsunami event. Relocating these services outside of the inundation zone would require moving them from the respective suburbs completely. This level of relocation would require detailed review of the impact on response times to service areas and is likely to be impractical.

- There are also a number of schools within the inundation zone that may be candidates for relocation or disbursement of students and staff to other schools. The three smallest schools within the inundation area are also the most severely impacted. Stockton Public, St Peter’s at Stockton and Carrington Public due to their smaller size may be candidates for closure in their current locations. Their current locations within the inundation zone will likely result in their total destruction during the tsunami.

The research has highlighted that there are insufficient redundancies built into the infrastructure networks. For example the electrical network has a number of redundancies built into its system the major sub transmission substation within the inundation zone has no backup systems. If this substation is damaged as a result of the tsunami inundation and becomes nonoperational the network it supplies will be without power until it’s repaired. This section of the network has a number of critical consumers that require constant power supply for safety reasons and a result this seems like a flaw in the electrical networks redundancy systems. The remaining four substations included in the report can have emergency supply rerouted and supplied from other network locations.

The failing of the infrastructure has the potential to cause significant loss of life. Sudden inundation will impact a number of heavily populated areas. Apart from the inundation itself, the modelling suggests that many of the buildings in these locations will be destroyed with serious consequences for people seeking refuge within. The sudden inundation of major transport infrastructure such as roads and rail has the potential to impact everyday users and also people attempting to exit the city to avoid the event. It will result in significant hazards including inundated and damaged roadways. The impact of this on the emergency services network will affect their ability to efficiently respond to the emergency and in some cases prevent response completely. Without the required emergency services there is a high risk of the number of casualties and the amount of preventable damage to infrastructure increasing.

7. Project Limitations / Areas For Future Study

Further refinement of the current inundation model would be the first step to any further research on the potential impact to Newcastle. The tsunami model created for the project is a complex script file containing numerous inputs and data packages. Like all calculations and detailed engineering modelling the tsunami model is only as good as the data it is based on. There are a number of areas where the data input into the model could be improved including

- The survey data used for the model was provided by Newcastle City Council and the Port Authority of New South Wales. The survey did not contain 3D building data for the Newcastle LGA and detailed riverbed data in the western extent of the project area.

  The absence of building data makes it impossible to determine impact on a specific building within the inundation zone. Only generalised conclusions on building impact and damage could be made. The ANUGA software has the capability to undertake detailed flow modelling taking into account building profiles which would allow for specific results to be produced. This would be particularly useful for the large scale buildings within the CBD that are only partially inundated.

  The absence of a detailed riverbed survey at the western extent of the catchment was accounted for by using average river depth information and overlapping this within the survey. It is not expected that the addition of detailed survey data would result in significant changes with the inundation results, however for improvement of the model and providing further confidence in the results this additional survey should where possible be included

- Another part of the model which should be included as part of any future development is the friction value adopted. ANUGA uses a standard Manning's friction value which it applies throughout the model area. Research into providing a detailed catchment wide friction value for the model should be included to provide greater reliability to the model results. For this research project a friction value of zero was adopted in order to produce conservative inundation results.

- A detailed peer review of the model and input data. There are many experts in the field of tsunami and flood inundation modelling. A detailed peer review of the model would instil a level of confidence in the results and allowed for more accurate findings and recommendations to be made.

Detailed analysis of individual infrastructure items such as bridges, coal loaders or major buildings was not undertaken as part of this research. This would be a logical future development of the current research and minimal adjustment to the current model would be required to provide specific site inundation results which could be used for a detailed structural impact or damage review.

There is a significant amount of technology that has been developed throughout the world to mitigate the impact of or even protect against a major tsunami event. Much of this technology has been implemented in Japan who are world leaders in tsunami protection investment (Mimura et al, 2011). The review of implementation of such technologies is outside the scope of this project. A high level cost benefit analysis of the implementation of a number of these technologies such as breakwaters or coastal dykes would be an ideal starting point to continue this project in the area of tsunami protection and mitigation.

The tsunami modelling was undertaken specifically for the Newcastle LGA. The development of the model to include the entire east coast of NSW would provide for a wide scale review into tsunami risk and potential. The majority of the background research undertaken into tsunami risk and potential for the Newcastle LGA is applicable for the entire NSW coastline and can be applied in any future modelling. This would allow for the development of more extensive tsunami inundation profile along the east coast.

While the generosity and willingness of service providers, agencies and different companies to provide critical information made this project possible, one of the major limitations experienced was also the lack of co-operation from a number of service providers and holders of key infrastructure. Telstra, Hunter Water and the numerous providers of gas within Newcastle were unwilling to provide network specific information for review as part of this project. This was typically a result of security concerns due to the scale of information being requested. For further details on the infrastructure included and excluded from the review refer to Results

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9. Appendices

Appendix A – Project Specification

FACULTY OF ENGINEERING AND SURVEYING

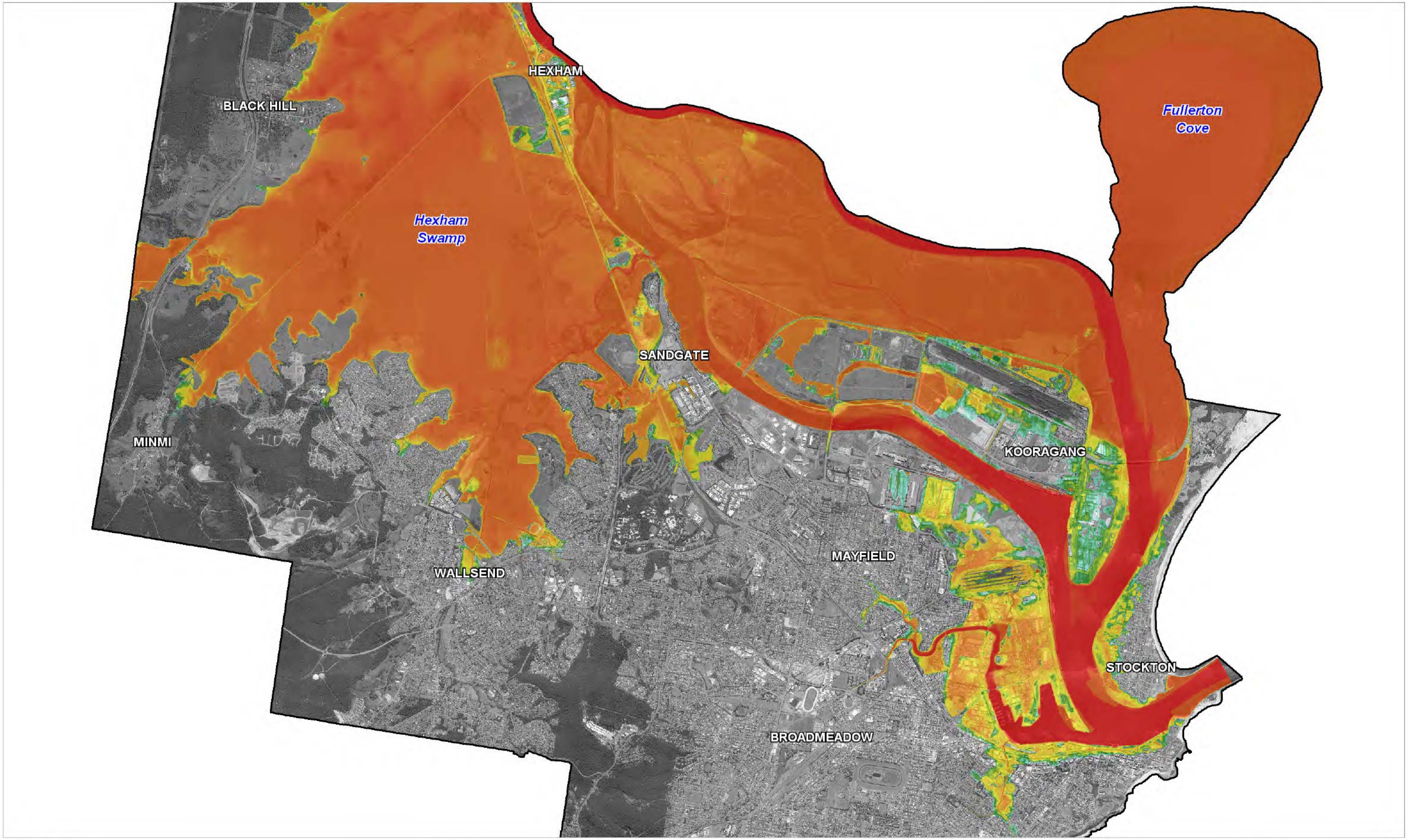
ENGINEERING RESEARCH PROJECT 2015 – PROJECT SPECIFICATION

FOR:	Gregory Couch (0050070018)
TOPIC:	Key Infrastructure Review (Newcastle, NSW) – Vulnerability to a Tsunami
SUPERVISORS:	Trevor Drysdale
ENROLMENT:	ENG4111_2015_S1
	ENG4112_2015_S2
PROJECT AIM:	To undertake a key infrastructure review of the Newcastle area in relation to vulnerability to tsunami damage.

PROGRAMME: (Rev A, Date: 17-03-2015)

1. Undertake background research in likely cause and source of tsunamis impacting the east coast of Australia.
2. Prepare inundation model of the Newcastle coastline to determine full extent of tsunami impact.
3. Locate and document key infrastructure within inundation zone. Key infrastructure to include:
    - Arterial roadways
    - Rail Network
    - Electricity Networks
    - Trunk Water Mains
    - Sewer Mains
    - Communications
    - Emergency Services (Police, Fire, Ambulance, etc.).
4. Detail and discuss potential damage, and social impact resulting from Tsunami strike;
5. Draw conclusions on Newcastle's susceptibility to significate tsunami damage. List any additional mitigating actions that could be feasibly undertaken to reduce impact/damage.

Appendix B – PMF – Ocean Flood Depths



LEGEND

Peak Flood Depth (m)

- 0.10 (flooding <0.1m deep not mapped)
- 0.50
- 1.00
- 2.00
- 5.00 (higher depths mapped as same colour)

Note: Adopted ocean level = 3.4m AHD
(PMF with 0.9m sea level rise included)

Title:

Newcastle Floodplain Risk Management Study
Map Series 3 - PMF Ocean Flood Depths

Figure: 3-D

Rev: A

N

0 1.25 2.5km

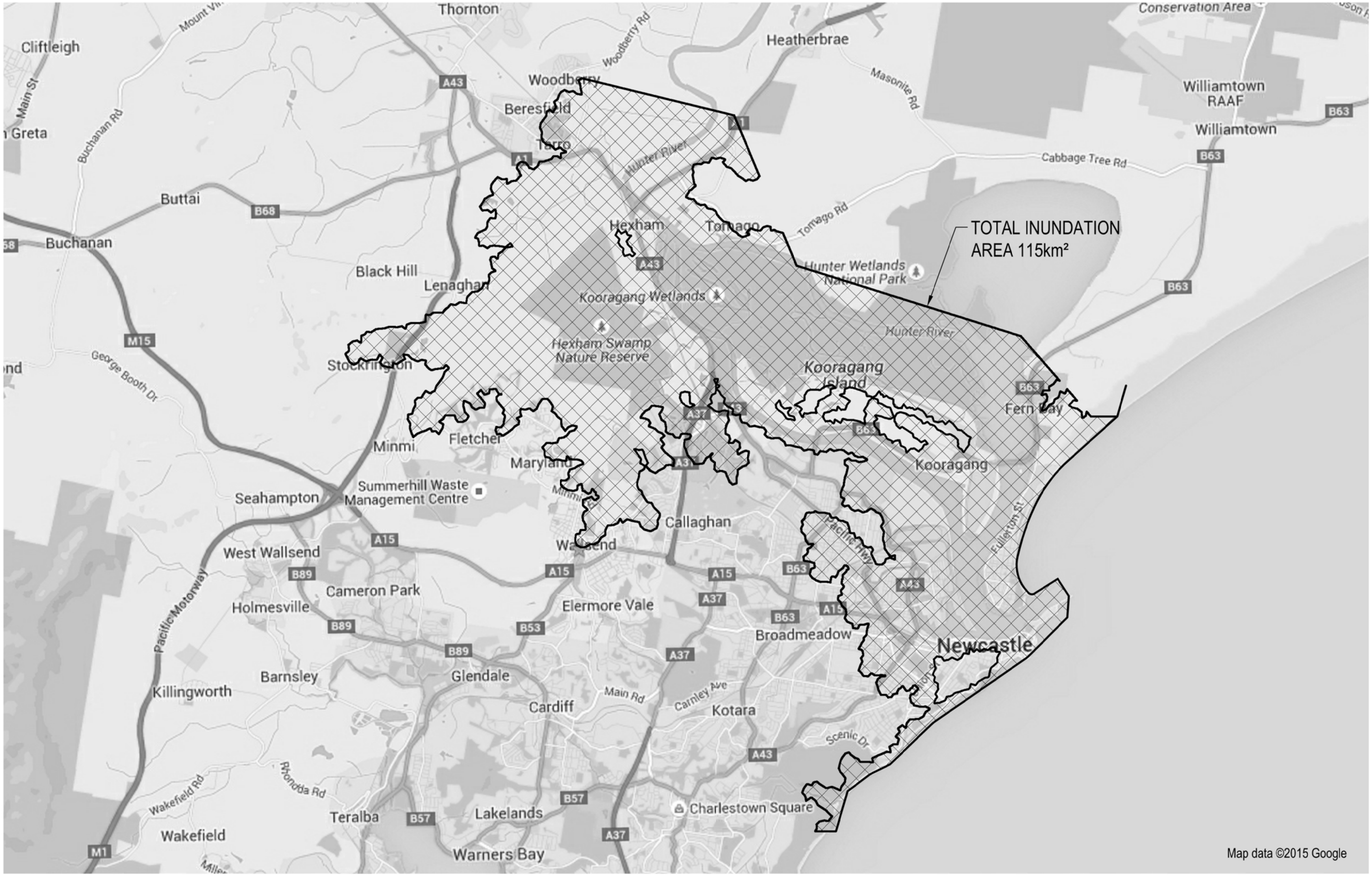
Approx. Scale

BMT WBM

www.bmtwbm.com.au

Filepath : K:\N2246_Newcastle_FRMS_Stage2\Mapinfo\workspaces\DRG_304_111220_Map3-D.WOR

Appendix C – Inundation Maps



SCALE 1:100,000 @ A3

0 1km 2km 4km 6km 8km 10km

Issue	Description	Date	Drawn	Approved

North

Project

NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

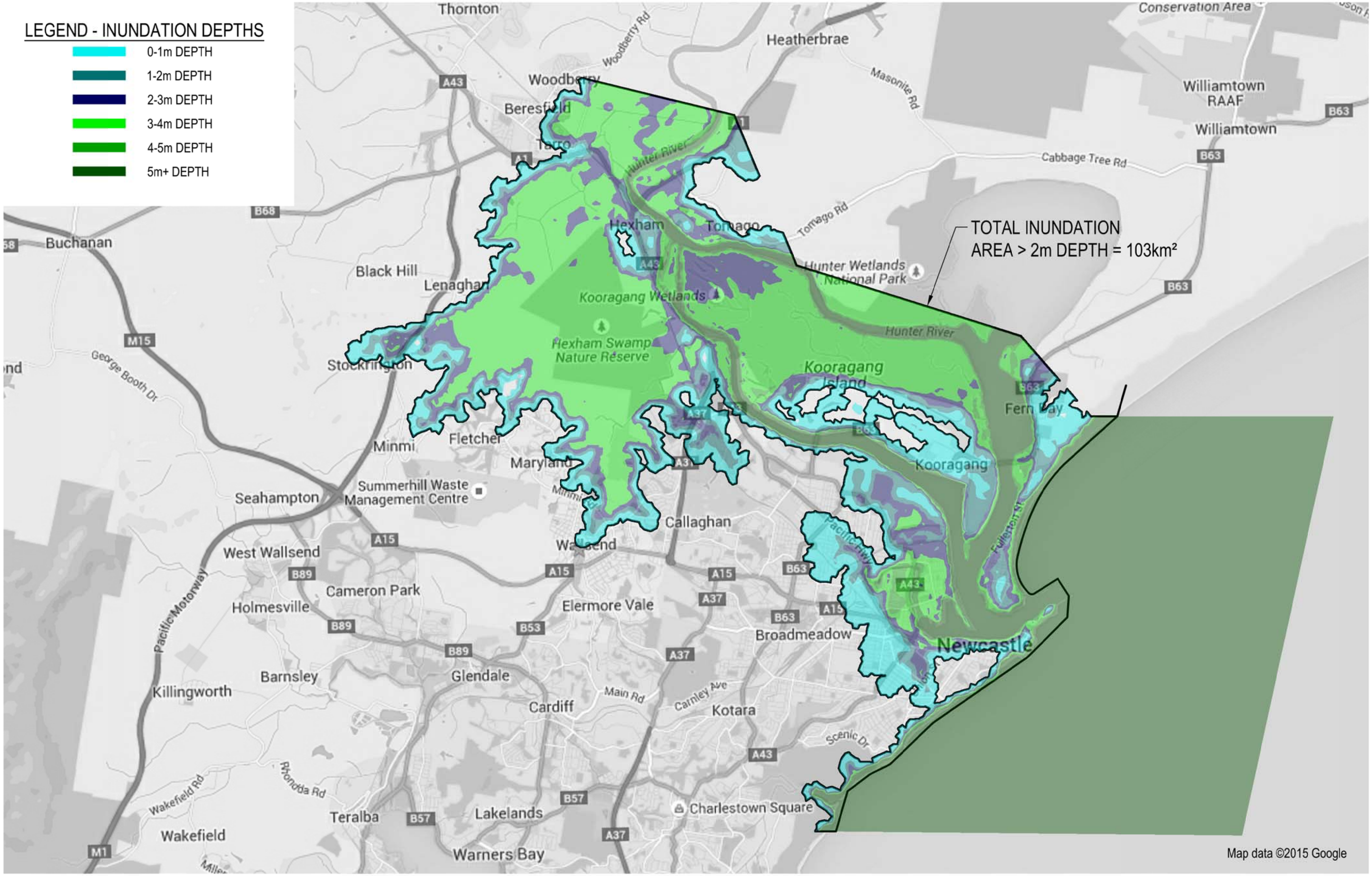
Drawing Title

MAP-1 INUNDATION MAP (PMF)

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	04/08/15	1:100,000	-	-

Designed	Project No.	Dwg. No.	Issue
-		MAP-1	A

Oct 15, 2015 - 6:19pm



SCALE 1:100,000 @ A3

0 1km 2km 4km 6km 8km 10km

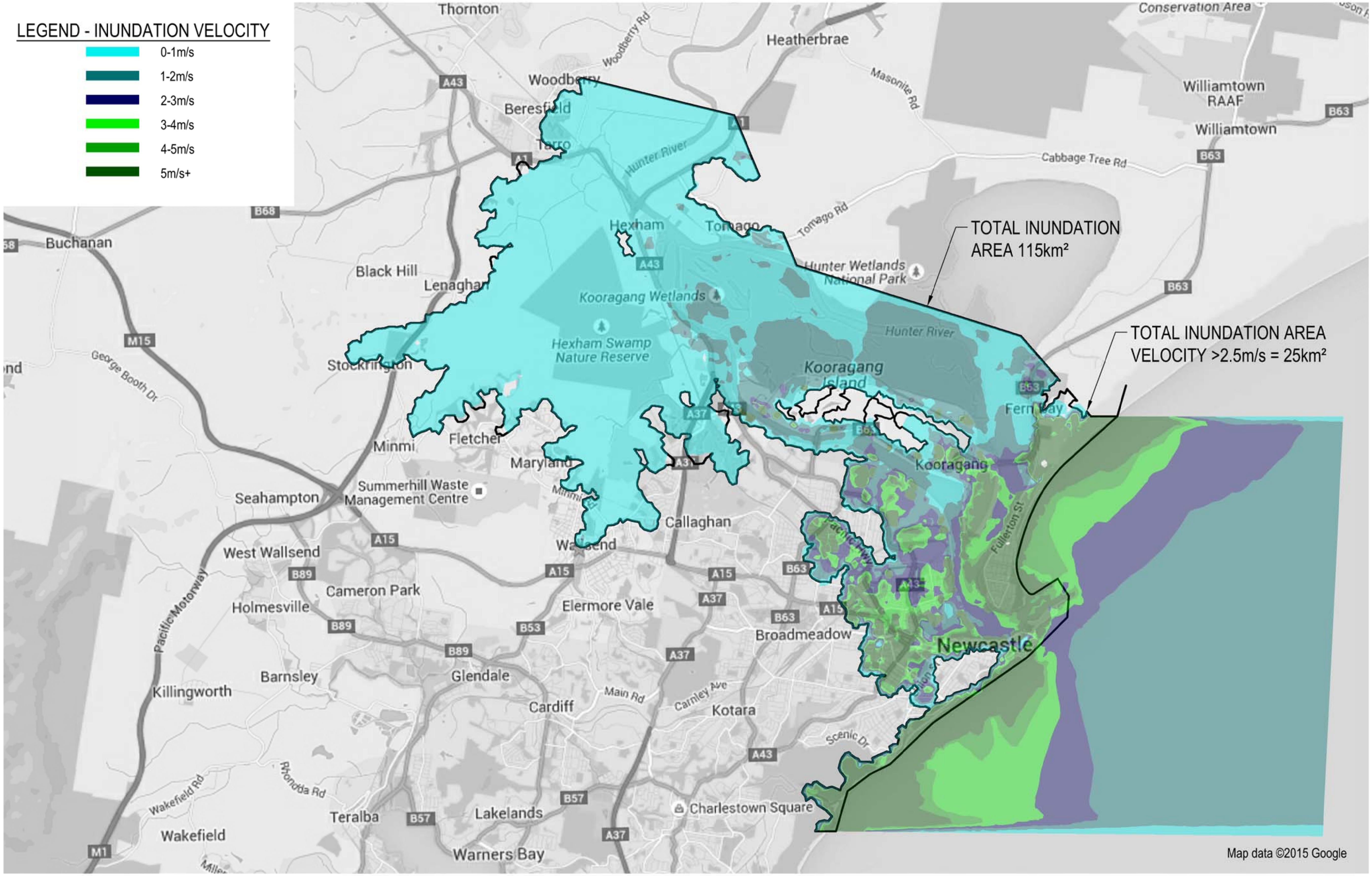
Issue	Description	Date	Drawn	Approved

North

Project
NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

Drawing Title
MAP-2 INUNDATION DEPTHS (PMF)

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	04/08/15	1:100,000	-	-
Designed	Project No.		Dwg. No.	Issue
-			MAP-2	A



SCALE 1:100,000 @ A3

0 | 1km | 2km | 4km | 6km | 8km | 10km

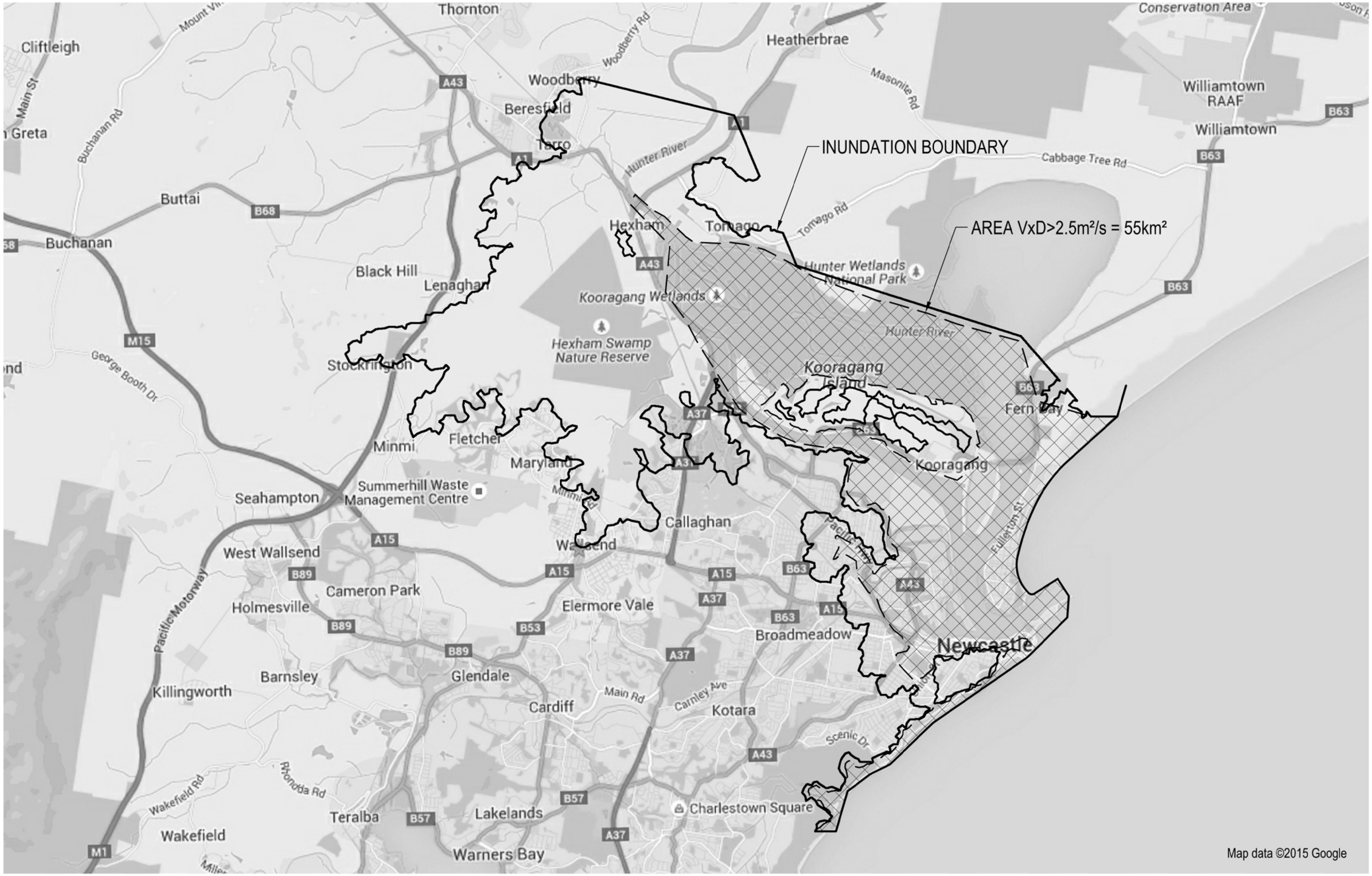
Issue	Description	Date	Drawn	Approved

North

Project
NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

Drawing Title
MAP-3 INUNDATION VELOCITY (PMF)

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	04/08/15	1:100,000	-	-
Designed	Project No.		Dwg. No.	Issue
-			MAP-3	A



SCALE 1:100,000 @ A3

0 1km 2km 4km 6km 8km 10km

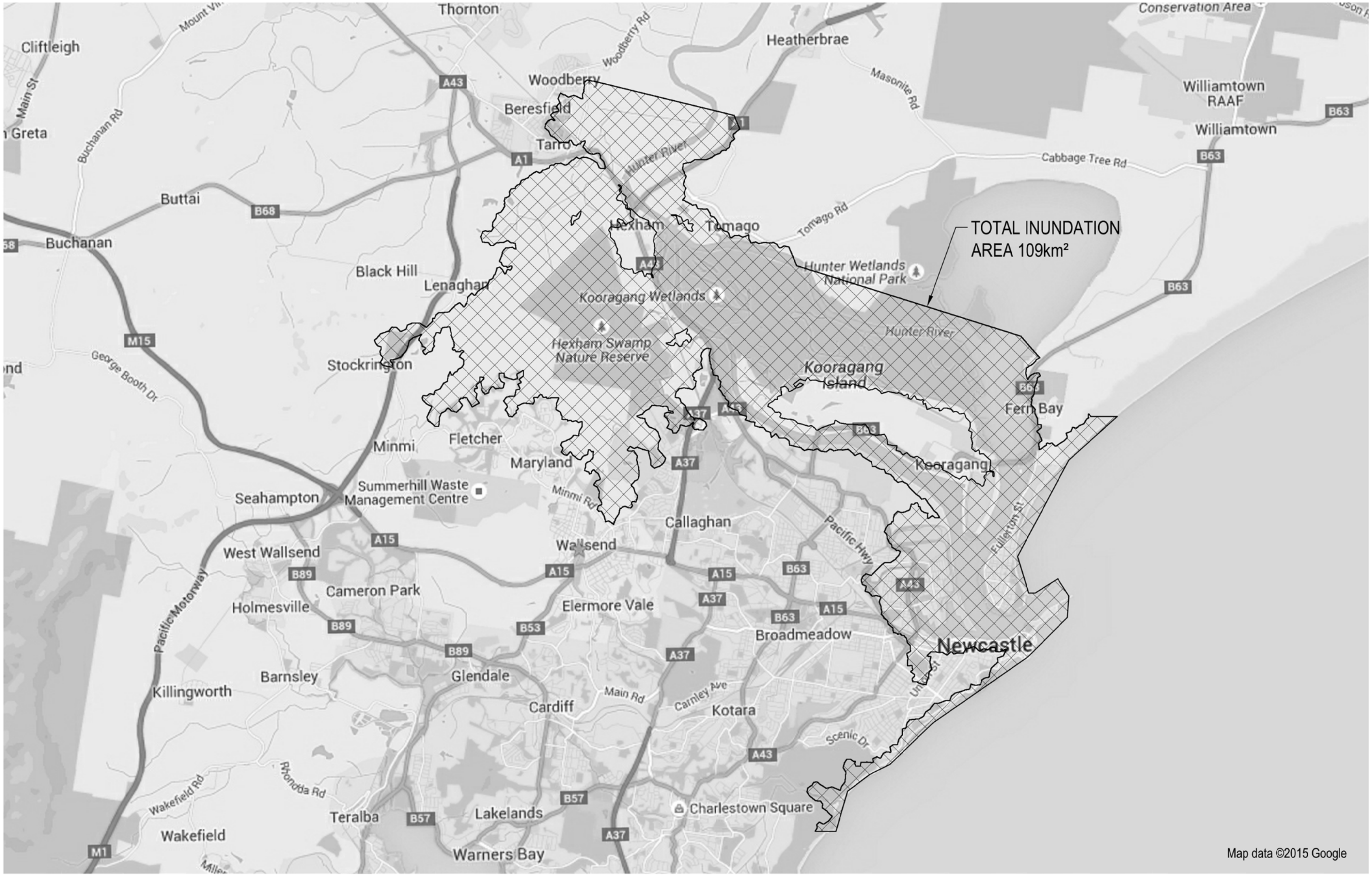
Issue	Description	Date	Drawn	Approved

North

Project
NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

Drawing Title
MAP-4 INUNDATION VELOCITYxDEPTH MAP (PMF)

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	20/10/15	1:100,000	-	-
Designed	Project No.		Dwg. No.	Issue
-			MAP-4	A



SCALE 1:100,000 @ A3

0 1km 2km 4km 6km 8km 10km

Issue	Description	Date	Drawn	Approved

North

Project
NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

Drawing Title
MAP-5 INUNDATION MAP (HIGH TIDE)

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	04/08/15	1:100,000	-	-
Designed	Project No.		Dwg. No.	Issue
-			MAP-5	A

Appendix D – Infrastructure Inundation Maps

SCALE 1:100,000 @ A3

0 1km 2km 4km 6km 8km 10km

Issue	Description	Date	Drawn	Approved

North

Project
NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

Drawing Title
ROADWAY INUNDATION MAP

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	04/08/15	1:100,000		
Designed	Project No.		Dwg. No. ROAD 1	Issue A

SCALE 1:100,000 @ A3

0 1km 2km 4km 6km 8km 10km

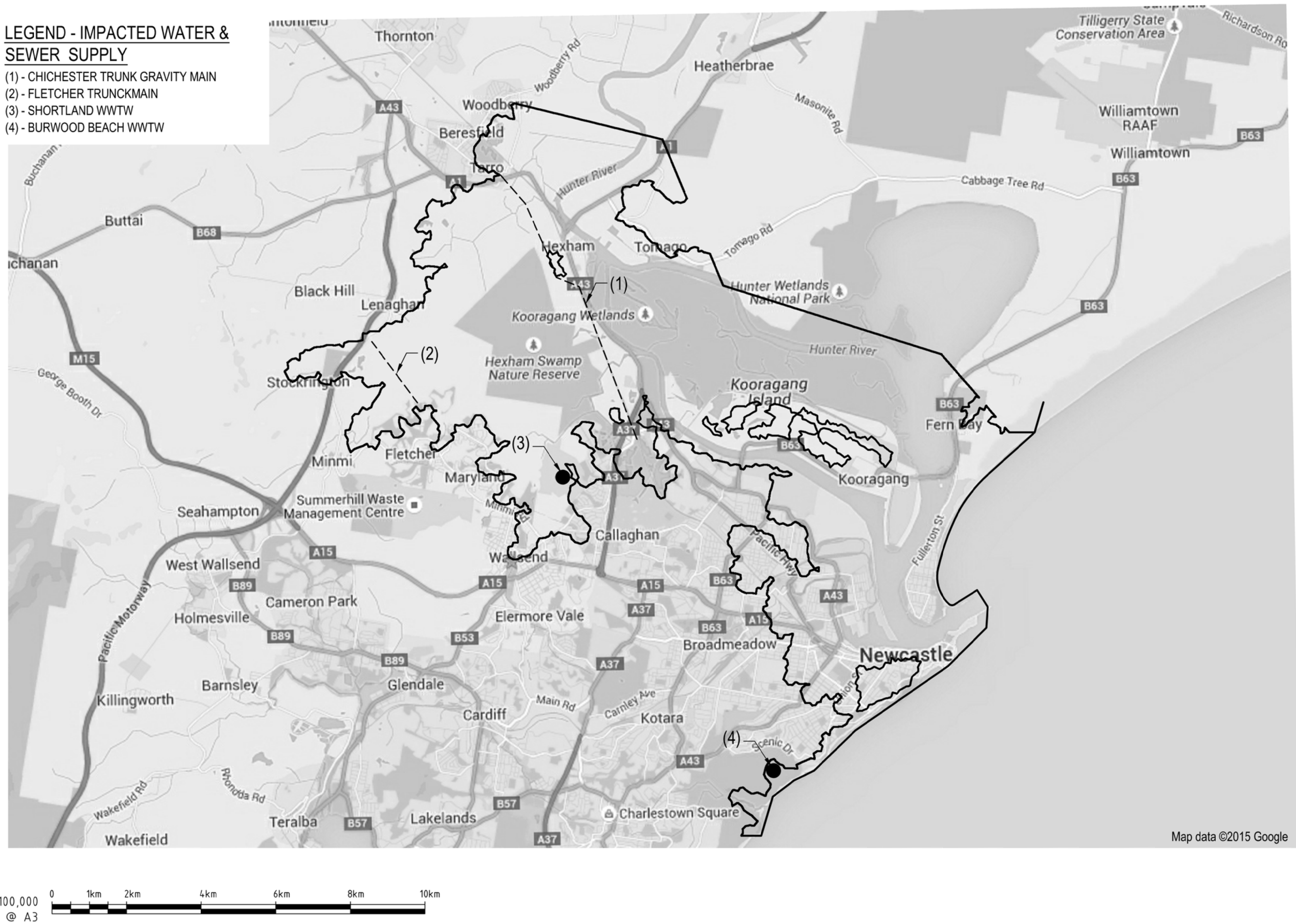
Issue	Description	Date	Drawn	Approved

North

Project
NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

Drawing Title
RAIL INUNDATION MAP

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	04/10/15	1:100,000		
Designed	Project No.		Dwg. No. RAIL 1	Issue A



North

Project
NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

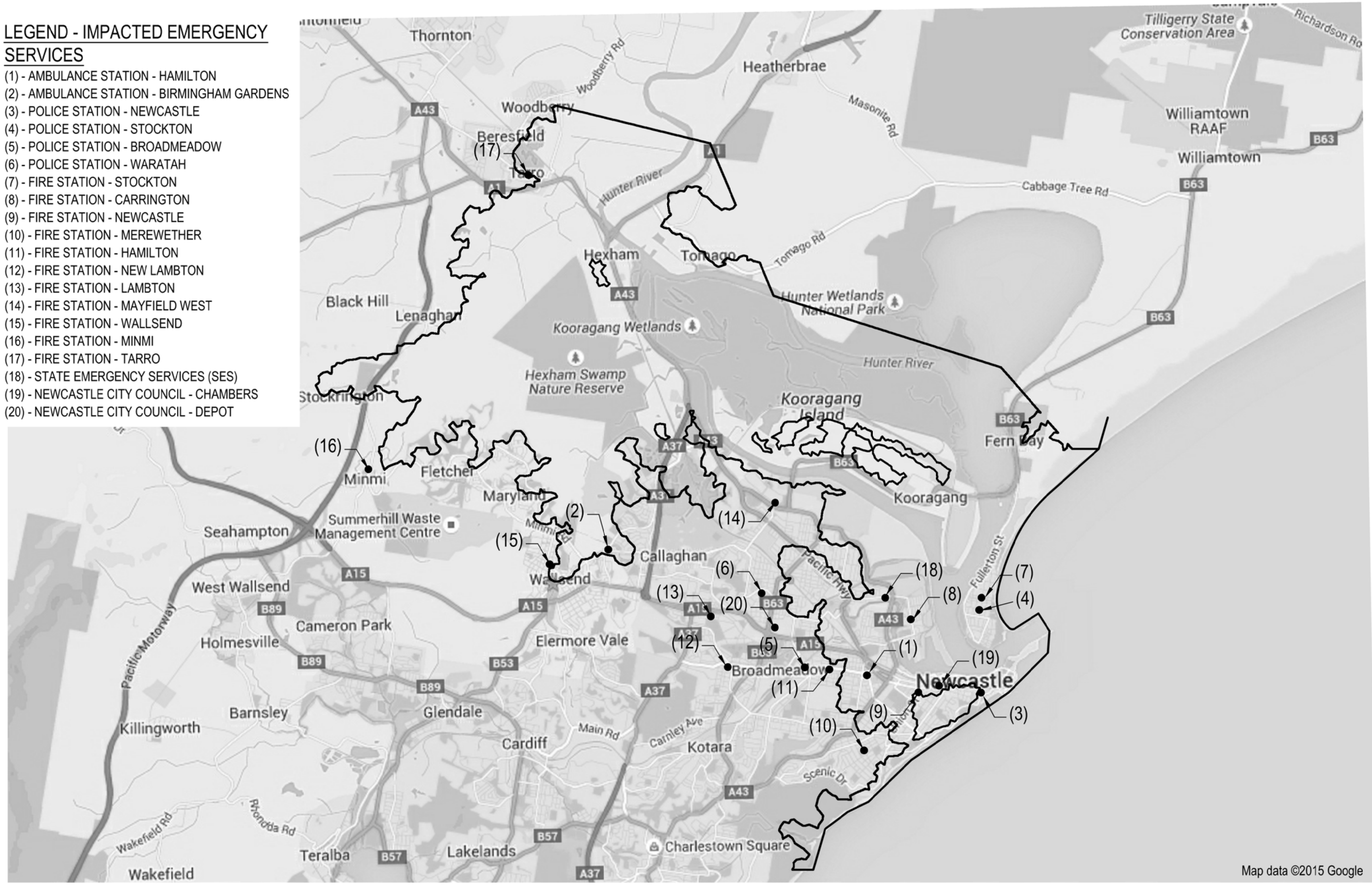
Drawing Title
WATER & SEWER SUPPLY
INUNDATION MAP

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	04/10/15	1:100,000		
Designed	Project No.		Dwg. No. HW 1	Issue A

Issue	Description	Date	Drawn	Approved

LEGEND - IMPACTED EMERGENCY SERVICES

(1) - AMBULANCE STATION - HAMILTON
(2) - AMBULANCE STATION - BIRMINGHAM GARDENS
(3) - POLICE STATION - NEWCASTLE
(4) - POLICE STATION - STOCKTON
(5) - POLICE STATION - BROADMEADOW
(6) - POLICE STATION - WARATAH
(7) - FIRE STATION - STOCKTON
(8) - FIRE STATION - CARRINGTON
(9) - FIRE STATION - NEWCASTLE
(10) - FIRE STATION - MEREWETHER
(11) - FIRE STATION - HAMILTON
(12) - FIRE STATION - NEW LAMBTON
(13) - FIRE STATION - LAMBTON
(14) - FIRE STATION - MAYFIELD WEST
(15) - FIRE STATION - WALLSEND
(16) - FIRE STATION - MINMI
(17) - FIRE STATION - TARRO
(18) - STATE EMERGENCY SERVICES (SES)
(19) - NEWCASTLE CITY COUNCIL - CHAMBERS
(20) - NEWCASTLE CITY COUNCIL - DEPOT



SCALE 1:100,000 @ A3

0 1km 2km 4km 6km 8km 10km

Issue	Description	Date	Drawn	Approved

North

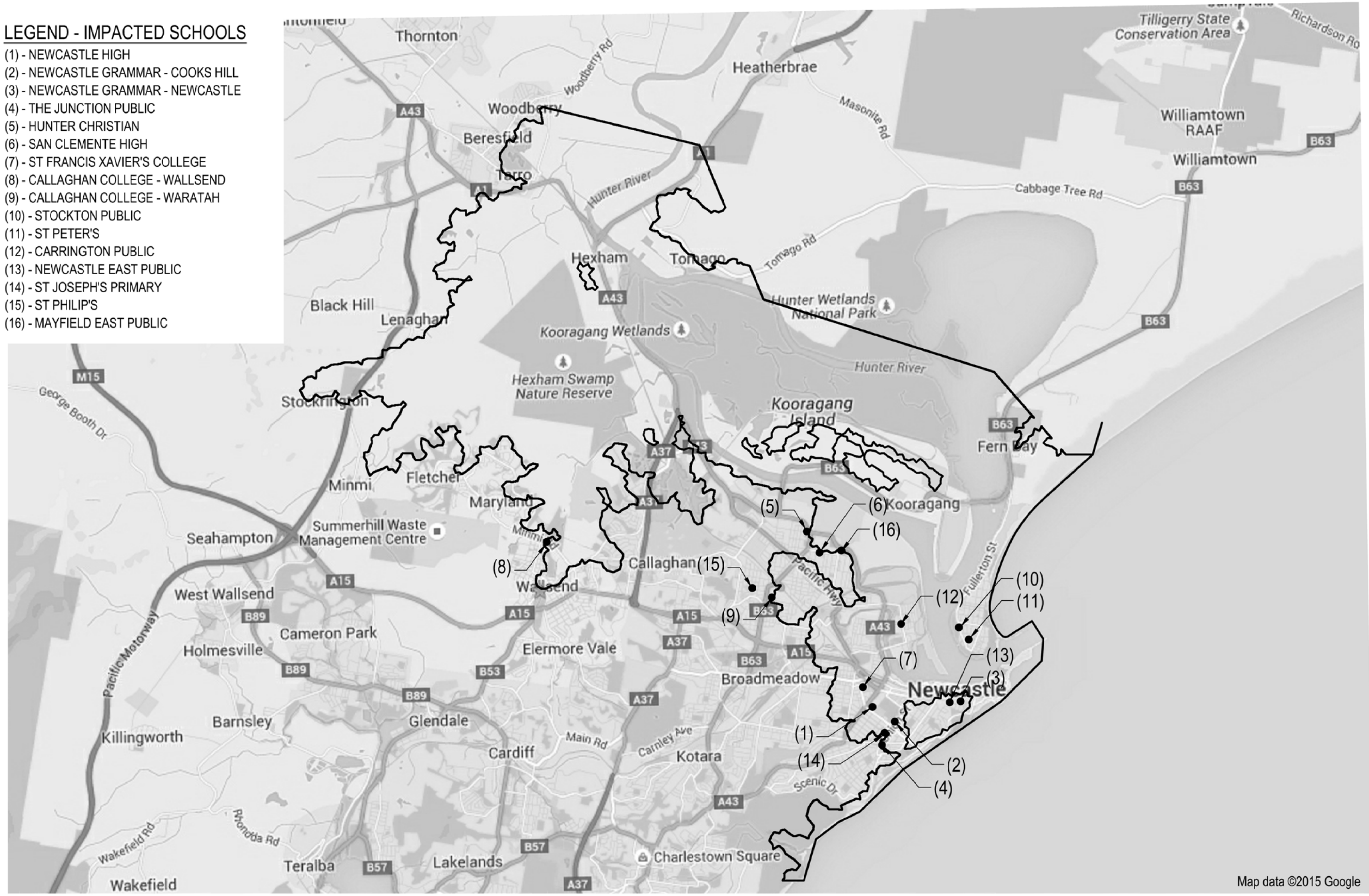
Project
NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

Drawing Title
EMERGENCY SERVICES
INUNDATION MAP

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	04/10/15	1:100,000		
Designed	Project No.		Dwg. No. EMERGS 1	Issue A

LEGEND - IMPACTED SCHOOLS

(1) - NEWCASTLE HIGH
(2) - NEWCASTLE GRAMMAR - COOKS HILL
(3) - NEWCASTLE GRAMMAR - NEWCASTLE
(4) - THE JUNCTION PUBLIC
(5) - HUNTER CHRISTIAN
(6) - SAN CLEMENTE HIGH
(7) - ST FRANCIS XAVIER'S COLLEGE
(8) - CALLAGHAN COLLEGE - WALLSEND
(9) - CALLAGHAN COLLEGE - WARATAH
(10) - STOCKTON PUBLIC
(11) - ST PETER'S
(12) - CARRINGTON PUBLIC
(13) - NEWCASTLE EAST PUBLIC
(14) - ST JOSEPH'S PRIMARY
(15) - ST PHILIP'S
(16) - MAYFIELD EAST PUBLIC



SCALE 1:100,000 @ A3

0 1km 2km 4km 6km 8km 10km

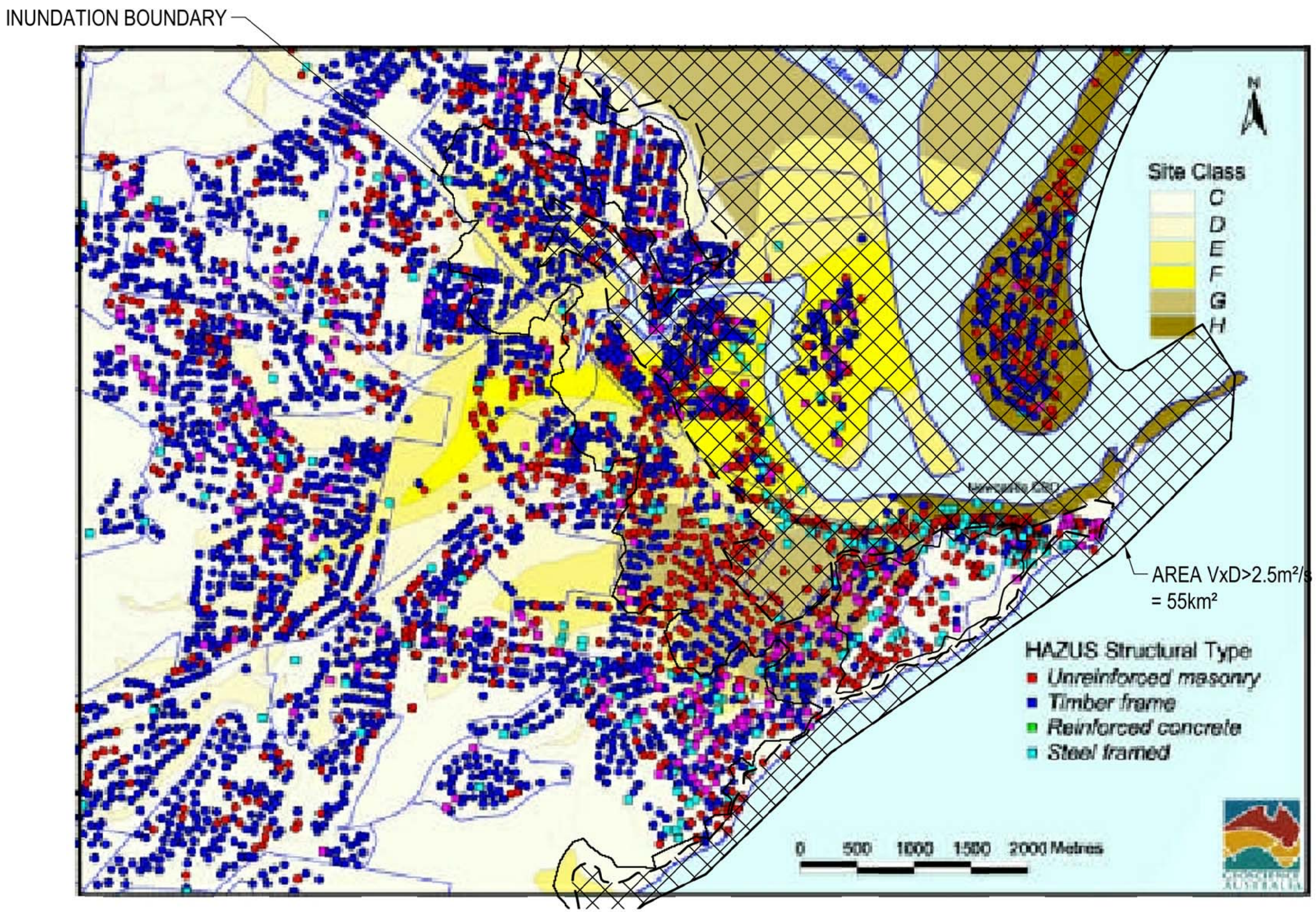
Issue	Description	Date	Drawn	Approved

North

Project
NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

Drawing Title
SCHOOL INUNDATION MAP

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	04/10/15	1:100,000		
Designed	Project No.		Dwg. No. SCHOOL 1	Issue A



SCALE 1:40,000 @ A3 — 0, 0.5km, 1km, 1.5km, 2km, 3km, 4km

NOT FOR CONSTRUCTION

Issue	Description	Date	Drawn	Approved

North

Project
NEWCASTLE LGA
TSUNAMI VULNERABILITY STUDY

Drawing Title
BUILDING INUNDATION MAP
NEWCASTLE CBD & INNER SUBURBS

Drawn	Date	Scale A3	Q.A. Check	Date
GPC	04/10/15	1:40,000		
Designed	Project No.		Dwg. No.	Issue
			BUILDING 1	A

Appendix E – Tsunami Modelling Code

```
"""Tsunami inundation script for Newcastle LGA coastline, NSW Australia.
Script compiled using example data provided with the ANUGA program files and
the ANUGA User Manual. Script is to produce an inundation model of the
Newcastle Local Government Area which will be adapted to undertake a key
infrastructure review relating to tsunami damage. Refer to project report for
further details.
"""

#------------------------------------------------------------------------------
# Import Required Project Modules
#------------------------------------------------------------------------------
# Operating System Model
import os

# Time Model
import time

# System - specific parameters and functions Model
import sys

# Import Anuga - Modeling Software
import anuga

#------------------------------------------------------------------------------
# The following code sets files names, domain definitions, project polygons
# and export extent.
#------------------------------------------------------------------------------

# Runtime parameters


cache = False

verbose = True



# Set Project Filenames

name_stem = 'newcastle'
meshname = name_stem + '.msh'

#  Filename for locations where timeseries are to be produced

gauge_filename = 'newcastle_gauges.csv'

#------------------------------------------------------------------------------
# Define extent of project modeling boundary and simulation resolution.
#------------------------------------------------------------------------------
#  bounding polygon for study area
bounding_polygon =  anuga.read_polygon('newcastle_extent.csv')

A =  anuga.polygon_area(bounding_polygon) / 1000000.0
print  'Area of bounding polygon  =  %.2f km^2' %   A

# No Interior regions setup. No interior polygons required.
# Define resolution. Only 1 area so only 1 resolution requied.

default_res = 10000

#------------------------------------------------------------------------------

# Define extent of project asci grid - for export
#------------------------------------------------------------------------------

eastingmin = 368000

eastingmax = 390000

northingmin = 6350990

northingmax = 6372160

#------------------------------------------------------------------------------
# Setting on time measurement method, time() sets
#------------------------------------------------------------------------------
time00 = time.time()

#------------------------------------------------------------------------------
# Setup 3d surface mesh and domain details using extent polygon. Boundary tags
# set on extent poly for future boundary condition specification.
#------------------------------------------------------------------------------
domain = anuga.create_domain_from_regions(bounding_polygon,
                                    boundary_tags={'north_one': [0],
                                                   'north_two': [1],
                                                   'north_three': [2],
                                                   'north_four': [3],
                                                   'north_five': [4],
                                                   'east_one': [5],
                                                   'south_one': [6],
                                                   'south_two': [7],
                                                   'south_three': [8],
                                                   'south_four': [9],
                                                   'south_five': [10],
                                                   'south_six': [11],
                                                   'west_one': [12]},
                                    maximum_triangle_area=default_res,
                                    mesh_filename=meshname,
# interior_regions=interior_regions,
                                    use_cache=cache,
                                    verbose=verbose)

# Print detials reltating to mesh and domain
```

```
print 'Number of triangles = ', len(domain)
print 'The extent is ', domain.get_extent()
print domain.statistics()

#------------------------------------------------------------------------------
# Setup initial parameters of computational model
#------------------------------------------------------------------------------
domain.set_name('newcastle') # Name of sww file
domain.set_datadir('.')                        # Store sww output here
domain.set_minimum_storable_height(0.01)       # Store only depth > 1cm
domain.set_flow_algorithm('DE1')               # Refer to report for details


#------------------------------------------------------------------------------
# Setup initial conditions for tsunami impact
#------------------------------------------------------------------------------

#Tide RL based of BMT WBM flood report for PMF ocean flood event.
#Refer to project report for detials

tide = 3.4
domain.set_quantity('stage', tide)

# For details on friction value refer to project report,

domain.set_quantity('friction', 0.0)


domain.set_quantity('elevation',
                    filename=name_stem + '.txt',
                    use_cache=cache,
                    verbose=verbose,
                    alpha=0.1)


time01 = time.time()
print 'That took %.2f seconds to fit data' %(time01-time00)

#------------------------------------------------------------------------------
# Setup for time-varying wave simulation - Tsunami!!
#------------------------------------------------------------------------------
print 'Available boundary tags', domain.get_boundary_tags()

Bd = anuga.Dirichlet_boundary([tide, 0, 0]) # Mean water level
Bs = anuga.Transmissive_stage_zero_momentum_boundary(domain) # Neutral boundary

#-----------------------------------

# Here we read a timeseries, and then pass
# that function as a set stage transmissive boundary

#import scipy
from scipy import interpolate,genfromtxt
import anuga.shallow_water.boundaries as asb

# The wave data file also known as the boundary_data_file should be a csv with
# 2 columns: time in seconds, stage in m.In this model the data file has a
# single header row which is skipped (see 'skip_header' below).
boundary_data_file = 'wave_time.csv'


# Read data
boundary_data = genfromtxt(
    boundary_data_file,
    delimiter=',',
    skip_header=1)

# Make interpolation function
#stage_time_fun = scipy.interpolate.interp1d(

stage_time_fun = interpolate.interp1d(
    boundary_data[:, 0],
    boundary_data[:, 1])

# Make boundary condition
Bw = asb.Transmissive_n_momentum_zero_t_momentum_set_stage_boundary(domain, stage_time_fun)

#-----------------------------------

domain.set_boundary({'north_one': Bs,
                    'north_two': Bs,
                    'north_three': Bs,
                    'north_four': Bs,
                    'north_five': Bs,
                    'east_one': Bw,
                    'south_one': Bs,
                    'south_two': Bs,
                    'south_three': Bs,
                    'south_four': Bs,
                    'south_five': Bs,
                    'south_six': Bs,
                    'west_one': Bd})

#------------------------------------------------------------------------------
# Development of model and calculation time specs.
#------------------------------------------------------------------------------
import time
t0 = time.time()

from numpy import allclose

    # Save every two mins leading up to wave approaching land
for t in domain.evolve(yieldstep=2*60, finaltime=9000):
```

```
    print domain.timestepping_statistics()
    print domain.boundary_statistics(tags='east_one')

    # Save every 30 secs as wave starts inundating ashore
for t in domain.evolve(yieldstep=60*0.5, finaltime=30000,
                       skip_initial_step=True):
    print domain.timestepping_statistics()
    print domain.boundary_statistics(tags='east_one')

print 'That took %.2f seconds' %(time.time()-t0)
```

```
import os
import sys
import anuga

name = 'newcastle'

print 'output dir:', name
which_var = 2

if which_var == 0:    # Stage
    outname = name + '_stage'
    quantityname = 'stage'

if which_var == 1:    # Absolute Momentum
    outname = name + '_momentum'
    quantityname = '(xmomentum**2 + ymomentum**2)**0.5'    #Absolute momentum

if which_var == 2:    # Depth
    outname = name + '_depth'
    quantityname = 'stage-elevation'  #Depth

if which_var == 3:    # Speed
    outname = name + '_speed'
    quantityname = '(xmomentum**2 + ymomentum**2)**0.5/(stage-elevation+1.e-3)'  #Speed

if which_var == 4:    # Elevation
    outname = name + '_elevation'
    quantityname = 'elevation'  #Elevation

print 'start sww2dem'

anuga.sww2dem(name+'.sww',
        outname+'.asc',
        quantity=quantityname,
        cellsize=10,
        #easting_min=eastingmin,
        #easting_max=eastingmax,
        #northing_min=northingmin,
        #northing_max=northingmax,
        reduction=max,
        verbose=False)
```

```
import os
import sys
import anuga

name = 'newcastle'

print 'output dir:', name
which_var = 3

if which_var == 0:    # Stage
    outname = name + '_stage'
    quantityname = 'stage'

if which_var == 1:    # Absolute Momentum
    outname = name + '_momentum'
    quantityname = '(xmomentum**2 + ymomentum**2)**0.5'    #Absolute momentum

if which_var == 2:    # Depth
    outname = name + '_depth'
    quantityname = 'stage-elevation'  #Depth

if which_var == 3:    # Speed
    outname = name + '_speed'
    quantityname = '(xmomentum**2 + ymomentum**2)**0.5/(stage-elevation+1.e-3)'  #Speed

if which_var == 4:    # Elevation
    outname = name + '_elevation'
    quantityname = 'elevation'  #Elevation

print 'start sww2dem'

anuga.sww2dem(name+'.sww',
        outname+'.asc',
        quantity=quantityname,
        cellsize=10,
        #easting_min=eastingmin,
        #easting_max=eastingmax,
        #northing_min=northingmin,
        #northing_max=northingmax,
        reduction=max,
        verbose=False)
```

```
import os
import sys
import anuga

name = 'newcastle'

print 'output dir:', name
which_var = 4

if which_var == 0:    # Stage
    outname = name + '_stage'
    quantityname = 'stage'

if which_var == 1:    # Absolute Momentum
    outname = name + '_momentum'
    quantityname = '(xmomentum**2 + ymomentum**2)**0.5'    #Absolute momentum

if which_var == 2:    # Depth
    outname = name + '_depth'
    quantityname = 'stage-elevation'  #Depth

if which_var == 3:    # Speed
    outname = name + '_speed'
    quantityname = '(xmomentum**2 + ymomentum**2)**0.5/(stage-elevation+1.e-3)'  #Speed

if which_var == 4:    # Elevation
    outname = name + '_elevation'
    quantityname = 'elevation'  #Elevation

print 'start sww2dem'

anuga.sww2dem(name+'.sww',
        outname+'.asc',
        quantity=quantityname,
        cellsize=10,
        #easting_min=eastingmin,
        #easting_max=eastingmax,
        #northing_min=northingmin,
        #northing_max=northingmax,
        reduction=max,
        verbose=False)
```