FINAL WAMSI PROJECT REPORT

Instructions for Use: Please complete each of the tables below and return to (insert Node Science Coordinator's name and email contact details).

Project Details

Project Number and Title:	6.1: Offshore and coastal engineering and the effects of climate change
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Project Leader:	Professor Charitha Pattiaratchi, School Environmental Systems Engineering & UWA Oceans Institute, University Western Australia
Project Team:	Charitha Pattiaratchi, Ivan Haigh, Cyprien Bosserelle, Shari L. Gallop, Leigh MacPherson, Ian McMullen, Tanya Stul
Project Start Date:	
Project End Date:	31 Dec 2011
Due Date for Final Report:	20 Dec 2011
Project Funding: WAMSI $ Additional Cash $ Additional In-Kind $ Total Funding $	

1. Project Objectives and Achievement Criteria

Confirmation of the project objectives and the delivery of milestones against the Key Performance Indicators:

Objectives:

1. Determine the variability and historic long-term trends in extreme still water levels (which comprise of combinations of mean sea level, astronomical tides and surges) around the coastline of WA.
2. Determine the variability and historic long-term trends in the surface wave climate around WA.
3. An assessment of the potential future changes to extreme still water levels (in particular storm surge magnitude and frequency) under different climate scenarios.
4. An assessment of the potential future changes to the surface wave field under different climate scenarios.
5. An assessment of coastal stability at selected regions along the WA coast resulting under the combined effects of altered wave fields and storm surges and sea-level rise as a result of climate change.
6. Conditional assessment and cost estimates for the upgrading and maintenance of shore stabilization works; including coastal and estuarine infrastructures.
7. Preparation of area-specific adaptation policies, strategies and implementation programs for incorporation in State and Local Government legislation and projects.
8. Implementation of adaptation strategies by urban and rural communities in partnership with State, local Government and Natural Resource Management agencies.

Deliverables:
Historic and future storm surge and wave climatology related to the beach stability

Milestones and Reports:

1 Determine the variability and historic long-term trends in extreme still water levels (which comprise of combinations of mean sea level, astronomical tides and surges) around the coastline of WA.
2 Determine the variability and historic long-term trends in the surface wave climate around WA.
3 An assessment of the potential future changes to extreme still water levels (in particular storm surge magnitude and frequency) under different climate scenarios.
4 An assessment of the potential future changes to the surface wave field under different climate scenarios.
5 An assessment of coastal stability at selected regions along the WA coast resulting under the combined effects of altered wave fields and storm surges and sea-level rise as a result of climate change.

2. Research Chapter(s)

a. Introduction

Beach morphodynamics are the result of the complex interactions between sediment, sea level, waves, currents, and in some cases natural or anthropogenic structures. Natural formations such as rocks and corals can form structural constraints in the nearshore and can result in 'perched beaches', defined as beaches that are underlain and/or fronted seaward by hard structures (Gallop et al., 2011a). These structures add another level of complexity to understanding the mechanisms of beach variability and change. In addition to local processes, beach variability is also influenced by larger spatial and temporal scale drivers including weather systems, oceanic currents and mean sea level (Fig. 1). Therefore, the aim of this study was to demonstrate the process and application of multi-scale modelling to understand the complex sediment dynamics on a perched beach.

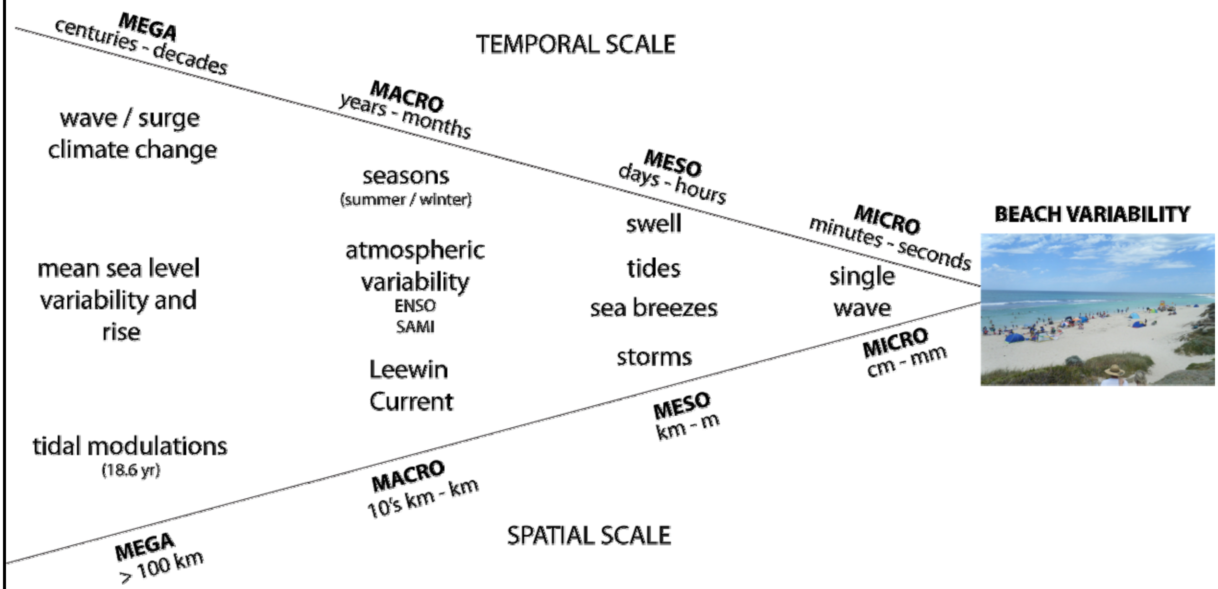

Fig. 1 Schematic of the key drivers of beach variability over a range of spatial and temporal scales in southwest Western Australia.

Natural perched beaches are found world-wide, from the United Kingdom and the Mediterranean, through the islands of the Indian Ocean, Australia and Asia, the Pacific Island atolls to the West Indies and Central and South America (Vousdoukas et al. 2007; Gallop et al. 2011a). The hard structures interact with incoming waves and currents to modify the sediment transport and beach morphology. Recent studies have demonstrated the high degree of spatial complexity of natural structures at the coast leads to extreme spatial variation in beach behaviour (Muñoz-Perez et al., 1999; Larson and Kraus, 2000; Vousdoukas et al., 2009; Muñoz-Perez and Medina, 2010; Gallop et al. 2011a, b). As a case study, we focused on Yanchep Lagoon in southwest Western Australia (Fig. 2) where a sandy beach is perched on Quaternary limestone reefs. This site consisted of a complex perched beach system that is well documented using field observations (Gallop et al. 2011a, b)

The influence of geological features on waves and currents occurs not only in the dynamic nearshore, but also offshore. For example, islands and seamounts perturb the flow field and refract surface gravity waves that control the amount of wave energy and currents in the nearshore. Waves are generated by wind and grow and transform into swell over thousands of kilometres and transport energy beyond the ocean basin where they originated (Snodgrass et al. 1966). When waves reach the coastline, they can refract along features several kilometres in scale and interact with islands. When waves reach the shore, they break over areas tens of meters wide and transfer their momentum to coastal currents that can transport sediment over large distances (Komar 1998). Therefore, understanding the dynamics of coastal waters and their forcing requires understanding of the dynamics of the adjacent continental shelf and the wider ocean basin.

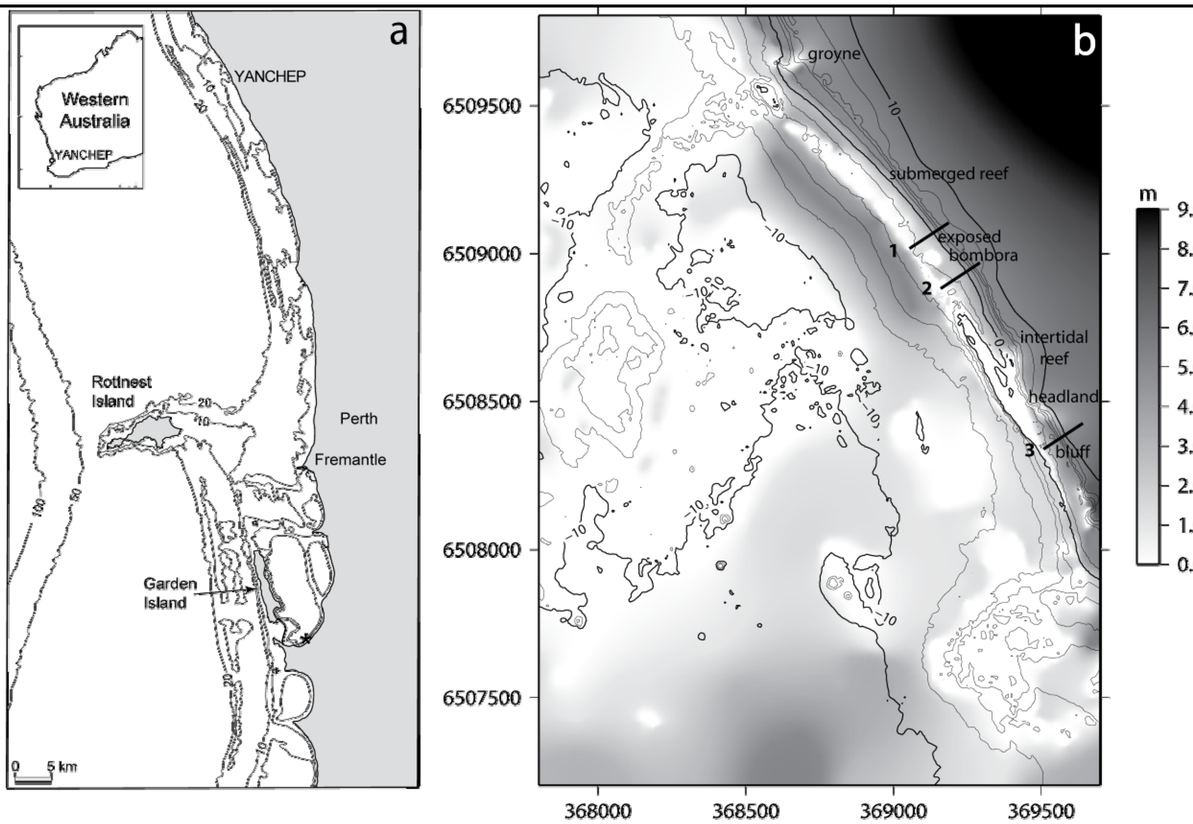

Fig. 2 a map of Western Australia and the Perth region with study sites of interest; and b bathymetry contours of Yanchep Lagoon where the color bar indicates the estimated depth of sediment above the rock substrate in February 2010 (data source: Department of Transport). White areas are where limestone rocks outcrop above the sediment surface. Lines 1−3 indicate the Exposed, Reef and Bluff Profiles that were measured during a storm in July 2010.

Information about ocean basin, continental shelf and coastal dynamics can be acquired by using numerical models that span across all of these spatial scales. Some oceanographic models can be implemented to take into account small and large scale bathymetric features by using a single triangular unstructured mesh, which allows refinement in areas where the physical processes are complex or of particular interest. Many other models, such as those which use rectilinear grids, use a nested approach to account for different spatial scales. For surface wave modelling, models such as Simulating WAves Nearshore (SWAN) (Booij et al. 1999) can simulate waves as they grow in the ocean basin then travel on the shelf and break on the beach. These models use unstructured meshes. However, it is highly inefficient to simulate an ocean basin scale down to the coastal scale using a single unstructured mesh. Also, due to the variety of physical processes involved, single grid models are unable to predict waves, changes in water levels resulting from tides and storm surges at ocean basin scales, as well as predict the resulting morphological changes on beaches. Instead, a suite of models with different grids and physics can be used over a range of spatial scales. Grids can be nested and can use the output from the larger coarser grids as a forcing.

In this study, tides, storm surges, waves and morphological changes on a perched beach were simulated over a range of spatial scales using a suite of appropriate numerical models. To simulate waves: (1) a WAVEWATCH IIITM (Tolman 2009) multi-grid model of the Indian Ocean was used to simulate an extreme storm event; (2) the wave spectral information from this was subsequently input into a high resolution SWAN wave model of the continental shelf; and (3) the wave spectral information was then input to XBeach (Roelvink et al. 2009) to calculate the wave energy and bound long waves at the boundary, from which the morphology was simulated. In parallel with these wave models, to simulate the tidal conditions and storm surge: (1) a 2D hydrodynamic model (MIKE21 Flow Model) was used with an unstructured mesh that covered the continental shelf and the nearshore regions; and (2) results from this model were used to force the sea level variations in the SWAN wave model of the continental shelf and the XBeach morphological model.

In addition to simulating an extreme storm event, we also demonstrated the use of DualSPHysics (Crespo et al., 2011) which is a fine scale Smoothed Particle Hydrodynamic (SPH) model. This model was used to evaluate the fine scale wave breaking and sediment transport on the reef south of Yanchep lagoon that was not resolved by the XBeach model but that is a key feature of the beach dynamics after storms and during the summer season.

b. **Methodology - further details provided below in (3)**

Field Measurements

An intensive programme of field observations was undertaken at Yanchep Lagoon to investigate the beach behaviour over a cascade of temporal scales, from decades to hours (Gallop et al. 2011b, c, submitted.) and included: (1) quantifying historic shorelines and vegetation lines since 1971; (2) measuring monthly beach profiles over two years; and (3) rigorous field deployments during sea breeze and storm events. In this study, we focused mainly on seasonal surveys and results from a winter storm, both of which illustrated some of the challenges of modelling a complex perched beach system such as Yanchep Lagoon. During a winter storm in July 2010, three beach profiles were surveyed every two hours over one week from July 8 to 14 (Gallop et al. submitted). These profiles extended from the top of the dune to AHD (Australian Height Datum) which is approximately Mean Sea Level (MSL). The three beach profiles each had a different geological setting:

1. Exposed Profile was located north of the bombora and was not directly fronted seaward by limestone;

2. Reef Profile was between the lagoon exit and the bombora and was fronted directly seaward by submerged limestone 3 m below MSL; and

3. Bluff Profile was on the southern section of the beach where the dry beach was perched on a limestone platform (Fig. 2b).

A high degree of beach variability was identified over all of these temporal scales and the beach behaviour was found to be strongly modified alongshore by the local rock topography. In the following paragraphs we summarise the key behaviour of the beach which pose challenges for numerical modelling.

Multi-scale Modelling

The overall aim of the numerical modelling was to simulate the behaviour of the beach at Yanchep Lagoon during an erosion event with high sea level and large waves; and during the sea breeze accretion phase. First, to force the beach erosion, we created an event that had a 100-year extreme wave height combined with a 100-year sea level. However, due to short data sets and the low spatial resolution of field measurements it was necessary to use broad-scale hydrodynamic modelling to define the magnitude of the 100-year event and then generate the forcing conditions at the smaller scales. Therefore, a suite of numerical models that covered a cascade of spatial scales was used to simulate tides, storm surges, waves and sediment transport (Fig. 3). To simulate the accretion phase of the southern beach, a very high resolution model was required to capture the steep natural seawall that fronts the beach and the complex flow resulting from the wave-seawall interaction. In the following sections we introduce the models used and described each in detail:

1. At the ocean basin scale, WAVEWATCH IIITM (Tolman, 2009), hereafter referred to as WW3, was used to hindcast wave heights (Bosserelle et al. 2011b). Tides and storm surges were hindcasted on the continental shelf using Mike 21 Flow Model Flexible Mesh (FM), driven with forcing from a Global Tidal Model (Haigh et al. in prep);

2. At the regional scale, the SWAN wave model (Booij et al. 1999) was used ; and

3. At the coastal scale, two sub-scales were modelled: (a) the beach scale; and (b) the beach profile scale. At the beach scale, the XBeach morphological model (Roelvink et al. 2009) was used to simulate the hydrodynamics and sediment transport during the extreme storm. At the beach profile scale, the SPH model DualSPHysics (Crespo et al. 2011) was used to simulate the finer-scale hydrodynamic during accretion of the southern lagoon (Bosserelle et al, 2011a).

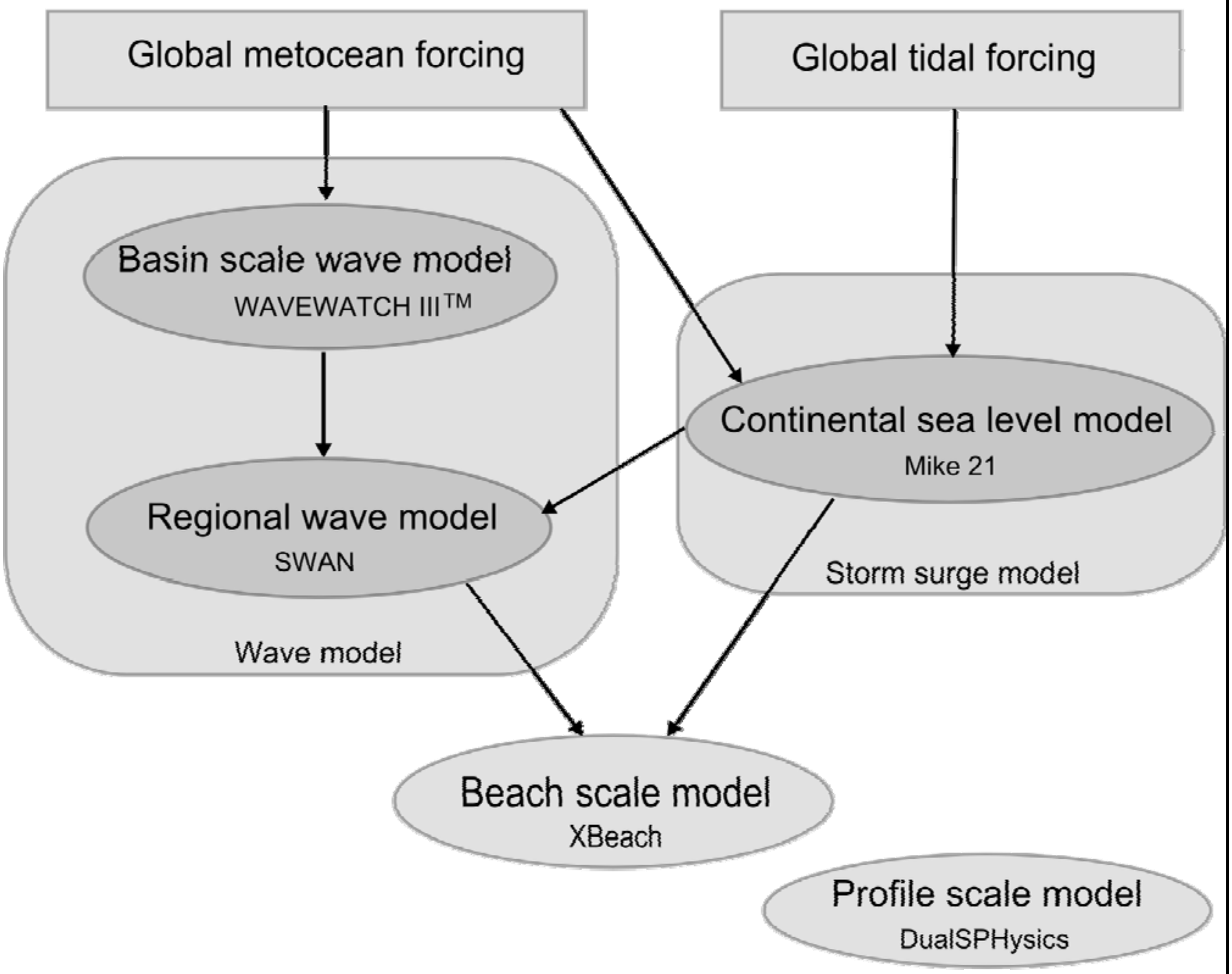

Fig. 3 Flow chart showing numerical models used with arrows indicating where model output was used as input.

c. **Results - further details provided below in (4)**

All goals of the project were accomplished. The results can be summarised as:

- Successful field measurement programs were conducted at Yanchep. The key results are summarised below:
  - Field measurements were undertaken during the summer season when strong sea breezes blow. These showed that the natural limestone formations that dominate the coast of southwest Western Australia cause a high degree of spatial variation coastal sediment transport.
  - The limestone formations can cause strong currents which can cause erosion 'hot spots'.
  - Field measurements during two consecutive winter storms revealed that while the limestone formations can reduce beach erosion by attenuating waves, they can also inhibit the post-storm recovery of the beach.
  - Differences in the elevation of the limestone formations influenced the sensitivity of the local beachface to wave height and sea level.
  - Monthly beach surveys showed that limestone outcrops have a strong influence on longshore sediment transport and while they can lead to the build-up of beaches in the summer, down-drift

beaches can have high rates of erosion i.e. an inverse relationship.
    - Inter-annual changes in the shoreline, vegetation line and beach width showed that beaches fronted by limestone platforms/ bluffs can have a higher variability than sandy beaches or beaches perched on reefs.
    - This inter-annual variability appeared to be mostly due to the intensity of the sea breeze season and needs further investigation.
- Successful application of Multi-scale modelling. The key results are summarised below:
    - Tide-surge modeling has been used to map the current extreme sea level exceedance probabilities around the whole of Australia;
    - A global tide model was been used to map for the first time the spatial distribution of the inter-annual tidal modulations.
    - Wave spectral information can be simulated accross the ocean basin scale, the continental shelf scale successfully and be implemented to local scale model to simulate sediment transport.
    - Yanchep Beach erosion under an extreme stom event was simulated for 3 scenarios of mean sea level.
    - Higher sea level reduced the capacity of offshore reef to dissipate wave energy at higher mean sea level.
    - alongshore variation in the reef elevation caused extreme variation in the amplitude of erosion due to extreme storm.
- Two PhD students from UWA have been involved in the project; They will complete theses by December 2012.
- Two Final Year undergraduate Honours students have been involved in this project; one has completed his individual research theses and the other will complete by July 2012.
- A total of 20 refereed journal and conference papers have been produced.
- A total of 24 presentations have been given at national and international conferences.

d. **Discussion - further details provided below in (5)**

This paper summarised a multi-scale investigation that used multiple numerical models to understand the sediment transport processes around complex reefs at a perched beach in Western Australia. The multi-scale methodology focused on the simulation of offshore tides, storm surges and waves to force the XBeach morphological model with realistic sea level and directional wave spectra. The advantages and challenges associated with this methodology are discussed below.

Larger scale numerical models of sea level and waves run in parallel were used to provide suitable forcing for the coastal scale morphodynamic model. These models also provided valuable information regarding the behaviour of storm surges and waves as they crossed the ocean basin and the shelf. The ocean basin scale wave model showed that the largest waves that reached the coast of Western Australia were generated by a relatively small weather system that created a trapped fetch. While crossing the continental shelf, the waves lost most of their energy by breaking on the offshore reefs which are only a few meters below MSL (Fig. 10a). These reefs are so shallow that the elevated water level from the storm surge did not significantly reduce the wave breaking, suggesting that a similar amount of wave dissipation is expected for a comparable wave event that would occur with a 1 m rise in sea level.

The extreme storm that was simulated at Yanchep Lagoon using XBeach eroded the beach dramatically until it reached a new equilibrium. The dunes receded by 20 m leaving a flat, gently sloping beach. The sand that was eroded from the dunes and the beach formed a sand bank north of the lagoon which caused the waves to break further offshore and reinforced the equilibrium of the beach. Given the extreme nature of the event simulated, this new equilibrium is likely to correspond to the maximum erosion resulting from a single extra-tropical storm. The southern lagoon was the first part of the beach to erode during the storm and some of the sand was transported to the northern lagoon. This confirmed the hypothesis that during the winter season, the sand that reached the southern lagoon could travel to the northern lagoon and settle during the next calm period. During the storm, a large sand bank formed to the north of the lagoon and a similar bank was observed after the storms in 2010 and in 2011. This bank was likely a source of sand to replenish the beach, even behind the lagoon. On the other hand, the small sand bank that formed offshore of the southern lagoon most likely did not contribute to the recovery of the southern section of the beach. If some of this sand could return to the lagoon it would probably have been transported to the northern lagoon. However, XBeach cannot estimate the volume of sand that can overtop the bluff in the southern lagoon.

The wave breaking on top of the bluff, which is comparable to a near vertical natural seawall, created complex flow structures that could only be resolved with very high-resolution model such as SPH. Results from the SPH simulations indicated that flow conditions near the natural seawall were suitable for sediment resuspension but that wave overtopping could only bring a small amount of sand into the lagoon. This is consistent with observations of the southern section of beach accreting only in summer when the sea breezes provided a large sediment flux from the south. The SPH simulation provided insight into the accretion process on the southern lagoon. However, it relied on a conceptual beach profile and did not use a realistic forcing. Despite this, the model provided useful insight showing the high velocity pulses near the bluff and the strong upward velocity that could result in the transport of sediment on the bluff where field measurements were impossible. Future work should include realistic bathymetry and forcing and the confirmation of the transport of sand should be conducted using a validated sediment transport formulation and morphological formulation. Hybrid-SPH (Crespo et al. 2008) and Boussinesq-SPH models (Narayanaswamy et al. 2010) could be used to force a realistic wave spectral energy to the SPH model and sediment formulation from Zou (2007) could be implemented in the future.

The wave models used in this methodology are designed to either be fully nested in each other, such as SWAN and WW3, or to use output of the coarser resolution model as a boundary condition for the finer resolution model. However, the transition between spatial scales is not seamless. In order to nest a SWAN model in a WW3 model required that they have the same projection and the resolution of the finer SWAN model must be less than 1/5th of the resolution of the coarser WW3 model. The grid selected for the simulation of waves on the continental shelf using SWAN had a 10 m resolution, whereas the coarse WW3 model had a resolution of 0.1º (~18,500 m). Instead of the built-in nesting, the time-series spectral information from a single point output from WW3 model was reformatted to conform to the non-stationary 2D SWAN spectra format and was then used as a uniform offshore boundary for SWAN. The spectral time-series output from SWAN required reformatting for input into XBeach as XBeach does not directly allow the user to force the model with a non-stationary SWAN spectral output file. However, stationary spectral output, containing only one 2D spectra can be used to create a suitable XBeach boundary. In addition, a time-series of existing XBeach boundary files can be used to force the model. In order to create the time-series of wave energy spectra and bound long wave boundaries, XBeach initialization was run for each SWAN output time step, for long enough to create a wave energy boundary file and the associated bound long wave boundary file. Then two files were created, each containing a list of all the boundary files created with XBeach to use as a time-series. This manipulation was computationally expensive and produced a large amount of data (~30 Gb). This is because, for each forcing condition, XBeach recreated a time-series of wave groups and bound long waves at a 1 s resolution for the duration of the condition, for each point on the boundary. This allowed the model to resolve the directional and temporal variability of bound long waves. Allowing XBeach to handle a non-stationary 2D SWAN spectrum would only slightly reduce the processing time compared to the methodology used in this study. Also, with our methodology the boundary processing could be optimised to run in a parallel with the morphological model as long as it created boundary condition faster than the model required them.

XBeach simulates the hydrodynamics, waves, sediment transport, morphological changes and the non-linear interactions between them. The model is much more complex than the tide-storm surge models or the wave models that were used in this study, and was therefore the slowest to run. Despite the relatively slower running times of XBeach and SPH and the boundary processing, all of the simulations presented in this methodology were performed on a desktop computer in less than 2 weeks. In addition, this methodology used only open-source codes with the exception of Mike 21 which could be easily replaced by an open-source 2D or 3D hydrodynamic mode (such as the General Estuarine Transport Model GETM http://www.getm.eu or Princeton Ocean Model; http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom). Therefore, this methodology can be applied universally on desktop computers provided that sufficient bathymetric and field data is available to configure and validate the models.

e. **Acknowledgements**

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f. **References**

Booij N, Ris RC, Holthuijsen LH (1999) A third-generation wave model for coastal regions, Part I, Model description and validation, J Geoph Research 104(C4):7649-7666.

Bosserelle C, Haigh ID, Pattiaratchi C, Gallop S (2011a) Simulation of Perched Beach Accretion using Smoothed Particle Hydrodynamics. Paper presented at the Coasts and Ports, 28-30 September, Perth, Australia.

Bosserelle, C., Pattiaratchi, C. and Haigh, I. D. (2011b) Inter-annual variability and longer-term changes in the wave climate of Western Australia between 1970 and 2009. Ocean Dynam. doi: 10.1007/s10236-011-0487-3.

Crespo AJC, Gómez-Gesteira M., Carracedo P, Dalrymple RA, (2008) Hybridation of generation propagation models and SPH model to study severe sea states in Galician Coast. J Marine Syst 72(1-4):135-144.

Crespo AJC, Dominguez JM, Gómez-Gesteira M., Barreiro A, Rogers BD (2011) User guide for the DualSPHysics Code v1.0. http://www.dual.sphsics.org.

Gallop SL, Bosserelle C, Pattiaratchi C, Eliot I (2011a) Form and function of natural and engineered perched beaches. Coasts and Ports 2011, 28-30 September, Perth, Australia.

Gallop SL, Bosserelle C, Pattiaratchi C, Eliot I (2011b) Hydrodynamic and morphological response of a perched beach during sea breeze activity. J Coast Res Special Issue 64:75-79.

Gallop SL, Bosserelle C, Pattiaratchi C, Eliot I (2011c) Rock topography causes spatial variation in the wave, current and beach response to sea breeze activity. Mar Geol 290:29-40.

Gallop SL, Bosserelle C, Pattiaratchi C, Eliot I (submitted) Natural coastal structures protect beaches during storms but inhibit recovery. Coast Eng.

Haigh ID, Wijeratne EMS, Hunter J, Pattiaratchi C (in prep) Estimating extreme sea level exceedance probabilities around the coastline of Australia using a 40 year (1970 to 2009) sea level hindcast. Plan to submit to Cont Shelf Res.

Komar, P.D., 1998. Beach Processes and Sedimentation, Second Ed., Prentice Hall, Upper Saddle River, New Jersey.

Larson M, Kraus N (2000) Representation of non-erodible (hard) bottoms in beach profile change modelling, J Coastal Res 16(1):1–14.

Muñoz-Perez JJ. Tejedor L, Medina R (1999) Equilibrium beach profile model for reef-protected beaches . J Coastal Res 16:1–14.

Muñoz-Perez JJ. Medina R (2010) Comparison of long-, medium- and short-term variations of beach profiles with and without submerged geological control. Coastal Eng 57:241–251.

Roelvink DA, Reniers A, Van Dongeren A, Van Thiel de Vries J, McCall R, Lescinski J (2009) Modelling storm impacts on beaches, dunes and barrier islands. Coast Eng 56:1133–1152.

Snodgrass FE, Groves GW, Hasselmann KF, Miller GR, Munk WH, Powers WH (1966) Propagation of Ocean Swell across the Pacific. Philosophical Transactions of the Royal Society of London Series A, Mathematical and Physical Sciences 259 (1103):431-497. doi:10.1098/rsta.1966.0022.

Tolman HL (2009) User manual and system documentation of WAVEWATCH III TM version 3.14. NOAA/NWS/NCEP/MMAB Technical Note 276.

Vousdoukas MI, Velegrakis AF, Karambas TV (2009) Morphology and sedimentology of a microtidal beach with bedrocks: Vatera, Lesbos, NE Mediterranean. Cont Shelf Res 29(16):1937–1947.

Vousdoukas MI, Velegrakis AF, Plomaritis TA (2007) Beachrock occurence, characteristics, formation mechanism and impacts. Earth Sci Rev 85:23-46

.Zou S. (2007) Coastal Sediment Transport Simulation by Smoothed Particle Hydrodynamics. PhD Theses. Johns Hopkins University.

3. Methodology

Summarise the method(s) utilised as part of the project and provide a listing of the sub-projects (if appropriate). Sub-project reports should be provided as annexures to this project report.

Objective 1: Determine the variability and historic long-term trends in extreme still water levels (which comprise of combinations of mean sea level, astronomical tides and surges) around WA.

Extreme still water levels (i.e. exclusive of surface gravity waves) arise as a combination of three factors: mean sea level, tide and surge. A detailed assessment of historic changes in each of these components of sea level was undertaken before changes in total water levels were examined. These different assessments are described below.

A detailed assessment of annual, inter-annual and longer-term changes in mean sea level around Western Australia using monthly mean sea level records from 14 tide gauge sites (Figure 1). The monthly mean sea level records have been de-trended and then decomposed into annual and inter-annual components and the variability in both components has been examined.

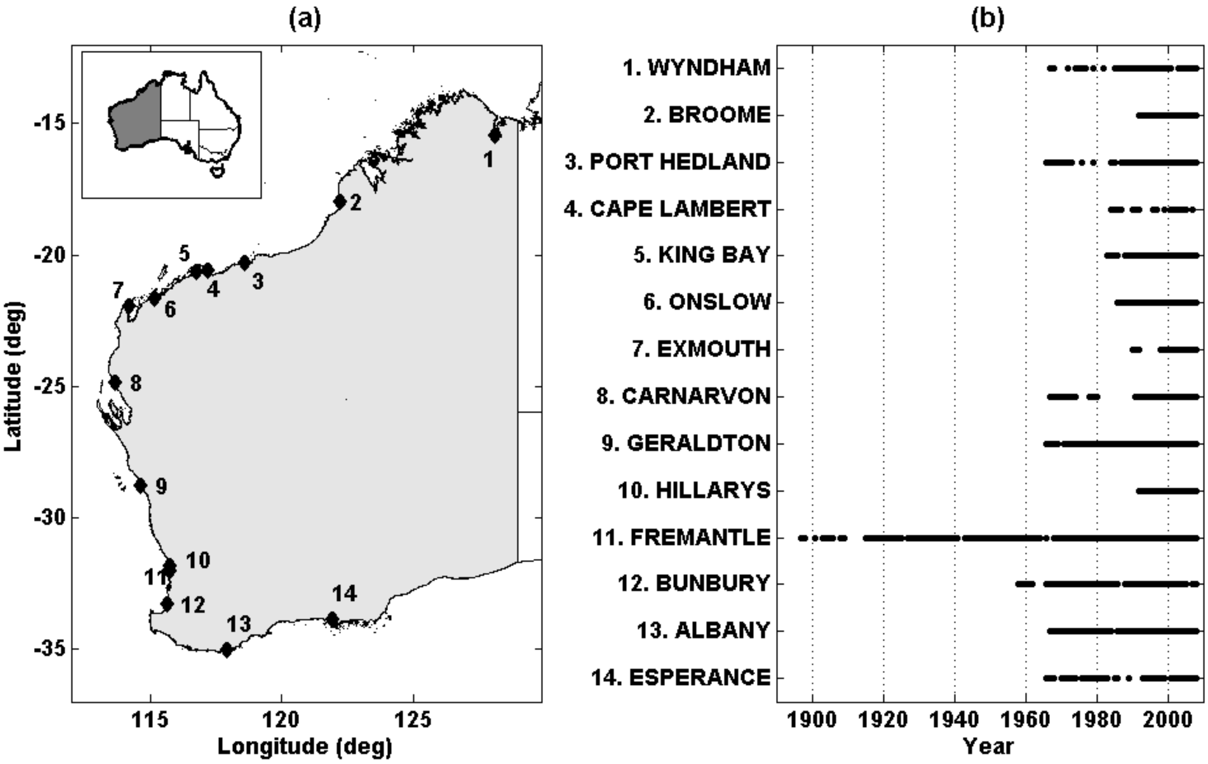

Fig. 1: The (a) location and (b) duration of mean sea level records used.

A detailed analysis of tides around Western Australia was also undertaken. Over inter-annual time-scales, variations in high tides arise as a result of the 18.61 year lunar nodal cycle and the 8.85 year cycle of lunar perigee, the latter of which influences sea level as a quasi-4.4 year cycle. Assessment of these systematic tidal modulations allows prediction of periods when enhanced risk of coastal flooding is likely. Tidal constituents from the TPXO7.2 global tidal model were used, with satellite modulation corrections based on equilibrium tide expectations, to predict multi-decadal hourly time series of tides on a ¼ degree grid. These time series are used to determine the amplitude and phase of tidal modulations, using harmonic analysis fitted to 18.61, 9.305, 8.85, and 4.425 year sinusoidal signals. The spatial variations in the range and phase of the tidal modulations were related to the distribution of the main tidal constituents and tidal characteristics (diurnal/semi-diurnal and tidal range).

Historic changes in storm surges around southwest Australia were examined using both measured tide gauge records and a 40 year surge/tide model hindcast (see below). A number of indices of storm severity, derived from the non-tidal component of the long Fremantle tide gauge record, have been compared and assessed for significant changes. Following this, the storm tracks associated with the largest storm surge events at this site have been digitized and then these have been categorized and compared by decade.

A hydrodynamic depth averaged tide/surge model has been configured for the whole coastline of mainland Australia and Tasmania using the Danish Hydraulics Institute Mike21 modeling suite of tools. Originally the model was just setup for Western Australia, but this was extend this to the whole of Australia. A flexible mesh has been set up with a resolution of about 2.5 km along the coastline (Figure 2). The open boundaries have been driven with astronomical tidal levels derived from the TPX07.2 global tidal model. To generate the surge component of sea levels, the model has been forced with atmospheric pressures and u and v components of wind, obtained from the US National Center for Environmental Prediction's global reanalysis. These meteorological fields were available every 6 hours and have a horizontal resolution of 2.5o. The model was run for the 40-year period from 1970 to 2009 and has been validated against observations from the 29 tide-gauge sites, located around Australia. Seasonal and inter-annual variations in mean sea level, over the 40 year simulation period, where artificially included, following a detailed assessment of changes in monthly mean sea level at 72 tide gauge sites around Australia. At each of the model grid points located around the coast, time series of annual maxima and the several largest levels each year were derived from the multi-decadal sea level hindcast and fitted to extreme value distributions to estimate current ARI.

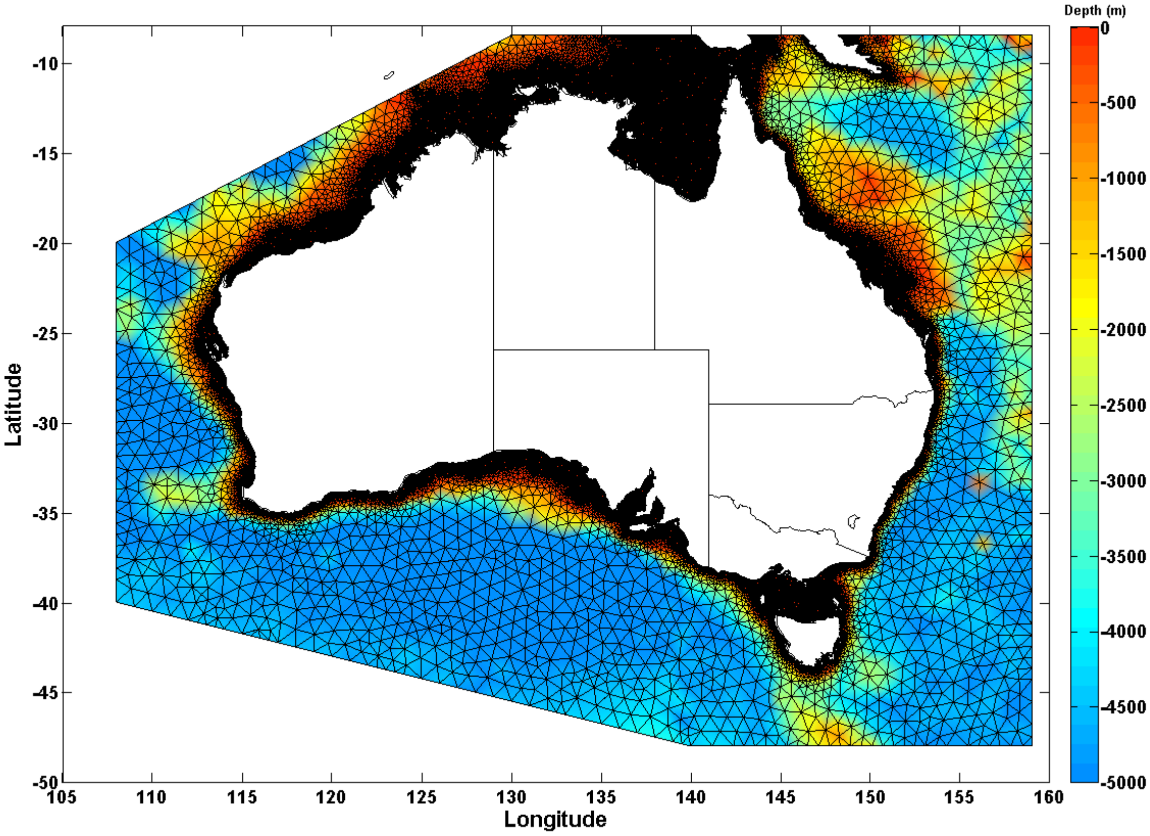

Fig. 2: *Tide/surge model grid and depths*

Objective 2: Determine the variability and historic long-term trends in the surface wave climate around WA.

In order to evaluate the annual and inter-annual variability of the surface ocean waves around Western Australia with high temporal and spatial resolution, a wave model has been set up for the Southern Indian Ocean using WAVE WATCH III. The model was configured with a domain made up of a mosaic of four grids shown in Figure 3. These include: a 10-min (~15 km) grid covering the extent of the continental shelf of WA, a 0.5° grid over the southeast Indian Ocean to provide an intermediate resolution to the finer grid, another 0.5° grid covering the storm track in the SO and a 1° grid over the rest of the SIO. The four grids are linked with an obstacle grid to account for islands and shoals that are not resolved by the grid resolution. The bathymetric data used to generate all four grid were derived from a 2-min global seafloor topography. The model was forced with the NCEP/NCAR reanalysis (NNR) wind fields. The NNR is a global meteorological reanalysis covering the period from 1948 to present. However, the wave model was only forced with wind fields from 1970 to 2009, representing a 40-year hindcast. The earlier two decades of the NNR were ignored as they are deemed to be unreliable in the Southern Ocean. The model was validated against measurements from five wave buoys located along the WA coast. Changes in the mean annual significant wave height, 90th percentile wave height, peak period and mean wave direction were assessed, and the tracks of all wave events generating wave heights above 7 m were digitised and analysed for significant changes.

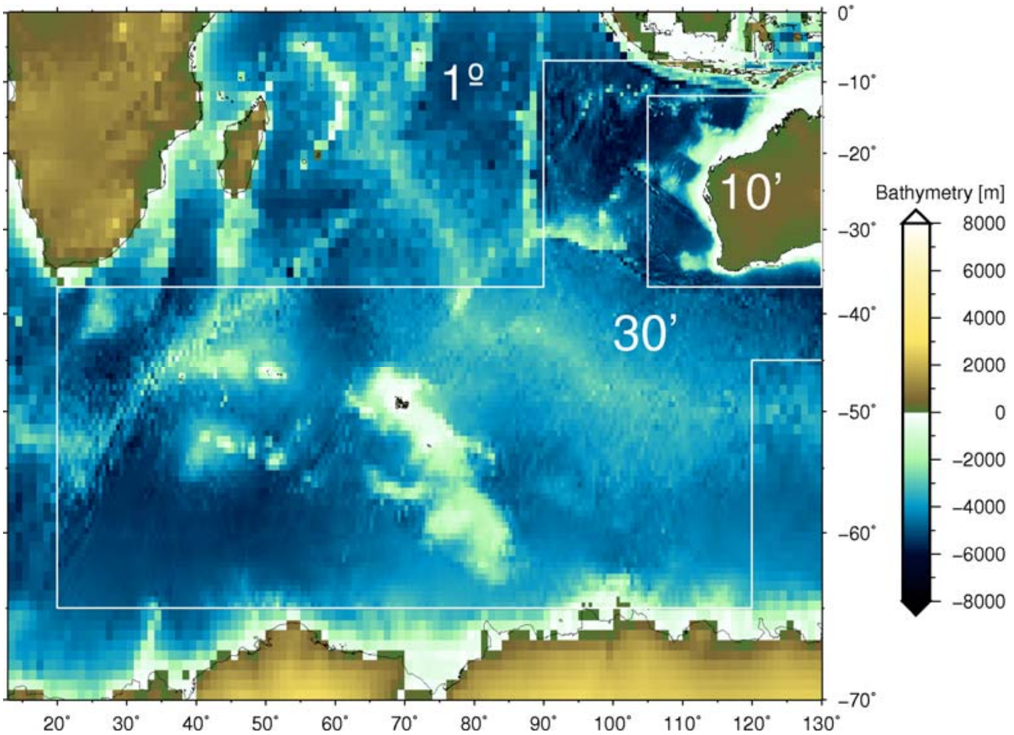

Fig. 3: Mosaic of bathymetry grids for wave model

Objective 3: An assessment of the potential future changes to extreme still water levels (in particular storm surge magnitude and frequency) under different climate scenarios.

Having examined historic changes in extreme still water levels in objective 1, this objective focuses on assessing potential future changes. This was done in two main stages, described below.

Stage 1 - Identification of potential future changes to extreme still water levels (in particular storm surge magnitude and frequency) around Western Australia under different climate scenarios: First, the mean sea level (MSL) offset method was used with sea-level rise projections from the Intergovernmental Panel on Climate Change's Fourth Assessment Report, to provide a first order estimate of possible future changes in extreme sea level every decade from 1990 to 2100 around the coast of WA. The MSL offset method predicts future extreme sea levels by simply adding projections of MSL to current return levels estimated using measured (or modeled) sea levels. Second, a more detailed assessment was undertaken by driving the tide-surge model, described above, with meteorological fields from global climate models. Modeled atmospheric pressure and wind fields were obtained from three dynamically downscaled CMIP-3 (Couple Model Intercomparision Project) global climate model (GCM) simulations. The downscaling was performed using CSIRO's Cubic Conformal Atmospheric Model (CCAM) over the Australian region at approximately 60 km resolution. The wind climates, derived from the CCAM downscaled GCM's, have been compared to observations (NCEP re-analysis) and have been found to contain both bias in mean wind conditions as well as bias in the variations of the wind conditions. A bi-variate quantile adjustment has been used to correct both direction wind components to align to the NCEP reanalysis winds. The tide/surge model for Australlia was forced using the bias corrected wind and pressure fields for the period 1981-2000 and 2081-2100 for the high emission SRES A2 scenario.

Stage 2: Identify coastal inundation at select region along the WA coast resulting from potential future changes to extreme still water levels. Mandurah located on the southwest coast of Western Australia is especially vulnerable to coastal flooding as canal estates and low-lying land around the Peel-Harvey Estuary place a large portion of the population and infrastructure in flood prone areas. With an increase in the rate of sea level rise predicted for the 21st century, extreme events are expected to become more frequent in this region, increasing the likelihood and severity of coastal flooding. A high resolution, process-based numerical model of the estuary has been configured using the Mike21 modelling suite of tools and has been validated against five tidal gauges within the estuary. The model has then been used to predict the inundation that occurs under mean conditions and with a 1 in 10, 1 in 50 1 in 100 and 1 in 1000 year events under current and then future sea level conditions and a extreme cyclone event. An ongoing honours project is looking at undertaking the same sort of assessment but for the Swan Estuary.

Objective 4: ***An assessment of the potential future changes to the surface wave field under different climate scenarios.***

A large component of this study was originally based around obtaining future atmospheric climate variables from the Northwest Australian Climate Change Study (NACCS), an initiative of Woodside Energy Ltd. It was planned that output from the NACCS study wind output would be used to predict climate change scenarios for waves. But the NACCS database has not and will not been supplied. However findings from objective 2 is used to correlate the rate of change of waves to climate indices and use the predicted behavior as a proxy for the evolution of wave under climate change scenarios.

Objective 5: ***An assessment coastal stability at selected regions along the WA coast resulting under the combined effects of altered wave fields and storm surges and sea-level rise as a result of climate change.***

Yanchep Lagoon was selected as a site that was representive of many of the beaches in southwest Western Australia. Yanchep Lagoon, like the majority of beaches in southwest Western Australia, is perched on natural limestone. The limestone structures are extremely variable alongshore, with some areas of beach not fronted directly seaward by outcropping limestone and the other areas are fronted by structures with a variety of forms including: (i) a broken, fully submerged reef chain; (ii) a continuous intertidal-reef that encloses a coastal lagoon, where the vertical elevation of the reef was at Mean Sea Level (MSL) to 0.4 m below; and (iii) a low bluff on which the dry beach is perched. Beach variability occurs over a range of spatial and temporal scales and it is crucial that processes at all of these scales be quantified and understood before any predictions under climate change scenarios can be made. In addition, to aid future planning a classification of different types of perched beaches is required which prior to this work did not exist. Therefore, the overall aims of this field work were to (1) quantify mechanisms of perched beach sediment dynamics over a cascade of temporal scales; and (2) develop a tool to classify different types of perched beaches which could ultimately be linked with vulnerability indices for coastal planning.

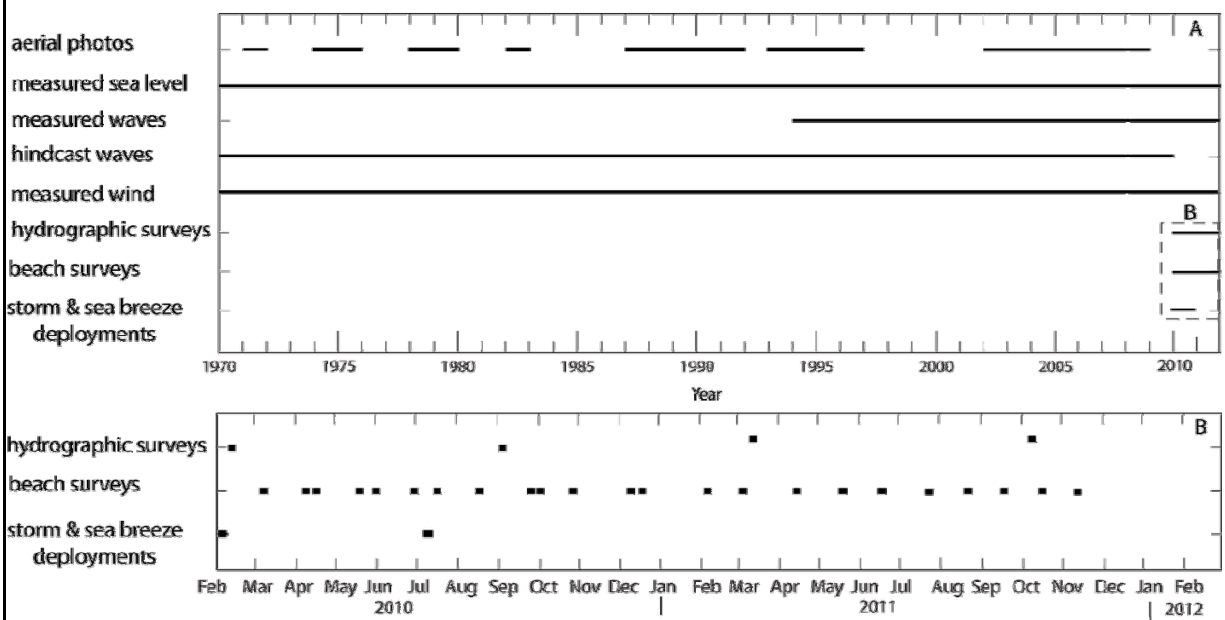

Fig. 4 Timeline of field and model data that was used to analyse field data. Note that monthly surveys will be ongoing until at least February 2012.

Project 1. - Sea breezes (meso-scale)
We hypothesized that beach profiles that were perched on rock structures would be better protected from waves and currents than profiles not fronted by rock. To test this, it was important to investigate: (1) temporal variations over the sea breeze cycle; and (2) spatial variations at different areas of the nearshore to indentify how the rock structures influence the waves and currents. Therefore, there were four main objectives of the work, to:

(1) Quantify temporal variations of waves and currents during the sea breeze cycle at locations:
  a) offshore;
  b) 20 m seaward of the limestone reef;
  c) inside the lagoon; and
  d) in the surf zone fronting the Exposed Profile and the Sheltered Profile.

(2) Quantify the response of the beach to the variation in currents and waves induced by the sea breeze cycle at an exposed beach profile and a sheltered beach profile.

Project 2. - Storms (meso-scale)
Field investigations that were undertaken at Yanchep Lagoon during the strong sea breezes in summer indicated that there was strong variation in the alongshore beach behaviour. Therefore, it was predicted that winter storms, the high degree of spatial variation in the rock geometry in the alongshore would cause a corresponding variation in the beach profile response. The main objectives of this study were to:

(1) compare the volumes of storm-driven changes on the beachface and post-storm recovery at three profiles with different local rock geometry; and

(2) develop a conceptual model to determine beach behaviour during a storm, in response to different coastal structures at Yanchep Lagoon. To address these two main objectives, intensive field investigations of one week duration were undertaken during the passage of two consecutive winter storms.

Project 3. - Seasons (macro-scale)
A comprehensive field measurement programme was implemented to quantify the monthly and seasonal variability and changes at Yanchep Lagoon. Nine profiles of the sub-aerial (dry) beach have been measured from the top of the dune to mean sea level since February 2010. In addition, hydrographic surveys out to the 10 m depth contour have been undertaken by the Department of Transport in on four occasions during winter and summer: (1) Feburary 2010; (2) September 2010; (3) March 2011; and (4) September 2011.

Project 4. - Inter-annual to Decadal (macro- to mega-scale)
Aerial photos from Landgate since 1971 until 2008 where used to investigate the inter-annual variability in beach morphology at different locations alongshore at Yanchep Lagoon. Shorelines and vegetation lines were digitised as a proxy for the lower and upper backshore limits. Beach width was calculated as the distance between the lower and upper backshore limits.

Project 5. - Development of a classification of perched beaches
A classification of the key types of topographic elements that support perched beaches was developed. This included a seperate classification for the longshore and cross-shore directions. This was necessary because field work results from above revealed that in southwest Western Australia, the natural limestone at the coast strongly influences sediment transport in both of these directions. This classification was illustrated with examples from Western Australia and was applied to the Vlamingh Region in southwest Western Australia at two spatial scales.

Project 6. - Numerical modelling of morphological changes on Yanchep beach
A numerical model was developed to simulate the sediment transport and morphological changes of Yanchep beach. The numerical model allowed the evaluation of the beach sensitivity to the various forcing.

4. Results

Present the results of the project and attainment of scientific objectives. Assess the success of meeting each objective identified in the proposal, as initially approved or later modified. For each objective: 1. Re-state the objective, 2. Tell the degree to which it has been met, and 3. Describe the technical findings and conclusion in a paragraph or two. This language should be informative, not just indicative (i.e., don't say "a new process was developed," but rather "the XYZ method increases productivity by 20 %"). A sample statement might begin, "Objective 1 -- To increase survival of juvenile...by 50%. This objective has been met. Survival of……...was increased 67% by altering culture tanks in the following way. If an objective was not 100% complete at the end of a project, indicate why.

***Objective 1:* Determine the variability and historic long-term trends in extreme still water levels (which comprise of combinations of mean sea level, astronomical tides and surges) around WA.**
Extreme still water levels (i.e. exclusive of surface gravity waves) arise as a combination of three factors: mean sea level, tide and surge. A detailed assessment of historic changes in each of these components of sea level was undertaken before changes in total water levels were examined. The key results for each component are described below.

Changes in mean sea level: There is a strong seasonal cycle in mean sea level around Western Australia which peaks in March along the northern part of the coastline and progressively later in the year moving south. Although there is variability in the amplitude and phase of this annual cycle from year to year, there is no evidence for significant systematic longer-term changes. There are considerable inter-annual fluctuations (up to 25cm) in mean sea level around the coastline of Western Australia. A large part of the variability is coherent across the region and is strong positively correlated to the Southern Oscillation Index and weakly negatively correlated to the Indian Ocean Dipole. Using annual mean sea level averages, longer-term changes in mean sea level have been assessed and compared to estimated rates of vertical land movement from a glacial isostatic model. Results show an apparent south to north gradient in the rate of mean sea level rise, with the southern site showing a rate of MSL change less than the global average and the northern sites a rise greater than the global average. MSL rose rapidly in the 1920's and 1940's and again in the 1990's, but were relative stable between 1970 and 1990. The recent high rates of rise are not unusual compared to those that occurred at other times in the 20th century.

Changes in tides: Over inter-annual time-scales, variations in high tides arise as a result of the 18.61 year lunar nodal cycle and the 8.85 year cycle of lunar perigee, the latter of which influences sea level as a quasi-4.4 year cycle. Assessment of these systematic tidal modulations allows prediction of periods when enhanced risk of coastal flooding is likely. Regions of the world's oceans where these interannual modulations make the highest contribution to high tidal levels have been identified. The spatial variations in the range and phase of the tidal modulations have been related to the distribution of the main tidal constituents and the form factor and range of the tide. Results have shown that the nodal modulation is largest (between 0.5 and 0.8 m in the 99.9th percentile tidal level) in diurnal regions with tidal ranges of >4 m, and the 4.4 year modulation is largest (between 0.3 and 0.6 m in the 99.9th percentile tidal level) in semidiurnal regions where the tidal range is >6 m (Figure 1). In areas where the form factor of the tide is >0.6, the nodal modulation dominates over the 4.4 year modulation in high tidal levels, and the phase of the nodal modulation correlates with N = 0° (i.e., maximum lunar declination). In these regions, the nodal modulation was at a maximum in 2006 and will peak again in 2024. In areas where the form factor of the tides is <0.6, the 4.4 year modulation dominates over the nodal modulation in high tidal levels. In these regions, the phase of the nodal modulation correlates with N = 180° (i.e., mini- mum lunar declination), and the nodal modulation was maximum in 1997 and will peak again in 2015. The phase of the 4.4 year modulation has also been shown to relate to the form of the tide at a given location. A comparison of the modeled results presented in this paper with the measured quasi global tide gauge data set GESLA will form the basis for future work.

Changes in surges: There are significant intra- and inter-annual variations in surge activity. Surge activity was particular high in the 1910's. From about 1915 to 1940 there was a decrease in surge activity. Between 1940 and 1970 surge activity was relatively weak. Surge activity increased slightly in the 1970s. From 1980 to about 2000, there has been a small increase in storm activity. The storm tracks associated with the 100 largest storm surge events at Fremantle between 1949 and 2008 have been digitised. Five different distinct types of events were identified. There has been an increase in the largest surge events in recent decades. The 1950's were a particularly calm period. We find no significant southward shift in the storm tracks responsible for generating large storm surges in southwest Australia over the last 60 years (Figure 2).

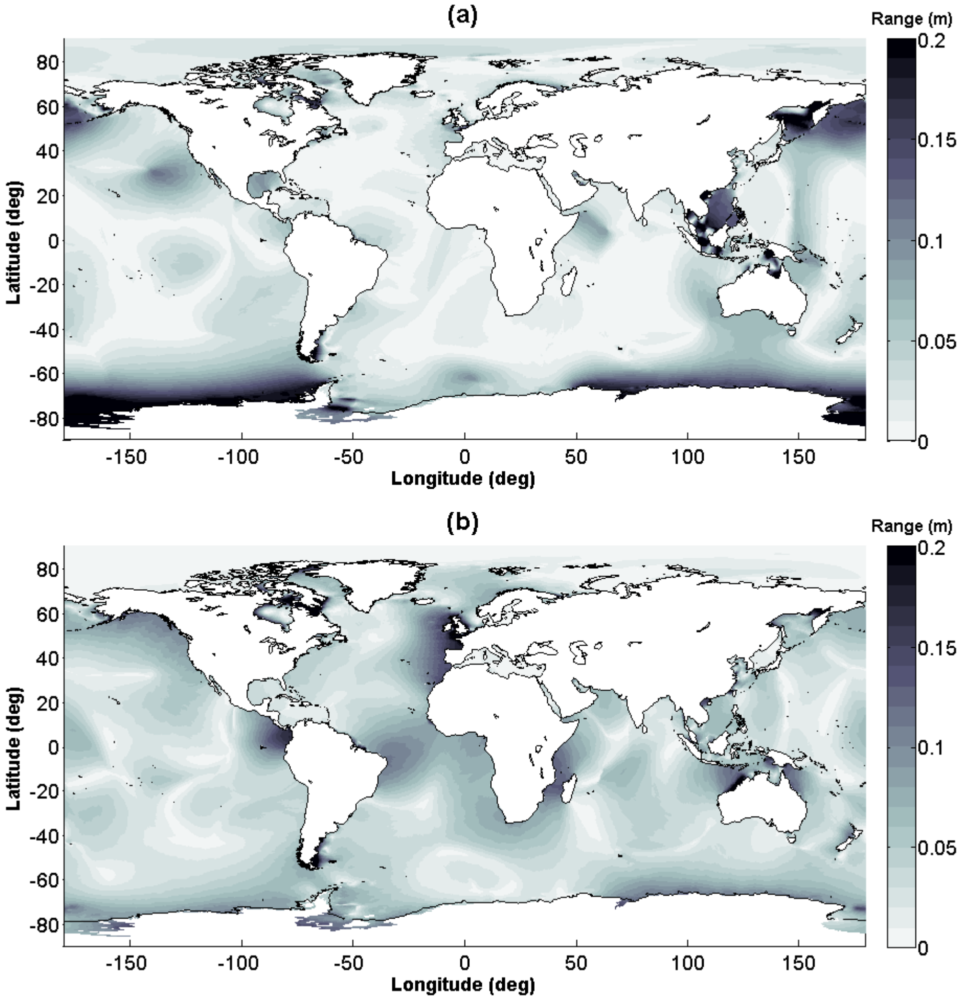

Fig. 1: (a) range of the 18.61 year modulation in the 99.9th percentile tidal level; (b) range of the 4.4 year modulation in the 99.9th percentile tidal level.

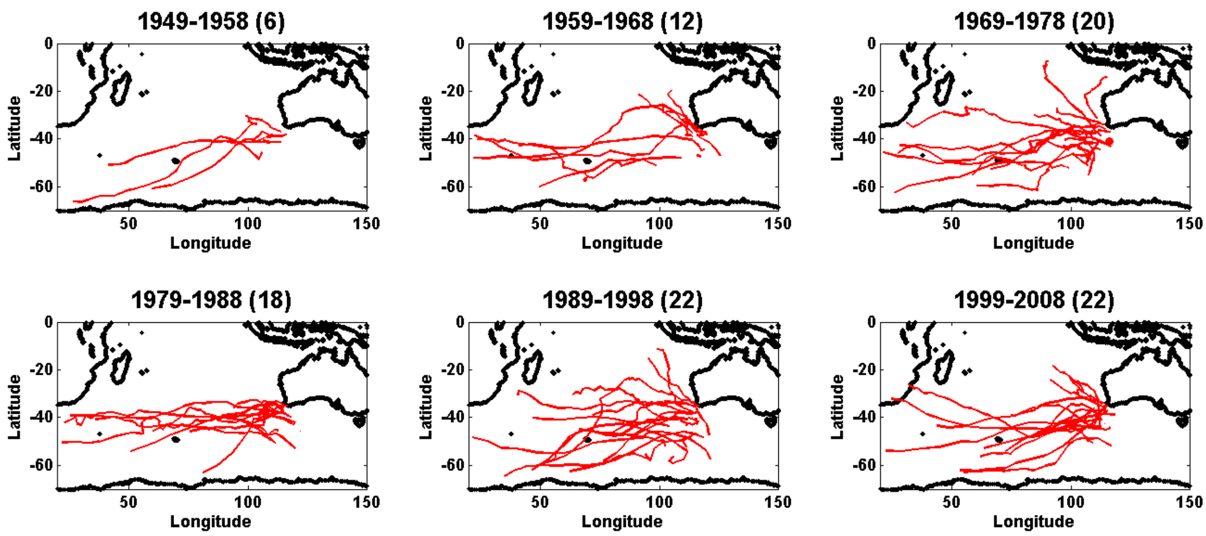

Fig. 2: Storm tracks associated with the 100 largest storm surge events between 1949 and 2008.

Objective 2: ***Determine the variability and historic long-term trends in the surface wave climate around WA.***

Quantifying the long-term variability in wave conditions incident on a coastline is critical for predicting its resilience to future changes in the wave climate. In this study, a 40 year wave hindcast of the southern Indian Ocean has been created to assess the inter-annual variability and longer-term changes in the wave climate around Western Australia (WA) between 1970 and 2009. The model was validated against measurements from five wave buoys located along the WA coast. Changes in the mean annual significant wave height, 90th percentile wave height, peak period and mean wave direction were assessed and the tracks of all wave events generating wave heights above 7m were digitised and analysed for significant changes. Results show strong annual and inter-annual variability in the mean significant wave height, the 90th percentile wave height and the number of large events (wave height>7m) that impact the WA coastline. A significant positive trend in annual mean wave height was found in the southwest region of WA over the 40 year simulation. This appears to be due to an increase in intensity of the storm belt in the Southern Ocean which is associated with an increasing positive polarity in the Southern Annular Mode. However, no significant trends were found in the 90th percentile wave height or the number of large wave events impacting Western Australia. Although the number of large wave events in the southern Indian Ocean have increased, their potential to impact the coastal regions of Western Australia are reduced due to storm tracks being located further south, therefore balancing the number of large wave events reaching the WA coast.

Objective 3: ***An assessment of the potential future changes to extreme still water levels (in particular storm surge magnitude and frequency) under different climate scenarios.***

The mean sea level offset method has been used with sea-level rise projections from the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4), to provide a first order estimate of possible future changes in extreme sea level every decade from 1990 to 2100 around the coast of WA. The MSL offset method predicts future extreme sea levels by simply adding projections of MSL to current return levels estimated using measured (or modeled) sea levels. For the low end of the IPCC's AR4 range (~20 cm sea level rise between 1990 and 2100), the level associated with a 100 year event in 1900 is predicted to occur about every 2 to 3 years by 2100 between Eucla and Albany, about a 50 fold increase in exceedance frequency. Between Albany and Bunbury, on the southwest corner of WA, the change in the recurrence interval becomes less dramatic. The level in 1990 associated with a 100 year event is predicted to occur about every 10 years by 2100, a 10 fold increase in exceedance frequency. Between Jurien Bay and Geraldton, there is a 100 fold increase in exceedance frequency. These results illustrate the dramatic changes in recurrence intervals of extreme high sea levels that can occur due simply to a small change in MSL and highlight the considerable spatial variation in the change around the coastline. For the upper end of the IPCC's AR4 range (~80 cm sea level rise between 1990 and 2100), the pattern of change around the coastline is similar to the lower projection, but the increase in exceedance frequency is significantly more pronounced. Between Eucla and Albany, the level associated with a 100 year event in 1990 is predicted to occur about every 2 to 3 years by 2050 (i.e. 50 years earlier than the lower projection). By 2100, the level associated with the 100 year event in 1990, is likely to occur at least once every spring/neap tidal cycle by 2100 along almost the entire southwest stretch of WA coastline (i.e. more than a 2,500 fold increase in exceedance frequency).

A more detailed assessment of future changes in storm surges was undertaken by driving the tide-surge model, described above, with meteorological fields from global climate models. The tide/surge model for Australia was forced using the bias corrected wind and pressure fields for the period 1981-2000 and 2081-2100 for the high emission SRES A2 scenario. No significant changes in storm surges were identified. Therefore extreme sea levels are likely to increase in the future, but the increase will be driven by changes in mean sea level and not storminess.

This study has also assessed the vulnerability of the Peel Harvey Estuary in Western Australia to coastal flooding for different magnitudes of extreme high sea level events under present conditions and for a range of possible future sea- level rise scenarios (Figure 3). With a sea-level rise of 1 m, or greater, several densely populated areas could experience regular coastal flooding. Farmland within the floodplains to the east of the Estuary will become increasingly vulnerable to coastal flooding as sea-levels rise. For extreme events, with annual recurrence intervals greater than 100 years, highly populated areas with substantial infrastructure will also become more vulnerable. Channel estates around the Mandurah Channel and the Murray River would experience flooding during large events, with a sea level rise of 0.5 m. However, as sea-level rise increases, these areas would be regularly flooded, along with other populated areas. Several large highways are likely to be affected by flooding for sea-level rise between 1.0 m and 1.5 m, even with relatively small events (1 in 1 and 1 in 10 year recurrence levels). Practical implications for this research are specific for the Peel-Harvey region, and can provide coastal planners with coastal flooding information and forecasts. These findings highlight the significant challenges that are likely to be faced by the flood risk management and engineering community over the 21st century in the Peel Harvey Estuary and by implication, widely around the world's coasts.

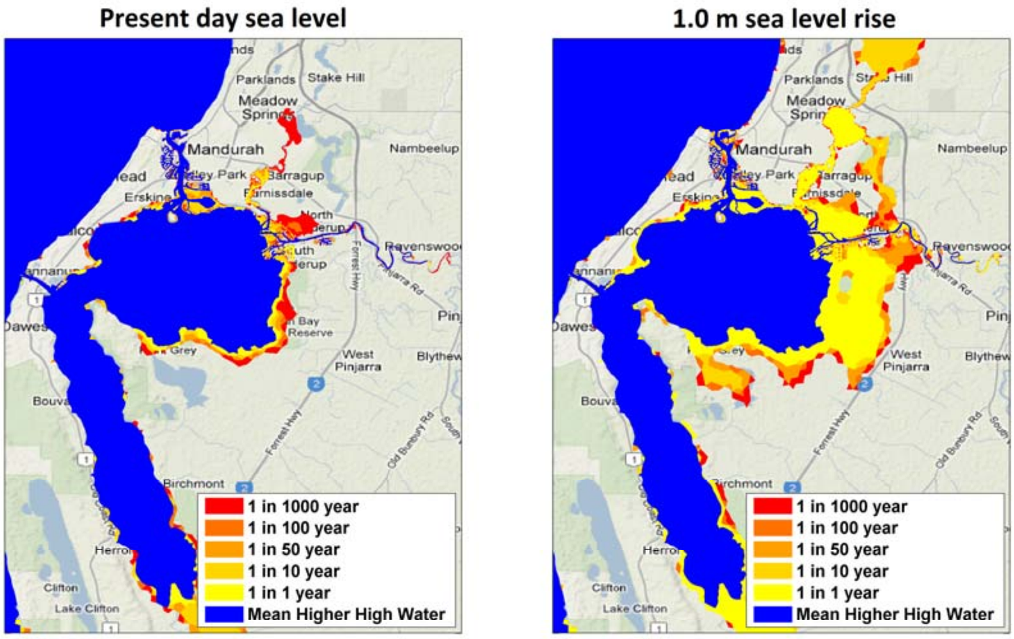

Fig. 3: Inundation around the Peel Harvey estuary for various return levels under present day and a 1.0m sea level rise.

Objective 4: ***An assessment of the potential future changes to the surface wave field under different climate scenarios.***

High resolution wind forcing is necessary to simulate wave growth and evolution on the scale of the Indian Ocean. Such wind information is available for generating a wave hindcast but is not yet available at a suitable resolution for climate change wave forecasts. However the behaviour of the wave climate and its relationship with climate indices can be used to predict future changes under different climate scenarios. Results from objective 2 showed positive trends in the annual mean, 90th and 99th percentile significant wave height, as well as in the wave peak period in the southern Ocean and positive trends in the annual mean significant wave height and peak wave period offshore of Western Australia. These trends were linked to the increase in positive polarity of the southern Annular mode. Global climate models show that the Southern Annular Mode index is likely to continue to increase at similar rate under the various climate scenarios. Therefore, it is likely that the rate of change in wave climate will remain steady. Offshore of Western Australia this corresponds to an increase of 0.2m in the annual mean wave height over the next 50 years and no significant changes in the extreme wave height. However, on the coast of Western Australia, sea level rise will reduce the capacity of offshore reefs to dissipate wave energy and lead to greater changes to the wave climate.

Objective 5: ***An assessment coastal stability at selected regions along the WA coast resulting under the combined effects of altered wave fields and storm surges and sea-level rise as a result of climate change.***

The results of this part of the study have revealed the following with regards to the beach variability and changes at Yanchep Lagoon:

- In the long term (over the past 40 years), the beach width at Yanchep Lagoon appears to be decreasing at a rate of 0.30 m yr^{-1} (11 m since 1971).
- Exposed areas of the beach (i.e. areas not fronted seaward by natural limestone structures) appear to be more prone to storm erosion. The limestone structures at Yanchep Lagoon appear

to provide a degree of beach and dune protection by attenuating waves and hence limiting the erosion potential.

- In the short-term (seasonal variation), field measurements of beach profiles in the study region indicated that the dune from the top to the toe has been stable over the past 21 months. The exception to this dune stability was at the North Walkway profile which was most likely mostly due to work undertaken at the walkway which involved sand being moved. The seasonal variability in the lower beach profile at Yanchep Lagoon (North Walkway) varied by 20 m in the horizontal and by 3 m in the vertical.
- The 100 year ARI water level was defined as 1.14 m AHD whilst the 100 year extreme wave height ARI offshore of Yanchep was estimated to be 7.44 m. The numerical model predicted that the nearshore wave height, offshore of the reef was reduced due to the presence of offshore limestone ridges dissipating almost 75% of the offshore wave height. The 100 year ARI inside the lagoon was 0.6 m and represented a 92.5% decrease compared to the offshore wave height.
- The morphological model indicated that the 100 year ARI event resulted erosion of the dry beach with the amount of erosion proportional to the availability of sand and exposure to waves. However, the model also indicated that majority of the sand eroded from the dry beach was deposited offshore. The model predicted that the dune behind the lagoon receded by 10 m as a result of the 100 year ARI.
- The morphological model XBEACH was used to examine the beach response due to a 0.5 and 1 m increases in mean sea level to examine the beach profiles under climate change. These values represent the most likely scenarios in 2050 and 2100, respectively. The model predicted that, behind the lagoon, the beach receded 20 m for both mean sea level rise scenarios of 0.5m and 1m, respectively. Thus, the beach response, inside the lagoon at Yanchep, as a result of mean sea level rise climate scenarios for a 100 year ARI was less than that observed due to long term variation at the same location.
- The results of the study indicated that the shoreline processes at Yanchep lagoon are such that the offshore wave heights are considerably reduced at the beach resulting in relatively small changes on the beach.

5. Discussion

Implications for Management and Advancement of the Field – Describe the key findings as they relate to the objectives and the management questions discussed at the outset of the project.

The overall key management questions addressed in project 6.1 was: How do we manage current facilities and optimise the design of future facilities in West Australian coastal waters under the influence of climate change?

The results of this project have showed the importance of using combinations of field experiments and numerical modelling to improve understanding of the key processes influencing coastal stability around Western Australia. No single model can be used to predict future changes in coastal erosion, instead different models covering multiple temporal and spatial scales needed to be used in combination to address the study objectives.

The broader scale tide/surge and wave modelling results cover the entire coast of WA. In regards to coastal stability we focused on Yanchep for the coastal scale. However, coastal managers all around Western Australia could use these broader-scale results in the future. In addition, while the coastal-scale results are somewhat site-specific to Yanchep Lagoon, the approach that we used could be applied to any section of coast. Further, research at Yanchep Lagoon was process-based and the mechanisms that we found about how different rock formations influence the beach behaviour can be applied to much of Western Australia on perched rock and coral reef.

The classification that was developed of the topographic elements that support perched beaches showed the complex variety of types of perched beaches. The application to southwest Western Australia showed that 80% of the tertiary compartments (as defined by Eliot et al., 2011) of the Vlamingh Region are dominated by perched beaches. In addition, even in small sections of coast, there can be a wide range of types of perched beaches. Our results show that the behaviour of perched beaches is spatially complex, however in the future with more investigations into perched beach behaviour this classification could ultimately be linked to indices of vulnerability.

Reference

Eliot, I., Nutt, C., Gozzard, B., Higgins, M., Buckley, E., Bowyer, J., 2011. Coastal compartments of Western Australia: A physical framework for marine and coastal planning. Report to the Departments of Environment and Conservation, Planning and Transport. Damara WA Pty Ltd, Geological Survey of Western Australia and Department of Environment and Conservation, Western Australia.

Problems encountered (if any) – Describe any major problems/issues encountered during the study and how they were addressed.

A large component of this study was originally based around obtaining future atmospheric climate variables from the Northwest Australian Climate Change Study (NACCS), an initiative of Woodside Energy Ltd. It was planned that output from the NACCS study would be used to predict climate change scenarios for winds, waves and sea level changes at regional scales for Western Australian coastal areas, particularly along the south-west and subsequently the beach response. However, the NACCS database was not supplied. Despite this a considerable amount of work has been undertaken in the project and another suitable future climate database was identified. Hence, the project objectives were redefined in light of this.

New Research Directions (if any) – Identify new research directions pursued during the course of the project and reasons for modifying original research plans. Describe how the changed research agenda improved the project.

The focus of this study was on Western Australia. However, in many cases work was undertaken over bigger spatial scales. For example, the Australian Department of Climate Change and Energy Efficiency, in partnership with the Antarctic Climate and Ecosystems Cooperative Research Centre, asked if we could extend the tide-surge modelling to the whole of Australia and use this to map current extreme sea level annual recurrence intervals around the coastline. The methodology used to examine inter-annual modulations in astronomical tide level around Western Australia, proved successful and efficient and so was used to map spatial variations in tides on a global scale.

6. Overall Project Accomplishments

Students supported – Record the name of each student involved with the project. Indicate whether PhD or other (give details) and briefly describe their role.
Cyprien Bosserelle (PhD) Organised field programs and undertook field deployments. Created a 40 year hindcast of wave climate in the southern Indian Ocean. Analysed the wave climate. Create a morphological numerical model of Yanchep Beach and evaluate the sensitivity of the beach to climate change. Shari Gallop (PhD) Organised field programs, undertook field deployments and analysed field data. In addition, developed a classification of types of perched beaches. Leigh McPherson (Honours) Identified coastal inundation around the Peel Harvey Estuary resulting from potential future changes to extreme still water levels. Ian McMullen (Honours) Identified coastal inundation around the Swan Estuary resulting from potential future changes to extreme still water levels.
PhD theses, Dissertations and Student Placement – Please give complete citation for theses and dissertations (student's name, month and year completed or expected, level of degree, institution). Please provide a copy of the abstract of the thesis or dissertation when complete.
PhD theses: ● Cyprien Boserrelle (plan to submit in 2012) - Hydrodynamic and sediment transport on perched beaches in Western Australia ● Shari Gallop (plan to submit in 2012) - The complex topography of natural rock structures influence the behaviour of perched beaches over a cascade of temporal scales Honours theses: ● Leigh McPherson (submitted 2011) - Coastal flooding in the Peel Harvey Estuary and the effects of sea level rise. ● Ian McMullen (plan to submit in 2012) - Coastal flooding in the Peel Harvey Estuary.
Publications - List in standard academic format the citations of literature produced during the reporting period. Include journal articles, book chapters, reports, etc. submitted, in press and printed. Please provide a paper and electronic version copy of each publication resulting from the project. If there is a link to the journal electronically, please also include this.
Refereed Journal Papers **Published, In Press and Accepted** Haigh, I.D., Eliot, M., Pattiaratchi, C., 2011. Global influences of the 18.61 year nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels, J. Geophys. Res., 116, C06025, doi:10.1029/2010JC006645. Bosserelle, C., Pattiaratchi, C., Haigh, I.D., 2012. Inter-annual variability and longer-term changes in the wave climate of Western Australia between 1970 and 2009. Accepted to *Ocean Dynamics* in Aug 2011. Gallop, S.L., Bosserelle, C., Pattiaratchi, C.B., Eliot, I., 2011. Hydrodynamic and morphological response of a perched beach during sea breeze. Proceedings of the 11th International Coastal Symposium ICS

2009, Szczecin, Poland. Journal of Coastal Research, Special Issue 64, pp. 75–79.

Gallop, S. L., Bosserelle, C., Pattiaratchi, C., & Eliot, I., 2011. Rock topography causes spatial variation in the wave, current and beach response to sea breeze activity. Marine Geology, 290, 29–40.

Gallop, S.L., Verspecht, F., Pattiaratchi, C. 2012. Sea breezes drive currents on the inner continental shelf off southwest Western Australia. Ocean Dynamics. (in press).

In Review

Bosserelle, C., Gallop, S., Haigh, I.D., Pattiaratchi, C., in review. Numerical modelling over multiple scales resolves the coastal sediment transport around complex reefs. Submitted to Ocean Dynamics Dec 2011.

Gallop, S.L., Bosserelle, C., Pattiaratchi, C., Eliot, I., in review. Natural coastal structures protect beaches during storms but inhibit recovery. Submitted to Coastal Engineering Dec 2011.

In Prep

Haigh, I.D., Pattiaratchi, C., Wahl, T., Price, R.M., in prep. Timescales for detecting a significant acceleration in sea-level rise. Plan to submit to Geophysical Research Letters.

MacPherson, L.R., Haigh, I.D., Ryson, M., Crompton, R., Hunter, J., Pattiaratchi, C., in prep. Estimating extreme water level exceedance probabilities around the coastline of Australia arising from tropical cyclones. Plan to submit to Continental Shelf Research.

Haigh, I.D., Wijeratne, E.M.S., Hunter, J., Pattiaratchi, C., in prep. Estimating extreme water level exceedance probabilities around the coastline of Australia using a 40-year (1970 to 2009) sea level hindcast. Plan to submit to Continental Shelf Research.

Haigh, I.D., Eliot, M., Pattiaratchi, C., in prep. Inter-annual and longer-term changes in mean sea level around Western Australia: 1897-2009. Plan to submit to *Continental Shelf Research*.

Haigh, I.D., Eliot, M., Pattiaratchi, C., in prep. Changes in the storm surge climate of southwest Australia. Plan to submit to *Ocean Dynamics*.

Pattiaratchi, C., Eliot, M., Haigh, I.D., Wijeratne, E.M.S., in prep. Physical processes controlling tidal and non-tidal sea level variability in Western Australia. Plan to submit to Progress in Oceanography or Continental Shelf Research.

Gallop, S.L., Eliot, I., Gozzard, B., Da Silva, C., Green, S., Stul, T., Eliot, M., Pattiaratchi, C., in prep. A classification of geological structures that support perched beaches and application in Western Australia. Plan to submit to *Marine Geology.* (full draft)

Gallop, S., Haigh, I.D., Bosserelle, C., Pattiaratchi, C., Eliot, I., in prep. Inter-annual perched beach behaviour and sensitivity to variability in waves, tides, storm surges and mean sea level. Plan to submit to Continental Shelf Research.

Refereed Conference Papers

Haigh, I.D., Pattiaratchi, C., 2010. 21st century changes in extreme sea levels around Western Australia. Proceedings of the 17th National Australian Meteorological & Oceanographic Society Conference, Canberra, Australia.

Haigh, I.D., Eliot, M., Pattiaratchi, C., 2011. Regional changes in mean sea level around Western Australia between 1897 and 2008. Proceedings of Australasian Coasts and Ports Conference, Perth, Australia (28-30 Sep 2010).

MacPherson, L.R., Haigh, I.D., Pattiaratchi, C., 2011. Coastal flooding in the Peel Harvey Estuary and the effects of mean sea level rise. Coasts and Ports Conference, Perth, Australia (28-30 Sep 2011).

Bosserelle, C., Haigh, I.D., Pattiaratchi, C., Gallop, S., 2011 Simulation of perched beach accretion using Smoothed Particle Hydrodynamics. Coasts and Ports Conference, Perth, Australia (28-30 Sep 2011).

Gallop, S.L., Bosserelle, C., Pattiaratchi, C., Eliot, I., 2011. Form and function of natural and engineered perched beaches. Proceedings of Australasian Coasts and Ports Conference, 28−30 September, Perth, Australia. (In press).

Presentations - Cite any presentations resulting from the project, including conferences, symposiums, etc.

International and National Conference Presentations

Invited keynote plenary presentations:

Pattiaratchi CB. 2011. Long-term variability in met-ocean conditions in Western Australia. *Coasts and Ports conference*, Perth, 28–30 September 2011.

Pattiaratchi CB. 2010. Climate change effects on coastal processes. *Ninth international conference on coasts, ports and marine structures (ICOPMAS)*, Tehran, 29 November–1 December.

Pattiaratchi CB. 2008. Sea level variability: from hours to decades. *Eighth international conference on coasts, ports and marine structures (ICOPMAS)*, Tehran, 24–26 November.

Pattiaratchi CB. 2008. Sea level variability. *Seventh Universiti Malaysia Terengganu international symposium on sustainability science and management (UMTAS)*, Kuala Terengganu, Malaysia, 8–10 June.

Presentations and seminars

Pattiaratchi CB. 2011. Sea level rise: implications for local government sector in Perth's eastern region. EMRC climate change forum, Perth.

Pattiaratchi CB. 2010. Storm surge climatology for Western Australia. Storm surge workshop, Brisbane.

Pattiaratchi CB. 2010. The science of sea-level rise: Perth to Cape Naturaliste region. City to cape sea-level rise seminar, Perth.

Pattiaratchi CB. 2010. Observations and modelling of waves along the south-west WA coast. Australian wind–waves symposium, Gold Coast.

Pattiaratchi CB. 2010. Long-term sea level variability and coastal flooding. WAMSI node 2 symposium, CSIRO, Perth.

Pattiaratchi CB. 2010. Sea level variability. GODAE international summer school for observing, assimilating and forecasting the ocean, Perth.

Pattiaratchi CB. 2009. Impacts of climate change on Fremantle. Adapting to climate change in coastal Fremantle: a deliberative symposium, Perth.

Pattiaratchi CB. 2009. Predicted change in climate systems. Environmental Consultants Association, Perth.

Pattiaratchi CB. 2009. Climate change impacts on coastal systems in Western Australia. 'A changing climate: Western Australia in focus', WAMSI symposium, Perth.

Haigh, I.D., Pattiaratchi, C., 2010. 21st century changes in extreme sea levels around Western Australia. 17th National Australian Meteorological & Oceanographic Society Conference, Canberra, Australia.

Haigh, I.D., Eliot, M., Pattiaratchi, 2010. Historic changes in storm surges around southwest Australia. Physics of estuaries and coastal seas *conference*, Colombo, Sri Lanka.

Haigh, I.D., Eliot, M., Pattiaratchi, 2011. Global influences of the 18.61 year lunar nodal cycle and 8.85 year cycle of lunar perigee on coastal flooding. EGU General *Assembly*, Vienna, Austria.

Haigh, I.D., Eliot, M., Pattiaratchi, C., 2011. Regional changes in mean sea level around Western Australia between 1897 and 2008. Coasts and Ports Conference, Perth, Australia (28-30 Sep 2010).

MacPherson, L.R., Haigh, I.D., Pattiaratchi, C., 2011. Coastal flooding in the Peel Harvey Estuary and the effects of mean sea level rise. Coasts and Ports Conference, Perth, Australia (28-30 Sep 2010).

Haigh, I.D., Eliot, M., Pattiaratchi, 2011. Storm surge climatology and sea level variability for Western Australia. Western Australian Marine Science Institution Conference, 19-20 September, Fremantle, Australia.

Haigh, I.D., Wijeratne, E.M.S., Hunter, J., Pattiaratchi, C., 2011. Estimating extreme water level exceedance probabilities around the coastline of Australia. Third Australian National Network in Marine Science Conference, 29 Nov-1Dec, Perth, Australia

Bosserelle C., Pattiaratchi, C., Haigh, I.D., 2009 The potential effect of climate change on perched beaches. ANNIMS (Australian National Network in Marine Science) Inaugural Conference, 1−2 December, Hobart, Tasmania, Australia.

Bosserelle C., Pattiaratchi, C., Haigh, I.D., 2010 Modelling long term wave climate in the Eastern Indian Ocean. Physics of Estuaries and Coastal Seas Conference, 14−17 September, Colombo, Sri Lanka.

Bosserelle, C., Gallop, S.L., Pattiaratchi, C., Haigh, I.D., 2010 Modelling the hydrodynamics of a summer storm at Yanchep beach. ANNiMS (Australian National Network in Marine Science) Inaugural Conference, 21−22 July, Townsville, Australia.

Bosserelle C., Pattiaratchi, C., Haigh, I.D., 2011 Inter-annual variability and longer term changes in the wave climate of Western Australia between 1970 and 2009. Australian Marine Sciences Association (AMSA) Conference, 3−7 July, Fremantle, Australia.

Bosserelle, C., Haigh, I.D., Pattiaratchi, C., Gallop, S.L., 2011 Simulation of perched beach accretion using Smoothed Particle Hydrodynamics. Coasts and Ports Conference, Perth, Australia (28-30 Sep 2010)

Bosserelle, C., Pattiaratchi, C., Haigh, I.D., 2011 Simulation of perched beach accretion using Smoothed Particle Hydrodynamics. Coasts and Ports Conference, Perth, Australia (28-30 Sep 2010)

Bosserelle, C., Gallop, S., Pattiaratchi, C., Haigh, I., 2011. Evolution of an extreme wave event from the ocean to the beach. Western Australian Marine Science Institution Conference, 19-20 September, Fremantle, Australia.

Bosserelle, C., Gallop, S., Pattiaratchi, C., Haigh, I., 2011. Simulation of perched beach accretion using smoothed particle hydrodynamics. Third Australian National Network in Marine Science Conference, 29 November -1 December, Perth, Australia.

Gallop, S.L. and Pattiaratchi, C., 2009. Wave-induced sediment transport and morphodynamics on a perched beach. ANNIMS (Australian National Network in Marine Science) Inaugural Conference, 1−2 December, Hobart, Tasmania, Australia.

Gallop, S.L., Bosserelle, C., and Pattiaratchi, C., 2010. Current response to sea breezes in south Western Australia. Physics of Estuaries and Coastal Seas Conference, 14−17 September, Colombo, Sri Lanka.

Gallop, S.L, Bosserelle, C. and Pattiaratchi, C. Hydrodynamic and morphological response of a perched beach during sea breeze., 2010. ANNiMS (Australian National Network in Marine Science) Inaugural Conference, 21−22 July, Townsville, Australia.

Gallop, S.L., Verspecht, F. and Pattiaratchi, C., 2011. The vertical current structure in response to sea breezes in south Western Australia. Australian Marine Sciences Association (AMSA) Conference, 3−7 July, Fremantle, Australia.

Gallop, S.L., Bosserelle, C., Pattiaratchi, C., Eliot, I., 2011. Form and function of natural and engineered perched beaches. Australasian Coasts and Ports Conference, 28−30 September, Perth, Australia.

Gallop, S.L., Bosserelle, C., Pattiaratchi, C.B., Eliot, I., 2011. Hydrodynamic and morphological response of a perched beach during sea breeze. Proceedings of the 11th International Coastal Symposium ICS 2009, Szczecin, Poland. Journal of Coastal Research, Special Issue 64, pp. 75–79.

Gallop, S.L., Bosserelle, C., Pattiaratchi, C.B., Eliot, I., 2011. Perched beach morphodynamics: sea breezes, storms and seasons. Western Australian Marine Science Institution Conference, 19-20 September, Fremantle, Australia.

Gallop, S.L., Bosserelle, C., Eliot, I., Pattiaratchi, C.B., 2011.Natural coastal structures provide storm protection but inhibit beach recovery. Third Australian National Network in Marine Science Conference, 29 November -1 December, Perth, Australia.

Gallop, S.L., Bosserelle, C., Pattiaratchi, C.B., Eliot, I., 2011.Natural coastal structures provide storm protection but inhibit beach recovery. Royal Society of Western Australia 13th Annual Postgraduate Symposium, 17 September, Perth, Australia.

Workshop Presentations and Invited Seminars

Haigh, I.D., 2009: Numerical modelling of storm surges in southwest Australia. Western Australia Marine Science Institute node 6 *symposium*, Perth, Australia.

Haigh, I.D., 2010: Changes in extreme sea levels around Western Australia: 1900 to 2100. Western Australia Marine Science Institute node 2 *symposium*, Perth, Australia.

Haigh, I.D., 2010: Characteristics of sea level around Western Australia. *Invited seminar* Bureau of Meteorology, Perth, Australia.

Haigh, I.D., 2010: Changes in sea levels around Western Australia. *Invited seminar* National Oceanography Centre, Liverpool, U.K.

Haigh, I.D., 2010: Down with sea level rise: past, present and future changes in sea level around Western Australia. *Invited seminar* National Oceanography Centre, Southampton, U.K.

Haigh, I.D., 2010: Changes in sea levels around Western Australia. *Workshop* of climate and weather extremes, Perth, Australia.

Haigh, I.D., 2010: Tide/surge modelling around Western Australia. National storm/tide modelling *workshop*, Melbourne, Australia.

Haigh, I.D., 2010. Influences of the 18.61 year lunar nodal cycle and 8.85 year cycle of lunar perigee on high tidal levels. Western Australia Marine Science Institute young career researchers' *symposium*, Perth, Australia.

Haigh, I.D. 2011. Extreme sea levels and waves around Australia. *Invited seminar* for Commonwealth Scientific and Industrial Research Organisation, Hobart, Australia.

Haigh, I.D., 2001. Climate and oceanographic modelling: Shark Bay. Workshop comparative ecosystems studies: Shark Bay and southern Florida, Perth, Australia

Bosserelle, C., Gallop, S.L., Pattiaratchi, C., Haigh, I.D., 2010. Hydrodynamics and sediment transport around Yanchep lagoon. Applied Sediment Dynamics Masterclass by Michael Collins, Perth, Australia.

Bosserelle, C., Pattiaratchi, C., Haigh, I.D., 2010. Modelling long term wave climate in the eastern Indian Ocean. Western Australian Marine Science Institution (WAMSI) Marine Science Symposium: Young Career Researchers, 3 November, Perth, Australia.

Bosserelle, C., Pattiaratchi, C., Haigh, I.D., 2011. Wave climatology of the southern Indian Ocean. Western Australian Marine Science Institution (WAMSI) Node 6 Symposium, 29 November, Perth, Australia.

Bosserelle, C., Pattiaratchi, C., Haigh, I.D., 2011. Wave climatology of the Southern Indian Ocean. *Invited seminar* for Commonwealth Scientific and Industrial Research Organisation, Hobart, Australia.

Bosserelle, C., Pattiaratchi, C., Haigh, I.D., 2011 Variability and longer-term changes in the wave climate of the Southern Indian Ocean between 1970 and 2009. 12th international workshop on wave hindcasting and forecasting. Waikaloa Village Hawai'i

Gallop, S.L., Pattiaratchi, C., Bosserelle, C. and Eliot, I., 2010. Perched beach morphodynamics: Sea breeze, storms and seasons. Applied Sediment Dynamics Masterclass by Michael Collins, Perth, Australia.

Gallop, S.L., Pattiaratchi, C., Bosserelle, C. and Eliot, I., 2010. Perched beach morphodynamics: Sea breeze, storms and seasons. Western Australian Marine Science Institution (WAMSI) Node 6 Symposium, 29 November, Perth, Australia.

Gallop, S.L., Pattiaratchi, C., Bosserelle, C. and Eliot, I., 2010. Perched beach morphodynamics: Sea breeze, storms and seasons. Western Australian Marine Science Institution (WAMSI) Marine Science Symposium: Young Career Researchers, 3 November, Perth, Australia.

Gallop, S.L., Bosserelle, C., Pattiaratchi, C. and Eliot, I., 2011. Sea breeze impacts on the nearshore, surf-zone and perched beach behaviour. Joint seminar – NOCS Physical Oceanography and Climate Seminars/ Coastal Seminar Series. May 27, National Oceanography Centre, Southampton, UK.

Gallop, S.L., Bosserelle, C., Pattiaratchi, C. and Eliot, I., 2011. Perched beach morphodynamics – geological beach control at different temporal and spatial scales. *Invited seminar* for Department of Transport, Fremantle, Australia.

Other Communications Achievements - Interviews, press releases, etc.

Many newspaper articles on climate change impacts on beaches and effects of sea level rise in Western Australia.

Knock on opportunities created as a result of this project – new grants, top up funding, new opportunities, new staff and on-going opportunities as a result of this project.

2010 21st century changes in extreme sea levels around Australia and the UK (Research Collaboration Awards, University of Western Australia)

2010 Storm surge inundation modelling; a comparison of Mike 21 and ANUGA (Goescience Australia)

2010-11 Sea level exceedence probabilities for Australia – Stage 1 (The Antarctic Climate and Ecosystems Cooperate Research Centre)

2011 Storm surge propagation and coastal flooding in the Peel Harvey Estuary (Research Development Awards, University of Western Australia)

2011 Travel to Europe to present research findings at a conference, write two collaborative papers and do a coastal modelling course (Grants for Research Student Training, University of Western Australia)

2011 Long-term changes in perched beach morphology and response to climate change in Australia and the UK (Research Collaboration Awards, University of Western Australia)

2011 Investigate how rocky structures on beaches can protect and/ or make coasts more vulnerable to climate change over a range of spatial and temporal scales (BankWest Postgraduate Research Travel Award)

2011-12 Comparing changes in extreme sea level; Australia and Northern Europe (Group of Eight DAAD German Research Cooperation)

2011-12 Caring for Country: Shark Bay – Effects of rising water levels on the Faure Sill and Stromatolites (Western Australia Marine Science Institute)

2011-12 Sea level exceedance probabilities for Australia with cyclones – Stage 2 (The Antarctic Climate and Ecosystems Cooperate Research Centre and Australian Department of Climate Change and Energy Efficiency)

2011-12 Sea level exceedance probabilities for Australia with cyclones – Stage 3 (Western Australian Department of Transport)

7. Implications for Science and Future Science: Please note: Implications go beyond Results and Accomplishments to provide information on direct physical, environmental, economic or social gains realised as a result of a research project or outreach activity.

Discovery and Application of New Products and Processes (if applicable) - Describe any actual or anticipated products or processes discovered or developed in the project.
Chari ?
Tools, Technologies and Information for Improved Ecosystem Management - Describe how project results are being (or will be) translated into sustainable use and management of coastal and ocean ecosystems. Tools might include benthic habitat maps or environmental sensitivity indicators. Technologies might include remote and bio-sensing, genetic markers, and culture systems. Information might include technical assistance, training and educational materials.
Chari ?
Forecasting for Natural Resource Management Decisions - Describe how results already are being used - or are expected to be used after project completion - by natural resource management to make decisions based on project forecasts. Forecasts may be due to field and laboratory studies and models. Examples include hypoxia forecast models, algal bloom alerts, forecasts of fishery harvest, and prediction of impacts from ecosystem stressors such as pollutants or invasive species.
The results from this study are current being used by the Western Australian Department of Transport and Planning for various development and planning applications.
Impacts - Impacts are higher order, usually long-term results of a project's activities that have significant scientific, economic or social benefits. Impacts may involve behavioural, policy or economic changes. Describe impacts (anticipated or realized. These impacts may involve behavioural, policy or economic changes. Seminal contributions to science are considered impacts especially if the research findings lead to major progress in a particular field, implementation of new technologies or have a substantive bearing on an economic or societal issue.
Chari ?

8. Project Metadata and Data Generated

These must be available at an open access repository/data centre/iVEC.
Project 6.1 metadata are available on iVEC:

9. Linkages to Associated Projects – can be WAMSI and non-WAMSI

10. Other Comments and General Discussion

11. Annexures

- pdfs of all journal and conference papers