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Tsunami impact, education and community consultation in the communities of Onslow and Exmouth:

A Geoscience Australia and Fire and Emergency Services Authority (WA) collaboration

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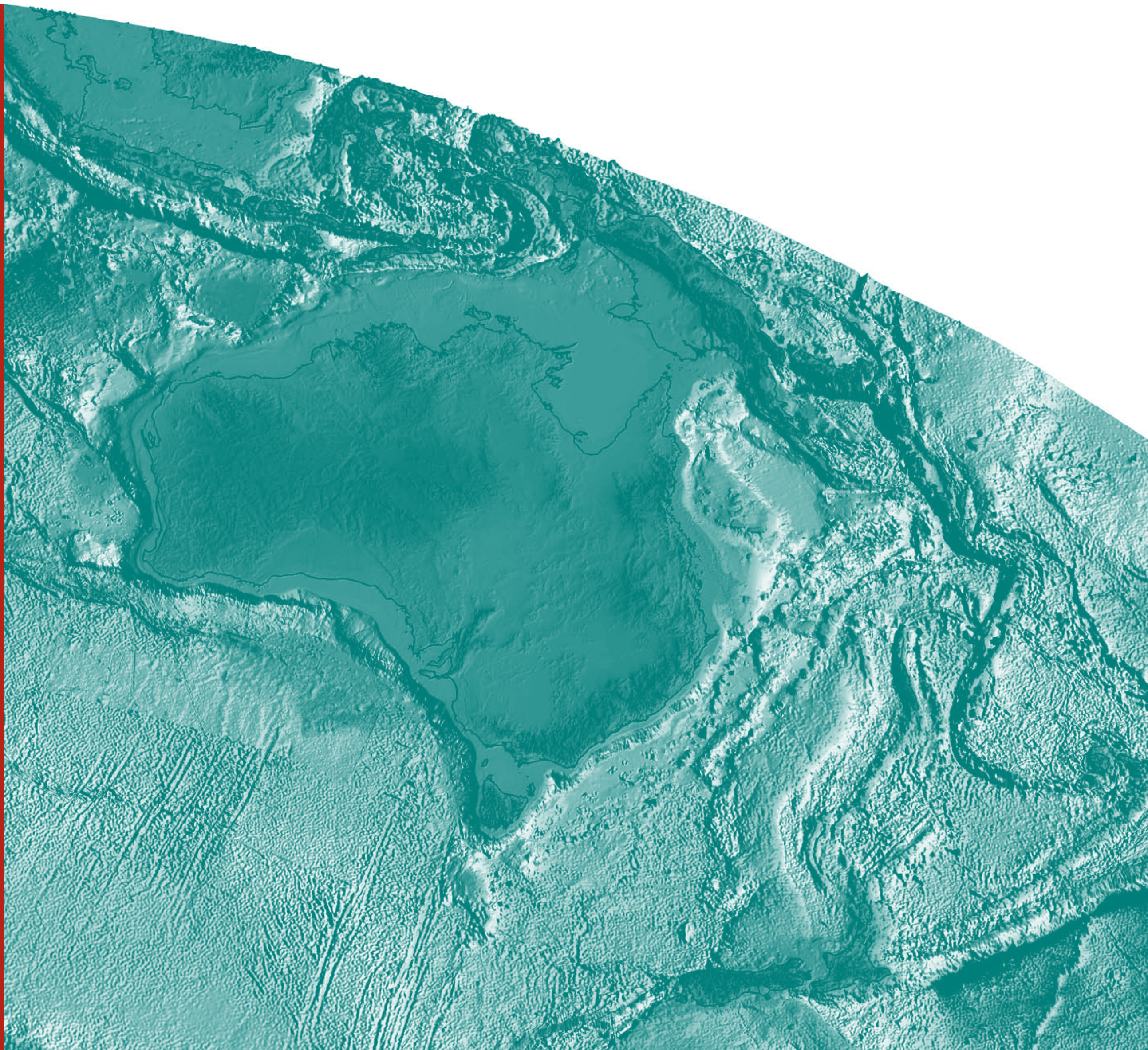

Tsunami impact, education and community consultation in the communities of Onslow and Exmouth: a Geoscience Australia and Fire and Emergency Services Authority (WA) collaboration

GEOSCIENCE AUSTRALIA
RECORD 2007/22

by

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Contents

Executive Summary

The Natural Hazard Impacts Project (NHIP) at Geoscience Australia has developed modelling techniques that enable coastal inundation to be forecast during a tsunami. A Collaborative Research Agreement between Geoscience Australia and the Fire and Emergency Services Authority (FESA) was formed in 2005 to understand tsunami risk and inform emergency management in WA. Through this partnership a significant tsunami risk was identified in NW Western Australia, leading to the development of inundation models for several coastal communities in this region, including Onslow and Exmouth. Recognising the importance of this research to Geoscience Australia, FESA and the communities of Onslow and Exmouth, this year's graduate project was designed to assist the NHIP and to further strengthen ties with FESA and community organisations.

The project had several distinct outcomes which can be divided into data acquisition and community interaction. High quality elevation data was gathered by GPS surveying in order to ascertain the quality of the Digital Elevation Model (DEM) that is currently used in inundation models. Improved densification and accuracy in the elevation data allows the capture of subtle changes in topography that may not be present in the existing DEM and so may improve model accuracy. Secondly, on-site verification of predicted inundation areas supplements the survey data, provides critical assistance in the production of accurate inundation models and potentially aids in the production of emergency plans.

Prior to fieldwork a community-specific tsunami awareness brochure was designed and produced for Onslow, Western Australia. This brochure was presented to Onslow local emergency managers and FESA personnel, and subsequently to Emergency Management Australia and the Bureau of Meteorology. The brochure has received widespread positive feedback, and consequently may provide a template for other community brochures in similarly vulnerable regions of Australia. Finally, graduates represented Geoscience Australia at several community meetings in Onslow where NHIP research was presented. These meetings provided insight into specific community concerns in the event of a tsunami, such as predicted water velocities, and provided an opportunity for the attendees to ask questions about tsunamis and their impacts. Fortuitously this community interaction also led to the discovery of anecdotal evidence of past tsunami events in Onslow, including the tsunami triggered by the 1883 Krakatau eruption, a 1937 tsunami that may be attributed to an earthquake near Java, and the 1994 and 2004 tsunamis.

Introduction

INTRODUCTION TO THE PROJECT

The 2007 Graduate Project was conducted within the framework of the Natural Hazard Impacts Project's (NHIP) tsunami risk modelling activity. This activity models tsunami hazard and impact in order to assess the risk to coastal communities. The immediate focus of this work has been NW Western Australia, an area considered most vulnerable to tsunami generated near Indonesia. In collaboration with the Fire and Emergency Services Authority (FESA), NHIP has produced inundation models for several communities in this region, including Onslow and Exmouth, to determine the level of tsunami risk to NW Western Australia (Figure 1.1).

Credible tsunami inundation models require accurate elevation data and the NHIP have recognised that the Digital Elevation Models (DEMs) currently available for vulnerable communities may not have sufficient accuracy and/or detail. This information is particularly critical in some areas where small changes in elevation may significantly alter model results. To test the sensitivity of the models, higher resolution surveys of significant areas were proposed, with the results then compared to the existing DEM. This survey and accompanying model verification formed an integral part of the 2007 Graduate Project.

Meaningful communication to local communities and local emergency managers of natural hazard research is vital in increasing preparedness to natural disasters. This is especially true in the case of tsunami, as the public is often unaware of the warning signs and associated hazards. It was thus proposed that a prototype brochure explaining tsunami risk for the township of Onslow be produced prior to fieldwork, and presented to emergency managers and community representatives during community meetings that were scheduled to coincide with our fieldwork.

Figure 1.1: *Location map of Onslow and Exmouth, together with other communities along the WA coastline for which tsunami inundation modelling is completed or proposed.*

PROJECT PURPOSE

The project involved travel to Onslow and Exmouth in Western Australia, with the following aims:

- To gather elevation data to in order to validate and improve the accuracy of DEMs currently used in inundation modelling. Priority areas included infrastructure that may not be included in traditional DEMs (e.g., seawalls), areas of high vulnerability (e.g., low-lying residential areas) and areas where the inundation models are particularly sensitive to changes in the DEM (e.g., the foreshore).
- To verify predicted inundation areas in Onslow and Exmouth. Coastal areas were observed to see if the inundation scenarios were plausible, for example, are there sea walls or dune features that may prevent tsunami inundation.
- To produce a community-specific tsunami awareness brochure for Onslow. The brochure includes the current tsunami inundation model for Onslow, as well as general tsunami and emergency information. This brochure may provide a template for similar brochures in other vulnerable communities in the future.

The project also included attendance at tsunami awareness briefings in Onslow, and discussion with regional emergency managers.

TERMINOLOGY OVERVIEW

The risk assessment methodology adopted by Geoscience Australia is broken into four main components: hazard, exposure, vulnerability and risk. This process is adopted regardless of the hazard and allows assessments between hazards to be compared. The exposure or elements of a community at risk are influenced by the number of people, buildings and other infrastructure within an area and are essential to any risk assessment. As the hazard changes, so does the vulnerability (e.g., a building responds differently to an earthquake over tropical cyclone). An impact assessment is made by modelling a scenario. A scenario for example could be a Mw 9.0 tsunami generated off Java and the impact assessment will estimate the inundation extent and damage to Australian communities. A risk assessment by contrast will assign a probability to this event and a range of scenarios would be modelled to build a picture of risk.

Survey

INTRODUCTION

The NHIP utilises hazard and impact modelling to quantify the tsunami risk facing Australia. The hazard maps developed by Geoscience Australia for FESA are the first to be generated worldwide and are based on a tool developed by URS corporation.

Initial inundation results (Figure 2.1), based on existing elevation data, were used to identify several key priority areas in Onslow and Exmouth where it was desirable to refine the DEM. Significant priority areas highlighted during inundation modelling in Onslow include:

- the dunes on the eastern side of Beadon Bay due to their role in reflecting wave energy into Onslow,
- the Bindi Bindi aboriginal community which was modelled to have significant inundation, and
- the recently constructed sea-wall thought to be absent from the DEM.

Tsunami inundation generated by a Mw 9.3 earthquake near Java was modelled for the Exmouth region resulting in significant tsunami inundation on the western side of North West Cape. This result is well supported by documented tsunami events in the area (Section 4.4). An area extending from the shoreline to the Cape Range is predicted to have significant inundation. This area contains several beach access carparks, fishing areas, a popular turtle information centre and access to Ningaloo Reef, and therefore there is a substantial risk to recreational users. Given these observations, the relevant methodologies and constraints used in generating tsunami impact models, the procedures and results will now be discussed.

EXISTING MODEL

Modelling process

Tsunami have fundamentally different behaviours in deep and shallow water and hence must be modelled differently. The two-stage approach adopted by the NHIP aligns with this distinction. Deep water modelling leads to the development of hazard assessments which allow emergency managers to prioritise communities at greater risk. Shallow water modelling then produces detailed impact models for these prioritised communities based on tsunami events identified through the hazard assessment.

The first step in the inundation modelling process requires the coupling of the source model with a deep-water propagation model. As the speed of the tsunami is high in the region between the source and around 100m water depth as well as the behaviour of the tsunami being typically linear, a global bathymetry dataset with a resolution of around two arc seconds it adopted. The bathymetry used by NHIP for this component of the process is a combination of the 250m Australian bathymetry grid created by GA and the global elevation grid called DBDB2 created by the US Naval Research Laboratory. The deep-water model is currently that developed by URS, however, other models such as the Method of Splitting Tsunami (MOST) model of Titov and Gonzalez (1999) can also be used.

To accurately capture the complexities of the tsunami behaviour as it approaches shallow water and impacts ashore requires a model with higher resolution. It has been established that complex bathymetry and topography play a crucial role in the determining the impact of a tsunami event (e.g., Matsuyama et al., 1999) and thus complicate the task of tsunami inundation modelling. To model the impact ashore, the deep water and shallow water models are coupled at a defined boundary, typically around 100 m water depth. The inundation model used for Onslow and Exmouth, ANUGA, was developed jointly by the Australian National University and Geoscience Australia. ANUGA is believed to be reliable, having successfully reproduced the effects of the 1993 Okushiri Island, Japan, tsunami (Nielsen et al., 2005). In this way, ANUGA takes the tsunami wave height and velocity throughout time and continues to propagate the tsunami towards the shore (Nielsen et al., 2006).

The inundation modelling component of the process utilises a much more closely spaced bathymetric/topographic dataset, with resolutions typically in the order of tens of metres (Nielsen et al., 2006). The model allows for variable resolutions to be utilised within the same mesh. This allows areas of high complexity (e.g., dune systems) to be accurately constrained with dense data, while using coarser and less computationally intensive resolutions for less complex areas. The benefit of this method is that high-precision datasets, such as the one produced for this report, can simply be ‘plugged in’ to a pre-existing DEM and therefore enable a progressive improvement of the mesh surface. To discuss the improvements to the modelling process using our survey data we first consider the original DEM used to construct the triangular mesh.

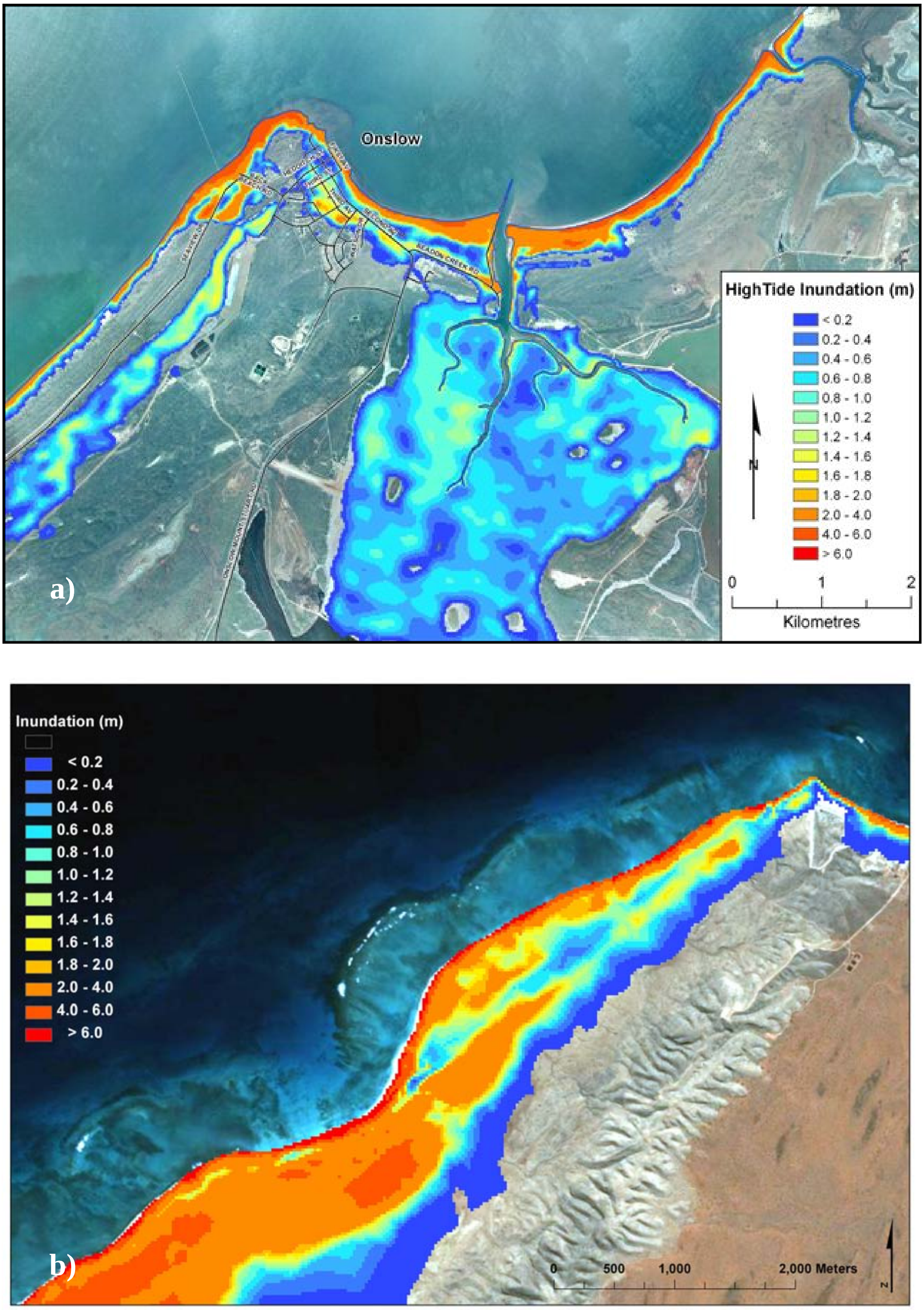

Figure 2.1: *Modelled inundation levels for tsunami generated by great earthquakes off Java. a) Onslow inundation from a magnitude 9.0 earthquake; b) North West Cape inundation from a magnitude 9.3 earthquake. Note: the model resolution was finer for the inundation levels shown in (a) than (b).*

Digital Elevation Model

Both onshore and offshore datasets were used to create the mesh used in the non-inundation component of the Onslow and Exmouth models. For the purposes of the Graduate Project, only onshore data is considered. The Onslow and Exmouth DEMs were generated from two separate sources: a high-resolution DEM from Landgate (previously the Western Australia Department of Land Information) and a coarser DEM provided by the Defence Imagery and Geospatial Organisation (DIGO). These DEMs were constructed using an orthophotography. A coastline was generated using the onshore DEM and adjusted as required to align with the aerial photography. In addition, beach survey data was used to provide another layer of information to validate the coastline. Where possible, the Landgate DEM was utilised in preference to that provided by the Department of Defence for several reasons:

- The accuracy is much greater. The Landgate DEM has a longitude, latitude and height accuracy of ±10m for 90% of the points, whereas the DIGO dataset has a 50 m error in the longitude and latitude dimensions and a variation of ±30 m in height;
- Data density is greater for the Landgate DEM with a resolution of 20 m, whereas the DIGO DEM has a resolution of one arc second (~30 m); and
- The DIGO dataset consists of whole integer values. In contrast, the Landgate DEM utilises decimal values, thereby allowing a smoother surface to be constructed.

Although superior to the DIGO DEM, the Landgate DEM is limited in coverage, with only mainland Australia constrained. As such, important features, such as offshore islands, are furnished using the coarser DIGO dataset.

It is important to recognise the shortcomings of the Onslow and Exmouth DEMs which compromise the accuracy of the tsunami inundation results. First, both DEMs are ‘bare earth’, and as such do not include surface features such as buildings and vegetation which may have an effect on tsunami inundation. Second, the relatively coarse spacing of elevation values for the DEM may merge important features such as seawalls, multiple dune systems, and other complex topographic features into continuous slopes or cause them to be missed altogether, particularly if the resolution is finer than 20 m (Figure 2.2). As such, it is important to increase the data resolution in complex areas, the results of which can be incorporated into the triangular mesh used in the modelling process.

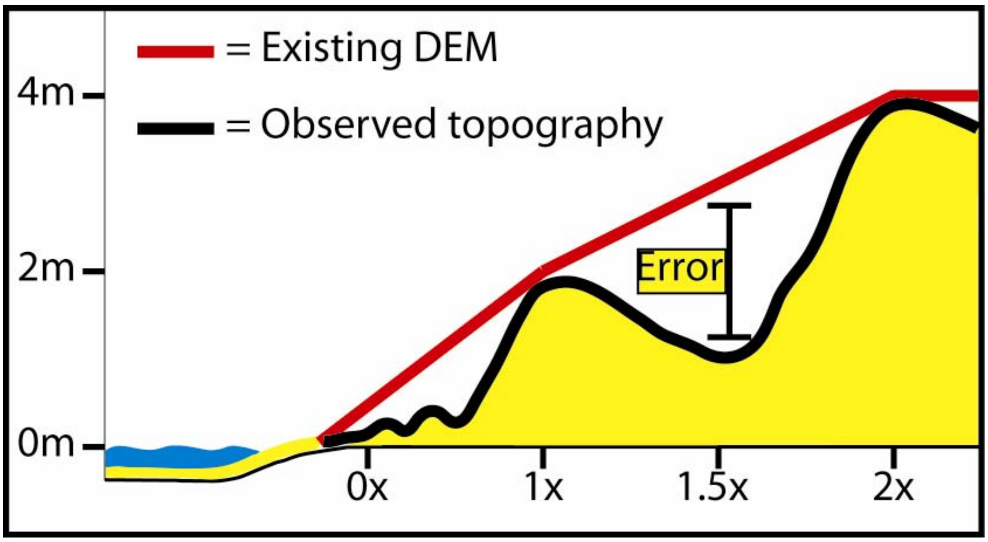

Figure 2.2: *Graphic representation of the potential differences between the true topographic variation and the DEM for a dune system. For this figure x=20m, which corresponds to the resolution of the Landgate DEM. As such, topographic features occurring at a fraction of x will not be detected.*

GPS SURVEY

Survey Areas

As discussed, priority areas included those identified as being poorly defined by the existing DEM and/or important to the modelling process. Based on project time-constraints and the proximity of existing survey control (see field procedure), the following areas were selected for GPS survey:

- Onslow Sea Wall - a 3-4 metre man-made sea wall running the length of the main township area, not currently included in the existing DEM.
- Onslow Infrastructure – major public facilities and meeting points (e.g., school, hospital) and the Bindi-Bindi aboriginal community.
- Onslow Far Beach – Eastern shore of Beadon Bay.
- Exmouth North West Cape carparks – a number of beach access carparks on the western shore of North West Cape.

Field Equipment & Procedure

A technique of kinematic differential GPS (DGPS) surveying, commonly referred to as 'fast-static', was employed to ensure that priority areas could be covered within a limited timeframe and still meet accuracy requirements. DGPS surveying requires two GPS receivers: one base station established on a control point of known position, and a kinematic (roving) receiver which is used to obtain the survey data. If both receivers gather observations simultaneously and are located within an acceptable distance of each other (approximately 10km), then both generate their position from the same constellation of satellites and the observed GPS signals are subject to the same atmospheric effects.

Any difference between the known control position of the base station and the observed GPS position calculated at the base is then used as a correction to the data collected at the roving receiver, dramatically improving the accuracy of the roving position. The GPS survey of the four areas was completed over four days, 16-18th June in Onslow and the 20th of June in Exmouth. See Appendix for further details of the survey methods.

RESULTS

Accuracy

The final accuracy of the point data set is a function of many factors in the surveying and processing procedure. Nonetheless, we conservatively estimate the accuracy of the three Onslow data sets to be better then 10 cm in the horizontal and 20 cm in the vertical, considering the following error budget:

Horizontal	**Vertical**
Gesmar Coordinates – 3cm	Gesmar Coordinates – 5cm
Standard GPS errors – 2cm	Standard GPS errors – 4cm
Survey Error (pole level etc) - 2cm	AHD/Geoid/N-value derivations – 4cm
	Survey Error – 1cm

The survey control used for the Exmouth survey was defined from a derived ellipsoidal height (AHD-N value), not determined by GPS observations and thus further uncertainties may have been introduced into the Exmouth dataset. A conservative estimate of this data set would decrease the vertical accuracy to 25 cm, and horizontal accuracy to 10 cm.

Case study from the eastern side of Beadon Bay

The township of Onslow is shielded from the direct impact of a tsunami originating from near Indonesia due to its geographic location: the protected western side of Beadon Bay (Figure 2.1a). Existing modelling predicts that significant inundation in the township results from large-scale reflection of wave energy from the dunes on the unpopulated eastern side of Beadon Bay; thus, this area was identified to be of critical importance in our surveying. A total of 24 beach transects were made using kinematic GPS along >3 km of beachfront between Beadon Creek and the next northern inlet, yielding a total of 201 elevation data points once high-error values had been eliminated. Statistical analysis of the variance between the GPS-derived height data and the existing DEM yields a mean of +1.104 m, with a standard deviation of 1.603 m, and a maximum of 6.165 m variation (n = 201). Graphically, it can also be seen that the survey data obtained during this study is generally higher than the DEM (Figure 2.3a).

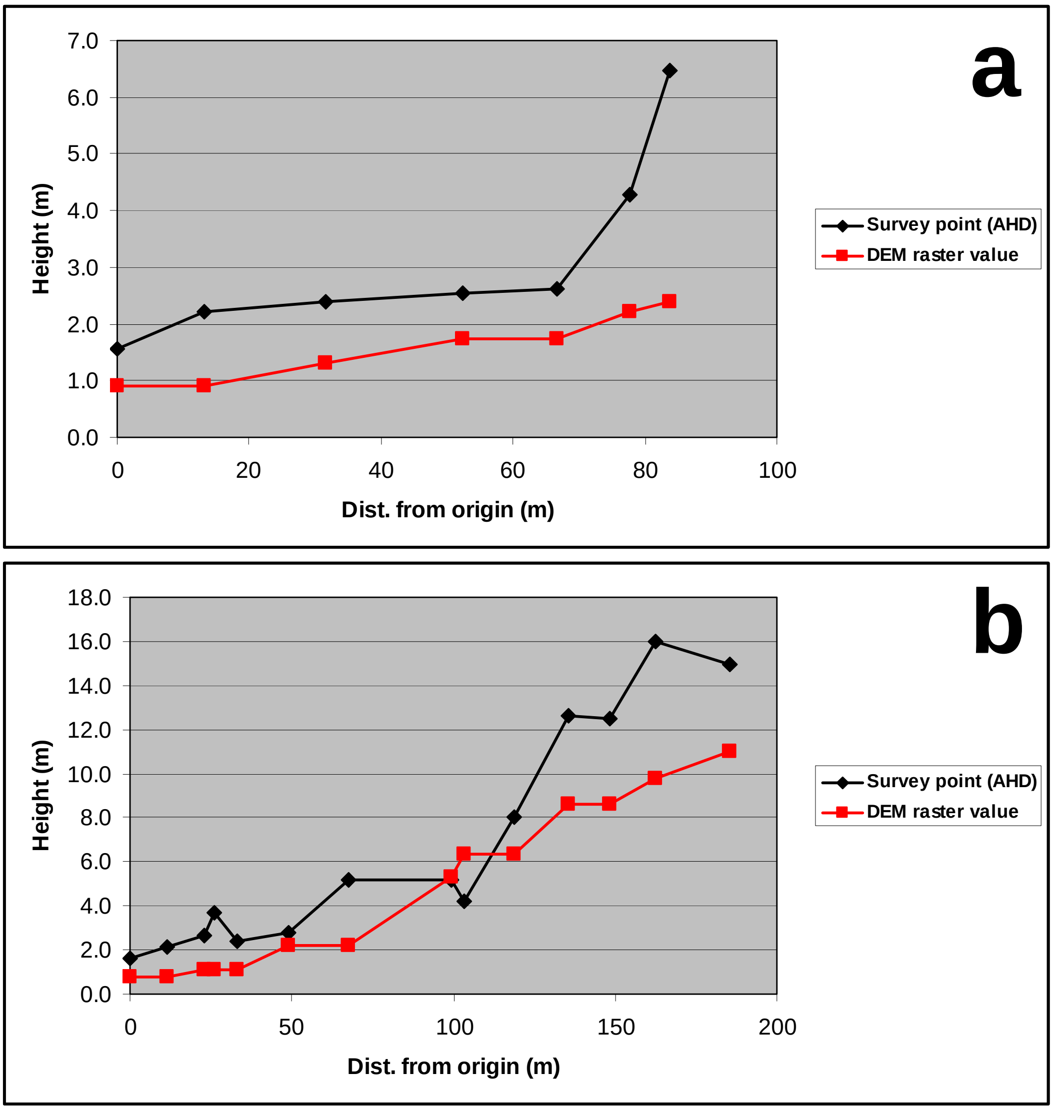

Figure 2.3: *Graphic representations of the variation between the survey data and the DEM from Onslow. a) demonstrates the general underestimation of true elevation by the DEM, while b) shows how the much coarser resolution of the DEM results in the smoothing of complex topography in some cases. Note: In many cases there were two or more survey points taken within a single DEM grid space.*

As well as providing visual confirmation of the summary statistics, graphs of the beach transects also reveal further errors associated with the existing DEM. Many topographic complexities, such as multiple dune systems, were not detected in the initial DEM (Figure 2.3). As stated earlier, the relatively coarse data coverage in the orthophoto DEM has the potential to reduce topographic complexities into broad, almost linear, slopes if the data spacing is not coincident with these features. When combined with greater error margins (±10 m for the Onslow DEM), this has the undesirable result of introducing possibly significant errors into the tsunami inundation model, especially considering the importance of this area in influencing the behaviour of an incoming wave. In contrast, data obtained during this survey contains several data points per DEM value (Figure 2.4) and this higher result enables the detection of topographic subtleties.

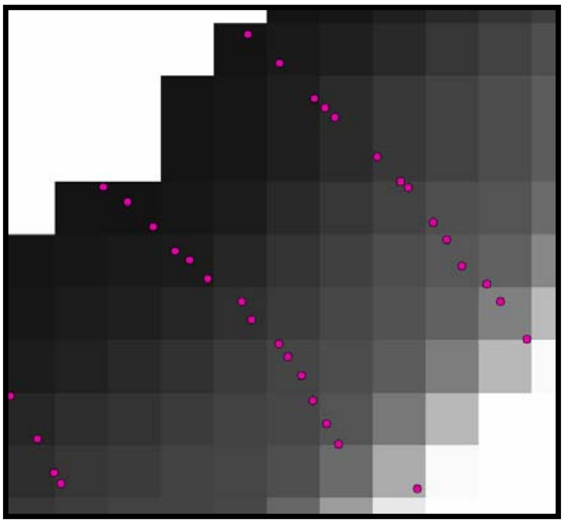

Figure 2.4: *Illustration of survey point density in comparison to the current DEM resolution. Survey point observations (purple dots) were made at much higher resolution than the existing DEM grid, allowing discrete topological variations to be observed.*

Whilst some areas have considerable differences between the DEM and survey data, other areas show a remarkably strong correlation between the two datasets, such as the beach transect in Figure 2.5. On this line, mean deviation between the survey data and the DEM is reduced to just 0.118 m, with a maximum deviation of 1.51 m from the survey data. In addition, numerous large-scale dune features are also correctly identified. Broadly speaking, areas on the western end of the beach reveal much less deviation from the DEM than those in the centre or on the eastern margin. The increase in variance in those areas is likely to reflect increased dune complexity in those regions.

Data Products

The data was provided to NHIP in four comma-delimited (.csv) files with the following attribute fields:

- EASTING – Easting coordinate GDA94 MGA Zone 50
- NORTHING – Northing coordinate GDA94 MGA Zone 50
- AHD – Australian Height Datum height (metres)
- Point ID – Point ID to reference to raw data and survey reports

The directory structure and content of the data CD is detailed in the Appendix.

These survey data sets have also been included as part of a GIS/Geodatabase product, primarily created to give a direct spatial reference to the inundation verification photo survey and to create a connection between the photos, model outputs and survey elevation data. Photos can be viewed in context to their actual location, and in reference to the location of the acquired elevation data (Figure 2.6).

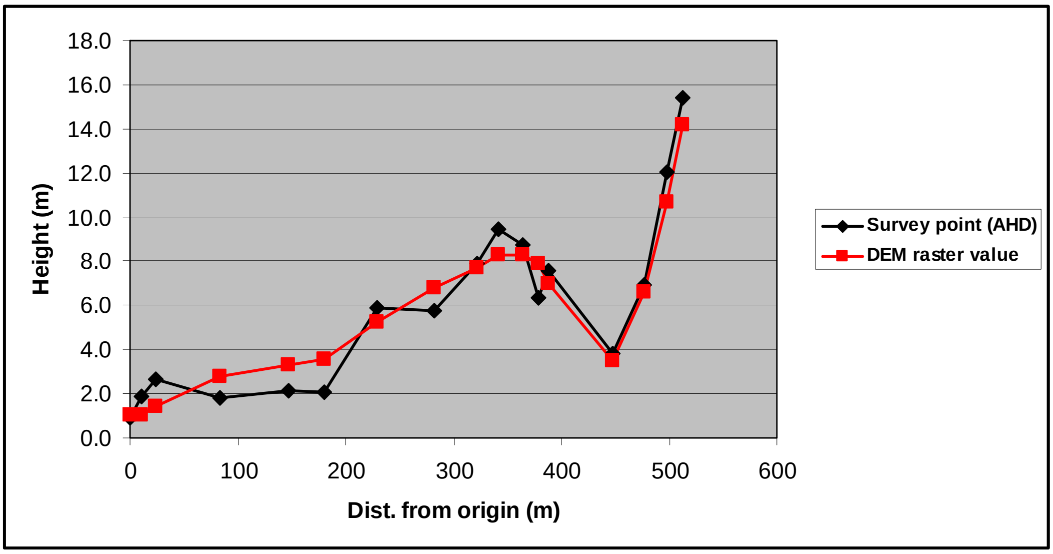

Figure 2.5: *Graph of survey and DEM height values from a beach transect on the eastern half of Beadon Bay. Note the strong correlation and consistency in topography. The larger errors in the first 200m of the survey may be attributed to the relative difficulties in determining elevation from aerial photographs near mean sea level.*

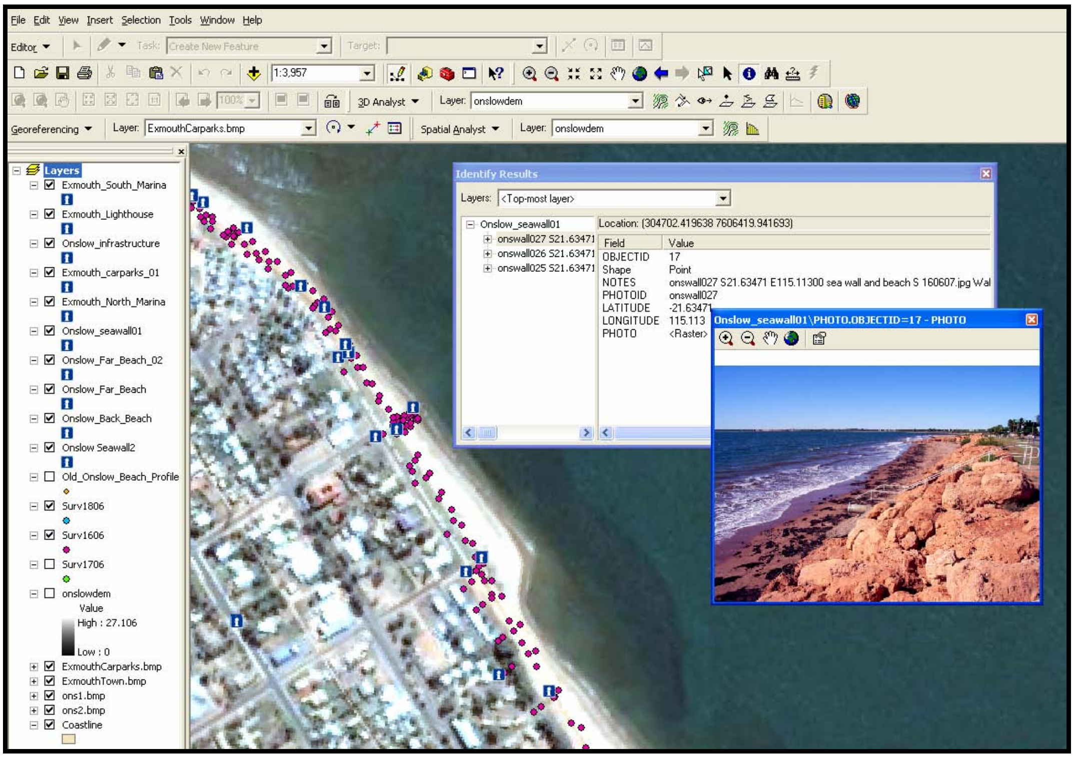

Figure 2.6*: Photo Geodatabase – datasets displayed in ArcGIS allow spatially referenced photos to be displayed in reference to other project layers (e.g., DEM, satellite image, and inundation model).*

Visual Inspection and sanity checking of inundation models

INTRODUCTION

The purpose of visual inspection in this project was three-fold: first to provide a backup to the GPS data acquisition should it fail in any way; second to visually validate the current inundation model results; and third to document features that might not otherwise be captured by surveying. Recorded observations included sediment deposition, topography type, presence and size of vegetation, significant breaks in dune structure and any evidence indicative of previous inundation events (e.g. shells and coral). These observations will assist in the production of more representative inundation models and potentially aid local emergency managers in the production of tsunami emergency plans.

As mentioned earlier, features and locations of interest in Onslow included a seawall, the Bindi Bindi aboriginal community, critical infrastructure (e.g. schools, hospital, and police station) and Beadon Bay. Back Beach Road became a priority after the receipt of relevant anecdotal evidence of past inundation (see Community Interaction section). In the Exmouth region, highest priority was given to the Lighthouse Caravan Park and car parks further south along the western coast of North West Cape as they were reportedly inundated during the 1994 tsunami. The new marina development south of the Exmouth township was also of interest to the NHIP.

ONSLOW

Sea Wall

The township of Onslow extends to within ~10-20 m of the beach and much of the town is less than 10 m above sea level. This area of coastline has been historically vulnerable to cyclones, with many coastal structures at risk of flooding and other cyclone-related damage. A new seawall was built after a cyclone storm surge study in 2000, and replaced an old seawall built in 1958. The new seawall was designed to protect the community from cyclone inundation. The report indicated that the new seawall should be built to a height of ~4 m AHD and be composed of limestone blocks of 1.5 m diameter or 6 tonne (Harrap, 2000). The wall is composed of a mass of large (>1 m diameter), loose limestone and sandstone boulders (Figure 3.1). At the time of fieldwork, the Landgate DEM did not factor in the seawall, making this a high priority feature.

High-tide varies along the coastline, in places reaching the base of the seawall (Figure 3.2). There is also considerable variation in slope and vegetation behind the seawall. Furthermore, in the event of water breaching the seawall, shallow slopes dipping towards the township may assist in increasing inundation. These slopes are particularly noteworthy as businesses and houses are located within metres of the seawall.

The seawall was designed to be ~4 m AHD; however, the height of the wall above the beach decreases from west to east. This is a result of increased deposition of sand against the boulders, possibly caused by longshore drift. Up to 80 cm of sand appears to have been deposited in some places (Figure 3.3). This is estimated using the burial of the stair railings as a guide. As a consequence of this deposition, the seawall here is only ~1.2 m above the beach. The height between the top of the beach and the top of the seawall continues to decreases further eastwards to less than 0.5 m. While the absolute height above sea level is not changed, the change in beach profile shape may alter inundation dynamics.

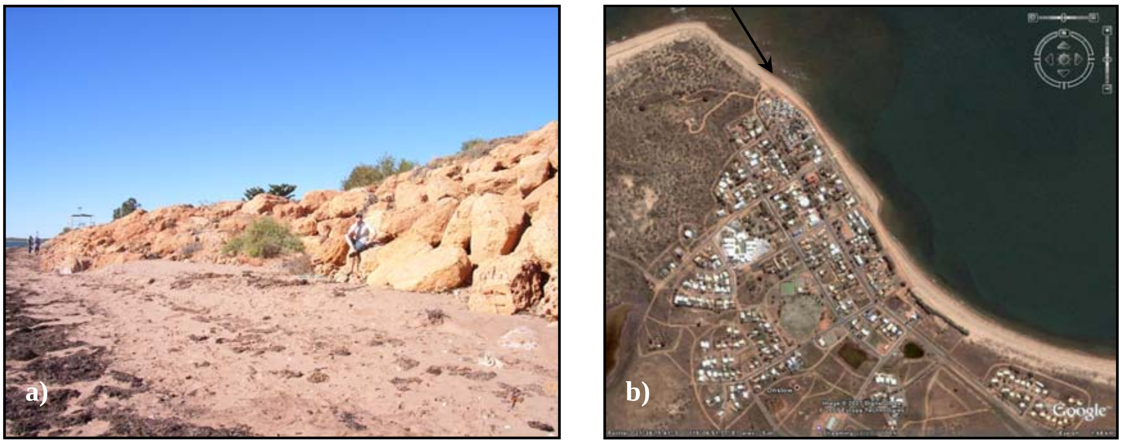

Figure 3.1: *a) The north-western end of the seawall facing southeast and b) the previously mentioned locality indicated on a Google Earth image of Onslow*

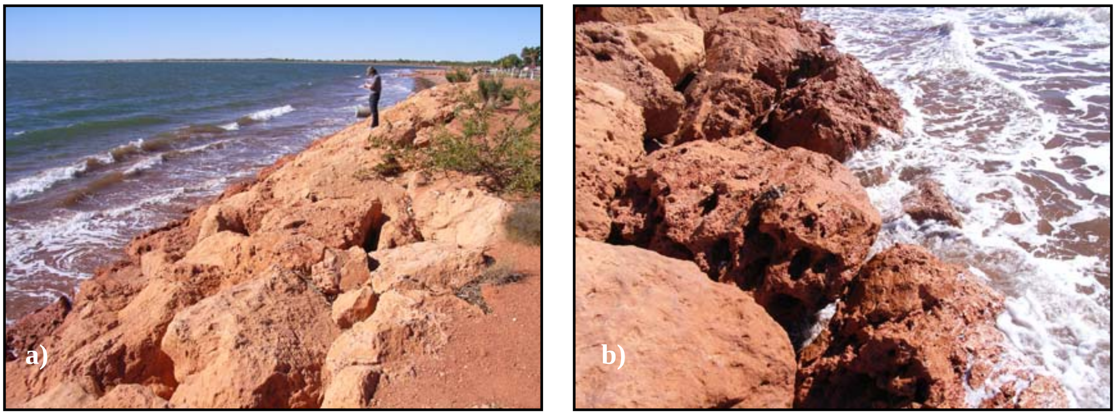

Figure 3.2: *a) Waters at high tide lapping against the base of the seawall at the north-eastern end of the Onslow sea wall; and b) a close-up at the base of the seawall.*

Figure 3.3: *Stairs at the end of First Ave (the eastern end of the seawall) showing more than 80cm of sand deposition.*

Bindi Bindi

The Bindi Bindi aboriginal community on the outskirts of Onslow was surveyed and documented, as significant inundation is predicted for this area (Figure 3.4). The seawall built to protect the Onslow community does not extend as far east as Bindi Bindi. The only protection provided for the aboriginal community is a ~2-3 metre high foredune and a smaller back dune. A large gully, located directly behind the second dune may funnel any inundation straight into the relatively flat-lying Bindi Bindi community (Figure 3.5). The vegetation around the Bindi Bindi community also provides little protection, as grasses and shrubs are the dominant vegetation type. In combination, these observations support the high risk assessment predicted by NHIP for the Bindi Bindi community.

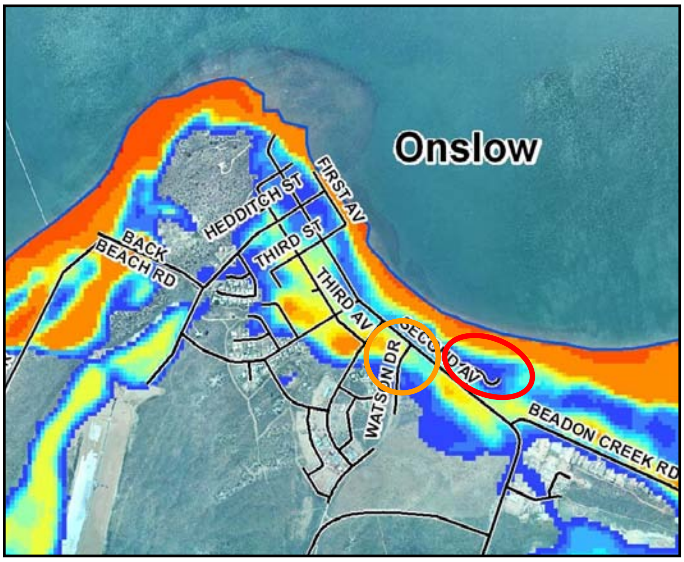

Figure 3.4: Inundation model for Onslow with the Bindi Bindi aboriginal community (red oval) and the hospital and access road (orange circle) indicated.

Figure 3.5: Panoramic photograph showing the relative distance between the coast, the Bindi Bindi community and major dune features.

Critical Infrastructure

In the event of a tsunami, it is important to identify infrastructure that will be critical in: a) providing support to the community (e.g., police, ambulance, hospital); and b) providing refuge (e.g., school, community centre). Since its founding, the Onslow community has repeatedly been damaged by flooding and cyclone, thus the new school was built above the predicted one in 100 year storm surge maximum (Figure 3.6). The hospital is also relatively elevated; however, our visual inspection showed that access road would be inundated in a tsunami, also consistent with the inundation model (Figure 3.4).

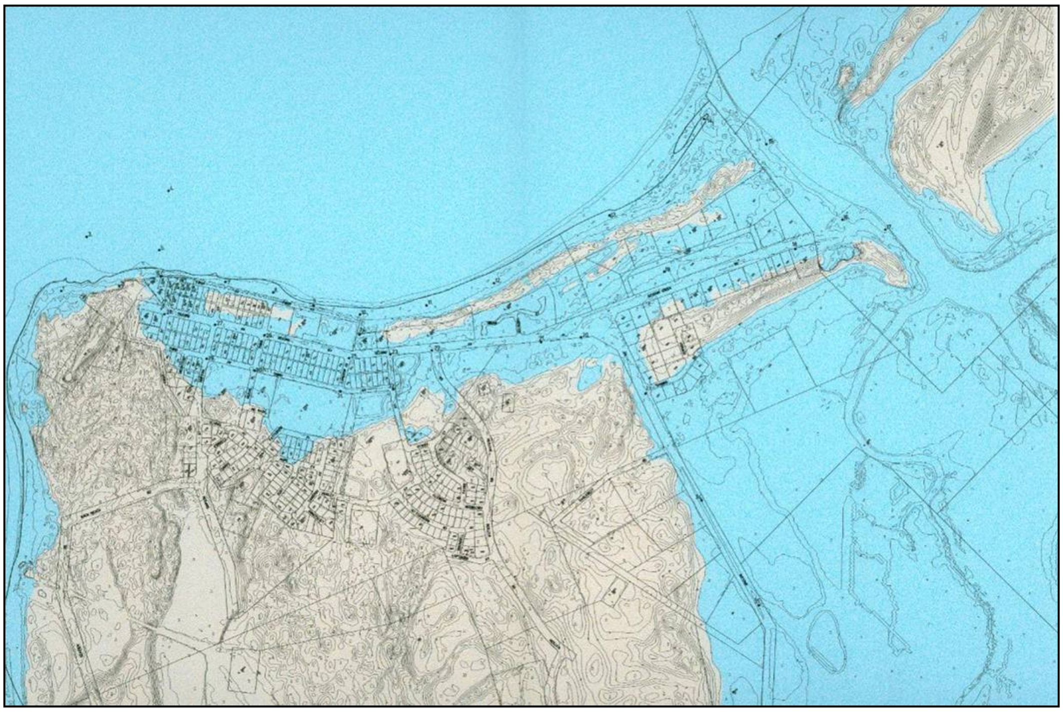

Figure 3.6: *Predicted inundation during a one in 100 year surge event in Onslow (Harrap, 2000)*

Beadon Bay

In the current inundation model for Onslow (Figure 3.7), wave motion from the north-west reflects off a set of foredunes along the coast east of Beadon Creek and increases inundation in the Onslow township. To assess the plausibility of this scenario, the coastline east of Beadon Creek was surveyed and visually inspected.

The beach immediately beside Beadon creek is low, lightly vegetated and relatively flat, perhaps a metre above sea level, however, south-east to north-east along the coast the topography becomes quite varied. The areas referred to below are marked on Figure 3.7a.

- A to B: ~200 m wide area of sandy, vegetated and hummocky (densely spaced, small and irregular) dunes, with an overlying thin layer of relatively intact shells (Figure 3.7b). Behind this hummocky zone is a comparatively continuous dune of variable height (~2-5 m; Line 1); shown in Figure 3.7c. The dunes become sandier and less hummocky towards the east where new dunes are forming (B) although there are a number of large (>2 m) hummocks.
- C: In this section the first dune becomes sharply delineated again. Here the first dune is located much closer to the coast with only 50-60 m of small hummocks before the dune begins (Figure 3.7d).
- Behind the first dune lies a second dune (Line 2); the two dunes are separated by a 2–3 m slack (the trough between dunes). Situated some 470–520 m from the coast, this second dune extends along the entire coast from Beadon Creek to a small creek to the north. This densely vegetated dune is consistent in shape and height throughout its entire extent.

Observations made at Beadon Bay appear to support the inundation model in that wave reflection is possible. However, the hummocky shoreline may affect the nature of any wave that washes over it, potentially reducing the severity of reflection. This level of detail is not currently incorporated in the inundation models as it can not be captured by the lower density DEM models.

Figure 3.7: *a) Google Earth image of Beadon Bay showing Beadon Creek and locations A-C. b) 0.5-1 m high hummocky dunes at locality A; c) low first dune of variable height at locality A; and d) 50-60 m wide hummocky dune field at locality C.*

Back beach Road

Sunset Beach (locally referred to as Back Beach) is on the western side of the Onslow peninsula near the salt mine loading jetty and is ~1.2 km from the township (measured from the high tide mark to Third Ave). The model predicts greater than 6m of inundation at this beach (Figure 3.8a); due to the low, flat topography of the beach, this prediction is plausible.

The foredunes running north from Sunset Beach are topped by a walking track that leads from the Sunset Beach picnic area to the Ocean View Caravan Park near the top of the peninsula. The model predicts inundation of large sections of this track; as these foredunes are relatively low (~1-2 m) they could be breached by a tsunami.

Anecdotal evidence of past tsunami (Section 4.3) suggests that a 6-8 inch high “tidal wave” may have inundated Onslow, via Simpson St, from Back Beach in 1971. It is possible for tsunami to use a road as a channel, as occurred at Steep Point, WA in 2006 (Prendergast and Brown, 2007) where water flowed ~200m inland. Notably though, the Steep Point road was indented into the topography, with a 1m high bank on either side of the road; Back Beach and Simpson Roads have no such banks and would therefore be less suited to act as a channel (Figure 3.9a,b). However, the generally low gradient topography and the many small dips and rises observed along Back Beach Road make this form of inundation possible, if not probable.

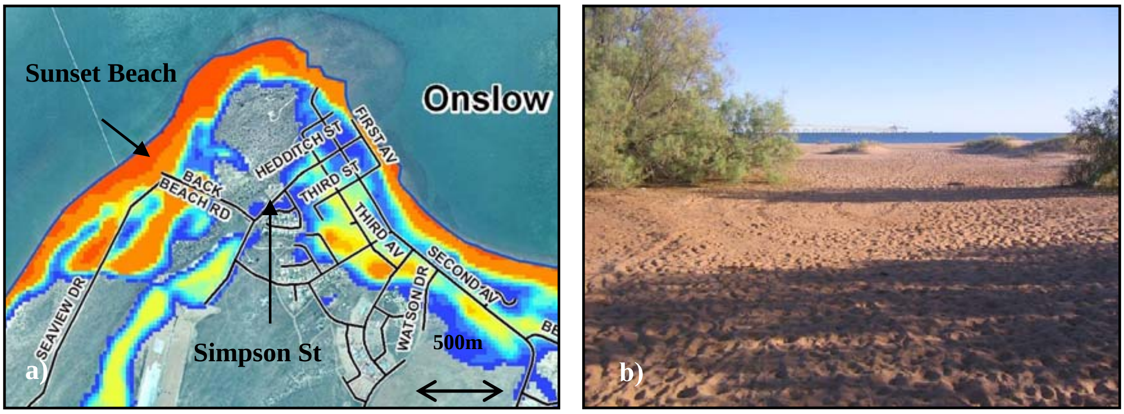

Figure 3.8: *a) Inundation map of Onslow based on a magnitude 9 (Mw) Java earthquake at high tide; and b) Sunset Beach as indicated on the inundation map.*

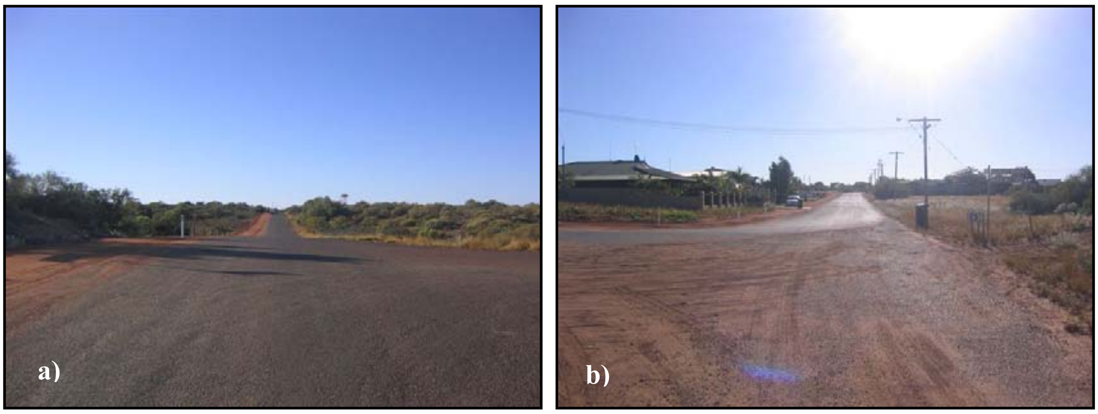

Figure 3.9: *View along a) Back Beach Road from the rise at Sunset Beach car park; and b) Simpson St from the intersection of Simpson St and Back Beach Road*

EXMOUTH

Lighthouse Caravan Park

On 3rd June 1994, a 7.8 Mw earthquake in Java triggered a tsunami with a 0.45 m run-up at Dampier (NOAA/WDC Historical Tsunami Database, 2007) and a 3 m run-up at Baudin, Western Australia (Allport and Blong, 1995). Exmouth locals reported that during this event, water reached the main road running along the western coast of North West Cape, including directly in front of the Lighthouse Caravan Park at Vlamingh Head (Section 4.4). Consequently, visual observations were made of the dunes in front of the Lighthouse Caravan Park in order to understand the inundation pathway.

The foredunes in this area are relatively continuous and ~5-10 m high, however a 3-4 m wide gully runs from the shore to the caravan park and is the most likely point of inundation (Figure 3.10). We also observed efforts to reduce dune and beach erosion, which included covering of bare dune slopes with branches and distributing rock slabs along the beachfront.

The caravan park is located on relatively flat topography. Thus, if the road is inundated then the caravan park is also at risk of inundation. The topography directly behind the caravan park quickly steepens, which might provide an area that would remain free from inundation.

Figure 3.10: *Major gully feature running perpendicular to the coast from the shoreline into the caravan park. a) Shows the width of the gully and b) depicts the height of the gully walls.*

Western Exmouth Peninsula car parks, Jurabi Point and Tandabiddy Creek

Given that car parks between Vlamingh Head and Jurabi Point on the western coast of the Exmouth peninsula were inundated by the 1994 tsunami (Section 4.4), these car parks became a priority area for visual observations (Figure 3.11). Northern car parks near Vlamingh Head (Figure 3.11a, A) have steeper seaward slopes with heights ~5-9 m and paths that incise the dune (Figure 3.11b). In contrast, car parks further south (Figure 3.11a, B) have lower dunes with heights of ~2-4 m. The majority of car parks surveyed were located close to the shore (within 15-50 m; Figure 3.11c). Evidence of past inundation was found in car parks just north of Jurabi Point in the form of large clumps of coral and abundant shells (Figure 3.11d) often located tens to hundreds of metres inland and behind large dunes.

A great number of broken shells and coral were found well inland at Jurabi Point, consistent with local SES volunteer, Russell Levine's description of the 1994 tsunami inundation (See Community Interaction section). Large intact shells (<30cm), cemented burrows (Figure 3.12a inset) and pieces of coral (Figure 3.12a) were located behind dunes hundreds of metres inland, to within ~150–100m of the main road. It is possible that a break in the reef north of Jurabi Point exacerbated the inundation here. In addition, at Jurabi Point the dune slacks open to the north facilitating the channelling of water between and possibly over the dunes. However, whilst it seems likely that the marine debris found here is related to the 1994 tsunami, cyclone-induced inundation cannot be ruled out at this stage.

Russell also described how water flowed up Tandabiddy Creek (Section 4.4); observation of the creek's wide, flat inlet (Figure 3.12b) and low gradient supports this observation.

Figure 3.11: *a) Google Earth image of the west coast of the Exmouth Peninsula; b) Car park at Jurabi Beach; c) Wobiri Beach; and d) large mass of coral found along the road to Five Mile Beach.*

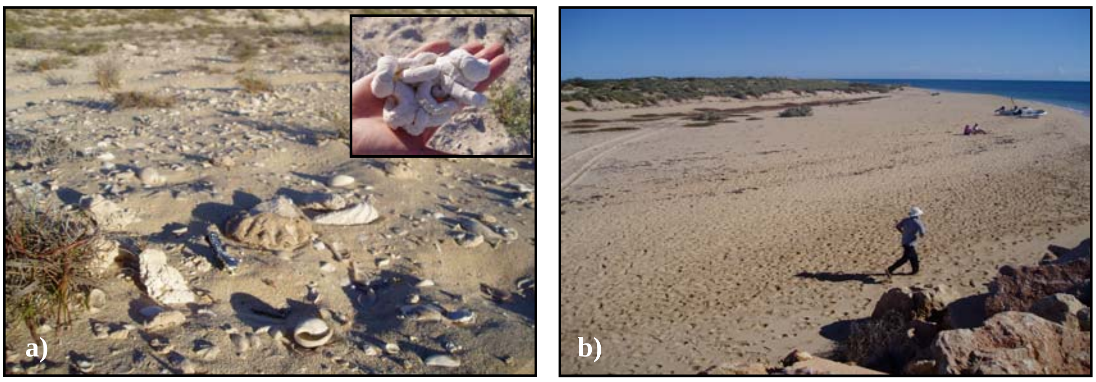

Figure 3.12: *a) Photograph of Tandabiddy Creek Inlet; and b) shell and Coral deposits at Jurabi Point. Inset: Cemented burrows.*

Eastern coast marina development

The Exmouth township is located much further inland than the Onslow township; therefore, inundation appears unlikely to reach the town at its current location. Figure 3.13 represents the predicted inundation from Mw 9.3 earthquake of Java. In the event of expansion, structures built closer to the coast will be at greater risk.

A new marina is being developed ~2km south of the centre of Exmouth (Figure 3.13) and will be comprised of residential, industrial and tourist zones. The marina is protected by a 2-3 m high seawall. Although this height may sound substantial, the high tide mark is less than 1 m below the top of the wall (Figure 3.14). Thus, even a relatively minor increase in sea surface height during a tsunami or cyclonic waves could result in inundation; a risk to structures around the marina.

Dunes to the north and south of the development are ~3-4 m high, vegetated and relatively continuous. However, beach access roads could provide pathways for inundation (Figure 3.15). At one such locality ~1.2 km south of the marina, a ~30 m wide track may funnel tsunami inundation into a planned residential zone located behind the dunes (Figure 3.13).

INITIAL FINDINGS

Visual inspection and sanity checking of the inundation models in Onslow and Exmouth has resulted in some key observations, which are outlined below.

- The initial inundation model for Onslow showed that the tsunami waves would reflect off the large, continuous dunes along the coast east of Beadon Bay. This is still plausible; however, the hummocky shoreline, smaller foredune and large slack may affect the wave/dune interactions and subsequent reflection.
- The seawall built to protect the Onslow township may provide some protection from inundation. However, sand deposition has decreased the height of the seawall relative to the beach changing the beach profile to a smoother and less reflective slope. Thus, deposition here may decrease the effectiveness of the seawall in preventing inundation from cyclone or tsunami. Depending on the sensitivity to beach profile shown in the model results, it may be appropriate to monitor changes in beach profile due to continued deposition and/or erosion.
- The Onslow community is at significant risk of damage in the event of a large tsunami. Furthermore, inundation is predicted to occur at the Bindi Bindi aboriginal community, breaching the relatively low-lying foredunes, or at Sunset Beach, with potential channelling along Back Beach Road. Community infrastructure which is clear of the tsunami inundation extent provides prospective evacuation sites.
- The Exmouth township is located inland, and therefore appears unlikely to be inundated in its current state. In the event of expansion, structures built closer to the coast will be at risk.
- The new Exmouth marina development is surrounded by a 2-3 m high seawall; however, the seawall is unlikely to significantly reduce damage during a tsunami, as the high tide mark is typically less than 1 m below the top of the wall. Although no survey data was collected in the marina development due to inaccessibility, detailed survey data would have been acquired prior to the marina developments by local council. The addition of this information to the inundation model would be highly significant.
- Relatively continuous dunes run along the coast to the north and south of the Exmouth marina. These large dunes are sporadically broken by beach access roads that may act as funnels for inundation and in some result in flooding in proposed residential zones. Managing the spatial relationship between these access roads and proposed residential zones is considered critically important for mitigating tsunami risk in Exmouth.

- Observations made along the western coast of North West Cape support anecdotal evidence that Jurabi Point, Tandabiddy Creek and many car parks along the western coast would be inundated during a large tsunami. Similarly at the Lighthouse Caravan Park a wide gully running from the shore to the park would provide access for inundation. Local managers are now developing emergency response plans based on the inundation models developed by GA in collaboration with FESA to which this project has contributed.

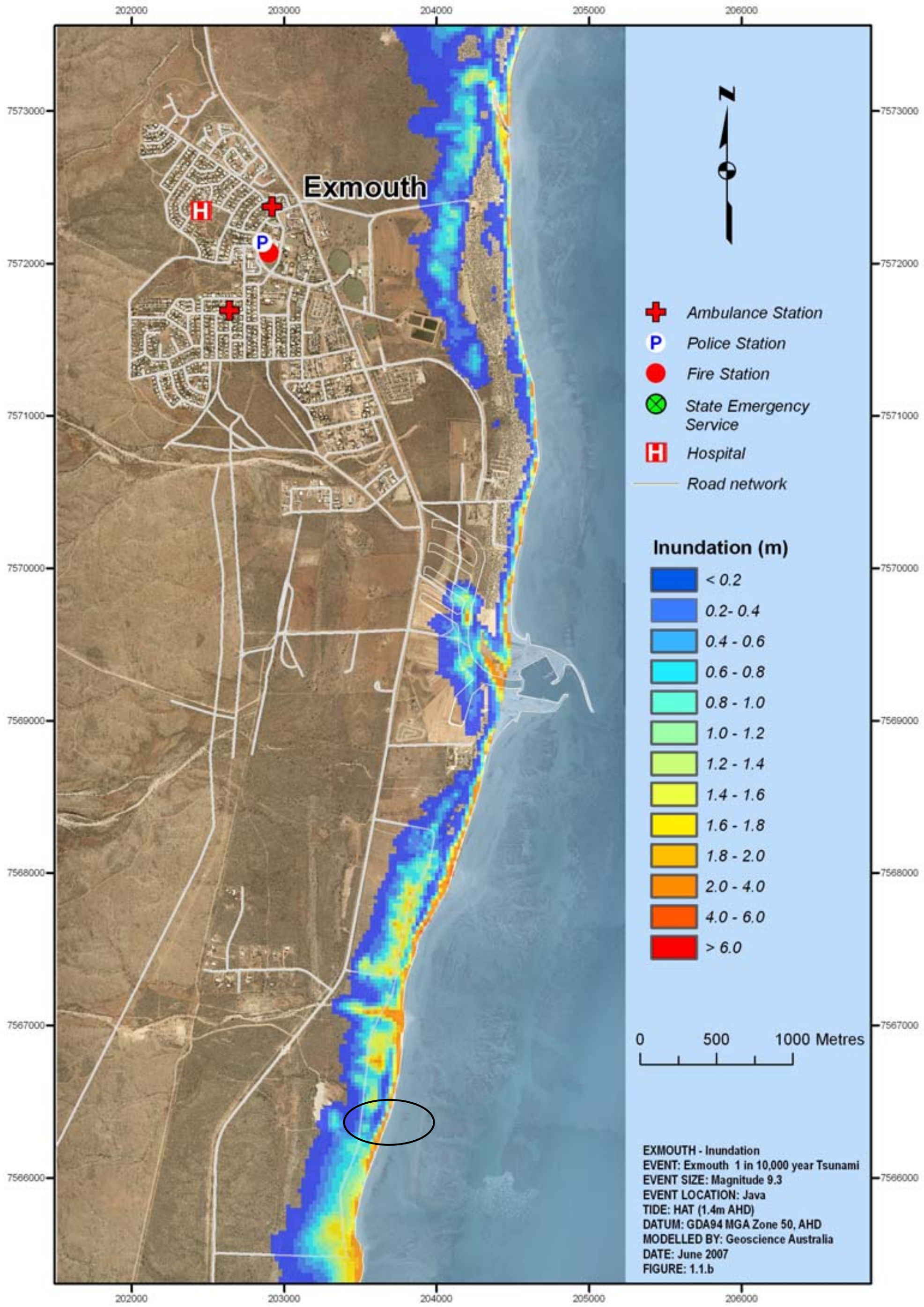

Figure 3.13: *Inundation model for Exmouth based on an Mw 9.3 earthquake off Java. The black oval indicates the wide beach access road that breaches the major dunes.*

Figure 3.14: *a) The seawall protecting the new marina development. The darker section of the seawall (b) is the high tide mark. In these examples the high tide mark is less than 1m below the top of the wall.*

Figure 3.15: *Access road breaching the ~3-4m high foredunes. Behind the smaller backdunes in the centre of this access road is an allocated residential zone.*

Community Interaction and Raising Tsunami Awareness

ONSLOW TSUNAMI BROCHURE

A key aim of this project was to develop a community specific tsunami brochure for communities in NW Western Australia most vulnerable to tsunami. It is envisaged that the brochure prototype developed for Onslow would contain community-specific information and maps that would be changed for other communities. The brochure purpose is to educate vulnerable communities on how they may be affected during a tsunami. As such the brochure includes maps of peak inundation, basic information on tsunami generation, warning signs, what to do in the event of a tsunami and sources of further information (e.g., key local phone numbers). The first draft of the tsunami brochure can be viewed on the Electronic Appendix. Copies of the draft brochure have been provided for feedback to: Gordon Hall of FESA; Russel Levine of the Exmouth FESA office; Regional FESA managers; and members of the Local Emergency Management Committee (LEMC) that attended the third Onslow meeting.

The brochure received very positive feedback from members of the LEMC at the Onslow meeting, Gordon Hall, and Onslow Police Sergeant Mick Hayes. The following suggestions were put forward by Gordon Hall:

- The addition of indigenous art work to the brochure to improve tsunami awareness among the local indigenous community. If this suggestion is to be incorporated, artwork would need to be purchased from the local community for each brochure;
- Remove "shake" from the tsunami warnings section and instead add that an impeding tsunami may be heralded by sudden changes in animal, bird and marine life behaviour, bubbling of water, and/or strong rips and currents[1]; and
- Remove the deterministic hazard map of Australia and replace it with a cartoon-like figure that illustrates that the potential for greatest inundation occurs in NW WA but that coastal impacts could occur all along the WA coastline.
- Gordon also suggested that the brochure be tabled at an Australian Tsunami Warning Working Group meeting later in the year.

There was discussion on the timing of the brochure release at the LEMC meeting, specifically related to the development and implementation of the Onslow emergency plan. The importance of including emergency plan details would need to be balanced against a perceived need to release the brochure as soon as possible.

RAISING TSUNAMI AWARENESS IN ONSLOW – THREE MEETINGS IN ONSLOW

Our fieldwork in Onslow coincided with three community meetings led by Gordon Hall from FESA, and thus it was possible for GA to have a presence at each of these meetings. Two of the meetings sought to raise awareness of tsunami hazard and the potential for response and impact mitigation in Onslow, and a third meeting involved presentation of material to two Onslow councillors that was not yet deemed appropriate for broader release.

Onslow FESA Emergency Responders Meeting – 18 June 2007

This meeting had several aims including: basic education for emergency responders on the science of tsunamis, illustration of past tsunami events in West Australia, the research conducted at Geoscience Australia, the level of tsunami hazard in Onslow and the best way forward in terms of mitigating the hazard. This meeting was attended by all the graduates, approximately six FESA personnel from Onslow, and several regional FESA coordinators.

The presentation, given by Gordon Hall, included research by Amy Prendergast on the 2006 Shark Bay tsunami event, the deterministic tsunami hazard map for Australia and maps of inundation caused by a magnitude 9.0 event near Java at Onslow low-, medium-, and high-tides. Gordon emphasised to the audience that there is a difference between a flooding event/storm surge and a tsunami event. In particular he discussed coastal impacts, changes to ocean currents, expected inundation water velocities, and the relatively temporary nature of tsunami inundation.

The feedback from the audience focussed on the type of response that might be required from FESA personnel and the use of the cyclone alert system for tsunami warnings. Several FESA members also

[1] This will depend on national implementation of education products and how these will differ to locally developed products.

appeared concerned that their houses were located within an area of significant inundation which is surprising given that these houses are also located within the flood area on the 1 in 100 year storm surge map (Figure 3.6).

Onslow Council Meeting – 19 June 2007

This meeting was held prior to a general meeting of the Onslow Local Emergency Management Committee (LEMC) to discuss the content of Gordon's presentation and the distribution of the Onslow Tsunami awareness brochure. This meeting was attended by two councillors from the Ashburton Shire, Gordon Hall, two regional FESA managers and Alanna Simpson.

During this meeting Gordon showed the Geoscience Australia fly-through movie of a modelled tsunami from a magnitude 9.0 earthquake near Java at high tide inundating Onslow. He queried whether or not the movie should be shown at the following LEMC meeting. The consensus was that it should not be shown due to a predicted negative emotional impact on the emergency managers attending the meeting. However, as the inundation maps were considered similar to the one hundred and two hundred year frequency storm surge events, they were considered less 'upsetting'. Other comments from the councillors on inundation in Onslow included questions on predicted water velocities[2], the impact on the town water supply (derived from the Cann River) and power supplies (derived from a station out on the salt fields).

At this meeting the draft Onslow Tsunami brochure was shown to the councillors who were happy for the brochure to be distributed at the following LEMC meeting. Furthermore, Amanda agreed to forward any community feedback on the brochure to Alanna Simpson.

Onslow Local Emergency Management Committee Meeting – 19 June 2007

The aim and content of this meeting was similar to the earlier FESA meeting. However, at this meeting there was a greater focus placed on the best way forward in terms of mitigating the hazard (i.e., drafting an Onslow tsunami emergency plan). In addition, the draft Onslow Tsunami brochure was introduced and distributed for feedback by Alanna Simpson (see Section 4.1). The meeting was attended by approximately 12 members of the LEM committee including two police officers, an Onslow Salt Mine official, several council members and a representative from Karratha Gold. In addition, several regional FESA members were also in attendance.

There was considerable discussion at the conclusion of the formal presentations, with the following points raised. First, there was less concern about the extent of the inundation with most attendees simply stating that the inundation was similar to one and two hundred year frequency storm surge events. Police Sergeant Mick Hayes later commented that there was a general lack of community concern about natural hazards given the regular threat of cyclones and riverine flood. Second, concern was raised about the impact of tsunamis on oil and gas development on the NW WA continental shelf. The chief concern was that by increasing tsunami awareness in the area, petroleum companies would choose to explore/develop in regions less vulnerable to tsunamis. Third, there was mention of a proposal to widen Beadon Creek to a width of up to 100 m. There is apparently concern within the community that widening of the creek would leave Onslow more vulnerable to riverine, cyclone and tsunami inundation. Finally, Mick Hayes mentioned he had seen a photograph showing the aftermath of a tsunami in Onslow during the 1930/1940s. Further discussion of anecdotal evidence of tsunami follows.

[2] This data has now been supplied to FESA in July 2007 as a result of the Collaborative Research Agreement. Significant/dangerous water currents are increasingly viewed as the more likely tsunami threat to Australia.

ANECDOTAL EVIDENCE OF PAST TSUNAMI IN ONSLOW

Anecdotal evidence of past tsunamis in Onslow was collected from various sources during our work in WA, including: the first report of a tsunami in 1937; documentation of the impact of a Krakatau sourced tsunami in 1883; eye-witness accounts of the 1994 and 2004 tsunami events; and a possible tsunami event in 1971.

Mick Hayes supplied the contact details for several long-time residents of Onslow in order to find further anecdotal evidence of past tsunami. Following are key points raised during phone conversations and meetings with Onslow residents.

- Meeting with Laura and Ron Shannon at the Caravan Park on Second St in Onslow.
  - Laura confirmed the report of the tsunami in the 1930-40s. She said that it occurred in 1937 and thought that it was triggered by an event in Timor. Following the tsunami Beadon Bay was reportedly awash with seaweed, coral and other debris such that swimming was prohibited for at least three days.
  - This event may correspond to a magnitude 7.2 earthquake that occurred off the coast of Java on 27 September 1937 (USGS Centennial Earthquake Catalogue).
- Phone call with Dawn McAulby, Onslow resident
  - Dawn mentioned a “tidal wave” came in via Simpson St from Back Beach in 1971. This “tidal wave” was apparently 6-8 inches high in Onslow and 1 m high in Exmouth.
  - This event was also confirmed by Val Blair, also an Onslow resident, who called it “an extra high tide”. Furthermore, in the local museum the following reference was found to the 1971 event: “sea water entered the town. The area inundated covered the recreational area and extended into the residential areas from the hospital to the primary school along Second St.”
  - Two lines of evidence suggest this flooding event may have been associated with a cyclone rather than a tsunami. First, Cyclone Rita passed close to the coast in 1971 but did not make landfall. This could have produced the flooding without the other phenomenon that typically accompanies a cyclone. Second, there does not appear to be a potentially tsunamigenic earthquake in the USGS Centennial Earthquake Catalogue for 1971.
- Phone call with Val Blair, Onslow resident
  - In 1994, Val’s husband Ian Blair, who was described as ‘a man of the seas’ reported that the tide was 1 m higher than it should have been, an event that may correspond to the 1994 tsunami.
  - On Boxing Day, 2004, Val was told by her son of the earthquake and tsunami in SE Asia so she self-evacuated to the highest hill in Onslow. Val reported that from her view from the hilltop, all the water drained out of the bay and then came in again very fast. This apparently happened several times.
  - Val also noted that several years earlier she and her husband had found a large quantity of shells inland from the present day salt mines.
- Phone call and letter from Mick Hayes, Onslow Police Sargent
  - Local police Sergeant Mick Hayes located a letter documenting a tsunami event in Onslow on the 18th September 1883. The relevant section of the letter from Sgd. Harry follows: “The most startling news we have is that we have had a shock of earthquake, also a tidal wave, the sheep were just being landed from the Laughing-Wave when it took place and one of the dingys was swamped while another was washed up high and dry, sheep and all. 12 sheep were drowned out of the dingy swamped. The noise was heard all over the district and we have heard also in the south.”
  - This event would appear to correspond to the 1883 eruption of Krakatau in Indonesia on the 26th and 27th of August. The eruption triggered a series of tsunamis that impacted areas well distant from the volcano. The blast from the eruption was reportedly heard as far away as Perth and Kalgoorlie, which may explain the noise remarked upon in the letter. However, the

mention of an earthquake in the letter raises the possibility of another event as shaking from the eruption is unlikely to have been felt in Onslow.

ANECDOTAL EVIDENCE OF PAST TSUNAMI IN EXMOUTH

Russell Levine a local SES member in Exmouth reported the impact of the 1994 tsunami along the NW of Cape Murat.

- During this event he reported that the tsunami went over ~7 m high dunes at Jurabi Point. Following inundation there were many broken turtle shells and fish found tens of meters inland. Russell speculated that inundation may have been more severe in coastal areas exposed to gaps in Ningaloo Reef. Other reports suggest that during this same event water flowed ~200 to 300 m up Tandabiddy Creek and reached the road near the Light House Caravan Park.
- It was Russell's opinion that the most vulnerable place along the coast for tsunami inundation was the Light House Caravan Park due to its popularity with tourists all year round and is relative seclusion from emergency services.

Conclusions

The key conclusions identified during this project are summarised below.

- The ANUGA model utilised by Geoscience Australia for inundation modelling in Exmouth and Onslow allows for the progressive improvement of elevation data via the use of an unstructured triangular mesh. The DEM used in the existing model had a resolution of 20 m and an accuracy of only ±10.00m in the horizontal and vertical dimensions. The dataset obtained during this study contains several points of elevation data per DEM value, and has an accuracy of within 0.10m in the horizontal dimension, and ±0.25m in the vertical.
- Greater density of data (as demonstrated in the case study of Beadon Bay) has allowed for topographic subtleties to be detected, while higher precision has reduced the vertical error to much less than one metre. In contrast, it was found that in the same locality the existing DEM underestimated the true elevation by up to 6.2 m.
- By incorporating this new high-precision dataset into the existing DEM using the flexibility afforded by the triangular mesh; it expected that more reliable tsunami inundation models will be obtained. This will ultimately contribute strongly to future assessments of risk posed by the hazard to these portions of the Western Australia coastline.
- The usefulness of this GPS survey would have been improved if the survey had continued further into the study area, particularly given the significant height difference identified between the survey data and the DEM data.
- The visual inspection component of this project supplements the survey data and provides validation of the current inundation models. Observations made during the visual inspection will assist in the production of more representative inundation models and potentially help local emergency managers to produce emergency response plans.
- A community-specific tsunami awareness brochure was favourably received by the Onslow community for which it was designed. Furthermore, this brochure was favourably received by representatives from FESA, Geoscience Australia, Emergency Management Australia and the Bureau of Meteorology.
- Representing Geoscience Australia at three community meetings in Onslow provided the opportunity for attendees to ask questions regarding tsunami impacts and discuss specific community concerns. Fortuitously this community interaction also led to the discovery of anecdotal evidence of past tsunami events in Onslow including: the tsunami triggered by the 1883 Krakatau eruption; a 1937 tsunami probably generated by an earthquake near Java; and the 1994 and 2004 tsunamis.

- The data gathered throughout the project provides an opportunity to further increase the capability to ANUGA in developing tsunami inundation maps for emergency managers. In particular, the observations gathered during visual inspection suggest that regions of varied friction values could be incorporated into ANUGA, and the anecdotal evidence gathered provides an opportunity for further validation of ANUGA.

Acknowledgements

We would like to thank everyone at Geoscience Australia and FESA who contributed to our project and helped make it the success that it was.

In particular, we would like to thank Jane Sexton for her invaluable assistance throughout this project. Within the NHIP, Trevor Dhu, Ole Nielsen and Amy Prendergast provided fantastic assistance. Nick Brown from Geodesy gave us excellent training in the use of the GPS equipment and Katharine Hagan from GAV helped us with brochure design and production. We would also like to acknowledge the financial support that we received from Barry Drummond and Gordon Cheyne through the ATWS and Len Hatch in Communications, Human Resources and Governance.

During our time in Western Australia, Gordon Hall provided valuable support which was greatly appreciated and we would also like to thank Russell Levine and Peter Cameron. Furthermore we would like to acknowledge the help and enthusiasm of Mick Hayes, the Onslow Police Sergeant, in tracking down anecdotal evidence of past tsunami.

Finally we would like to acknowledge the reviewers, Shannon McNamara (Emergency Management Australia), Gordon Hall (FESA), Mark Leonard (Geoscience Australia) and Ramesh Govind (Geoscience Australia), all of whom provided thoughtful comments that have further improved the manuscript.

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Appendices

DETAILED DESCRIPTION OF GPS SURVEY AND DATA PROCESSING

Field Equipment

Base station

The base station used for all surveys consisted of a tripod-mounted Leica AT504 choke-ring GPS antenna, with observations recorded at 1-second epochs by an Ashtech USCGRS GPS receiver (Figure A.1). The base was established over survey control marks, obtained from the Western Australia Department of Land Information (Landgate), selected for both their proximity to the survey areas and positional accuracy. Further information on base station specifications and Landgate Gesmar survey control reports are contained in the Electronic Appendices.

Roving receiver

A Thales Z-Max kinematic GPS receiver was used for all roving survey data collection. When corrected by base station data, this receiver is capable of an internal accuracy of 1-2 cm horizontally and 3-4 cm vertically; however, many other factors contribute to the final determined accuracy of the survey data (Section 2.3.1). Survey points were observed using a 1-second epoch rate and 10 second occupations at each point of interest. This procedure was used to maximise the potential of a 'fixed' accurate position determined by the rover, whilst minimising the time required at each point.

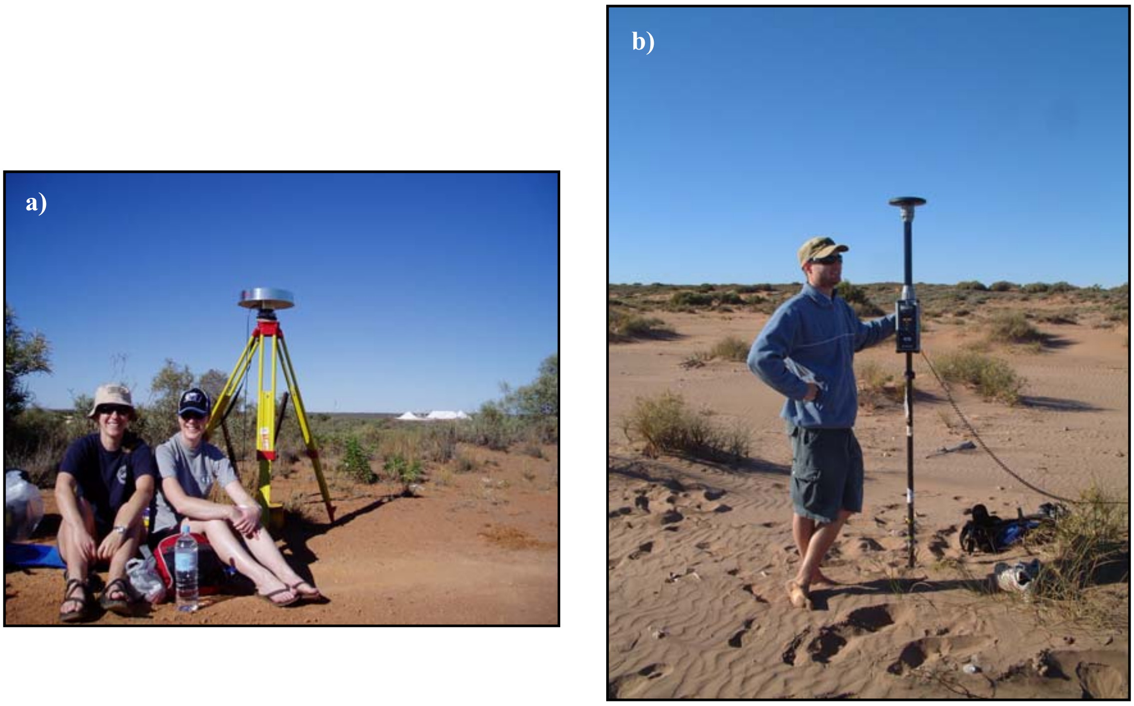

Figure A.1: *a) Base station setup – Onslow; b) Roving Receiver Setup*

Data Processing and Quality Control

Kinematic Processing

Base station data for the four survey days was downloaded from the receiver and converted to Receiver Independent Exchange (RINEX) format to enable its use in the GNSS Studio processing software. The kinematic data files were then processed in GNSS studio with the corresponding base station data to derive the accurate kinematic survey positions. In this process the control position of the base station (specified in the Gesmar report) and antenna heights of both the base and roving receiver are supplied to the GNSS studio program. In the processing procedure, any positional corrections found between the processed base station position and the supplied known control position are applied to the kinematic data of the same epoch, generating the accurate roving point positions. The resulting survey points are then provided in MGA Zone 50 coordinates, with a vertical component of ellipsoidal height (h), relative to the GRS80 ellipsoid.

Deriving AHD height

The ellipsoidal height (h) produced by GPS observations is relative to the ellipsoidal model of the earth; however, the Australian Height Datum (AHD) height, relative to Mean Sea Level (MSL) is required for the tsunami risk modelling activity.

The first step in this process is the conversion of ellipsoidal height (h) to orthometric height (H), which is relative to the geoid, and has the relationship h = H + N (Figure A.2). To obtain an orthometric height for each point, the geoid-ellipsoid separation, or N-value, was obtained for each survey point using Geoscience Australia's WINTER software, which interpolates an N value from an existing grid of Ausgeoid98 N values.

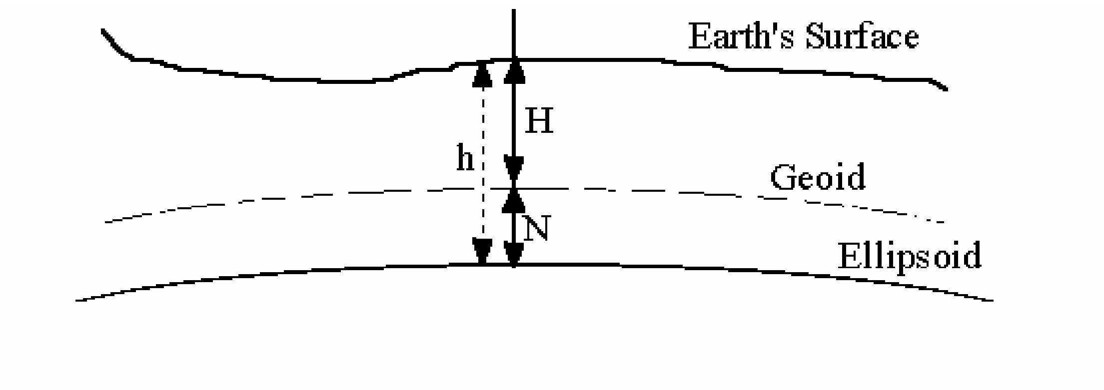

Figure A.2: *Geoid – ellipsoidal height relationship*

The geoid is a mathematical surface of equal gravimetric potential, which also approximates the ocean at mean sea level, and hence is a very close reference surface for AHD elevation. Due to the standard survey methods used to establish and realise AHD across Australia, some AHD-geoid separation does exist. Due to the close proximity of the survey points to the known survey control, the AHD-geoid separation determined at the control points could be considered a good representation of the separation that would exist throughout the survey area. Thus, the AHD-geoid separation calculated at the relative control points was then applied to the derived orthometric heights (H) of all the survey points to obtain an accurate AHD elevation.

The process was simple at the Onslow control point (R299) due to the availability on the Gesmar report of both an accurate AHD height and a GPS determined ellipsoidal height. A GPS ellipsoidal height for the Exmouth control (FS6) was not available on the Gesmar Report, and was obtained as part of the AUSPOS quality control check detailed below. Calculations of the AHD-geoid separations of both control points are included in the Appendix.

Quality Control

To ensure the quality of the base station data used as control for the survey, all base station RINEX files were processed through Geoscience Australia's AUSPOS GPS processing service. This service processes the data using high quality International GPS Service (IGS) products to return a highly accurate and reliable position of the base station position. Comparison of the base station coordinates returned by AUSPOS to those specified in the Gesmar reports showed the offset to be well within the stated accuracy (3cm horizontal and 5cm vertical) of the Gesmar positions. This confirms that the base station data was of good quality for use in correcting the kinematic rover data.

The rover point positions supplied by the GNSS studio software are tabled in a land survey report for each survey day (see electronic Appendices). Each point and vector is assigned a 95% confidence interval for the easting, northing and vertical dimensions to reflect the quality of the processed position. Any points with a value greater than 0.025 m were discarded; thus, only high-quality fixed position points are included in the final data sets.

ELECTRONIC APPENDICES

The appendices include: (1) transcribed field notes; (2) photos with labels containing a short description and GPS location; (3) a PDF copy of the tsunami brochure draft; (4) a copy of the 1883 letter describing a tsunami at Onslow; (5) data associated with the GPS survey; and (6) relevant GIS files.