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Storm surge modelling for Bunbury, Western Australia

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Storm surge modelling for Bunbury,
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1. Executive Summary

Geoscience Australia (GA), the Western Australian (WA) Department of Planning (DoP) and the Western Australian Planning Commission (WAPC) have collaborated through a Memorandum of Understanding (MoU) to develop a storm surge modelling methodology that can be applied to Bunbury. The aim of this document is to provide the DoP and WAPC with a description of the methodology, how the model and the results may be used, and an assessment of the estimated inundation from a range of storm surge and climate change scenarios at Bunbury. At the conclusion of the MoU, this modelling methodology will be made available to the DoP and WAPC through the provision of tools and data that can be used for planning purposes.

The modelling methodology used here integrates the outputs from Global Environmental Modelling Systems (GEMS) 2D Coastal Ocean Model (GCOM2D) regional scale storm surge model with the free and open source hydrodynamic modelling software ANUGA to estimate inundation at the City of Bunbury resulting from a range of possible storms surge events. These models are used in conjunction with the Shoreface Translation Model (STM), developed by Peter Cowell, Peter Roy and Bob Jones at the University of Sydney, to predict potential inundation under a number of climate change scenarios that alter the local coastline surrounding Bunbury. All care has been taken to validate and calibrate each component of this modelling methodology and further validation is required for the integrated modelling methodology. The results described in this report are an important first step in that validation process. It must be remembered that all aspects of the modelling methodology involve uncertainty and approximations, and model results are by nature only indicative. As a result, the model outputs described here should not be relied upon solely for planning decisions.

The model outputs described here can provide an indicative relative assessment of potential inundation. The outputs highlight that certain parts of the coastline are vulnerable to inundation and that some areas have the potential for greater inundation than others. The model outputs may be used in the development of appropriate town planning policy response, community awareness raising, development assessment processes, emergency planning responses and physical flood protection infrastructure. However, the resolution and accuracy of the model is not sufficient to predict damage to individual properties. The model results must be used as only one of a number of inputs that must be considered when attempting to understanding the risk of storm surge inundation to the City of Bunbury.



The assessment covers model results for six cases:

1. Simulation of inundation arising from the 1978 Tropical Cyclone (TC) Alby event (baseline event)
2. Simulation of inundation resulting from a 'worst case' track given the current surface model and no sea level rise
3. Simulation of inundation resulting from a 'worst case' track given the current surface model and a 0.4m level rise
4. Simulation of inundation resulting from a 'worst case' track given the current surface model and a 0.9m sea level rise
5. Simulation of inundation resulting from a 'worst case' track using the current surface model and a 1.1m sea level rise
6. Simulation of inundation resulting from a 'worst case' track given a potential future surface model and a 1.1m sea level rise

The effect of the storm surge gate at Bunbury will also be investigated for cases 1-5. For each of these cases, the model outputs will be:

- Maximum inundation depth maps,
- Maximum flow speed maps, and
- Time series plots for particular locations.

The key observations of the modelled outputs are:

- The foredunes on the open coast play a significant role in protecting the City of Bunbury from storm surge inundation for all cases considered.
- These foredunes continue to exist in the potential future surface model; however they are translated in distance (landward) and have increased in height.
- The potential future surface model developed here assumes that no other coastal engineering processes have occurred.
- The storm surge gate acts to reduce the inundation extent for the 1978 TC Alby event and the worst case track and timing TC Alby event for the current surface model.
- The modelled inundation resulting from the integrated GCOM2D and ANUGA method described here compares well with inundation from GCOM2D.
- The model outputs compare well with the observed tide gauge reading at Bunbury.
- The model comparison with observed inundation from 1978 lies between Case 3 and Case 4.



2. Glossary

This table defines technical terms and abbreviations used in this document.

ANU	Australian National University.
ANUGA	A free and open source hydrodynamic modelling tool developed jointly by the Australian National University and Geoscience Australia.
Bathymetry	The depth of the ocean floor from the water surface.
DCCEE	Australian Government Department of Climate Change and Energy Efficiency.
DoP	Western Australian Department of Planning.
FOSS	Free and Open Source Software.
GA	Geoscience Australia.
GCOM2D	GEMS 2D Coastal Ocean Model .
GEMS	Global Environmental Modelling Systems Pty Ltd,
Geomorphic features/ geomorphology	Surface features and landforms including those on the seafloor (see geomorphology glossary below for definitions of geomorphic terms).
Return period	Also known as a recurrence interval, this is an estimate of the interval of time between hazard events of a certain size.
SLR	Sea level rise.
STM	Shoreface Translation Model developed and applied by the University of Sydney.
Topography	The elevation of the land surface from sea level.
WAPC	Western Australian Planning Commission.
Wave height	The positive amplitude of the storm surge wave. When the storm surge reaches the shore it often reaches run-up heights much greater than this.



3. Introduction

The Western Australia (WA) coast line is particularly vulnerable to the impacts of storm surge. This is especially so due to the close proximity of the urban environment to the coast and, generally speaking, the low relief of the coastal hinterland. Numerous historic storm surge events have been recorded in WA. The effects of climate change and the changing nature of cyclones, coupled with projected sea level rise, may lead to increased vulnerability to storm surge inundation. This has been recognised nationally with the Department of Climate Change and Energy Efficiency (DCCEE) initiating a suite of studies to support a National Coastal Vulnerability Assessment (DCCEE, 2010).

GA has been developing and applying a tsunami impact and risk modelling methodology since 2005 largely based on the ANUGA hydrodynamic inundation model. Recently, ANUGA has also been trialled and further developed to work as a tool for the simulation of riverine flooding from rainfall events predominantly by individuals in local councils.

This report outlines the development of a modelling methodology which can be used to simulate storm surge along the coast of Australia. The aim of the project is to equip ANUGA, traditionally used for inundation, with the necessary tools to accurately model storm surge. An associated aim is to validate the new methodology against a historical event and finally provide a case study of potential impacts of storm surge on the City of Bunbury. The results of this study may be used to develop appropriate planning and development policies that respond to the identified flood risk.

A range of commercial storm surge models are currently employed by consultants around Australia. A key intent of this project is to develop a modelling capability that is provided through the free and open source ANUGA software that can be applied by the Western Australian State or local governments or provided to third-party contractors. The open source software will provide increased transparency to the WA government, ability to rerun models when new data is available, test mitigation options and potentially reduce costs of any future storm surge studies. This approach aligns with the goals of the 2002 COAG review of Natural Disasters in Australia in developing data, information and tools that could be used by government to manage natural hazard risk in Australia.

ANUGA is specifically designed for robust modelling of the wetting and drying processes arising from shallow water flow over dry land. This allows for modelling of tsunami, flood and storm surge. ANUGA has been extensively applied and validated against tsunami flow and is increasingly being used for flood modelling. The software has been designed for detailed localised inundation studies and is currently less suited to large, regional scale assessments. Consequently, ANUGA is currently not capable of modelling the entire storm surge process. ANUGA must be coupled with another coarser large scale open ocean storm surge model before it can be applied to simulate onshore inundation.

For this project then, the storm and the resultant storm surge will be modelled by Global Environment Modelling System (GEMS) using GCOM2D (Hubbert, 1990 and 1991). The storm surge height and current estimated by GCOM2D will be used to drive ANUGA



which will then estimate inundation at the City of Bunbury. Over the life of this project, it is intended to equip ANUGA with the ability to incorporate wind fields directly from other models (preferably free and open source, FOSS) as well as wave setup processes (such as SWAN¹) so that a free an open source integrated storm surge inundation model can be developed.

GCOM2D can estimate storm surge inundation. A key activity of this project will be to compare ANUGA inundation estimates with the GCOM2D inundation estimates. Differences will be expected as each model implements a different numerical modelling approach. All numerical schemes have advantages and disadvantages and it is not the purpose of this report to provide a treatise on that.

ANUGA also does not model the change to the coastline through sea-level rise and long term erosion and sediment transport. The timescales of such processes are of the order of tens to hundreds of years, whereas the timescales typically modelled by ANUGA are hours to days. To estimate the effect of storm surge, subject to climate change, in addition to an open ocean storm surge model, ANUGA must also be coupled with a model which can be used to predict long-term change in coastline morphology. The Shoreface Translation Model (STM), developed by the University of Sydney is one such model. It must be noted that ANUGA has the ability to dynamically change the elevation during a simulation; however this is only suitable for processes that occur over short timeframes of hours to days.

REPORT STRUCTURE

The remainder of this document proposes an inundation modelling methodology for simulating storm surge along the Australian coast. A number of storm surge scenarios that could potentially impact the City of Bunbury are investigated. Numerous measures such as maximum inundation depth and current maps and time series at selected locations, are used to quantify impacts. Finally we present recommendations and discuss the utility of ANUGA for modelling storm surge inundation and avenues for future work.

All figures are named by: *Scenario_speed/depth* where *Scenario* is labelled as shown in Table 1.

Scenario	Description
Case_1	Simulation of the 1978 Tropical Cyclone (TC) Alby event (baseline event)
Case_2	Worst case track and timing TC Alby on current surface model with 0m sea level rise
Case_3	Worst case track and timing TC Alby on current surface model with 0.4m sea level rise
Case_4	Worst case track and timing TC Alby on current surface model with 0.9m sea level rise
Case_5	Worst case track and timing TC Alby on current surface model with 1.1m sea level rise
Case_6	Worst case track and timing TC Alby on future surface model with 1.1m sea level rise

Table 1. Scenario labels and descriptions.

Maximum inundation depth maps are provided on the accompanying DVD. These show the maximum water depth onshore (Figures appended *depth*). Maximum flow speed maps are also provided on the accompanying DVD showing the maximum flow speeds expected offshore as well as the inundation zone (Figures appended *speed*).

¹ SWAN is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters, see <http://vlm089.citg.tudelft.nl/swan/index.htm>



The modelled outputs (in the form of ArcGIS raster grids) used in the creation of the above figures are also provided on the accompanying DVD. This is to enable the DoP and WAPC to incorporate outputs into their decision support systems, thereby assisting storm surge planning activities.

By the completion of the MoU in June 2011, the modelling software, model configurations in the form of computer scripts, and all input data will be supplied. Instructions on installing the relevant software and locations of data and scripts will be provided.



4. Methodology

4.1. Storm Surge Modelling Framework

Numerous models are currently used to simulate storm surge inundation, such as GCOM2D and Mike21. Here we introduce the modelling methodology employed by Geoscience Australia to model storm surge. The general outline of the proposed modelling methodology is illustrated in Figure 1.

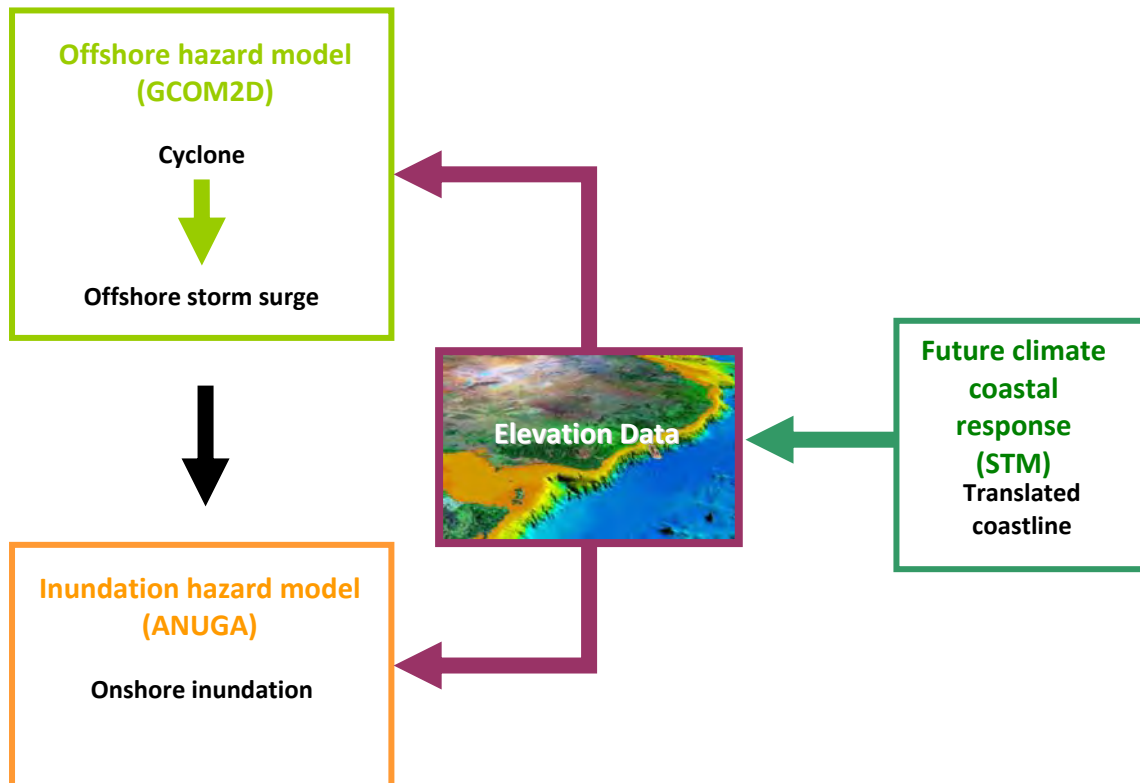


Figure 1: Storm surge modelling methodology. This project applies the GCOM2D model as developed and applied by GEMS to estimate the offshore hazard and ANUGA to estimate the storm surge inundation. The change to the coastline is estimated using the STM as developed and applied by the University of Sydney.

The methodology used by Geoscience Australia has three distinct components. Firstly a bathymetry and elevation data set must be obtained. When investigating the effects of climate change, an appropriate model must be used to estimate the shoreline recession and/or growth caused by long-term climatic processes. Here we use the Shoreface Translation Model (STM). The STM modelling methodology, outlined in Appendix B, estimates shoreline recession based on climate change scenarios. The STM developed by the University of Sydney is capable of modelling the effects of sea-level rise, disturbances to sediment budgets, effects of mixed sediment-sizes (including sand and mud), variable resistance to erosion for material comprising strata in the substrate (which can include bedrock and reefs), and complex topography. The Bruun Rule, normally used to predict coastal retreat due to sea-level rise, cannot handle any of these complications.

Once the shoreline geometry has been determined the sea surface deformation caused by the storm surge on the regional scale must be approximated. Here we use GCOM2D (Hubbert, 1990 and 1991) to provide an accurate representation of surface wind and



atmospheric pressure fields over the region of interest. The GCOM2D has been applied to a large number of locations around Australia including: Port Hedland, Karratha, Cape Lambert, Derby, Onslow, Dampier, Cairns, Gold Coast, Darwin, Mornington Island and Port Phillip Bay. The model is based on the storm surge model described by Hubbert et al. (1990, 1991) and Hubbert and McInnes (1999). Surface wind speeds and pressures are derived indirectly by applying a tropical cyclone vortex model based on the empirical relationships presented by Holland (1980). Atmospheric forcing is derived from the GEMS Mesoscale Atmospheric Prediction System (MAPS) or from a tropical cyclone model.

Once the GCOM2D model has been applied, the predicted sea surface height and momentum are used to generate a boundary condition for a localised ANUGA inundation simulation. ANUGA is a Free and Open Source Software (FOSS) package capable of modelling the impact of hydrological disasters². The software is based on the conserved form of the shallow water wave equations discretised to unstructured triangular meshes using a finite-volume numerical scheme (Nielsen et al 2005). ANUGA has primarily been used for tsunami inundation modelling (Jakeman et al 2010) and there is an increasing interest in developing ANUGA into a tool for flood modelling, dam break studies and modelling of coastal processes (see, for e.g. Middelmann-Fernandes and Nielsen, 2009).

Elevation data is needed by all three models. As the scale of the physical processes is different for each model, the resultant resolution of the elevation data is different for each model. Where physical processes act quickly, as in the deep ocean, coarse bathymetry data can be used. As the storm surge reaches shallow water and the complex nearshore environment, increasingly finer scale data is required. A key benefit of the numerical implementation adopted by ANUGA is that the unstructured mesh allows high resolution data to be taken advantage of in areas of interest.

High resolution bathymetry and topography data has been provided by the WA State Government. The Department of Water provided onshore LiDAR³ and the Department of Transport (DOT) provided offshore LiDAR. This was supplemented by additional bathymetry from DoT such as fair sheets and chart data. In addition, the 250 m Australian bathymetry and topography grid (Geoscience Australia, 2005) was also incorporated for the deeper water sections.

The elevation data is bare earth, meaning it does not include buildings or other structures. A tsunami inundation model of the 2004 Indian Ocean Tsunami impact on Patong Beach, Thailand illustrates that the inclusion of structures into the elevation data can have a significant impact on the modelled inundation extent (Jakeman et al 2010). It is anticipated that there would also be some impact to the inundation for the City of Bunbury, however, it is not as highly urbanised as at Patong Beach. This information could be incorporated into the model should building footprints, or higher-resolution elevation data which includes structures, become available.

The use of the three aforementioned models is intended to enhance the modelling process by using models which are individually well suited to one of the three distinct phases of storm surge modelling subject to climate change. The STM is designed specifically to estimate shoreline recession based on climate change scenarios. GCOM2D is well suited to

² The software can be downloaded online at <http://sourceforge.net/projects/anuga>

³ Light Detection and Ranging with a horizontal resolution of 1m.



modelling storm surge over large distances. In comparison, ANUGA is designed to accurately model the complex wetting and drying process of inundation.

4.2. City of Bunbury Case Study

In estimating the inundation from a particular storm event, the process is as follows:

1. build an offshore storm surge model using GCOM2D
 - a. generate a storm event using a vortex model
 - i. set the storm path (geographic fixes of the storm centre in time) from which the direction and speed of movement can be derived
 - ii. set the central pressure
 - iii. set the Radius of Maximum Wind (the distance from storm centre to the band of strongest winds which occurs in the eye wall)
 - iv. set the Shape Parameter “B” (which along with the radius of maximum wind) defines the rate of change of wind speed with distance from the centre.
 - b. model the storm surge
 - i. determine locations of interest where model is refined
 - ii. set the initial conditions (time of day, initial sea level, elevation)
 - iii. set the boundary conditions (e.g. tide)
 - iv. simulate the model for a specified time
 - v. determine the time varying wave height and momentum
 - vi. if modelling an historic event, calibrate the model by comparing to a tide gauge in the area
2. build an inundation model using ANUGA
 - a. determine locations of interest where model is refined
 - b. set the initial conditions (time of day, initial sea level, elevation)
 - c. set the boundary conditions (in this case the outputs from GCOM2D)
 - d. simulate the model for a specified time
 - e. determine the run-up (maximum elevation above mean sea level reached by the wave), inundation distance (maximum distance from the coast reached by the wave) and time varying inundation depth and horizontal momentum at a given coastal locality
 - i. compare with observed data if available
3. investigate the impact of storm surge gate
4. investigate the impact of various climate change scenarios
 - a. use a shoreline recession model to predict the changes to the coastline induced by climate change induced sea-level rise and return to 2b
 - b. change initial sea level in step 2b and rerun

Step 1a – generate a storm event using a vortex model:

As one of the most intense cyclones on record to impact the southern reaches of the west coast of Western Australia, Tropical Cyclone Alby (TC Alby) that occurred in 1978 has been used as a baseline event for this project. Modelling an historic event has the benefit of the impacts being remembered by the community. This is very important when the model results are being communicated as the community can more easily relate to the scenario and can compare the model outputs with what they may have experienced or heard. If the results match people’s experiences, then the community may have a greater trust in model results for future, hypothetical events. From a modelling point of view, it is crucial to



model historical events where observed data is available to be able to calibrate and validate the model.

TC Alby was the fifth tropical cyclone of the 1977/78 cyclone season in the north western Australian region. A detailed description of the life cycle and impact of TC Alby is contained in the Bureau of Meteorology report of TC Alby with the key points summarised at Appendix A.

An estimation of a return period for TC Alby is problematic because of the relatively small number of cyclonic events that have had a major impact on the west coast of WA. Appendix A provides an analysis of the history of these events for the period 1950-2008 to estimate that the estimated return period for TC Alby to be of the order of 200 years.

The question of whether rainfall induced flooding will be coincident with the TC Alby storm surge also needs to be considered. Based on an understanding of the cyclone system (see Appendix A) it can be concluded that for storms that cross the coast, the incidence of storm surge associated with the strongest on-shore winds, areas of significant rainfall and the location surge is unlikely to be coincident. For storms that remain off the coast and which have the capacity to produce sea level elevation as result of a 'trapped wave' that propagates southwards along the coast heaviest rainfall is also expected to remain offshore. Moreover, the fact that the cyclones are moving rapidly means that even when rainfall rates are relatively intense, total rainfall within a catchment will be limited by the duration of that rainfall.

Based on this assessment it is considered that coincidence of the rainfall induced flooding and significant surge is quite unlikely and is therefore not considered from a modelling perspective in this study.

The track shown and described for TC Alby in Appendix A was used for simulations to validate the model (described below). In order to investigate the impact of a 'worst case' strike this track was shifted in space so that the storm maximum winds impacted more directly on the City of Bunbury as shown in Figure 2. A large number of alternate tracks were investigated in order to determine the worst cyclone track using the same cyclone intensity and dimension parameters exhibited by TC Alby. It emerged from these studies that the same 'worst track' applied to both Mandurah and Bunbury (and Busselton) due to the nature of the sea level response to TC Alby in the region from Mandurah to Bunbury. To understand this it is important to note that the data from the tide gauges at Mandurah, Bunbury and Busselton showed that the peak sea levels at each location occurred at all three locations within an hour of each other. This is due to the fact that TC Alby was moving very fast as it passed along this region producing a sea level response along the coast which was almost concurrent at each of the three locations. The shifted track is shown in Figure 2 along with the 'actual' track used for verification (the verification 'track' is explained further below).



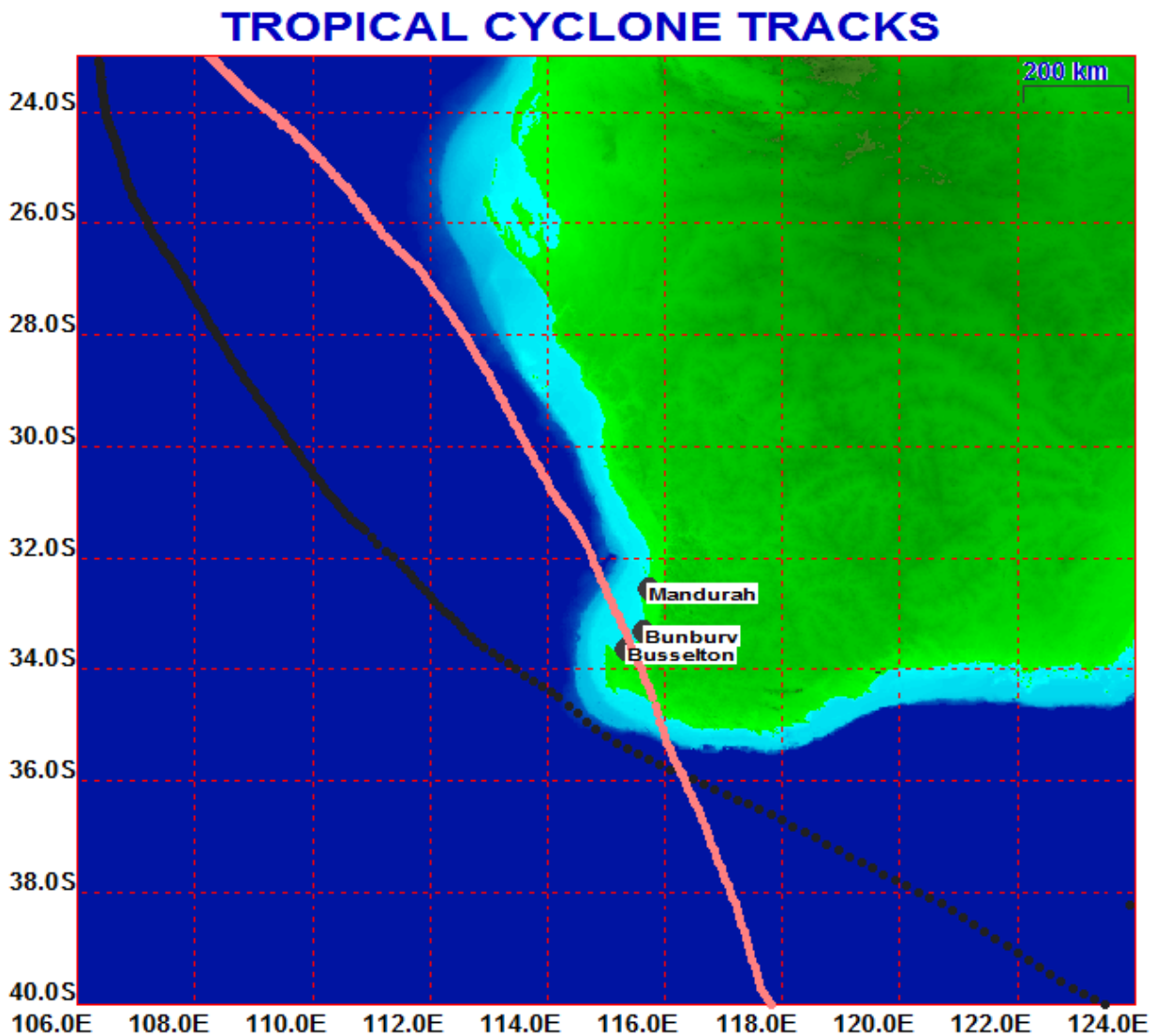


Figure 2: 'Actual case' (black) and 'worst case' (pink) tracks for TC Alby used for verification and prediction of extreme outcomes respectively.

Step 1b – model the storm surge:

The model simulations were carried out with the GEMS Storm Surge simulation model (GEMSURGE). This model simulates the inundation during extreme coastal and riverine events driven by atmospheric pressures, winds, tides and bottom friction (more important in shallow water and across hitherto dry land). The atmospheric pressures and the wind fields are predicted from the cyclone track information with a cyclone model based on the Holland vortex model (1980 and 2008). The bottom frictions are calculated from terrain type information if it is available.

The tidal forcing for the studies was generated from the GEMS tidal constituent database which was initially developed for the Western Australian coast for Australian Maritime Safety Authority (AMSA) to support the AMSA Search and Rescue Ocean prediction system which is based on the GEMS ocean model. The tidal constituent data was derived from a long term modelling study on a 1.8km grid around Australia which involved multiple iterations of model predictions, comparison with tide gauge data and adjustment



of boundary conditions based on error analyses. The model iterations were continued until errors reached a minimum status.

The official track for TC Alby provided by the Bureau of Meteorology was given in decimal degrees of latitude and longitude quoted to one decimal place. The potential numerical error in this track is therefore approximately ± 5 kms. The initial simulation with the precise official track did not produce a good verification at Bunbury and Mandurah with the errors being higher at Mandurah. Adjustment of the track within the ± 5 kms error margin however resulted in a much better verification being obtained.

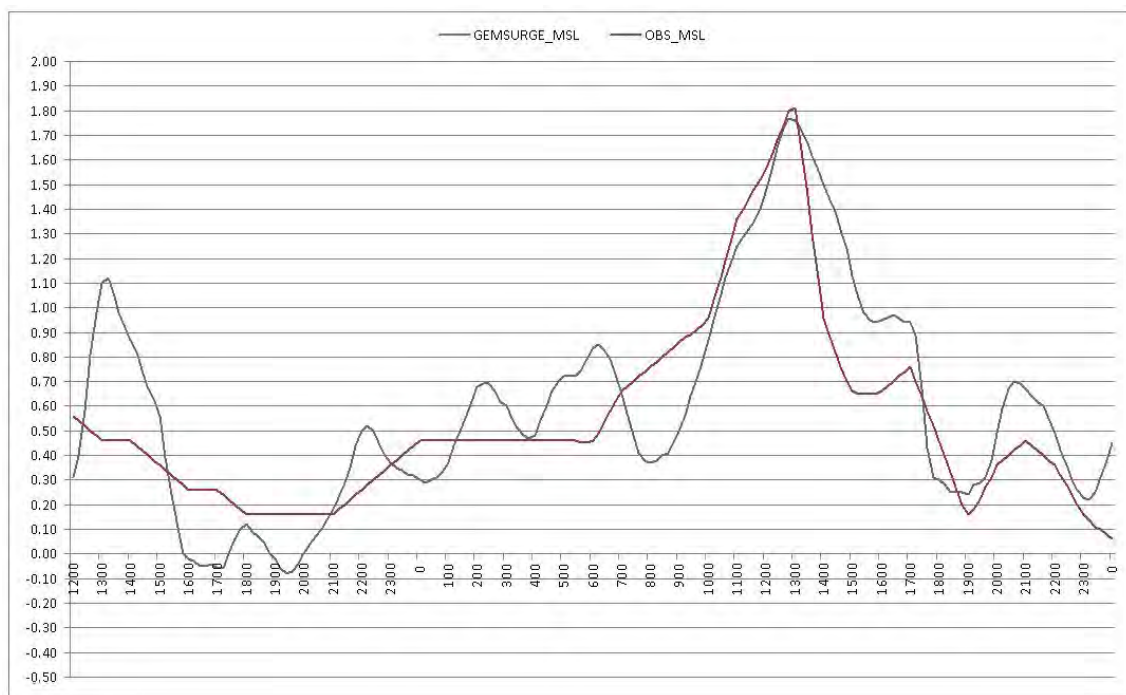


Figure 3: Model output from GEMSURGE and the tide gauge reading at Bunbury for TC Alby.

The model compares well against the observation at the tide gauge at Bunbury as shown in Figure 3. The model introduces some artificial oscillations prior to the largest peak. Importantly the model estimates the height of the main surge and captures the subsequent ocean surface fluctuations.

Step 2 - build an inundation model using ANUGA:

Any model should be set up according to end user requirements and it should also consider the potential vulnerability of the inundation based on the elevation and what may have been inundated in the past. The extent of interest was discussed with DoP and DoT officers at a meeting in Fremantle in October 2009 and shown in Figure 4.





Figure 4: Area of interest for storm surge inundation.

As mentioned earlier, ANUGA uses an unstructured triangular mesh to underpin the computations. A minimum mesh resolution is specified to describe the mesh, defined as the maximum allowable area of a triangle. In order to accurately capture the wave



dynamics, the model is built with a series of embedded internal polygons that have varying minimum mesh resolution. These polygons are constructed in such a way so that the polygon surrounding the community has the finest minimum mesh resolution. Subsequent polygons are constructed in a nested fashion. Figure 5 shows the polygons used in building the ANUGA inundation model. Note that the minimum resolution of the mesh is smallest within the area of interest, with a maximum allowable area of 200 m² (approximately 20 m triangle side length⁴). The resolution within the subsequent polygons decreases away from the community, where the wave dynamics allow a coarser mesh. The model configuration specifies the maximum allowable triangle area, and hence the minimum mesh resolution for each region in the model.

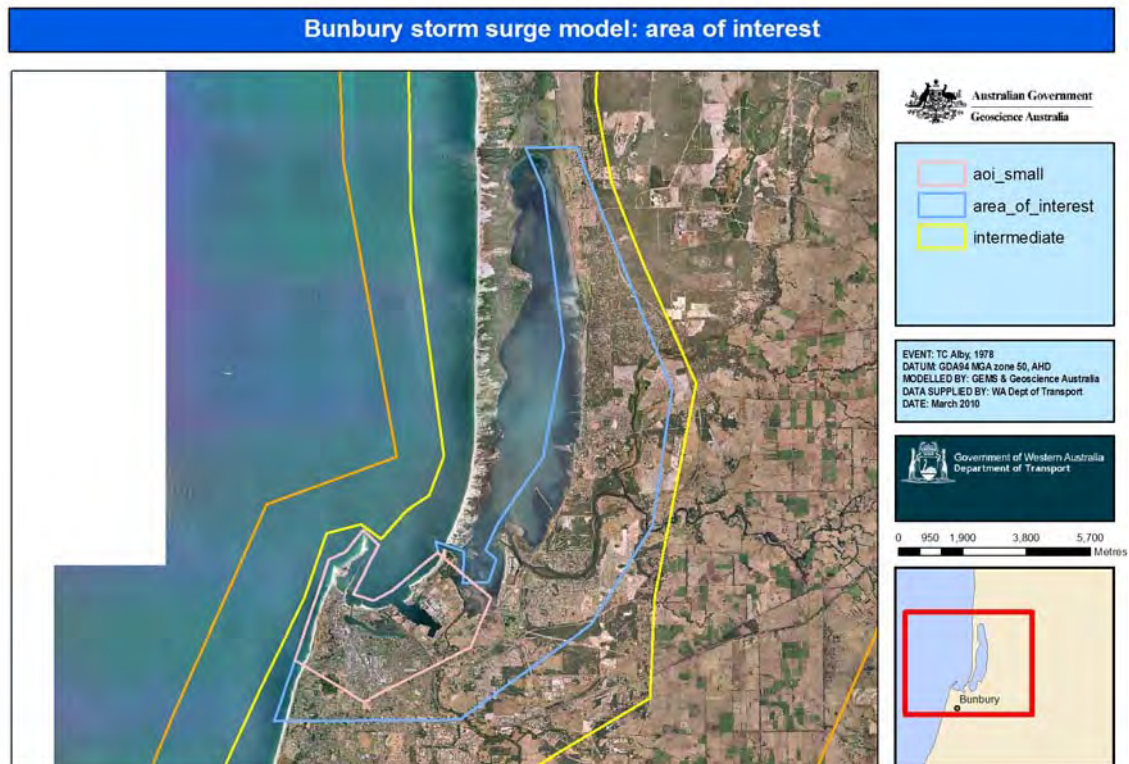


Figure 5: ANUGA refinement for Bunbury inundation model.

The model simulation is initiated at midday 4 March, 1978 with the initial sea level at mean sea level. Astronomical tidal forces are implicitly captured by the ANUGA simulation via the coupling with the GEMS model. The time varying boundary condition, derived from GEMS, and used to drive the ANUGA simulation, captures the change in ocean momentum and surface elevation due to the cumulative effect of the astronomical tide and the storm related processes. The total model simulation time is two days. This time was chosen to allow the full dynamics of the storm surge event to reach the area of interest and cover the major effects of the complex interaction with the nearshore environment.

The inundation model estimates the time varying nature of the wave amplitude and flow speed for the total simulation time. The maximum inundation depth and maximum flow speed maps are therefore the maximum wave amplitude and flow speed over the entire simulation time. It is also possible to determine how the water depth varies with time at

⁴ Note, most of the triangles will have an area much smaller than 200 m² meaning that the model resolution is much less than 20m.



selected observation points (synthetic ‘water level gauges’) within the model area. This data can be used to determine the number of peak surges within the storm event as well as the time for the water to recede at specific locations. In conjunction with the maximum inundation depth maps, these outputs can be used to inform planning and preparation activities. In the current model a gauge is co-located with the actual tide gauge at Bunbury, primarily for the purpose of validating the model against the historical tide gauge record for TC Alby recorded at Bunbury. Similar data has been generated for a series of locations as shown in Figure 6.

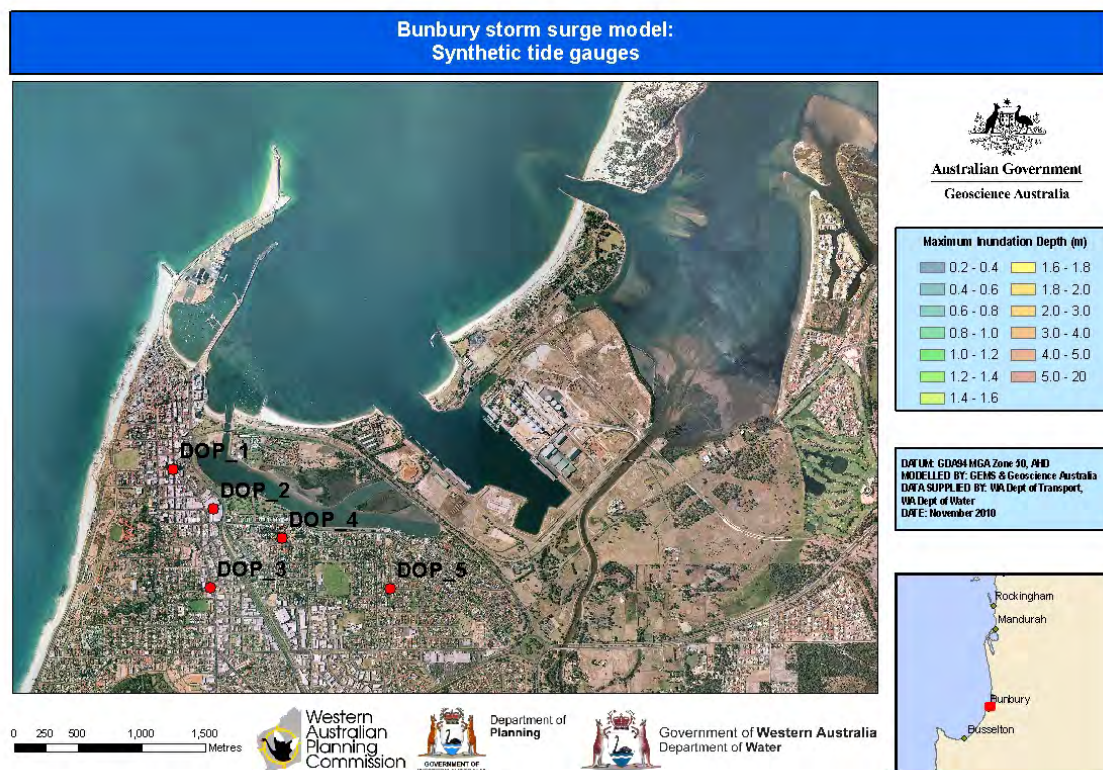


Figure 6: Synthetic gauges supplied by DoP.

In addition to the actual tide gauge at Bunbury, the model outputs can be compared to the high water observations shown in Appendix C.

Step 3 - investigate the impact of a storm surge gate:

The Bunbury Storm Surge Barrier is located at the Western end of the Leschenault Inlet. The barrier was constructed in 1980, as part of coastal protection works aimed to prevent seawater inundation of low lying areas of the City of Bunbury. The barrier is operated during periods of extreme high ocean water levels, isolating Leschenault Inlet from the Indian Ocean. The barrier consists of a pair of steel gates, between two sheet pile bulwarks, which are opened and closed using hydraulic machinery.

Operation of the barrier is intended to prevent seawater inundation of the low-lying areas of Bunbury. This operation is complicated by the stormwater drainage of the City of Bunbury, a portion of which drains into the lower Leschenault Inlet. The ocean water level at which the barrier is closed and the duration of closure determines the capacity of the Inlet to hold stormwater runoff, before the embankment around the Inlet is overtopped. High ocean water levels are caused by a combination of tidal conditions, oceanographic conditions and atmospheric factors such as barometric pressure, onshore wind conditions



and wave forcing. Elevated water levels generally occur in conjunction with storm events, due to low pressure and strong winds. Review of the processes affecting ocean water levels indicated that significant water levels may be generated by typical winter storms in conjunction with high astronomic tides. Analysis of the drainage into the Inlet determined the recommended ocean water level at which the storm surge barrier should be closed. This takes into account the possibility of extreme rainfall and ocean water levels, for a sustained period.

Whilst the Storm Surge Barrier has been designed to provide protection of Bunbury against ocean flooding, it is integrally linked to the drainage of Bunbury CBD. During closure, all stormwater runoff from the CBD will be captured within the Inlet. Closure of the Barrier for an extended period of time provides the potential for backing up of the CBD drainage system and runoff flooding. When closing the barrier to prevent ocean flooding, it is appropriate to ensure that the capacity of the Inlet to receive runoff is maximised.

Step 4 - investigate the impact of various climate change scenarios:

The effects of climate change are incorporated in two key ways. Firstly, a range of sea-level rise scenarios can be applied to GCOM2D and ANUGA as changes to the initial still water level. Secondly, elevation changes in the coastal zone as a result of increased storminess and sea level rise can then be incorporated in GCOM2D and ANUGA to estimate the inundation for a future landscape.

The University of Sydney undertook a quantitative coastal-recession risk assessment in the Busselton-Rockingham coastal cell using the sediment-budget model described in Appendix B. For the purpose of the study this sediment cell was subdivided into seven littoral sub cells distinguished on environmental conditions, e.g. sediment budget, dune volumes and evolution and shoreline controls, in order to obtain the optimal balance between precessions of the sediment budget assessment of the reliability of results.



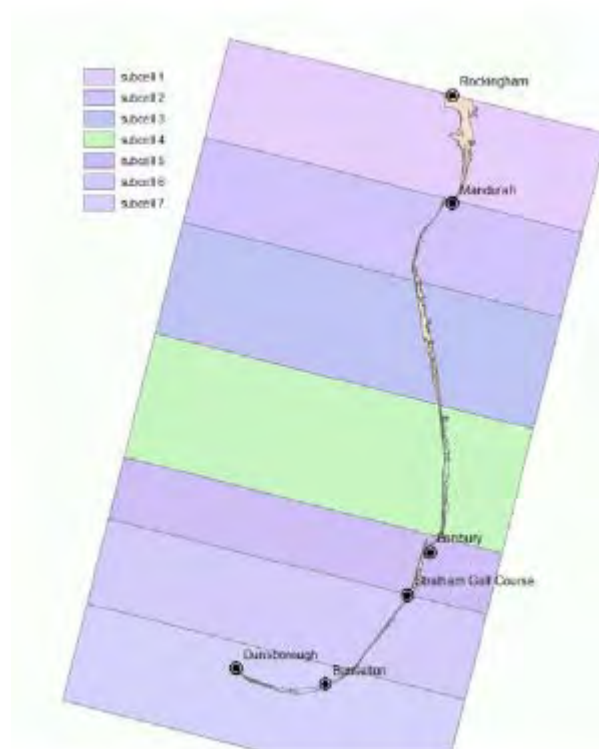


Figure 7: Sub cells within the Busselton-Rockingham coastal cell..

Recession is defined as the distance that the present day face the frontal dune or its counter part recede inland (negative recession = accretion). Computed estimates for future recession distances are expressed in terms of their probability of occurrence: i.e. risk. Comparative risk is higher for cases in which risk curves plot further to the right in the risk diagrams. Conversely, cases in which curves plot the further to the left entail lower overall risk. This study reports the recession figure with a probability of occurrence $p = 0.10$, i.e. there is a 10% chance that the extent of coastal recession will be greater than what has been modelled.

By 2030 despite modest sea level rise, the Bunbury sub cell will have started to recede, although the risk is slightly lower than the other cells due to larger dune volumes and smaller potential sediment losses to estuaries. By 2100 there is significant shoreline recession in the Bunbury sub cell (Figure 8 and Figure 9), with recession in the range of 400 - 500m predicted by the model.



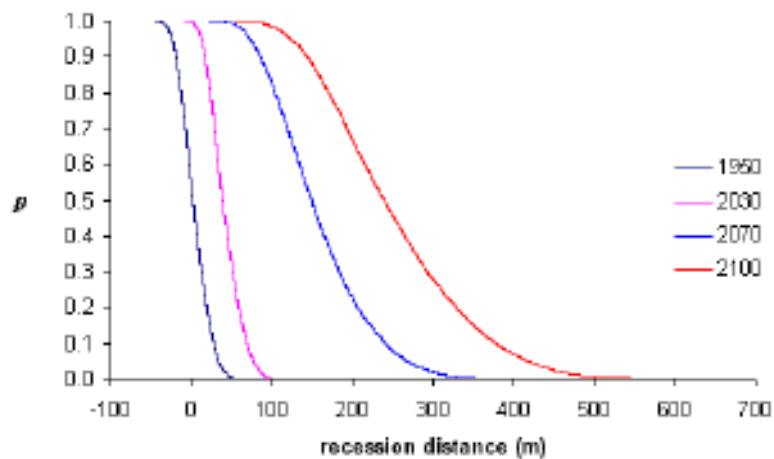


Figure 8: Bunbury – Stratham Golf Course sub cell (#5) coastal recession risk forecast with time in the future.

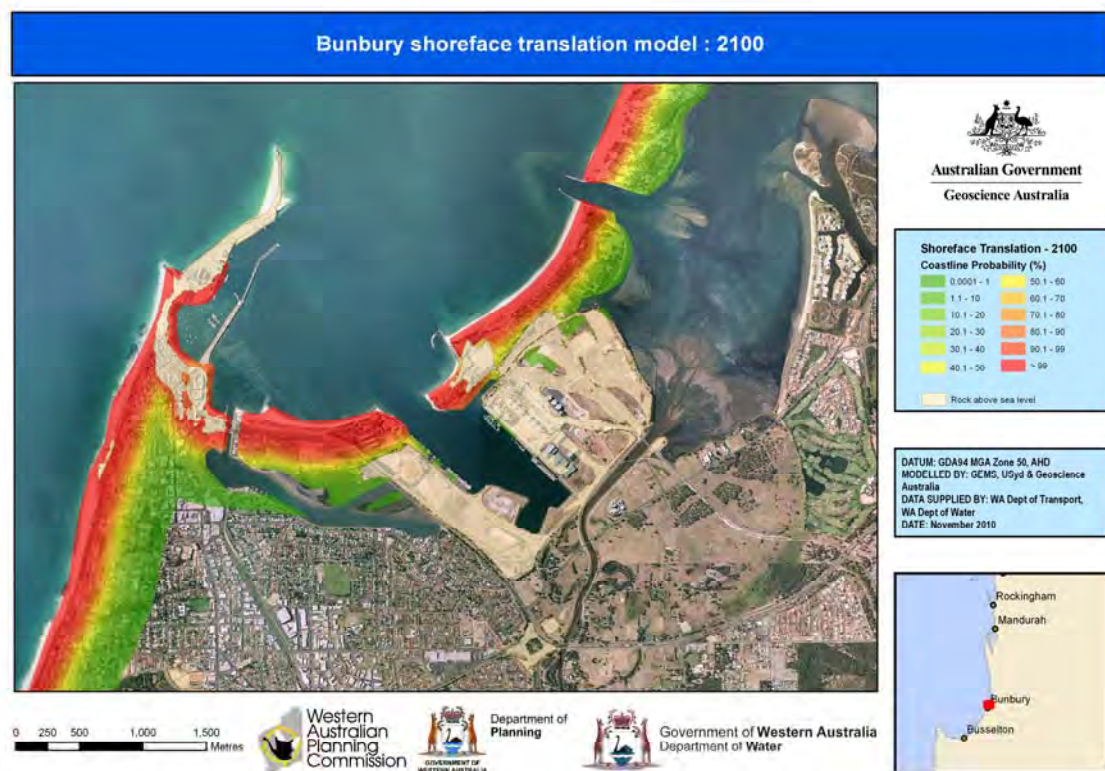


Figure 9: Extent of potential recession for Bunbury by 2100. The potential coastal recession distances are represented as gradated probabilities from a minimum recession of approximately 150m to a maximum extent of up to 450m. NB: the influence of the underlying geology on the extent of potential recession.

5. Results

This report considers six possible storm surge scenarios:

1. Simulation of inundation arising from the 1978 Tropical Cyclone (TC) Alby event (baseline event)
2. Simulation of inundation resulting from a 'worst case' track given the current surface model and a no sea level rise
3. Simulation of inundation resulting from a 'worst case' track using the current surface model and a 0.4m sea level rise
4. Simulation of inundation resulting from a 'worst case' track using the current surface model and a 0.9m sea level rise
5. Simulation of inundation resulting from a 'worst case' track using the current surface model and a 1.1m sea level rise
6. Simulation of inundation resulting from a 'worst case' track given a potential future surface model and a 1.1m sea level rise

The maximum inundation depth (in metres) estimated by the method are shown in Figure 10 to Figure 19. The figures show the six cases with Cases 2-5 shown with the gate open and closed.

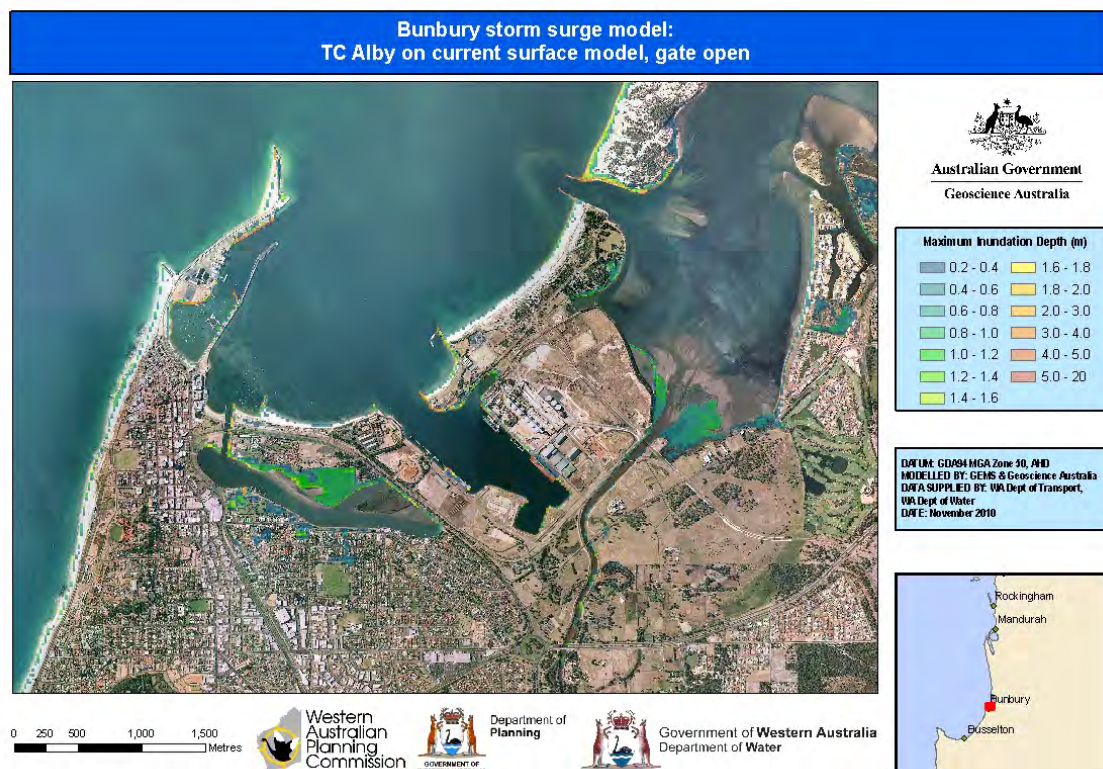


Figure 10: Maximum inundation depth (m) for Case 1 – gate open

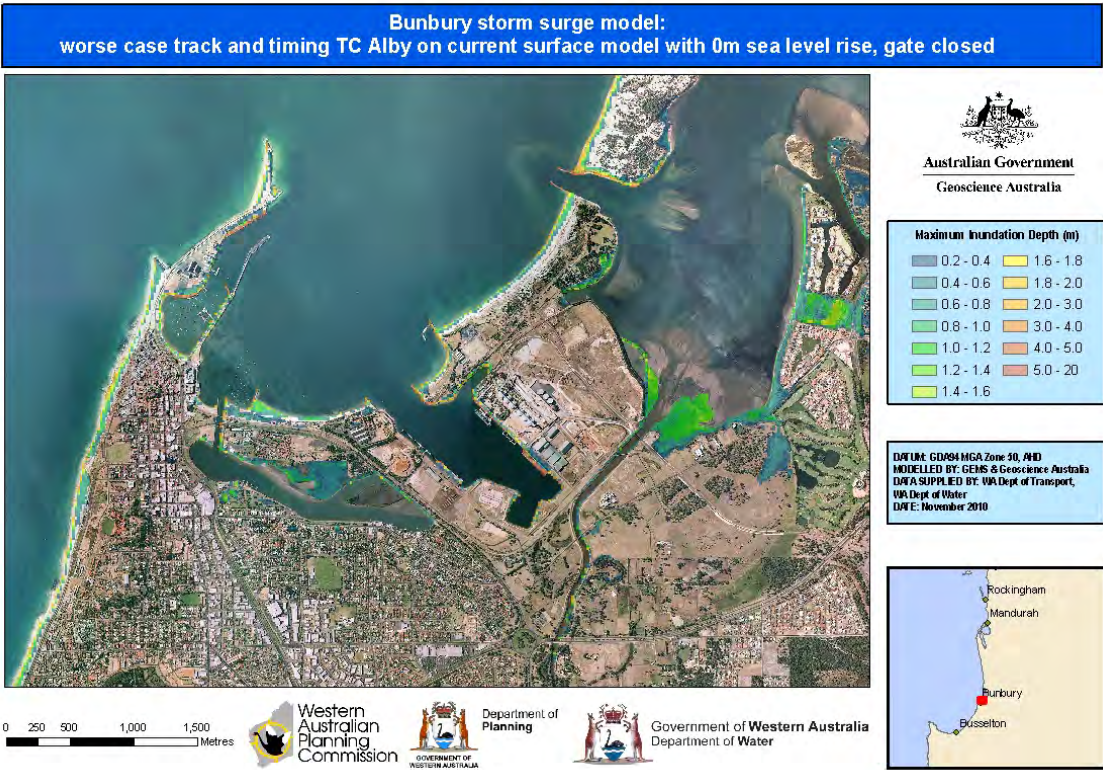


Figure 11: Maximum inundation depth (m) for Case 2 – gate closed

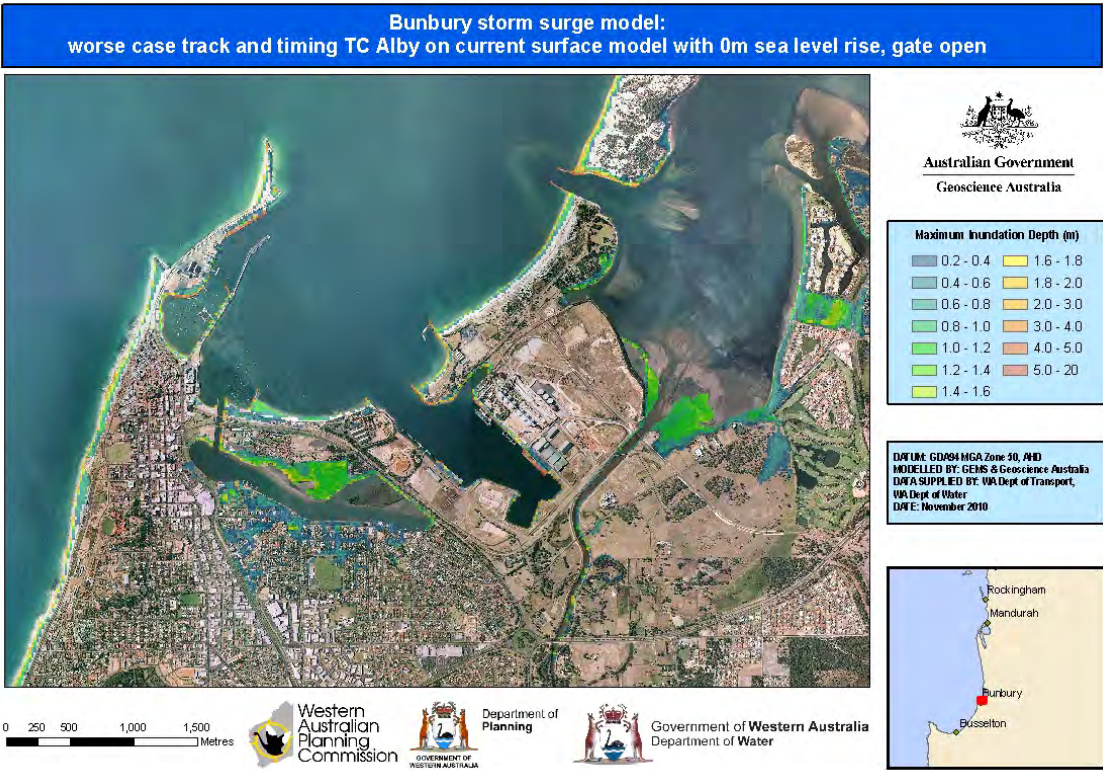


Figure 12: Maximum inundation depth (m) for Case 2 – gate open

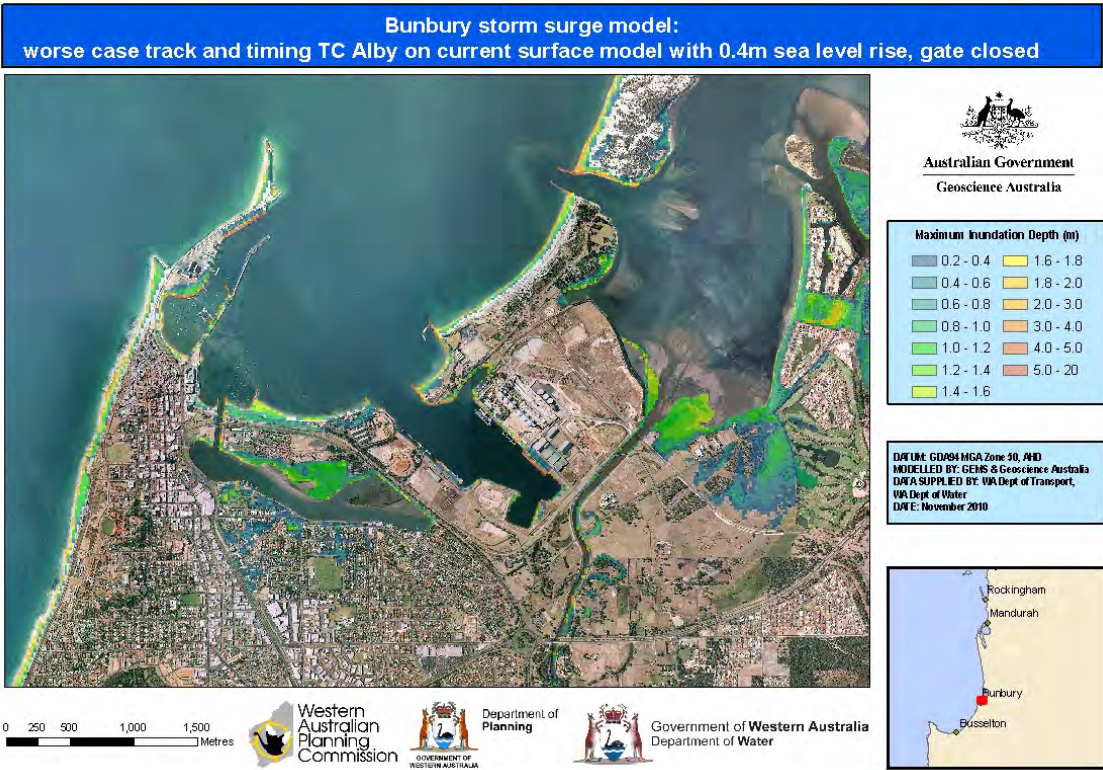


Figure 13: Maximum inundation depth (m) for Case 3 – gate closed

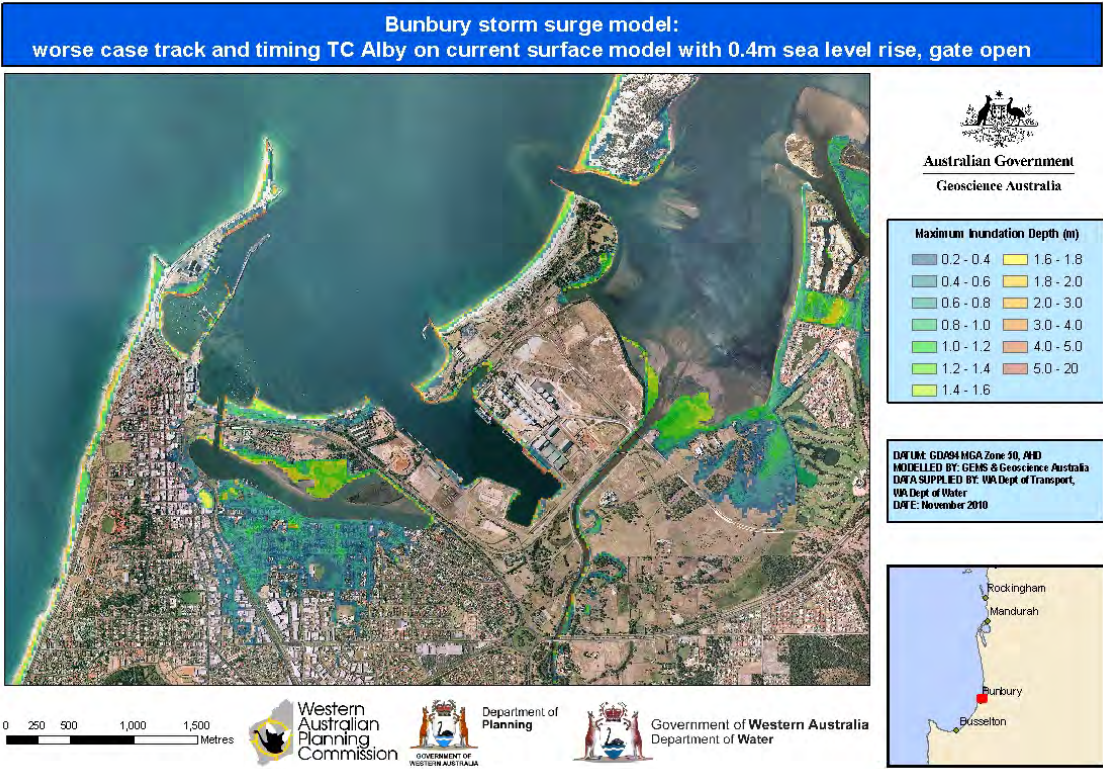


Figure 14: Maximum inundation depth (m) for Case 3 – gate open



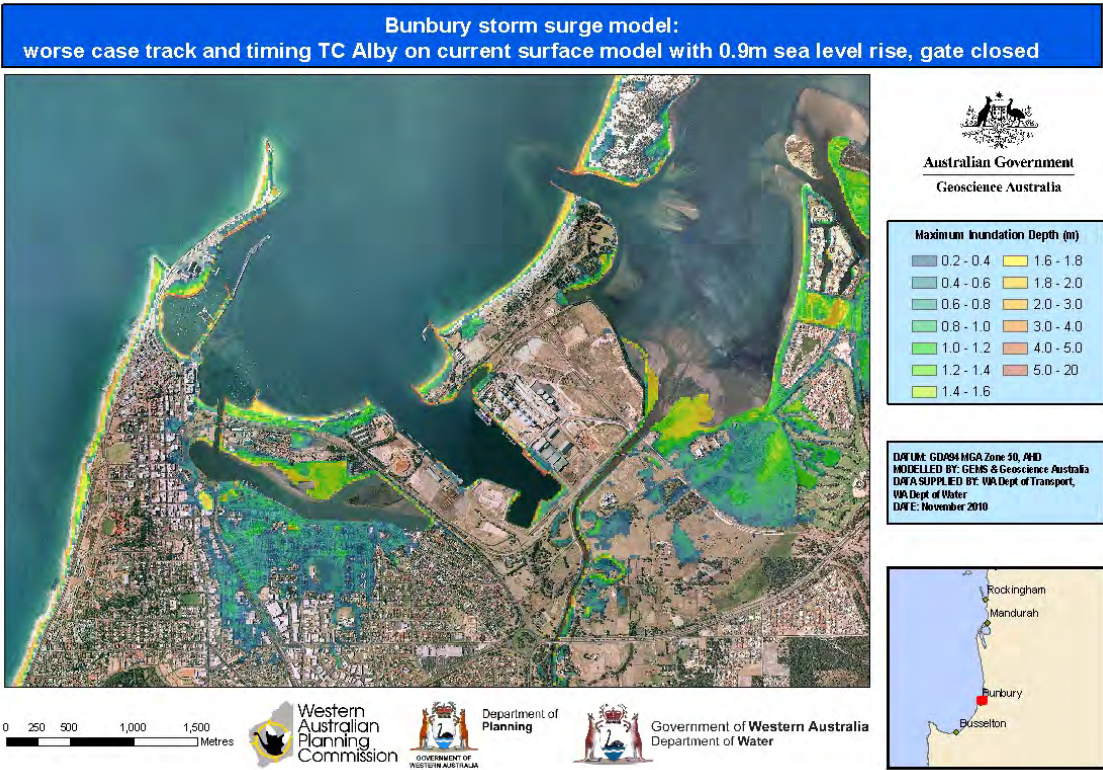


Figure 15: Maximum inundation depth (m) for Case 4 – gate closed

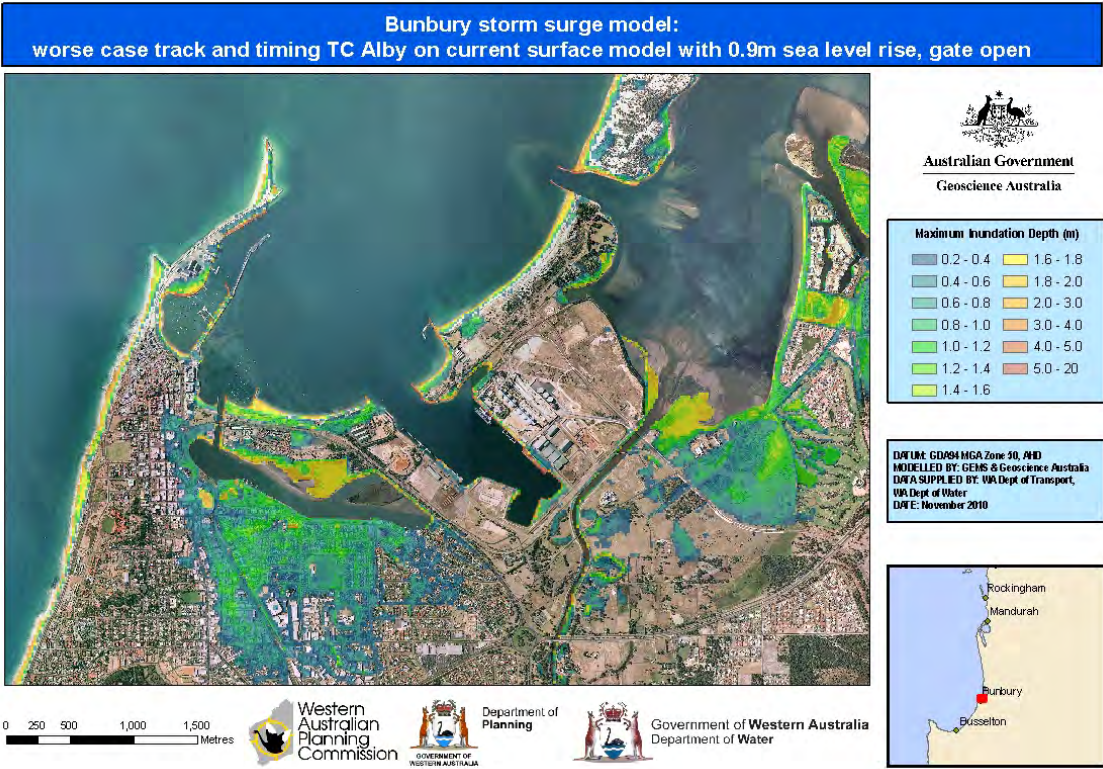


Figure 16: Maximum inundation depth (m) for Case 4 – gate open

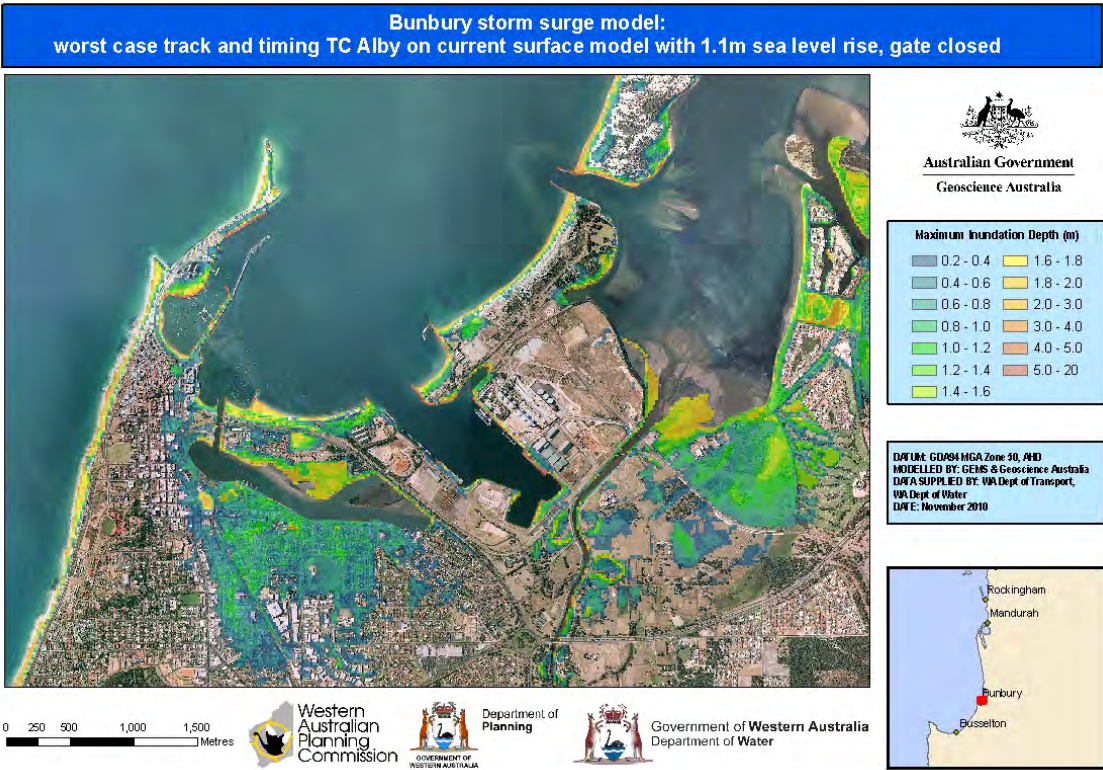


Figure 17: Maximum inundation depth (m) for Case 5 – gate closed

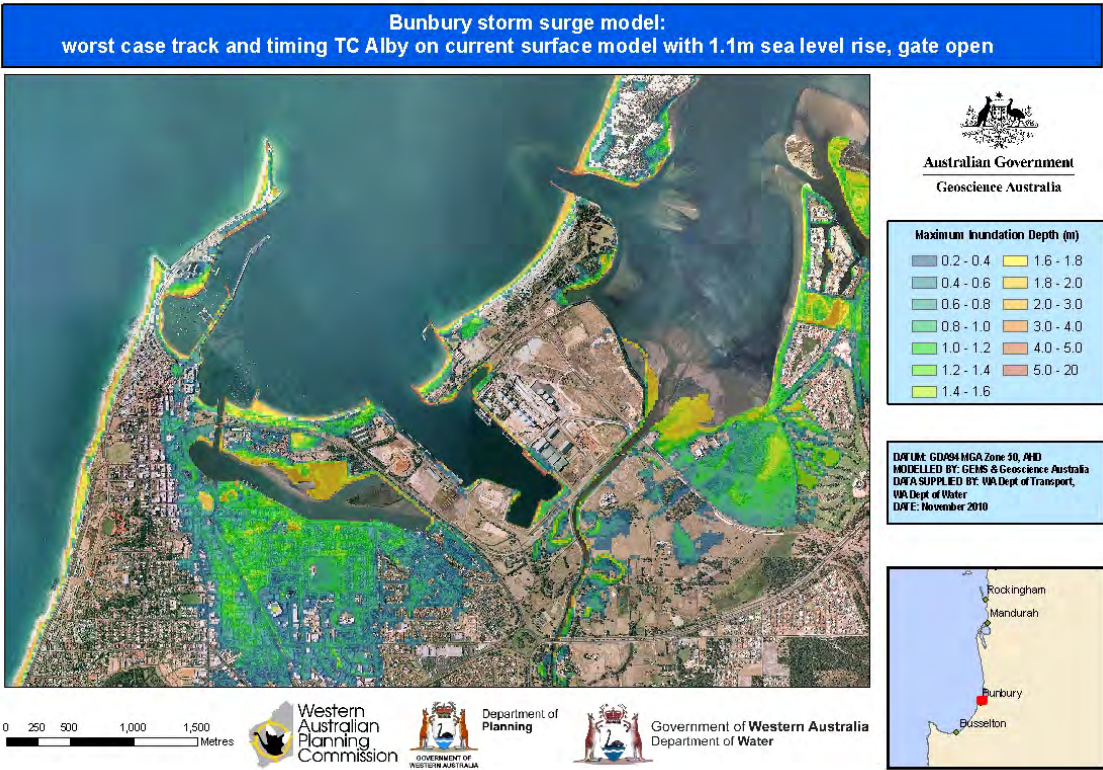


Figure 18: Maximum inundation depth (m) for Case 5 – gate open



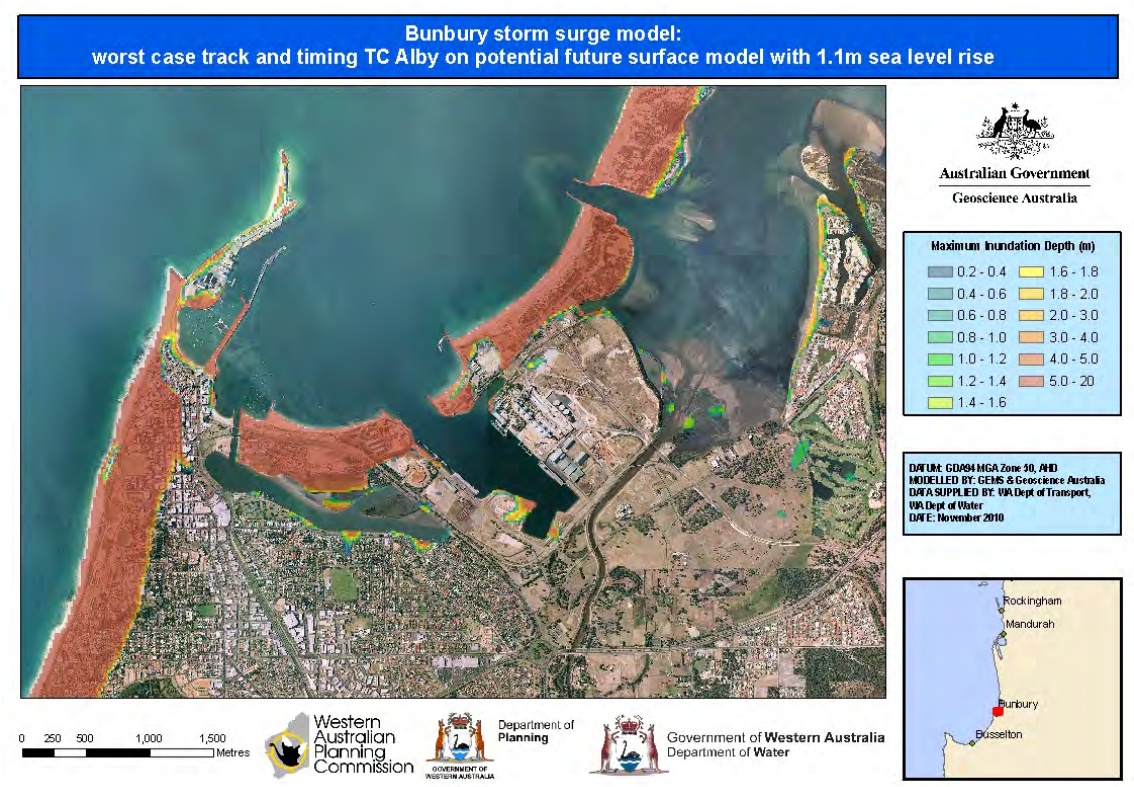


Figure 19: Maximum inundation depth (m) for Case 6

A time series of the water depth estimated at the locations supplied by DoP are shown in Figure 20 and Figure 21. These results are shown for Case 5 only.

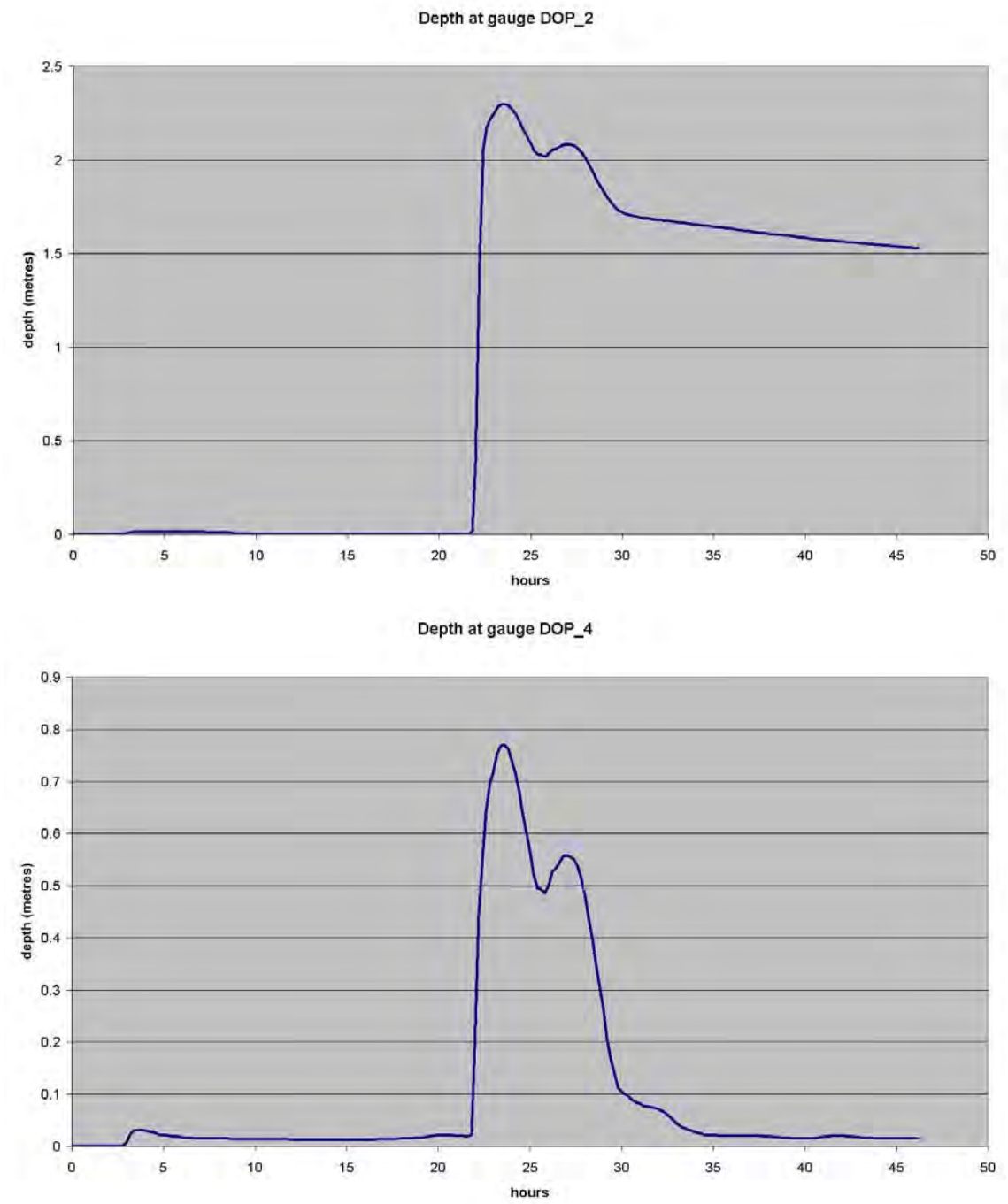


Figure 20: Time series at two of the synthetic tide gauges supplied by DoP (DoP_2 and DoP_4) for Case 5 – gate open.

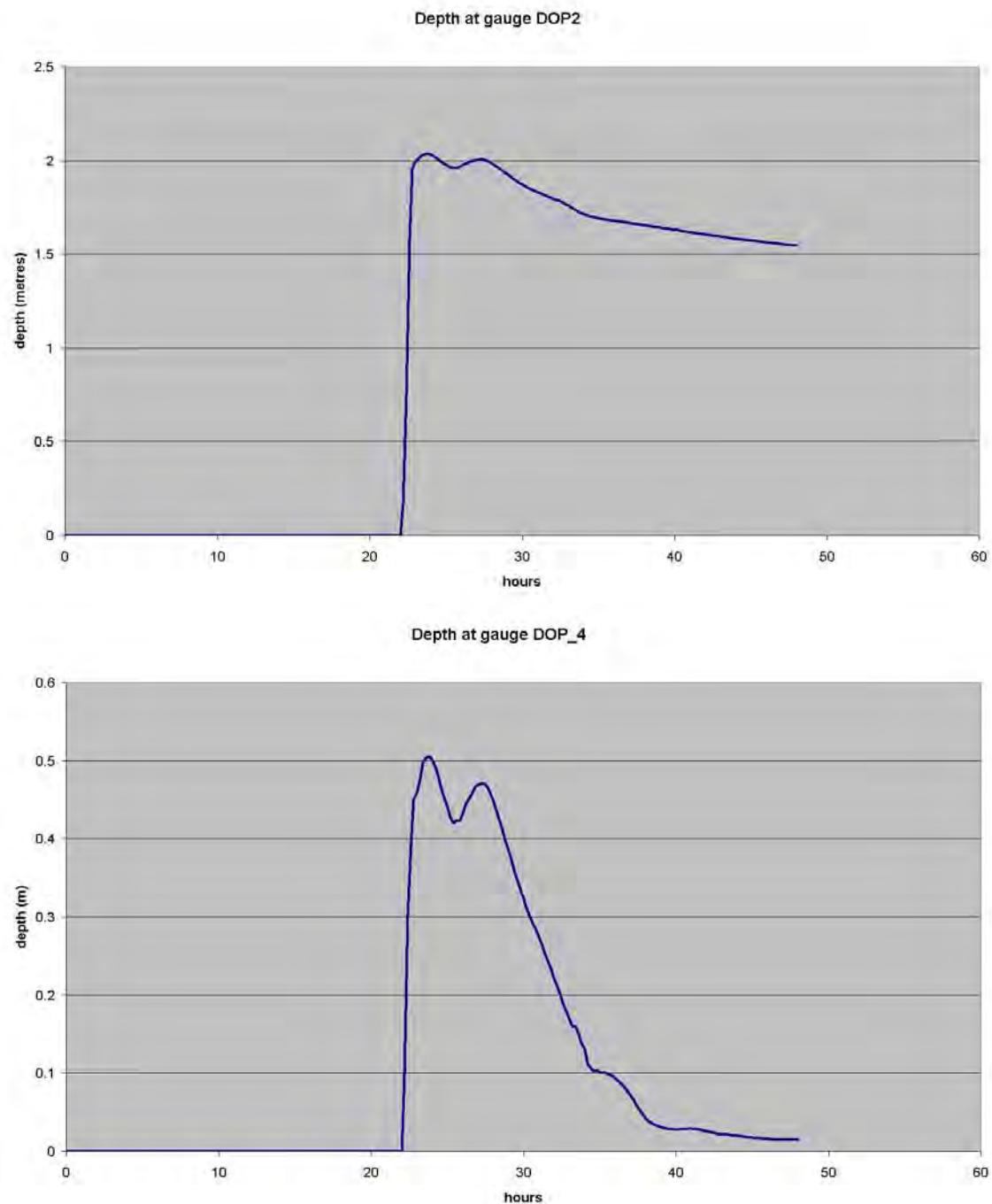


Figure 21: Time series at two of the synthetic tide gauges supplied by DoP (DoP_2 and DoP_4) for Case 5 – gate closed.

These results clearly show that the storm surge gate acts to reduce the depth of inundation. These results also show that the inundation drains more quickly in the area surrounding DoP_4 than DoP_2. This may be useful for recovery purposes.

Time series at offshore synthetic gauges can be used in understanding the dynamics of the storm surge inundation process. Figure 22 shows two example synthetic tide gauges that will be used to illustrate the differences in the resultant sea surface elevation from the two storm events modelled here. Figure 23 shows a typical waveform from the 1978 TC Alby



event and Figure 24 shows a typical waveform from the ‘worst case’ track and timing event.

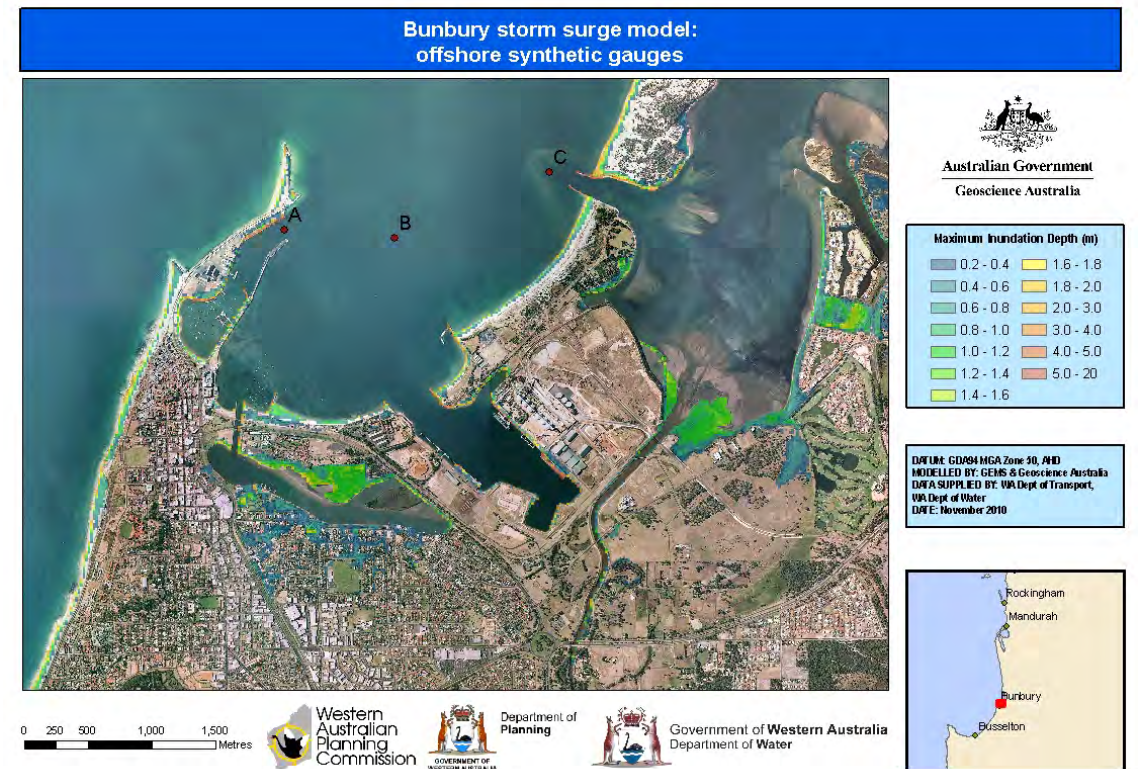


Figure 22: Offshore synthetic tide gauges.

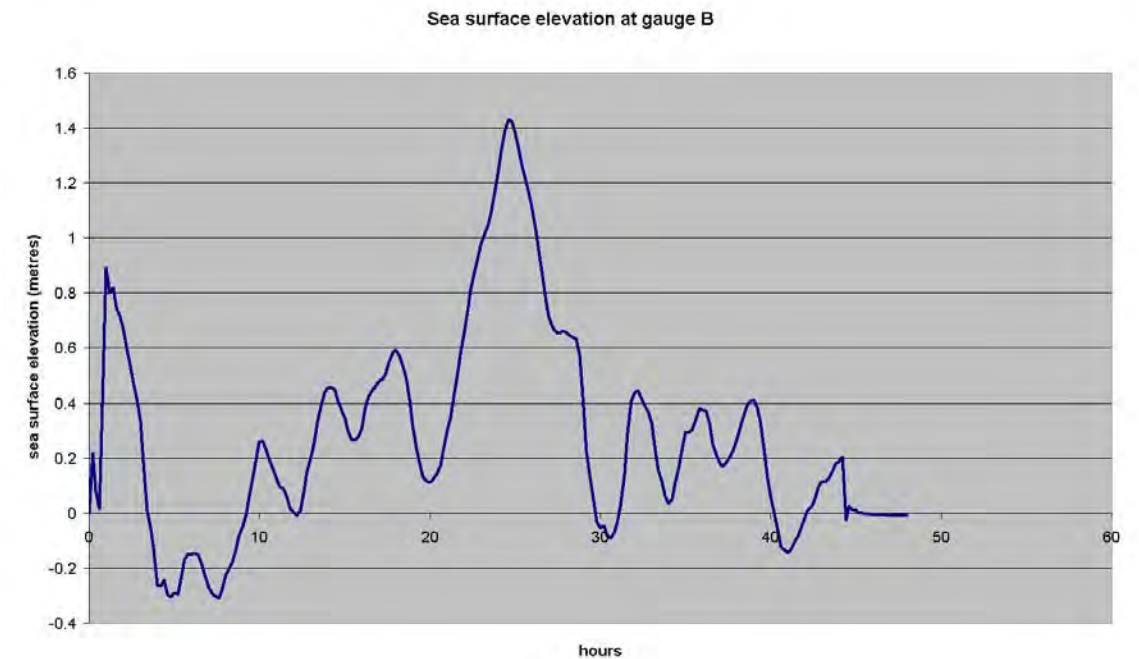


Figure 23: Time series at one of the synthetic offshore tide gauges (B) for Case 1.



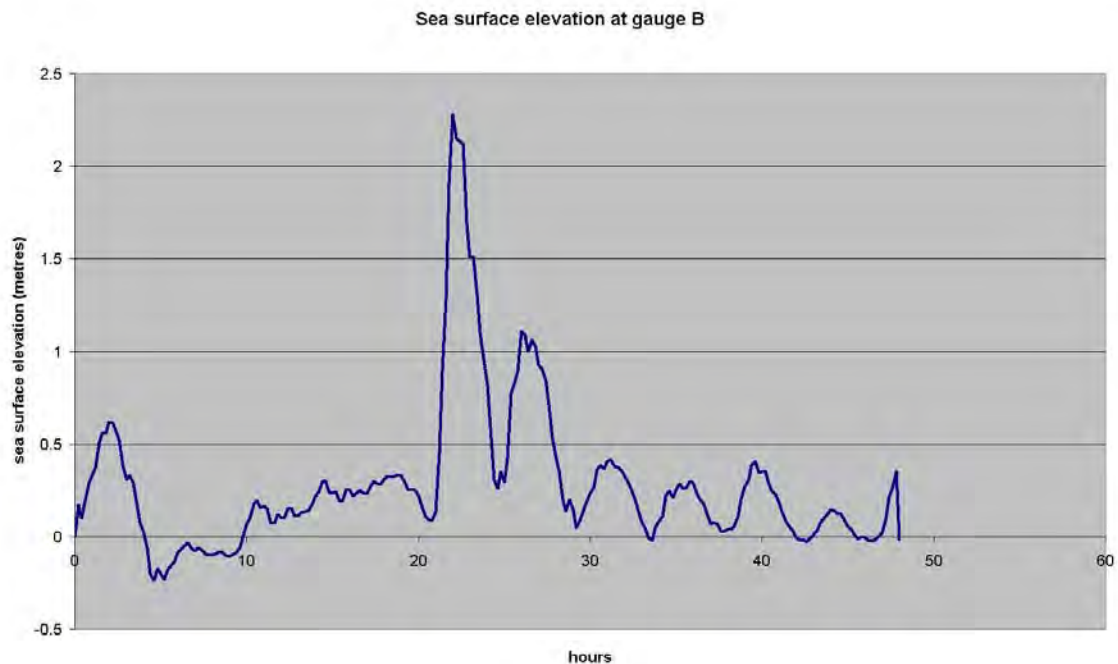


Figure 24: Time series at one of the synthetic offshore tide gauges (B) for Case 2.

6. Discussion

The inundation extent predicted by the modelling framework used here when applied to Case 1 is small in comparison to the observations of inundation recorded in 1978 (see Appendix C). However the storm surge model compares well with the tide gauge reading at Bunbury (see Figure 3). Since 1978 there have been changes to the surface model, both offshore and onshore which can have significant impacts to the predicted inundation. The simulations performed use current topography and elevation data which may not capture the true topography that existed during the 1978 event. The current elevation data is characterised by large sand dunes which likely prevented the simulation from predicting the severe inundation observed during TC Alby. Case 6 illustrates how a change in the shape of the coast line (in this case caused by sea level rise) can have significant impact on the predicted inundation. Although sea level rise has been much smaller since 1978 it is possible that long term sediment transport processes have caused changes to the coastline elevation that have similarly affected inundation extent. The current coastline topography may naturally buffer against storm surge inundation better than the coastline topography in 1978.

Any inaccuracy in the onshore and offshore topography has much less impact on the predicted sea surface elevation at the tide gauge. Inundation extent is much less sensitive to small perturbations in the coastal topography. The momentum of the currents generated by storm surges is considerably smaller than those caused by tsunami, for example. Consequently the effect of reflections and diffractions of waves and thus local topography is less significant in storm surge events. The degree to which the estimates are sensitive to topographical changes could be investigated further.



The model result that is closer to the observed inundation in 1978 is somewhere between Case 3 and Case 4 (worst case track and timing TC Alby with 0.4m and 0.9m SLR respectively). This suggests that the model is sensitive to the inputs of initial sea level and event, as well as the surface model, as described above. As expected, the inundation extent increases as the SLR increases.

The results confirm the effect of the storm surge gate, that is, there is increased inundation when the gate is open (compare Figure 17 and Figure 18, and Figure 20 and Figure 21, for example).

As mentioned earlier, GCOM2D can also model inundation. Figure 25 and Figure 26 show the modelled inundation developed by GEMS using GCOM2D for Case 1 and Case 2 respectively. A comparison of Figure 10 and Figure 11 shows that the integrated method (GCOM2D and ANUGA) compares well with the GCOM2D results. This indicates that with the provision of boundary data (the storm surge event), we have increased confidence in ANUGA being able to successfully determine storm surge inundation.

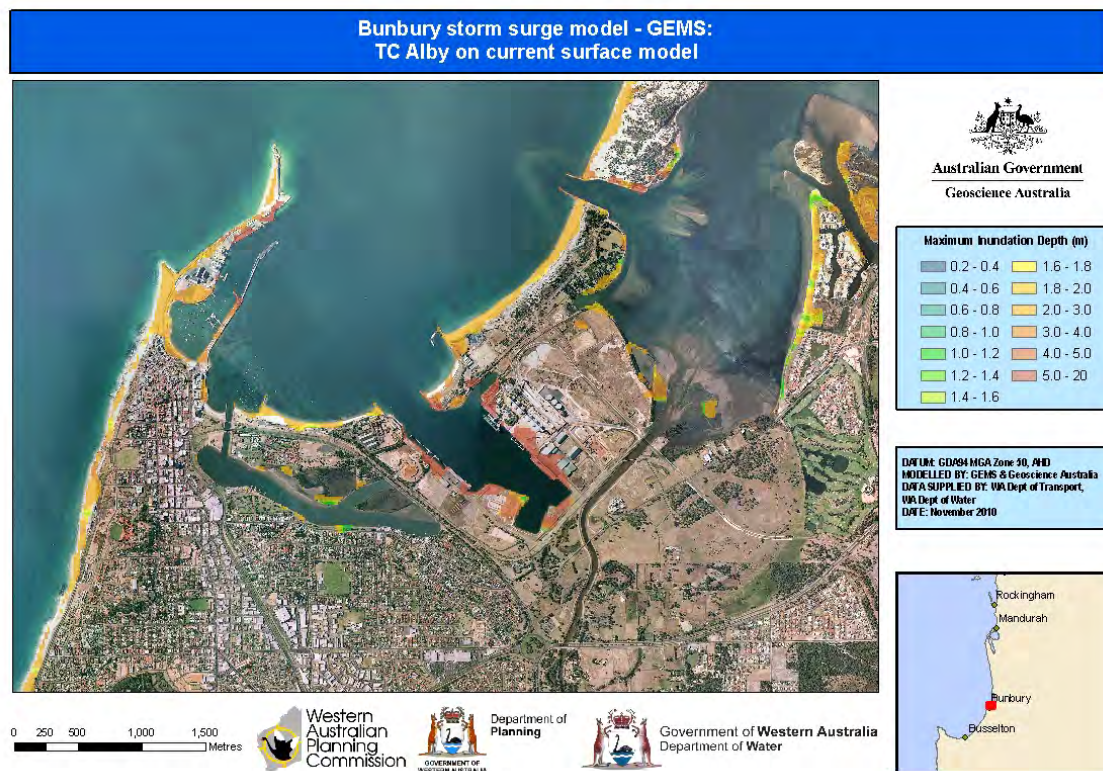


Figure 25: Maximum inundation depth (m) for Case 1 as modelled by GEMS.

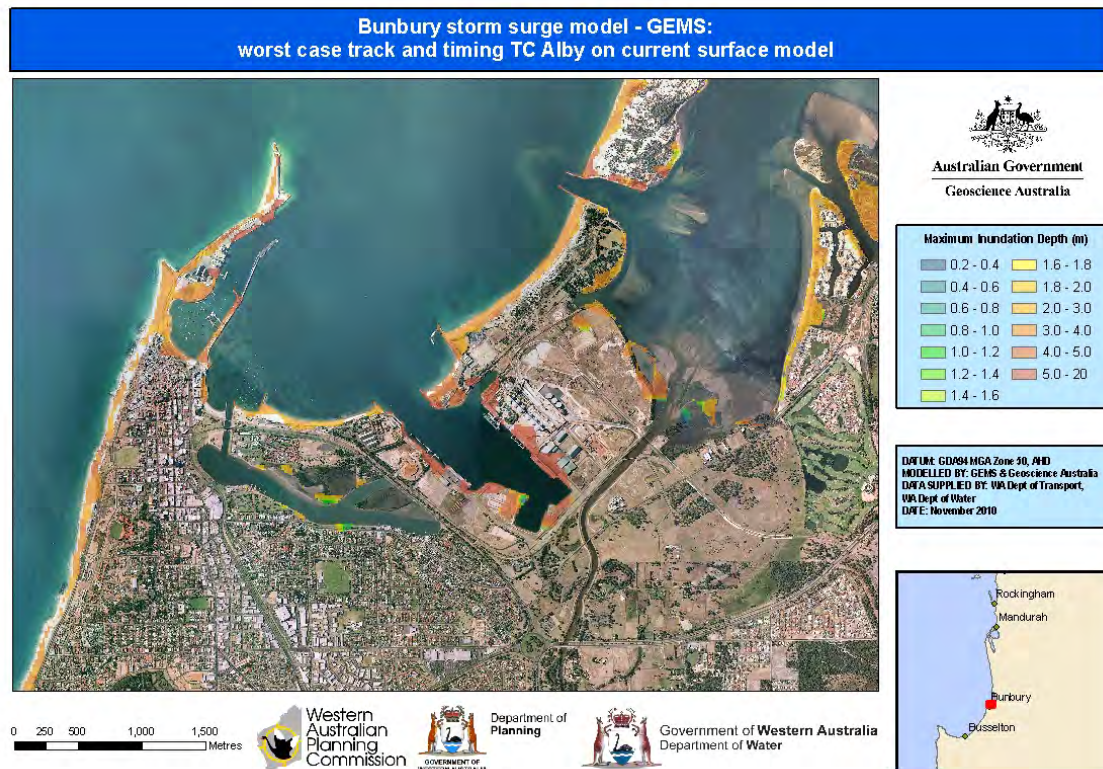


Figure 26: Maximum inundation depth (m) for Case 2 as modelled by GEMS.

The key observations of the modelled outputs are:

- The foredunes on the open coast play a significant role in protecting the City of Bunbury from storm surge inundation for all cases considered.
- These foredunes continue to exist in the potential future surface model; however they are translated in distance (landward) and have increased in height.
- The potential future surface model developed here assumes that no other coastal engineering processes have occurred.
- The storm surge gate acts to reduce the inundation extent for the 1978 TC Alby event and the worst case track and timing TC Alby event for the current surface model.
- The modelled inundation resulting from the integrated GCOM2D and ANUGA method described here compares well with inundation from GCOM2D.
- The model outputs compare well with the observed tide gauge reading at Bunbury.
- The model comparison with observed inundation from 1978 lies between Case 3 and Case 4 (i.e. between SLR of 0.4m and 0.9m).

6.1. Model Issues and Limitations

Some of the key approximations and limitations are summarised below. It is important to appreciate that the model results described here are indicative and should not be relied upon solely for making any decision.

It must be emphasised that the developed capability can only be applied for the City of Bunbury for TC Alby and worst track TC Alby, at this stage. This is because the open ocean



storm surge model data is only currently available for these two events for the City of Bunbury. Geoscience Australia is investigating the possibility of developing a national storm tide database to enable a range of possible events under different climate change scenarios to be modelled using this approach. Such a database would make it possible to estimate inundation at selected locations when suitable elevation data is available.

The model outputs contained in this document are based on two storm events and do not represent all possible storm events. Therefore, the results can be used as an indicative guide only to possible future storms. A suite of events for a range of tracks, intensities and return periods would be required to develop a deeper understanding of the storm surge impact and risk.

The combined hazard of storm surge inundation and riverine flooding has not been modelled. Coincident rainfall was not applied for this phase of the project as it was not applicable for TC Alby. However, flooding scenarios can be incorporated into ANUGA to investigate the effect of the combination of the two hazards.

ANUGA does not yet incorporate wave setup. Wave setup is a super-elevation of the mean water surface over normal 'still' water level due to wave action alone. GCOM2D incorporates this feature and thus the wave dynamics have been propagated close to the coast. Continued development of ANUGA will require wave setup to be incorporated. Neglecting wave setup within the ANUGA domain will likely cause a slight under-prediction of inundation extent. The effect of the wave setup is problem dependent and will be investigated in future studies. By restricting the computational domain employed by ANUGA to the 10m depth contour we believe that the integrated effect of wave setup over the small computation domain is small and that the majority of the effects of wave setup are captured by GCOM2D.

ANUGA does not model the storm itself and the resultant wind effect on inundation. At this stage, ANUGA must be integrated with an open ocean storm surge model as shown in Figure 1. It is expected that there will be little impact to the estimated inundation as modelled here by not incorporating wind in ANUGA. Wind shear stress is usually very small but its integrated effect over a large body of water can be large (Dean and Dalrymple 1991).

Neglecting the effects of wind shear and barometric pressure will typically tend to underestimate the inundation extent. By restricting the computational domain employed by ANUGA to the 10m depth contour we hope to keep the integrated effect of wind and pressure small. This project will investigate the impact on model outputs by varying the point at which the integration occurs. This will inform the continued development of ANUGA.

We must note that the elevation data (bathymetric as well as topographic) used for these models has been the best available. This project is one of the first to use the high-resolution data acquired by the WA State Government and its coverage and accuracy is excellent. Some bathymetry data, as shown in Figure 27, has been captured using other methods that give coarser resolution to that of LiDAR. The predicted inundation depth and extent is sensitive to variations in elevation data and therefore the model outputs should be used with caution. It is difficult to estimate the variation in model results based on the accuracy of the elevation data without simulating many more models or incorporating local



knowledge to verify the elevation data that the model has estimated within those gaps. This could be subjected to further investigation.

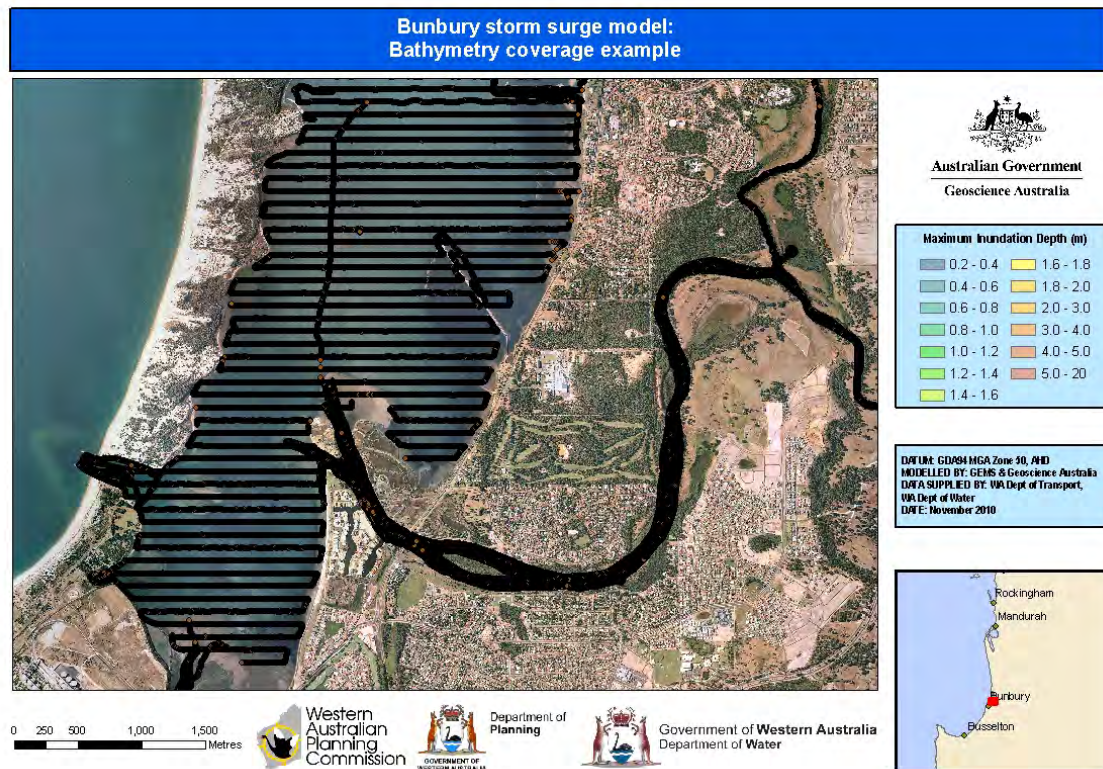


Figure 27: Elevation data coverage example.

Additionally, the presence of buildings in the model will almost certainly have an impact on the modelled results. There is no simple rule or guideline to estimate what the impact to the inundation extent would be by incorporating buildings. Recent studies for a tsunami scenario have shown that the inundation extent can be reduced in some parts of the model when buildings are incorporated (Jakeman et al 2010). These studies also show that the buildings can channel flow thereby increasing the inundation extent in those parts of the model. Any water volume captured within buildings is not included in the model. It would be expected that the model simulation time would increase if buildings and any water trapped within them were included as a more sophisticated model would be required. This should be subjected to further investigation. Questions should also include how the flow velocity is impacted, both in magnitude and duration, especially around buildings. Flood models also incorporate friction based on the land-use for the model area. This is an extremely important feature to capture as its presence acts in a similar way to that of incorporating buildings. This feature is not considered here.

The science behind the STM is evolving and there is debate in the scientific literature about the nature of modelling these kinds of processes. The University of Sydney have incorporated a range of datasets and knowledge in applying their STM and have benchmarked their results against the 1950 coastline. They have assigned probabilities to their modelled translated coastlines and have strong evidence based arguments to defend the modelling results.



The STM provides an estimate of the altered coastline due to climate change over tens to hundreds of years. It provides a new elevation dataset that could be inputted to GCOM2D and ANUGA in the future. Sediment transport and erosion at timescales of hours to days is not incorporated in GCOM2D or ANUGA.

Figure 19 presents the preliminary results from combining the worst case coastal recession scenario with the worst case track and timing of TC Alby and 1.1m of sea-level rise (case_6). This result closely reflects the modified shoreline as shown in Figure 9 which suggests that the methodology to generate the modified elevation surface requires refinement in order to more accurately represent the extent of future inundation.

Although all care has been taken to validate individual components of the modelling methodology using e.g. wave tank experiments and tide gauge data where available, the entire modelling methodology has not yet been validated.

7. Conclusions

Geoscience Australia, the Western Australian Department of Planning and the Western Australia Planning Commission have collaborated to develop a series of storm surge inundation maps for the City of Bunbury that may be used as an input to planning. These maps are based on validating the model outputs against the 1978 TC Alby event. A worst case track and timing scenario of TC Alby, based on current and potential future surface models have also been modelled for a range of SLR values.

The key observations of the modelled outputs are:

- The foredunes on the open coast play a significant role in protecting the City of Bunbury from storm surge inundation for all cases considered.
- These foredunes continue to exist in the potential future surface model; however they are translated in distance (landward) and have increased in height.
- The potential future surface model developed here assumes that no other coastal engineering processes have occurred.
- The storm surge gate acts to reduce the inundation extent for the 1978 TC Alby event and the worst case track and timing TC Alby event for the current surface model.
- The modelled inundation resulting from the integrated GCOM2D and ANUGA method described here compares well with inundation from GCOM2D.
- The model outputs compare well with the observed tide gauge reading at Bunbury.
- The model comparison with observed inundation from 1978 lies between Case 3 and Case 4, highlighting that the model is sensitive to elevation and the storm scenario track.

In addition to these model outputs, this report has described the modelling methodology that will be made available to the WA State Government at the completion of the MoU. This is to present a means to investigate further issues of interest for the two storm events using a free and open source approach. For example,

- testing of proposed coastal protection or flood protection structures,
- assessment of specific development sites or development proposals, and
- to update these model results based on new and updated elevation data.



The model could be continued to be updated for future use. For example,

- New storm scenarios could be incorporated. The sensitivity of the inundation depth and extent could then be analysed based on the expected spectrum of potential storm scenarios. This would provide greater certainty to planners on the range of potential inundation extents.
- Storm scenarios that include rainfall events and associated fluvial flooding. This would investigate the effect of the combined hazard of storm surge inundation and riverine flooding.

A range of model improvements are required to address the model limitations discussed earlier. In particular,

- incorporate required functionality into ANUGA to capture the necessary nearshore processes such as wave setup, and
- analyse the optimal location to connect the storm surge model and inundation model.

To progress towards a storm surge *impact* capability, a vulnerability and exposure model are required. A vulnerability model characterises the nature and magnitude of the damage that a structure will experience from a wave of given amplitude and velocity. The Department of Climate Change and Energy Efficiency has initiated a project with Geoscience Australia to build an understanding of such models for flood. It is expected that this will extend to storm surge in the future. Geoscience Australia has developed the National Exposure Information System (NEXIS) that can be used to provide the exposure information for this kind of assessment (Nadimpalli, 2009). A storm surge *risk* analysis would result when the impact is combined for a range of storm surge scenarios with different return periods.



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Appendix. A Storm scenario - background

As one of the most intense cyclones on record to impact the southern reaches of the west coast of Western Australia, Tropical Cyclone Alby (TC Alby) has been used as a baseline event for the storm surge investigations described in this report. The track of the cyclone is shown in Figure 28.

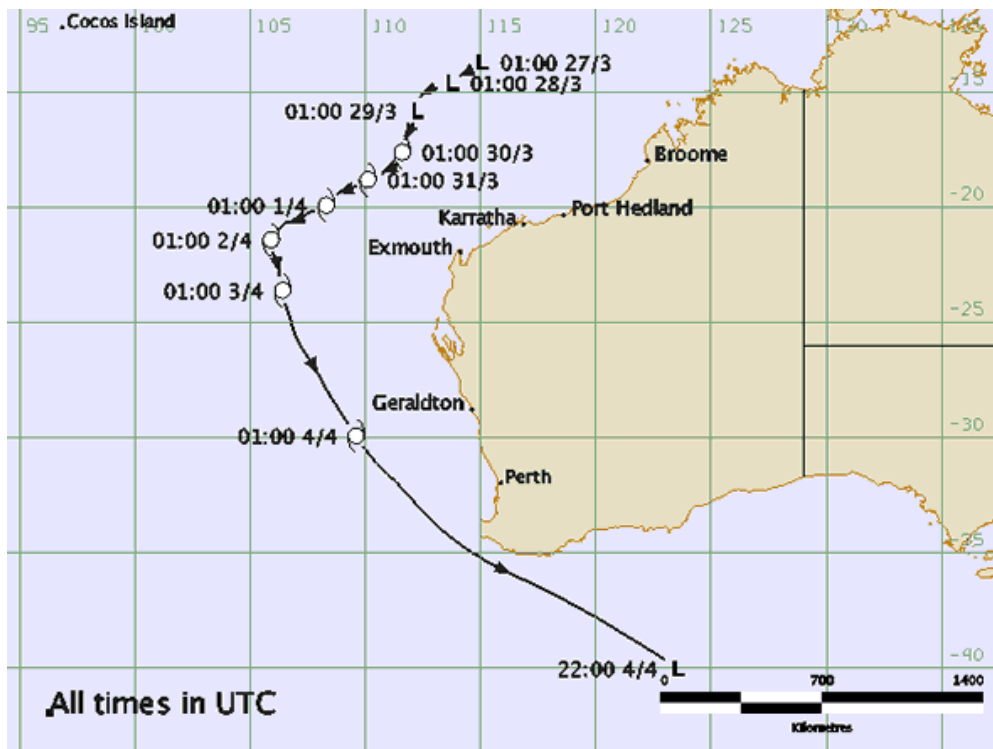


Figure 28: Official track of Tropical Cyclone Alby from the Bureau of Meteorology.

TC Alby was the fifth tropical cyclone of the 1977/78 cyclone season in the north western Australian Region. A detailed description of the life cycle and impact of TC Alby is contained in the Bureau of Meteorology report for TC Alby. Facts relevant to the work carried out for the current study are summarized as follows:

- Development and Track
 - TC Alby formed well off the northwest coast some 800 to 900km to the west northwest of Karratha and then drifted slowly in a general west to southwest direction.
 - By the time it had reached the latitude of Exmouth it had reached full maturity with a central pressure of 930 hPa.
 - TC Alby then re-curved towards the south to southeast and then began to accelerate as it moved towards higher latitudes.
 - During the night of 3 April and the early morning of 4 April its speed increased to 50 km/h as it passed about 600km to the west of Perth.
 - During Tuesday 4 April, TC Alby accelerated towards the lower west coast as it slowly degenerated into an extra-tropical depression.
- Observed Wind and Rainfall



- As TC Alby accelerated towards the south to southeast on 4 April it caused strong to storm force winds over a large area of the southwest of Western Australia.
- A wind gust observed at the Perth Regional Office was the highest on record for the month of April.
- Some wind gusts noted at the Bunbury Power Station exceeded the 130 km/h maximum scaled reading of the anemometer.
- Mean wind speeds at Albany were about 90 km/h and were maintained for several hours in the evening of the 4 April. A peak gust of 150 km/h was recorded at Albany and this was the highest wind gust recorded throughout the lifetime of the cyclone.
- The rainfall produced by TC Alby over the southwest of Western Australia was of only minor consequence with only light to moderate reported falls.
- Storm Surge and Waves
 - Several ships reported very high seas and swells (in excess of 10m) although none of these were within 300km of the storm centre as it tracked southwards off the west coast.
 - Coastal areas south of Carnarvon experienced widespread wave impacts with extensive severe erosion to beaches and damage to groynes, jetties and small boats.
 - At Busselton four large sections of the 1.8m jetty were washed away.
 - Abnormal tidal fluctuations were produced along the coast from Geraldton to Esperance with the most significant storm surge levels between Lancelin and Cape Naturaliste.
 - At Busselton the tide reached almost 2.6m above chart datum, that is about 1.1m above expected high tide.
 - At Fremantle the tide reached 1.8m above chart datum, that is, 0.4m above the highest astronomical tide.
 - Following the storm surge, oscillations in the water level having a period of about 4 hours occurred at Bunbury and Busselton for at least 36 hours. Similar oscillations with smaller amplitude and a period of one or two hours were recorded at Albany and Esperance.
 - The surge caused some of the lower lying areas of the coast between Rockingham and Dunsborough to be inundated with sea water and at Palm Beach the sea washed across the front lawns of houses along the coastal road after it had been partially eroded.
 - At Bunbury the sea breached the retaining wall along Leschenault Inlet and flooded 100 homes in the nearby residential area and Ocean Drive, the main coastal road at Bunbury, was badly eroded and closed to traffic.

Return Period

Estimation of a return period for TC Alby is problematic because of the relatively small number of cyclonic events that have had a major impact on the west coast of WA. Figure 29 shows tracks of cyclones in the south-west WA area (defined somewhat arbitrarily by the outlined box and centred approximately on Mandurah) for the period 1950 to 2008. This area effectively covers the southern half of the WA west coast. There are 13 cyclones in this period that nominally affect the south west WA area and of these, the minimum pressure recorded for 10 of these events are shown in Figure 30 (the other three cyclones' central pressures were all above 1000 hPa when they were within the defined area).



These minimum pressures were then subjected to analysis and the resulting probability density plot for cyclone minimum pressure is shown in Figure 31. Based on this analysis, the estimated Average Recurrence (ARI) for TC Alby is of the order of 200 years. This is for a storm of such intensity occurring in the defined area but the probability of direct impact on Mandurah (for example) is lower. The number of events in the database makes determination of the corresponding probability problematic but the return period for direct impact storm maximum winds passing directly over locations in this region is likely to be an order of magnitude greater.

Consideration of Coincident Riverine and Storm Surge Flooding

Consideration has been given to the possibility of flooding from a cyclone event to be enhanced by the joint effects of storm surge and rainfall run-off. Cyclones that maintain significant intensity as they move southwards and potentially affect the lower half of the west coast would typically be expected to interact with a cold front and evolve into an intense, fast-moving system. This change in structure (shown in Figure 32) is known as extra-tropical transition. This process is observed in other tropical cyclone basins around the world and can result in a re-intensification of the system even though it loses tropical cyclone characteristics.

These cyclones can move at speeds greater than 70 km/h in contrast to the average 10-15 km/h speeds in the north. As they accelerate, the structure of the cyclone changes so that the regions of dense cloud and heavy rainfall are displaced towards the right quadrants of the system (when looking along the direction of the track) leaving the left quadrants largely free of significant cloud.

As a result, for a cyclone crossing over a coastal location, the heaviest rainfall is expected to occur to the south of that location. In contrast, the strongest winds associated with these fast moving systems occur in the left quadrants (and therefore to the north of the cyclone centre for a coastal crossing cyclone) where the clockwise rotating winds are augmented by the system's translational speed. This area is typically cloud-free. This conceptual model is demonstrated in the description of cyclone TC Alby.

As result of this analysis it can be concluded that for storms that cross the coast, the incidence of storm surge associated with the strongest on-shore winds, areas of significant rainfall and the location surge is unlikely to be coincident. For storms that remain off the coast and which have the capacity to produce sea level elevation as result of a 'trapped wave' that propagates southwards along the coast, the heaviest rainfall is also expected to remain offshore. Moreover, the fact that the cyclones are rapid moving means that even when rainfall rates are relatively intense, total rainfall within a catchment will be limited by the duration of that rainfall.

Based on this assessment it is considered that coincidence of the rainfall induced flooding and significant surge is quite unlikely and is therefore not considered from a modelling perspective here.



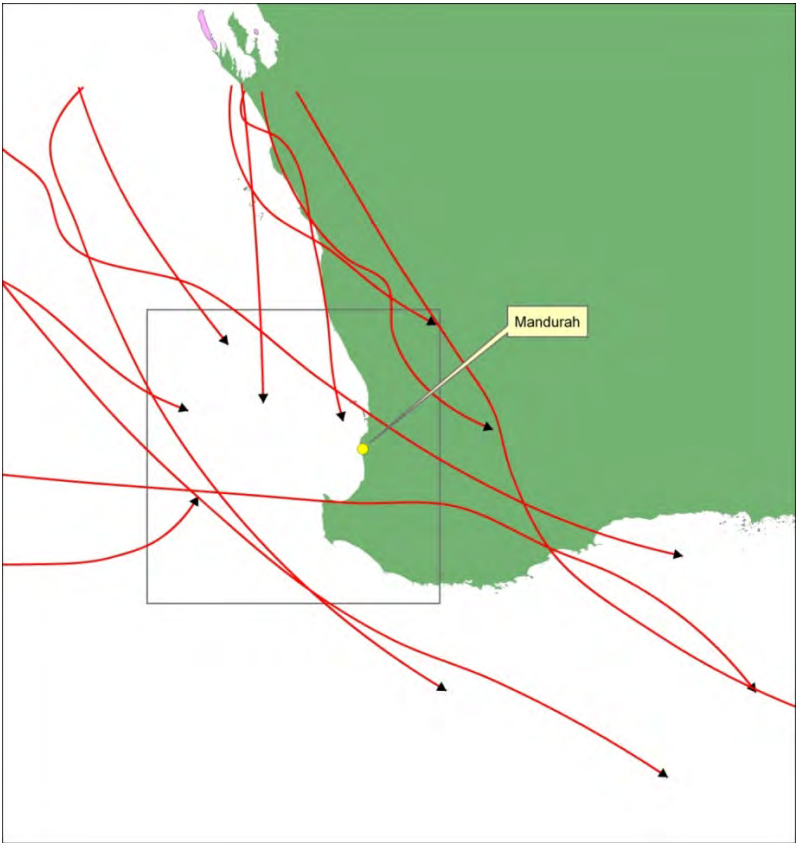


Figure 29: Tracks of cyclones in the Mandurah area (defined by box) for the period 1950-2008.

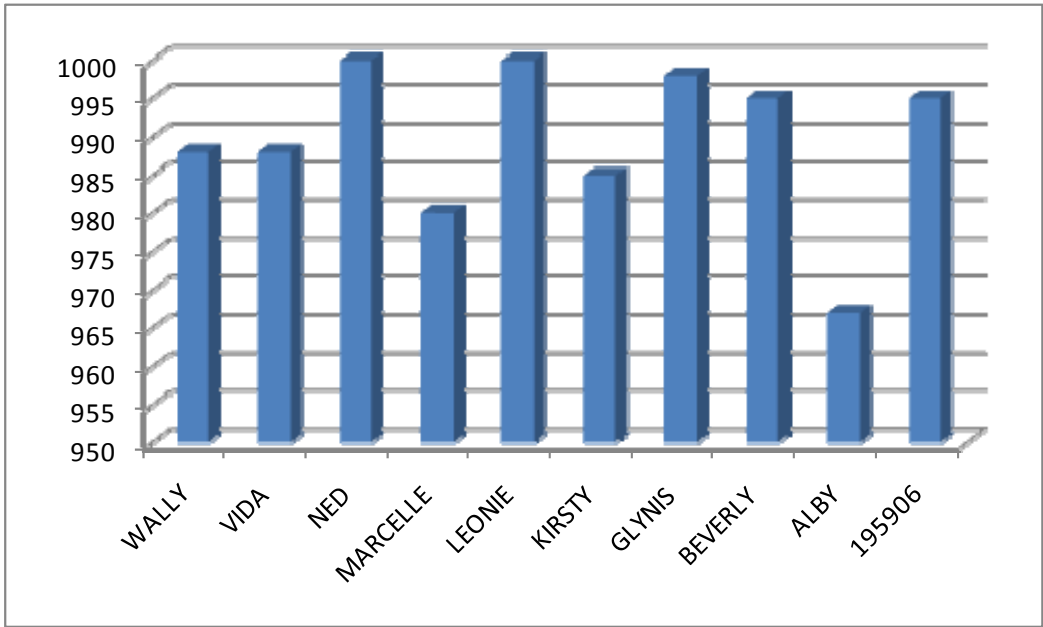


Figure 30: Minimum central pressure of storms in the Mandurah area (1950-2008) – that is within box shown in Figure 29.

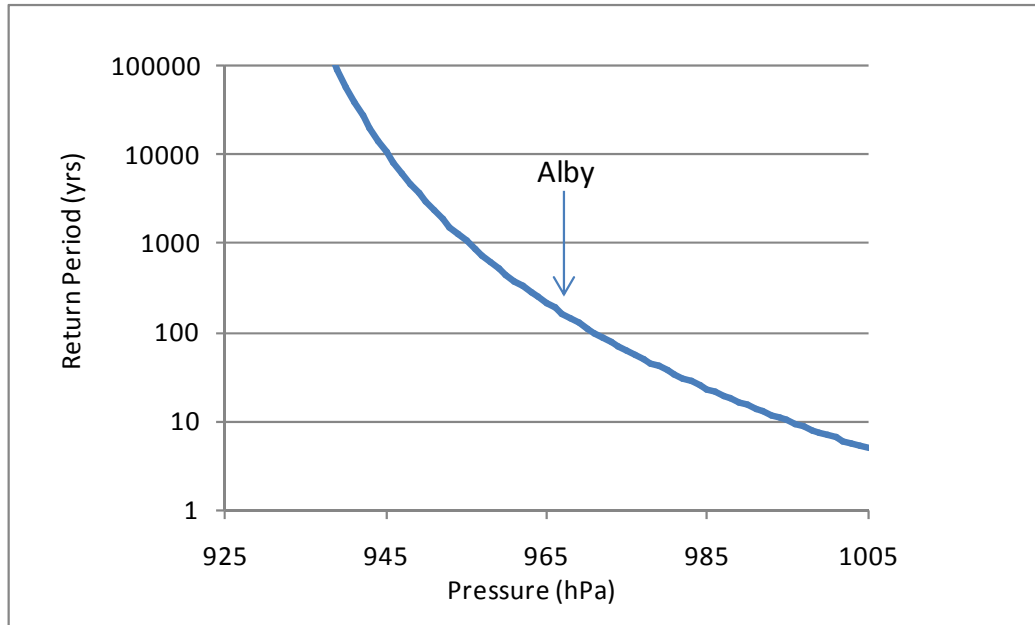


Figure 31: Return for cyclone central pressure for the region shown in Figure 29.

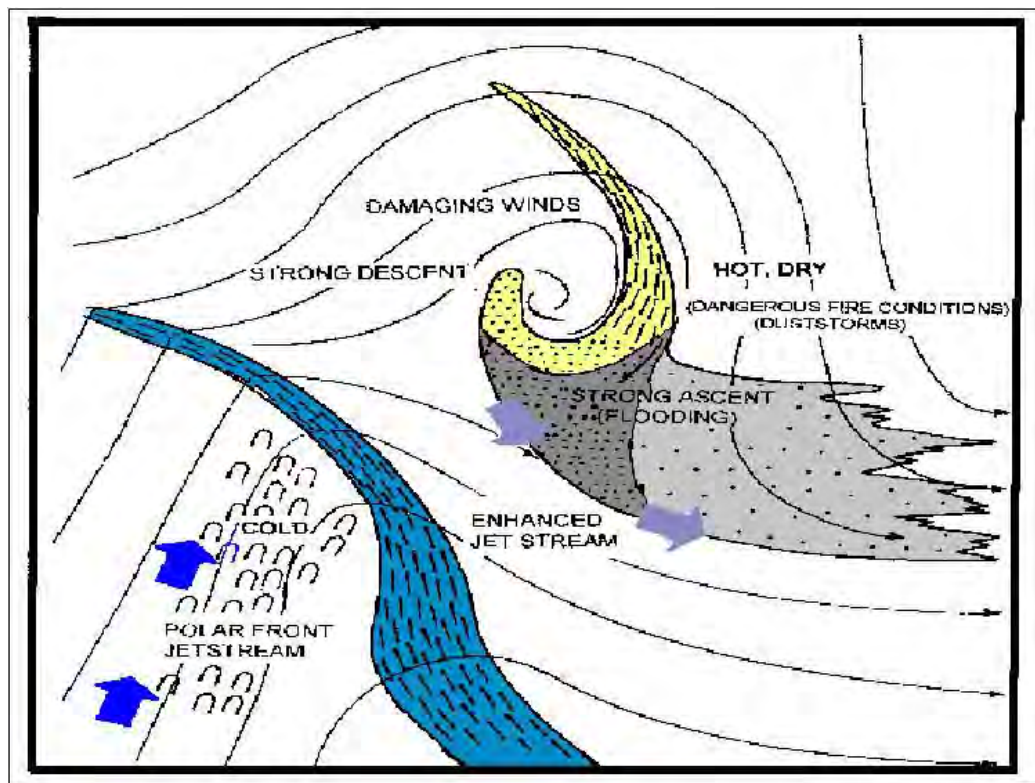


Figure 32: Schematic diagram showing features of a tropical cyclone undergoing extra-tropical transition.



Appendix. B Shoreface Translation Model (STM) Methodology - Overview

Understanding large-scale coastal behaviour (LSCB), which entails changes in coastal topography and process over lengths (100 to 1000's m) and times (decadal to century), is of critical importance in coastal management. LSCB is characterised by non-linear morphodynamic processes driven by ever-changing boundary conditions. This coupled with our incomplete understanding of the morphodynamic processes involved (especially sediment transport) introduces uncertainty in our ability to predict coastal evolution. Furthermore any broadly-applicable quantitative understanding of LSCB based on conventional theoretical and empirical methods is still some way off. There is a considerable debate in the scientific literature as to whether we will ever be able to model the LSCB in scales (both spatial and temporal) useful to Coastal Managers and Planners.

However, Cowell and co-workers (see: Cowell et al., 1992; 1995; 2006) have attempted to sidestep some of the intractable problems associated with process uncertainties in order to provide a quantitative assessment/prediction of coastal evolution under a changing climate for the coastal management community. Their methods have included adopting a behaviour-orientated approach based upon fully deterministic theory as well as heuristic knowledge drawn from qualitative patterns that exist in nature (Figure 33).

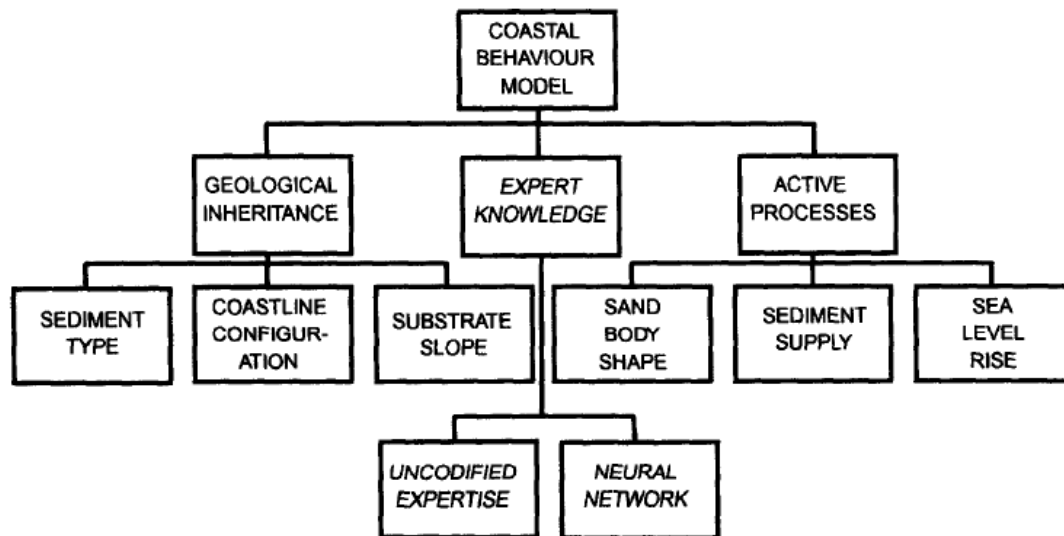


Figure 33: Components incorporated pragmatically into morphological behaviour modelling. The objective of the STM is to enable quantitative experimentation on how factors in the third level influence morphological behaviour. (Source: Cowell et al., 1995)

The STM is designed to simulate the horizontal and vertical translation of coastal sand bodies (e.g. barrier dunes and mainland beaches) over an existing geological substrate, driven by;

- Changes in sea level (Figure 33)
- External gains and losses of sediment (e.g. to alongshore drift processes)
- Changes in the geometry of the active sand body itself.



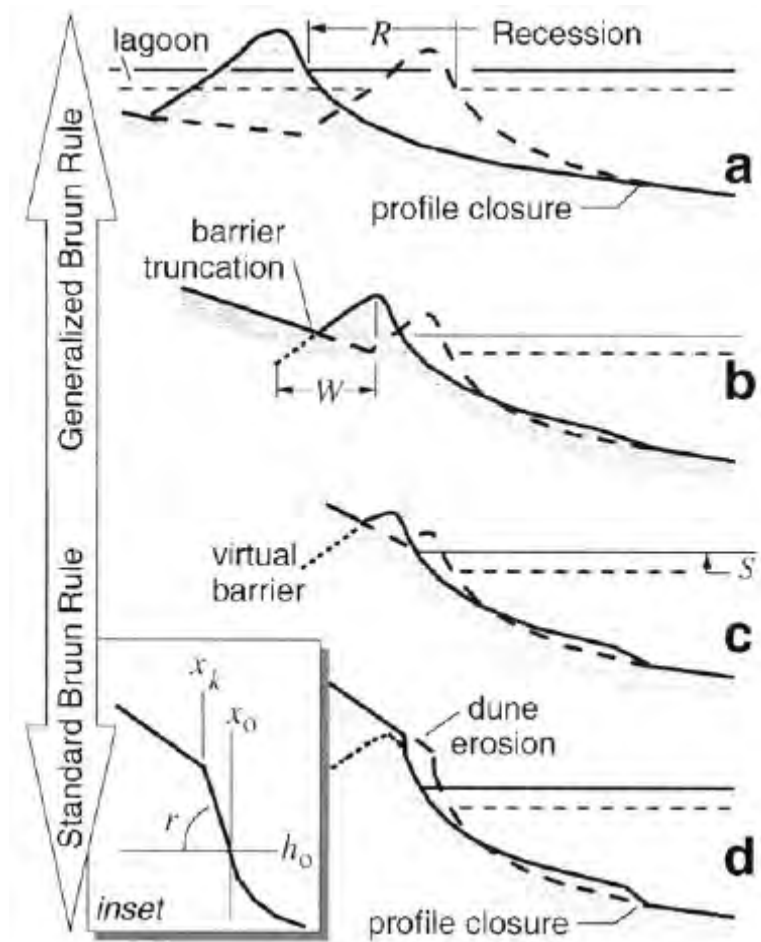


Figure 34: Responses of a sand body to sea-level rise: (a) barrier rollover where landward bypassing occurs as washover, flood-tide delta or transgressive-dune deposits; (b and c) transitional barrier truncation with a steeper backshore; (d) a mainland beach where the littoral cell is closed. (Source and further explanation: Cowell et al., 2006).

The dimensions of a sandy body can be varied (Figure 35) to simulate the effects of storms and other morphodynamic adjustments. The substrate is a passive morphology that undergoes modification as a consequence of sandy-body translation. This modification produces changes in the position of the coastline as well as reconfiguring the backshore and inner shelf morphology and stratigraphy.

The overall profile geometry at any instant is determined by the dimensions of the active morphology in relation to the substrate setting. A continuum of possibilities exists between the two limiting types defined in Figure 35. One type is termed here “barrier mode”, where the shoreface is relatively steep relative to the substrate (Figure 34a and Figure 35) and the other is termed “encroachment mode”, that occurs when the shoreface is of a lower gradient than the substrate (Figure 35b).



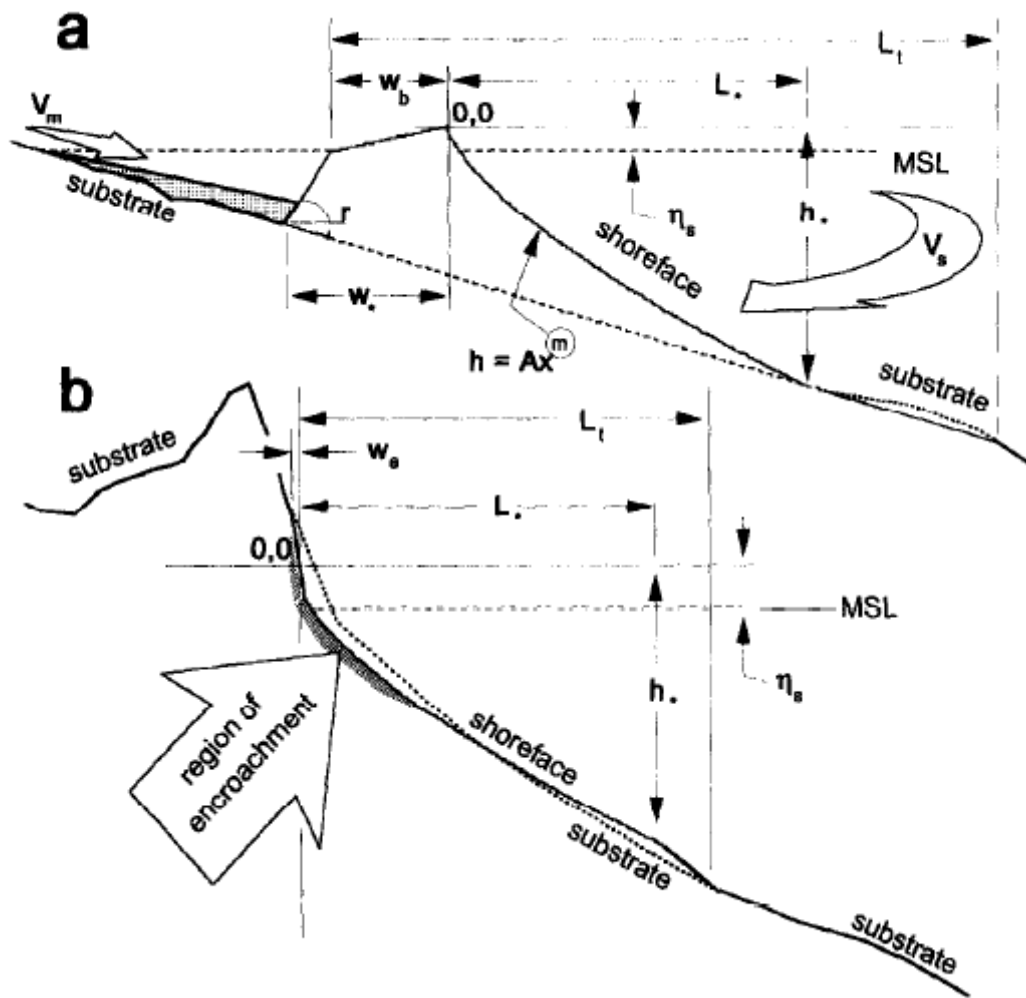


Figure 35: Definition sketch of basic profile geometry and internal parameters for the limiting types of behaviour; (a) barrier mode and (b) encroachment mode (Source: Cowell et al., 1995)

In the STM Schema, shown in the Figure 35, the morphology is represented by a time-dependent set of geometric parameters $P(t)$;

$$P(t) = \{L_t, L_s, h_s, m^* L_b, h_b, m_b, d, c, w, W, h_s, s_t\}$$

These internal parameters constitute proxies for morphodynamic processes and in-principle, values for these parameters can be estimated from theory and other morphodynamic models operating on shorter timescales than those associated with significant changes in sea level, for further discussion see Cowell et al., (2006).

The STM translates the active portion of the profile a horizontal distance R following a change in parameters values (from a set P_t to P_{t+1}), an external net sand exchange ΔV_s and or a change in sea level. With change in sea level, the active profile is also displaced vertically by $\Delta \eta$.



Further refinements to the STM have been made by applying stochastic simulations to manage the predictive uncertainty in cases involving complications resulting from open sediment budgets, rock reefs and seawalls (all commonly occurring along the WA coastline). Stochastic simulation makes it possible to establish confidence limits and determine the statistical significance of differences caused by varying effects, e.g. substrate resistance and shoreface geometry. It also enables the likelihood of critical impacts to be specified in terms of probability, moreover, probabilistic forecasts provide a transparent basis for coastal management decision making.



Appendix. C TC Alby observed high water levels

Department of Water provide a number of marked maps that were then scanned and digitised by Geoscience Australia. Figure 36 shows the locations of the observations and Table 2 shows the water depth at those locations.

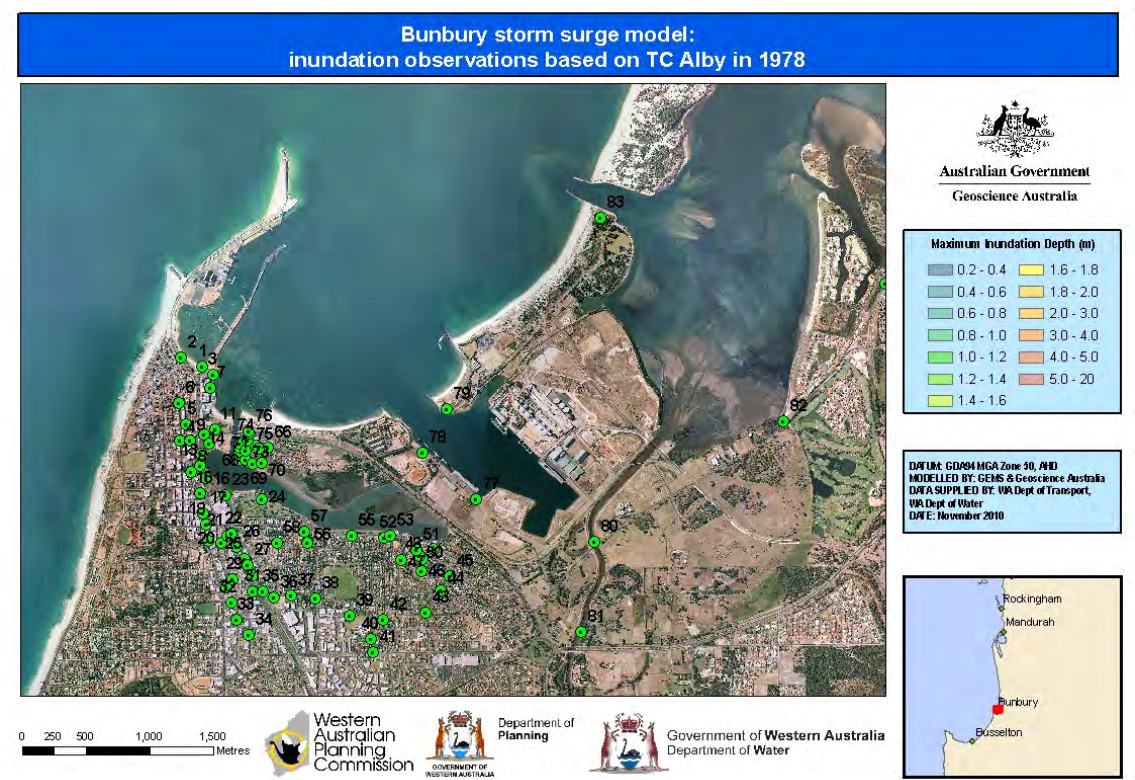


Figure 36: Location of inundation observations from TC Alby in 1978.



Location number	height_m
1	2.66
2	2.40
3	2.62
4	1.66
5	1.28
6	1.63
7	2.37
8	1.68
9	0.91
10	1.68
11	2.61
12	1.78
13	1.58
14	1.68
15	1.72
16	1.91
17	1.66
18	1.68
19	1.66
20	1.42
21	1.56
22	1.44
23	1.85
24	1.84
25	1.81
26	1.67
27	1.56
28	1.54
29	1.02
30	1.08
31	1.26
32	1.11
33	1.12
34	1.08
35	1.45
36	1.46
37	1.46
38	1.67
39	1.66
40	1.49
41	1.54
42	1.63
43	1.32
44	1.78



45	1.50
46	1.89
47	1.81
48	1.71
49	1.96
50	1.88
51	1.43
52	1.82
53	1.91
55	1.71
56	1.78
57	1.69
58	1.62
61	1.77
62	1.89
63	1.31
64	1.81
65	1.31
66	1.95
67	1.90
68	1.89
69	1.84
70	1.84
71	1.85
72	1.82
73	2.00
74	1.70
75	2.48
76	2.57
77	2.57
78	1.99
79	2.53
80	1.53
81	1.51
82	1.41
83	1.63
84	1.32
85	1.10
86	1.43
87	1.39
88	1.29
89	1.35
90	1.19
91	1.16
92	1.16
93	1.07
94	1.31



Table 2: Observations from TC Alby in 1978.