

DETAILED ASSESSMENT OF EXTREME COASTAL EROSION AND STORM SURGE VULNERABILITY OF CENTRAL GOLD COAST BEACHES

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ABSTRACT

The Gold Coast's beaches have achieved iconic status worldwide with residents nearing 40 million trips to the foreshore annually and tourists an additional 7 million. The littoral environment is described as high-energy open coast, regularly subjected to storms and large waves (H_{\max} of 14 m, 2004) with a net annual sediment transport rate of approximately 500,000 m³. This system is found to be in long-term equilibrium with the major impact coming from the cross-shore movement of sand during large events such as cyclone, where large seas and storm surge prevail.

Urban development has seen the beaches, creeks and river entrances of the coast modified to provide the necessary coastal protection, community, economic and environmental services to sustain the city. In 2005, Gold Coast City Council (GCCC) commenced a Shoreline Management Plan (GCSMP) to review the social, environmental and economic processes that impact the way the city's beaches are managed. The major outcome of the review is the development of a new shoreline management plan to guide coastal works for the next 50 years.

DHI Water and Environment were commissioned to implement a high resolution numerical model to provide outputs for possible control systems or structure design in the vicinity of Palm Beach - the least resilient of the Central Gold Coast Beaches. Recent beach and creek profile surveys and the near-shore wave data were collected for calibration and verification of the numerical models. Scenario testing was carried out using the damaging East Coast Low for the period March to May 2009 which was of great significance to the region. Such high level detailed modelling is required to encompass the complex two dimensional nature of sediment transport in this region. This study is a vital part of an integrated Decision Support System to guide ongoing foreshore protection and nourishment of the Gold Coast beaches.

INTRODUCTION

Gold Coast beaches are under great pressure from short-term erosion due to severe storm events and long-term erosion from net sediment transport deficit (Delft, 1970). Palm Beach, located on the central Gold Coast between Tallebudgera Creek to the north and Currumbin Creek to the south has been flagged as the stretch of coast with the most present danger to loss of property, infrastructure and amenity due to recurring beach erosion events.

Beach nourishment is the primary strategy used by The Gold Coast City Council (GCCC) to protect coastal infrastructure from shoreline erosion. Beach nourishment at the

southern end of Palm Beach occurs once or twice a year depending on availability of equipment, government funding and usually in response to a recent storm event. During this process sand dredged from Currumbin Creek is deposited on the upper section of southern Palm Beach. Following dredging operations a bull-dozer is used to distribute the sand along the beach, a process called re-profiling (GCCM, 2008). This form of coastal replenishment is both costly and lacks long-term resilience. A better understanding of the hydrodynamic and littoral response to major erosion events is required in order for a long-term solution to be sought.

Background Information

Since the time the first sub-divisions were declared to the tourist boom of the 1950’s and the “Sea-Change” exodus of the early 1990’s, the 4.4km stretch of coast along Palm Beach has been inundated with infrastructure and human interaction within the coastal zone. Early on, the variability of South-east Queensland’s (SEQ) weather conditions was made apparent and locals knew this area to be prone to large-scale erosion events due to its exposure to energetic ocean swells.

From analysis of long-term wave buoy observations, three main swell regimes can be considered dominant. **Figure1** below shows the wave-rose plot taken from 15 years of available offshore wave data recorded at the Tweed River waverider buoy.

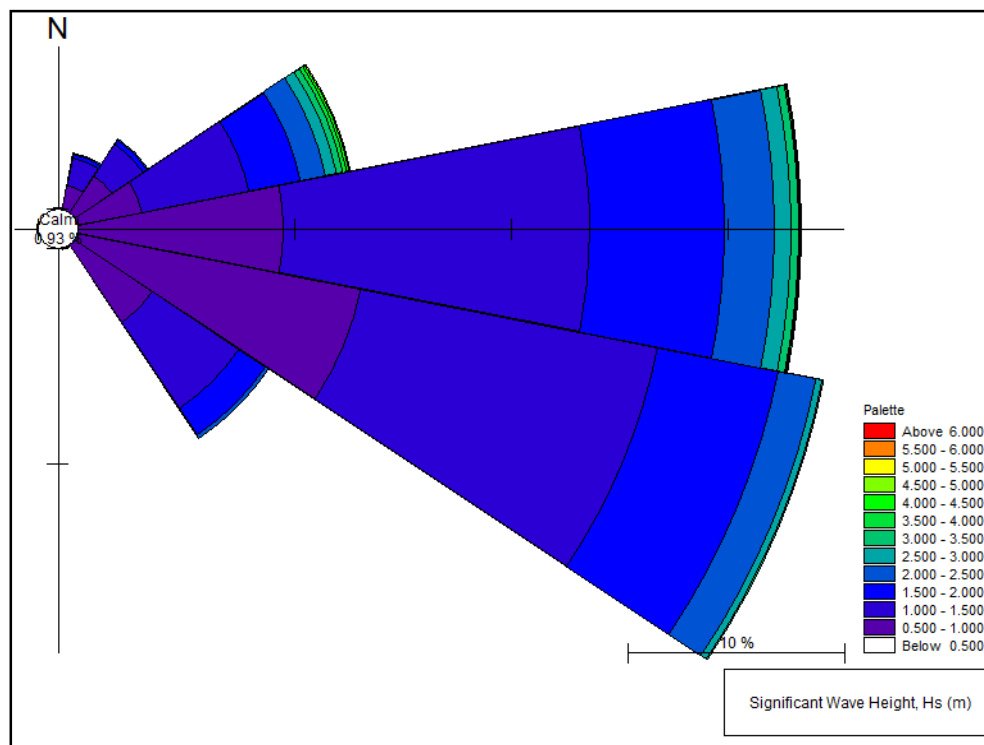


Figure1: Tweed River Waverider Buoy - Wave Rose.
 (Location: 28°10.766'S, 153°34.592'E. Water depth: 23m. Instrument: Datawell 0.9m GPS
 Data Period: 13-01-1995 to 1-08-2010).

- The first of these dominant swell events is S-SE swells occurring in winter and spring, generated by intense low pressure systems off the NSW coast. These contribute to the main component of the net northerly littoral drift found in this region (approx. 500 000 m³/year)

- The second swell regime is generated by tropical cyclones during the November to April period. Tropical cyclones develop in the Coral Sea during this period due to increases in Sea Surface Temperatures (SST) and can move southward into the SEQ coastal region. Most systems weaken considerably as they move southwards and many pass well out to sea. They usually generate a NE-E swell.
- The third swell regime generated is known as an East Coast Low (ECL). Predominantly occurring between March and July, they produce severe gale conditions over periods of up to several days and are associated with NE-SE swells (Allen, 2000)

Due to the high occurrence of these energetic swell events occurring from the east, the high proportion tending S-SE and the orientation of the southern Gold Coast, the area experiences net littoral transport travelling northwards. The current figure for the net Gold Coast longshore drift is agreed to be approximately 500,000 m³/year on average comprising of approximately 650,000 m³/year toward the north and 150,000 m³/year southward (Turner, 2006).

Numerous hydraulic studies of the region have been made public, ranging from government-funded investigations to Master's theses. The Delft report (1970), made several recommendations from yearly dredging and beach nourishment regimes to long-term estuarine training walls and beach revetment wall construction.

Littoral Environment

The southern extremity of Palm Beach is dominated by the Currumbin Creek system. The creek is characterised as a tidal inlet rather than an estuary (which have persistent freshwater flows), this is due to weak river discharges. Prior to the 1970's, the Currumbin entrance acted both as a sediment source and sink, as the sand drift that filled the entrance during high littoral transport was released into the beach system during flood events (D'Agata, 2001). The entrance was highly variable, in terms of position and morphology and caused periodic erosion at the southern end of Palm Beach.

The stabilisation the creek entrance was achieved in 1972 with the construction of a seawall as a recommendation of the Delft Report (1970). The groyne extends a distance of 200 m and connects Currumbin Rock to the mainland. In 1981 a shorter training wall was built directly north of the Currumbin Creek entrance in order to improve the stability of the entrance and to allow an increase in the volume of the upper beach towards Palm Beach.



Figure2: The evolution of Palm Beach and Currumbin Creek
1956 (top left) - GCCC image Library; **1969** (top right) - GCCC image Library;
2010 (bottom) – Google Earth.

Initially a success, the groyne trapped the sand up-drift (to the south) of Currumbin rock as predicted, but this in turn created a large sand deposit to the north of the rock offshore. This offshore sink proved to be a major contributing factor to the erosion of Palm Beach. It was established that at most times of the year, the longshore drift was stopped by the groyne resulting in a negative Palm Beach sediment budget. During sufficiently energetic conditions, sand by-passing was efficient, however the “jet-stream” of sediment being transported would form a circulation cell, infilling the creek entrance and not gaining momentum again until midway along Palm Beach. The circulation cell tended to cause major escarpment and beach scour in easterly extreme wave conditions resulting in the removal of upper beach sand to the offshore storm bar leaving Palm Beach vulnerable to wave attack from successive storms. South Palm Beach nourishment schemes since the 80’s have not resulted in a long-term net benefit for this area.

In 1980, the federal government financed the design and implementation of two additional Groynes built adjacent to 21st and 11th Avenues at Palm Beach in response to continuing erosion problems.

At the far northern end of Palm Beach, the Tallebudgera Creek estuary enters the ocean adjacent to the Burleigh Headland. The entrance was stabilised with a training wall in 1981, subsequent accretion re-aligned the northern 500 m of beach and is now considered to be of sufficient width to withstand moderate to extreme wave inundation (GCCM, 2008).

East Coast Low, 2009

From the period beginning in March of 2009 and lasting until the end of May, three successive large swell events battered the south-east coast of Queensland. After two months of recorded wave heights in excess of 1.5m, peaking at 5m, on the 20th of May 2009, an east coast low formed near Cape Moreton and moved slowly southwest over the Brisbane area. The low, in conjunction with a very strong high in the southern Tasman Sea brought gale to storm force E-SE winds to SEQ. A series of smaller lows impacted the coast and caused large seas. As a result, many beaches suffered from significant erosion, and local flooding of low lying areas occurred (BoM, 2009). This succession of high wave events coupled with significant storm surge resulted in a major erosion event along Palm Beach.

The loss of both public and private infrastructure prompted the GCCC to revisit current beach maintenance regimes and to further investigate possible long-term beach protection strategies. DHI Water & Environment in conjunction with the Griffith Centre for Coastal Management (GCCM) were commissioned by the GCCC in 2010 to provide a detailed hydrodynamic model of the Palm Beach area during these extreme storm events in order to make more informed decisions about future approaches to erosion control.

Monitoring Campaign

The construction of an accurate model of the Palm Beach coastal zone required the accumulation of accurate source data. This data included:

- Bathymetric survey data; provided by GCCC Hydrographical survey team and C-map
- Shoreline position; supplied by CoastalCOMs
- Wave and tidal data measurements; provided by The Department of Environment and Resource Management, Qld. (DERM) and The Bureau of Meteorology (BOM)
- Field measurements of wave and hydrodynamic conditions; gathered by DHI Water & Environment and GCCM.

For the period from July 1st to July 30th 2010, DHI and GCCM deployed two Acoustic Doppler Current Profile (ADCP) devices in the near-shore zone of Palm Beach to monitor wave transformation from deep water and also to measure the inshore current profile. The location, depths and characteristics of the devices can be seen below.



Figure3: Location of ADCP Deployments

DHI ADCP:

Location:

-28.1176°S, 153.47685°E

Depth:

6.1m

Specs:

RDI WORKHORSE SENTINEL

GCCM ADCP:

Location:

-28.09983°S, 153.46804E

Depth:

5.9m

Specs:

FLOWQUEST ADCP

The successful monitoring campaign encapsulated two moderate to significant E/ENE swell events with measured maximum wave height, H_{max} for the period peaking at 2.75m. The collected wave and current data was used to calibrate the MIKE 21 Spectral Wave (SW) and Hydrodynamic (HD) model MIKE21 HD FM.

Numerical Models

DHI's MIKE 21 spectral wave (SW) model is a third generation spectral wave model that simulates the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas across an unstructured triangular mesh. The model includes the following physical phenomena:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation due to white-capping
- Dissipation due to bottom friction
- Dissipation due to depth-induced wave breaking
- Refraction and shoaling due to depth variations.

DHI's MIKE 21 HD FM model is a two dimensional hydrodynamic flow model used to model free-surface flows based on a finite volume solution to the non-linear shallow water equations. The model simulates water level variations and flows in response to a variety of forcing functions including tides, winds and waves. The horizontal domain is discretised using an unstructured triangular grid. The model includes the effects of:

- Bottom shear stress
- Wind shear stress
- Barometric pressure gradients
- Coriolis force
- Momentum dispersion
- Wetting and drying
- Wave radiation stresses.
- Turbulence models resolving subscale mixing processes

DHI's MIKE 21 ST FM model is used for calculating the sand transport rates and associated initial rates of bed level change in response to pure current or combined current and wave driven flow.

Coupling of the above MIKE 21 SW, HD and ST model allows calculating the detailed 2D sediment transport field based in response to combined tidal and wave driven currents and agitation by wave induced oscillatory velocities at the sea bed. The MIKE 21 Coupled SW, HD ST can be used for investigating:

- The morphological evolution of the nearshore bathymetry due to the impact of engineering works (coastal structures, dredging works etc.).
- The effects of engineering works such as breakwaters (surface-piercing and submerged), groins, shoreface nourishment, harbours etc.
- The morphological evolution of tidal inlets.

Domain

The spatial domain of the coupled model can be seen below. It stretches from roughly Stradbroke Island in the north to Fingal Beach in the south and seaward to a depth of approximately 50m. Detailed bathymetry taken from GCCC survey data and C-map information has been incorporated to give a fine scale representation of the coasts bathymetry.

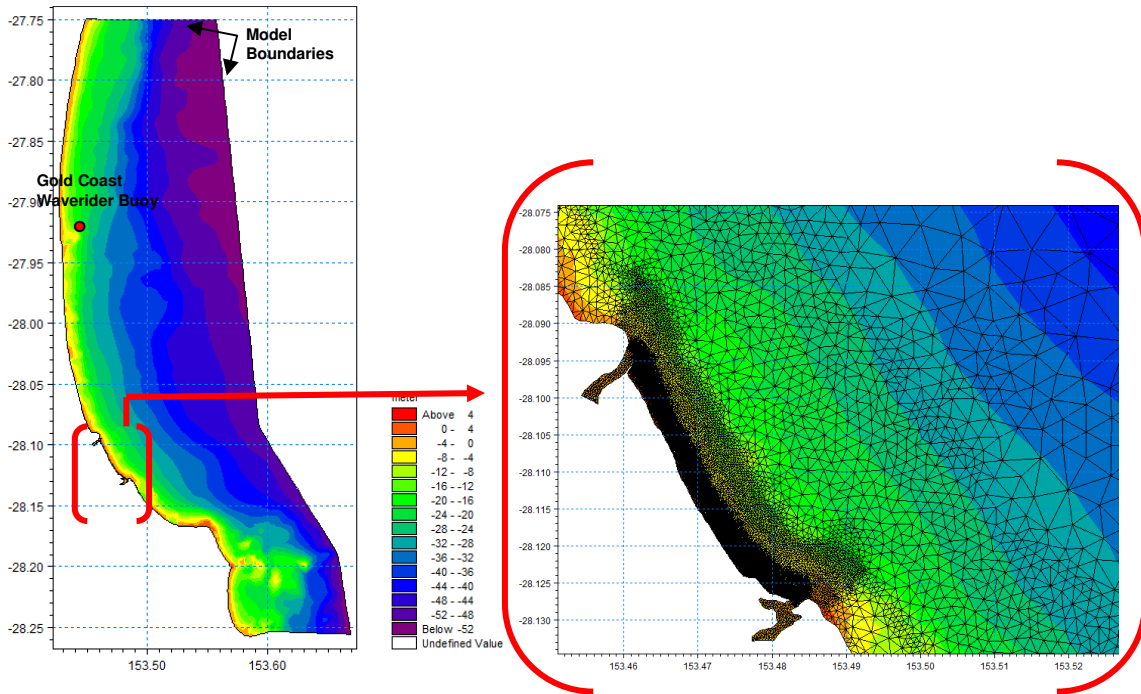


Figure4: Model domain and fine structured mesh

The flexible mesh has a fine resolution of between 5-10 m in the surf zone and dune areas adjacent to Palm Beach. The mesh gradually coarsens to between 100 m and 500 m at each of the five (5) offshore boundaries (approx. depth = 50_m).

Spectral Wave Transformation

In order for past wave events to be recreated in the model, an accurate representation of the two dimensional wave field at Palm Beach needed to be established. Based on a large SW scenario simulation matrix covering the historical envelope of recorded wave conditions it was possible to establish a shoaling/refraction wave transformation matrix governing the relationship between the wave conditions at the offshore model boundary and the DERM waverider buoy. The methodology made it possible to transform any wave time-series measured at the wavebuoy into an offshore model boundary condition using higher order polynomial fitting functions in MATLAB.

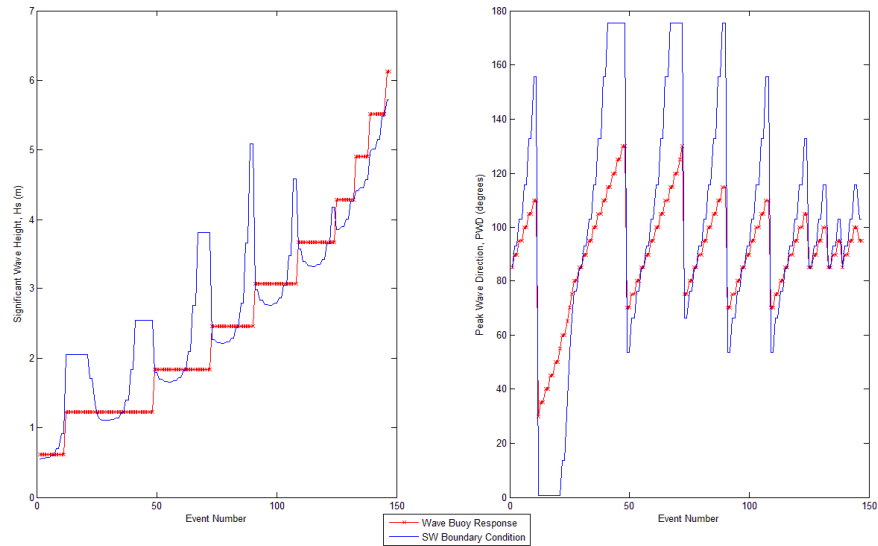


Figure5: Shoaling and Refraction Polynomial Application Calibration

The wave transformation method and SW-HD Palm Beach model was verified through the following steps.

1. DERM waverider buoy data for the period of the monitoring campaign was transformed to the model boundary using the aforementioned polynomial fitting calculations.
2. A fully coupled SW-HD model was carried out using the calculated wave time-series at the offshore boundary. Coherent tidal elevation time-series were extracted from the DHI global tide model and used as inputs to the model
3. Wave/Current results were extracted from the model at the location of the DERM waverider buoy and the DHI ADCP deployment site and compared to actual recorded measurements for the period (July 1st to 30th, 2010).

The comparison of the SW-HD coupled model results and the DHI ADCP extracted data can be seen in Figures 6-7:

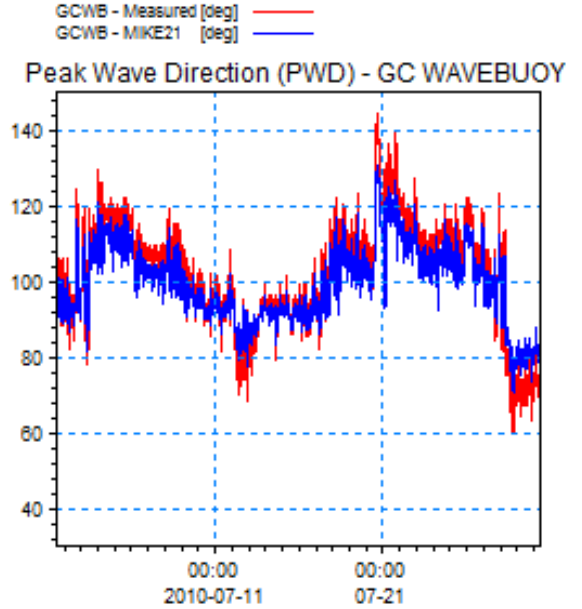
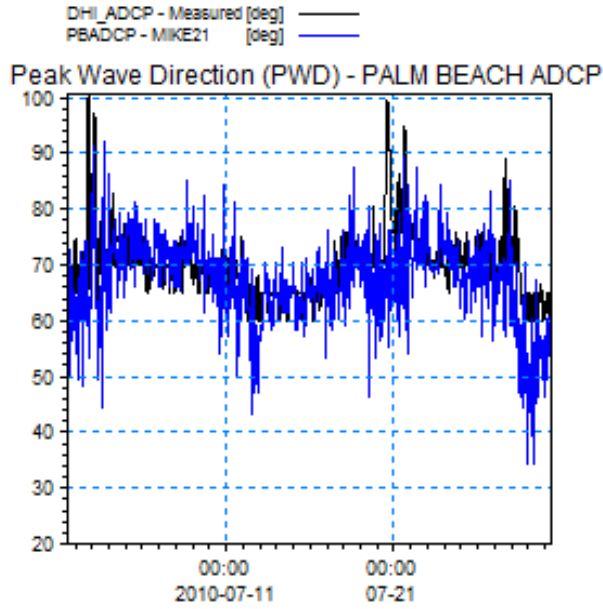
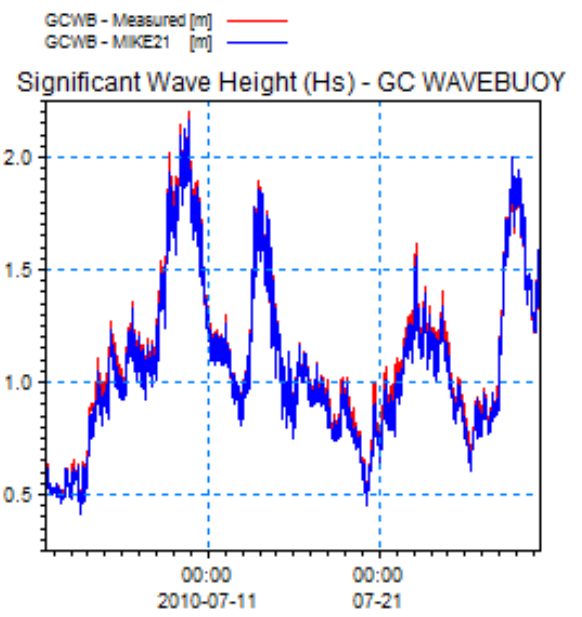
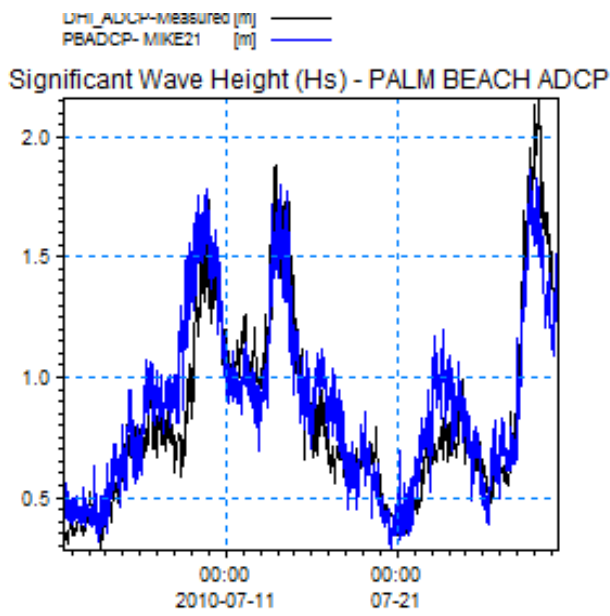


Figure6a: Hs and PWD Calibration of the SW model

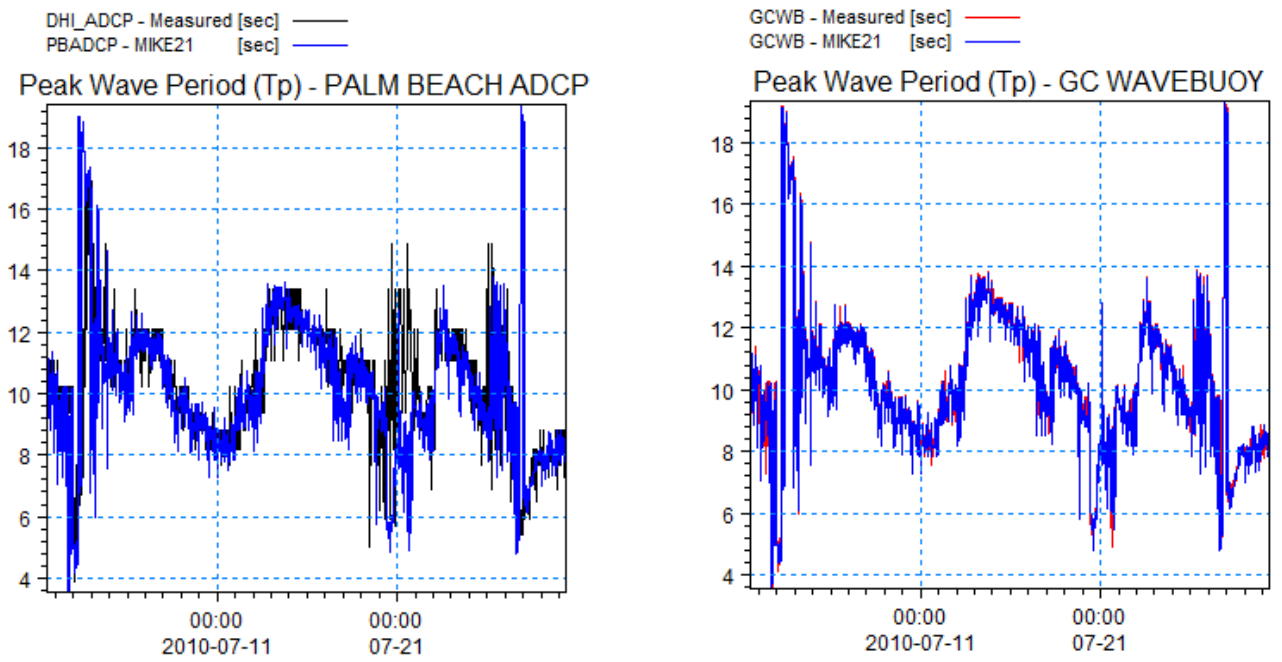


Figure6b: Tp Calibration of the SW model

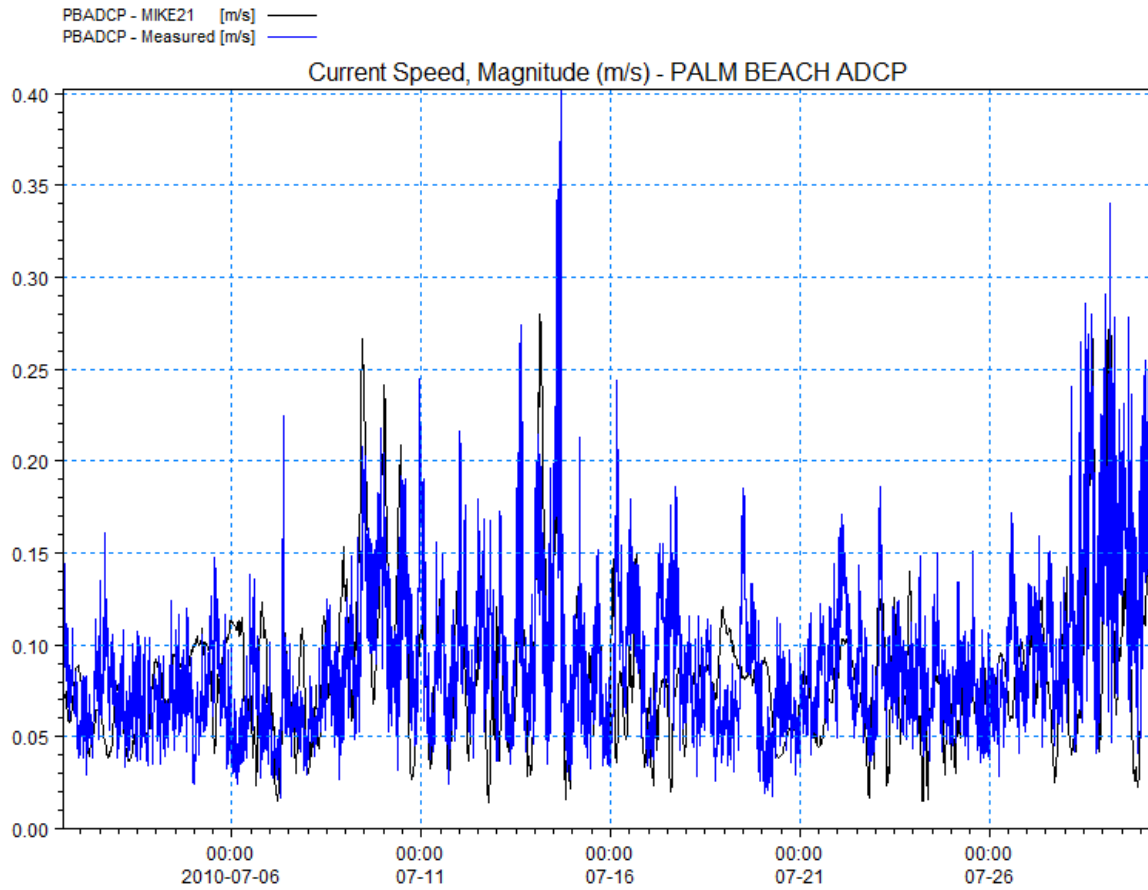


Figure7a: Magnitude Calibration of the HD model

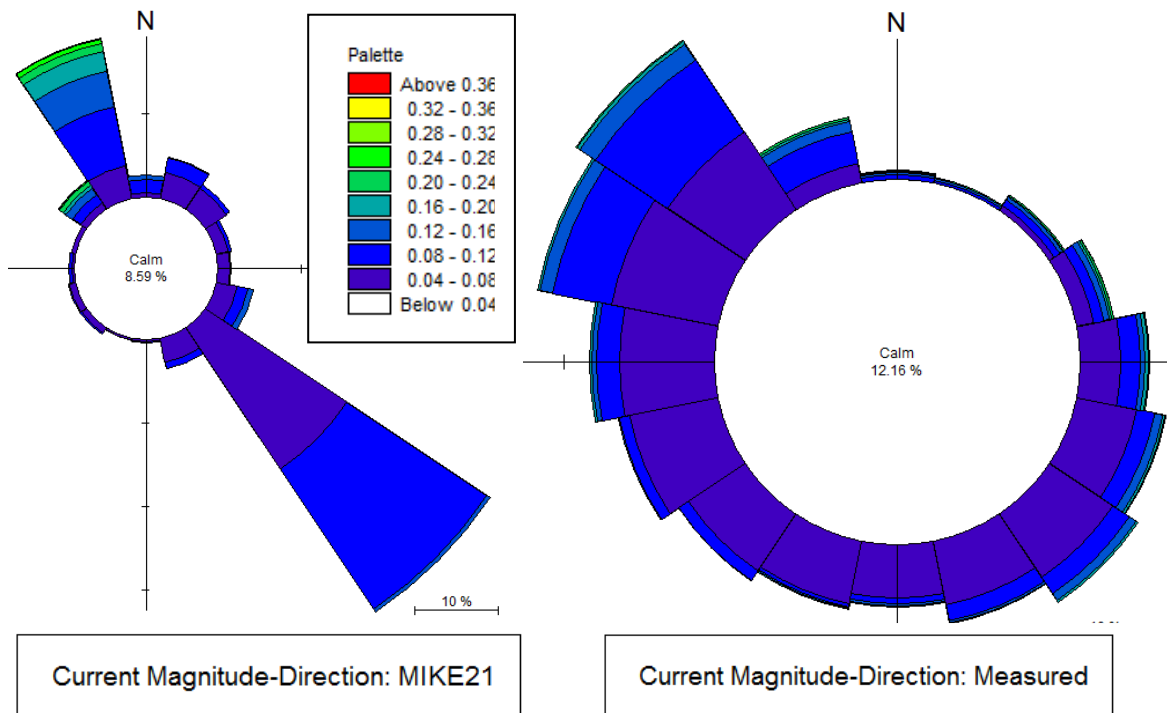


Figure7b: Direction Calibration of the HD model

Erosion Model

The sediment budget and beach evolution at Palm Beach are governed by a complex interaction of longshore and cross-shore driven sediment transport processes. Wave refraction due to land interaction, in particular around Currumbin Headland and to some extent the partial sheltering from the Palm Beach reef, result in a non-uniform wave driven current field that governs the longshore sediment transport budget along the beach. At the same time, the recurrence of large wave events cause a rapid and significant cross-shore response with substantial volumes of sand being eroded from the upper beach and dune systems and placed into offshore storm bars. The location of these storm-response bars subjects the deposited sand to the strong longshore driven processes.

In order to capture both the longshore and cross-shore sediment transport processes a numerical hybrid model has been developed using MIKE21 ST to calculate the longshore driven sediment transport and an empirical dune erosion model based on Larson et al. (2004).

Due to substantial processing time required for the hybrid model, a method of interpolation of time-series data into an 'Event Matrix' was created.

Time-series data from the DERM waverider buoy recorded from March 1st to May 27th 2009 was decomposed into 147 scenarios by arranging the historical wave data into bins

each with the dimensions of (0.5 m, 1 s, 5 deg) with regards to significant wave height (Hs), spectral peak wave period (Tp) and peak wave direction (PWD).

The resulting ‘envelope’ of wave conditions was chosen as to provide a sufficient resolution of the variability of wave conditions that occurred during that event. In the table below the event matrix envelope is compared to the raw scatter plot of the measured wave data time-series.

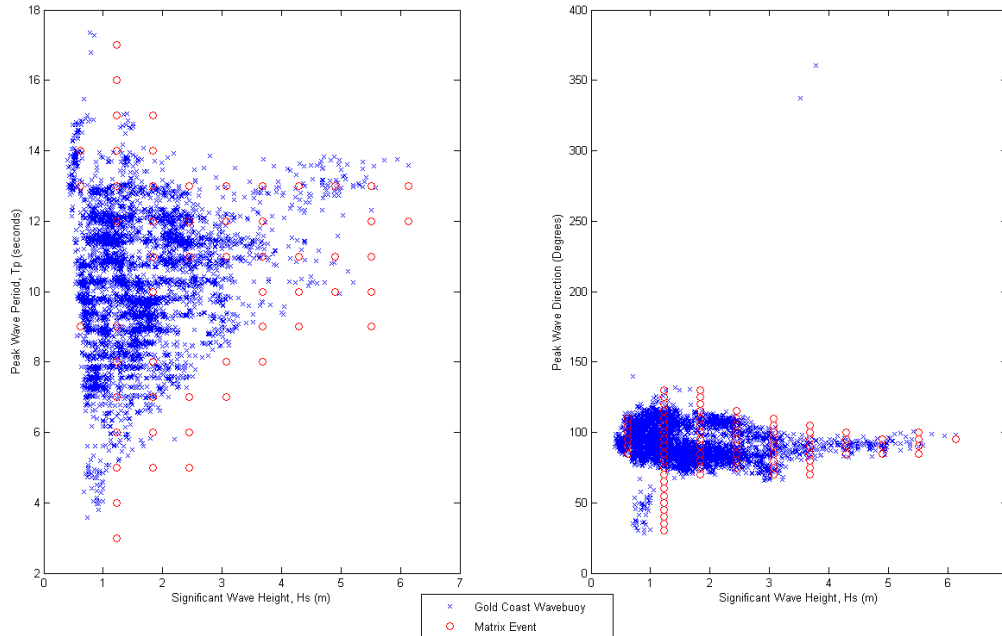


Figure8: Event matrix validation

Fully coupled SW-HD-ST models for these 147 events were run and a ST event matrix was created, logging wave setup, breaking wave height and sediment transport flux at 11 transect lines along Palm Beach for each event. Applying 3-dimensional interpolation for each time-step variation in Hs, PWD and Tp of the DERM wavebuoy time-series into the ST event matrix result-log files, the ST values could then be found.

Several transect lines running normal to the Palm Beach coast were selected to log the resultant sediment transport output components. These transects were selected to be at an even spacing and ensured the entirety of the coastline was incorporated. These transect lines (T1-11) and the corresponding “Control Volumes” (C1-C10) that they encompass can be seen in Figures 9a and 9b.

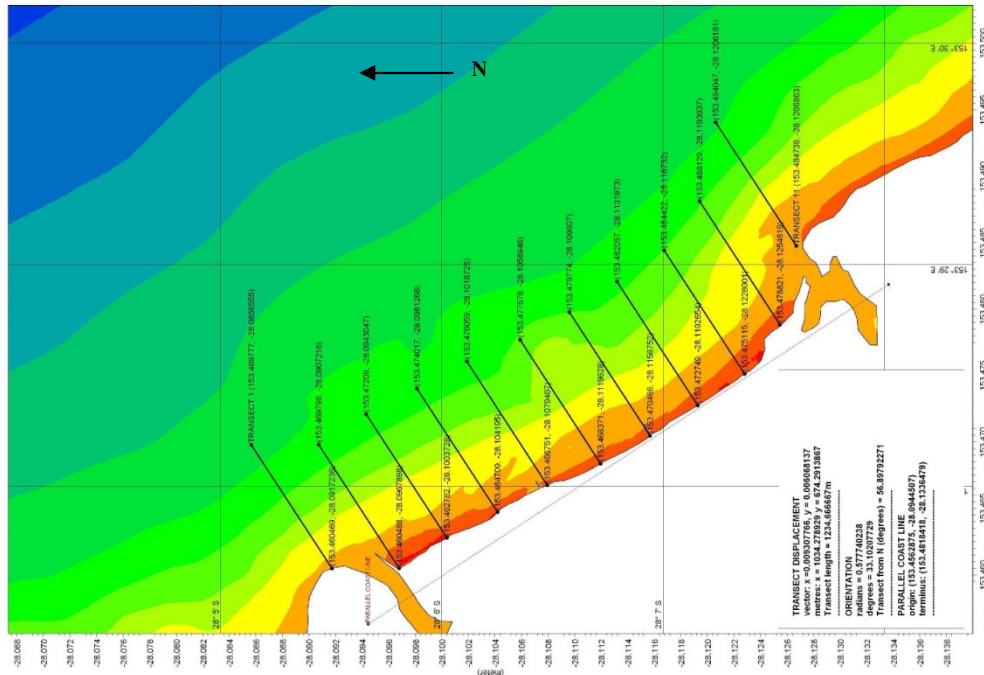


Figure 9a: Palm Beach transect locations (Bathymetric View)



Figure 9b: Palm Beach transect and control volume locations (Satellite View) – Google Earth

The control area between each transect was divided into a further 5 sub-transects. Between each sub-transect, a quasi-rectangular grid was created; 1 cell in the longshore direction and 600 cells in the cross-shore. As seen below (**Figure 10**)

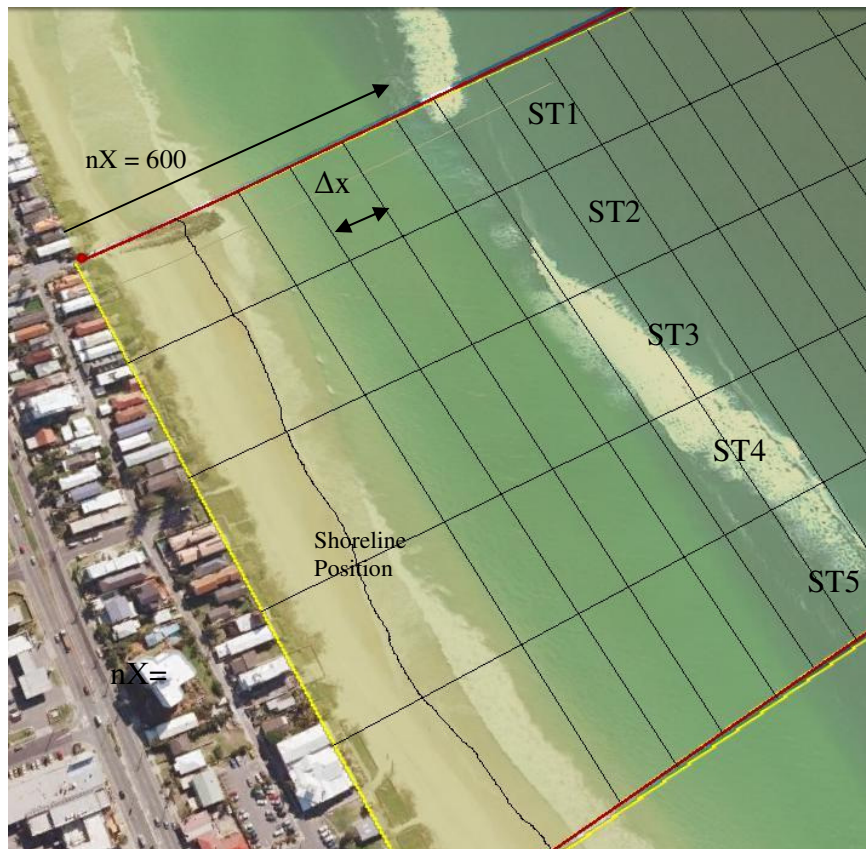


Figure10: Sub-transect and grid layout – Google Earth

The beach slope, run-up and dune erosion were calculated empirically for each sub-transect at each step in the time-series. The sediment budget for each grid cell is then calculated by:

$$Q_{\text{total}} = Q_{\text{Flux}} - Q_{\text{cross}}$$

Where:

Q_{Flux} = Sediment Flux across each cell. Found from interpolation of the Event Matrix.

Q_{cross} = Sediment volume eroded from the dune-front and upper-beach profile. Found empirically.

The subsequent bed level change across the sub-transect domain is then calculated as follows:

$$\Delta y = \Delta_{\text{Vol}} / A_{\text{active}}$$

Where:

Δ_{Vol} = Total volume change through each sub-transect

A_{active} = Active Area = $nT \times (X_R - X_{\text{Hb}})$

nT = Grid Width. User defined in the model.

X_R = Wave Run-up mark, calculated empirically (Nielsen, 1995).

X_{Hb} = offshore location corresponding to depth of Closure. Defined as transect position corresponding to the 90th percentile of ST.

At the end of each cycle, the updated shoreline position and subsequent change in beach width is determined and compared to measured values.

Results

The Palm Beach erosion model was used to assess the beach width evolution during the period from March 1st to May 27th 2009 and the predictions were compared to filtered shoreline measurements obtained by the Palm Beach CoastalCOMS camera. The CoastalCOMS system records regular beach-width measurements made along the stretch of Palm Beach. Each measurement is referenced to a fixed “A-line”, the location of a buried seawall built as a recommendation of the Delft report (1970) as a final defence against extreme erosion events.

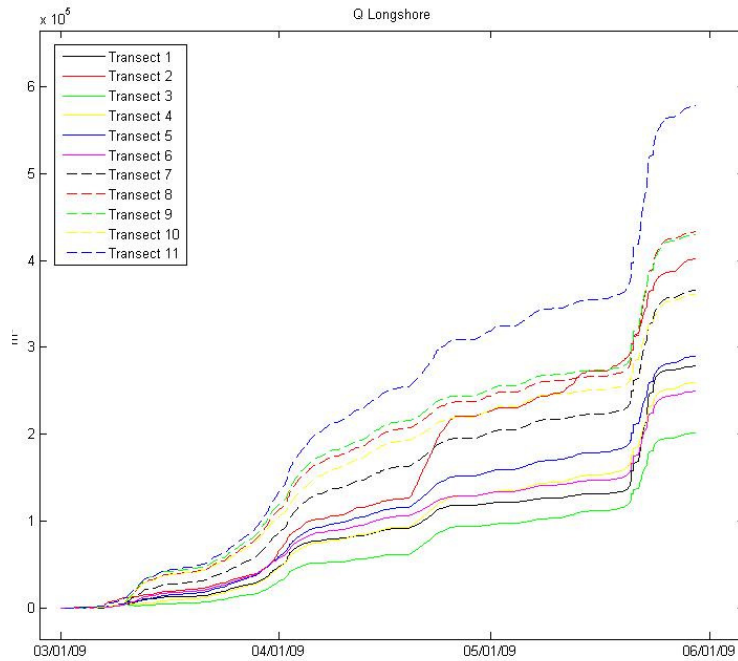


Figure11a: Longshore Sediment Flux through the Palm Beach Transects

As shown in **Figure11**, the calculated accumulated longshore sediment flux across each transect for the period varied from 1.1×10^5 m^3 to 5.8×10^5 m^3 , the greatest flux occurring through Transect 11 (Currumbin Rock) and the smallest through Transect 3 located approximately 300 m south of the Tallebudgera Creek training wall.

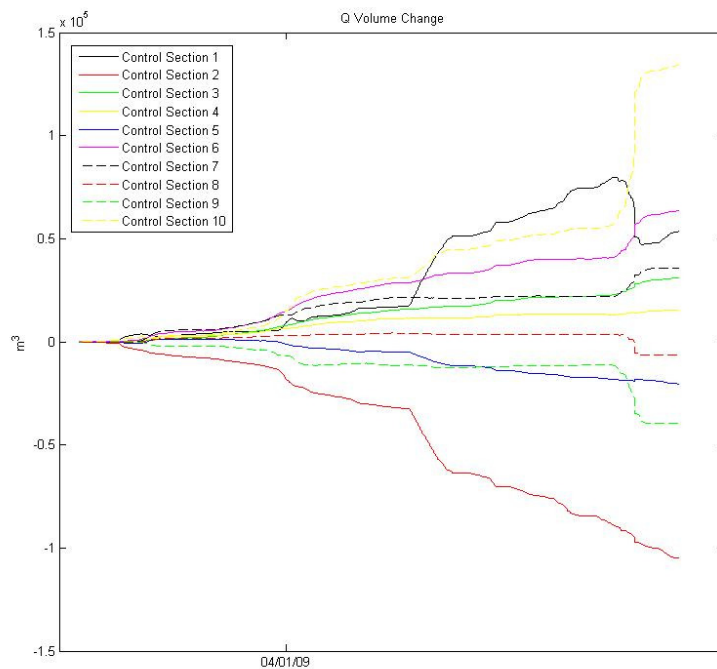


Figure11b: Longshore Sediment Flux through each Control Volume

Assessment of the Accumulated Sediment Volume Change time-series shows the longshore-driven sediment transport processes resulted in erosion in three separate Control Volumes, while inducing accretion in the remaining volumes. The largest accretion taking place in Control Volumes C1 and C10, demonstrating that the Tallebudgera and Currumbin Creek entrances exhibit catchment deposition. The deposition in C10 is due to the significant weakening of the wave induced current-wrapping around the Currumbin headland.

Control Volume (C2) experiences the largest amount of erosion due to its location, where the sheltering effect of the Currumbin headland starts to diminish, resulting in a positive gradient in the magnitude of the wave-driven current (northward), thus causing erosion. Proceeding north, the wave field once again becomes uniform and the differences in longshore sediment transport are predominantly governed by the local bar formation influence on the wave-driven current patterns.

The variations in dune-erosion patterns are predominantly governed by spatial differences in breaking wave height (H_b) across the domain. This variation produces generally larger dune-erosion along the northern end of the beach where increased wave heights are experienced due to the lack of sheltering from Currumbin Headland during S-SE events. The resulting magnitude of shoreline recession however, will be regulated predominantly on the available dune “buffer” present along the beach.

The sheltering effects of Currumbin Headland with respect to wave height and the subsequent affect on local current dynamics can be seen in **Figure12**.

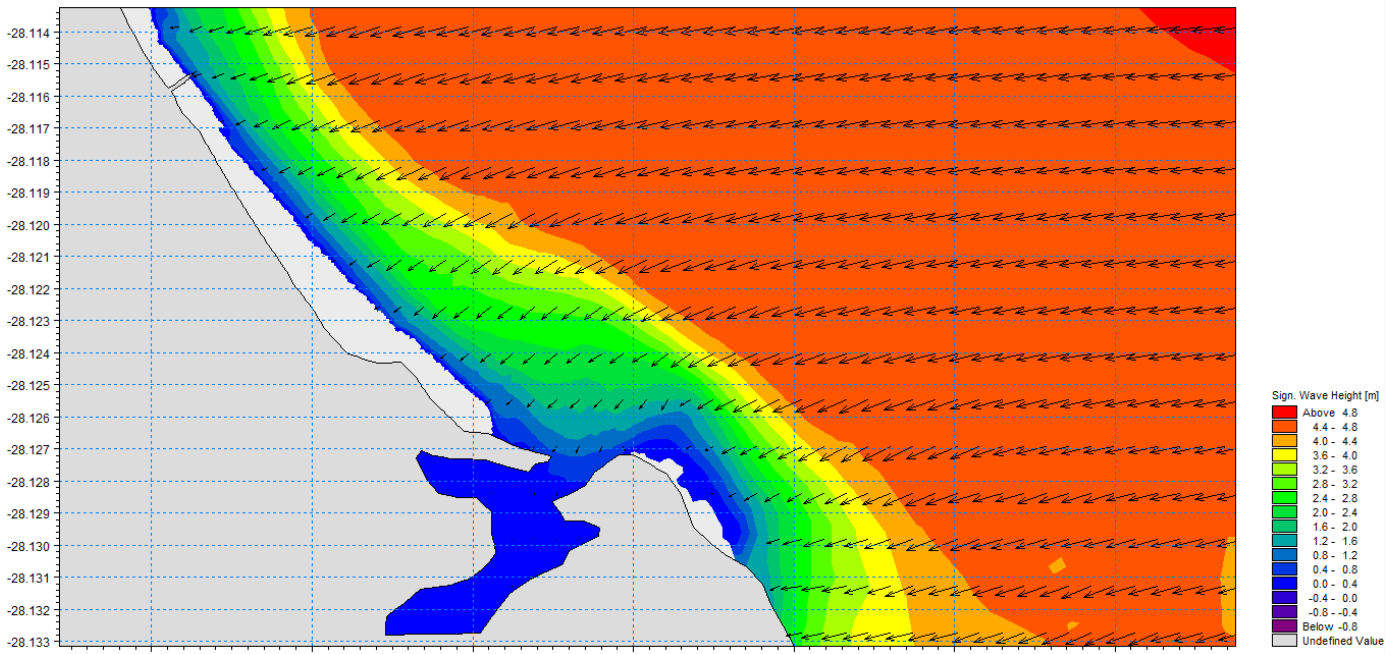


Figure12a: Sheltering effect of Currumbin Headland on Significant Wave Height (Hs), (May 2009).

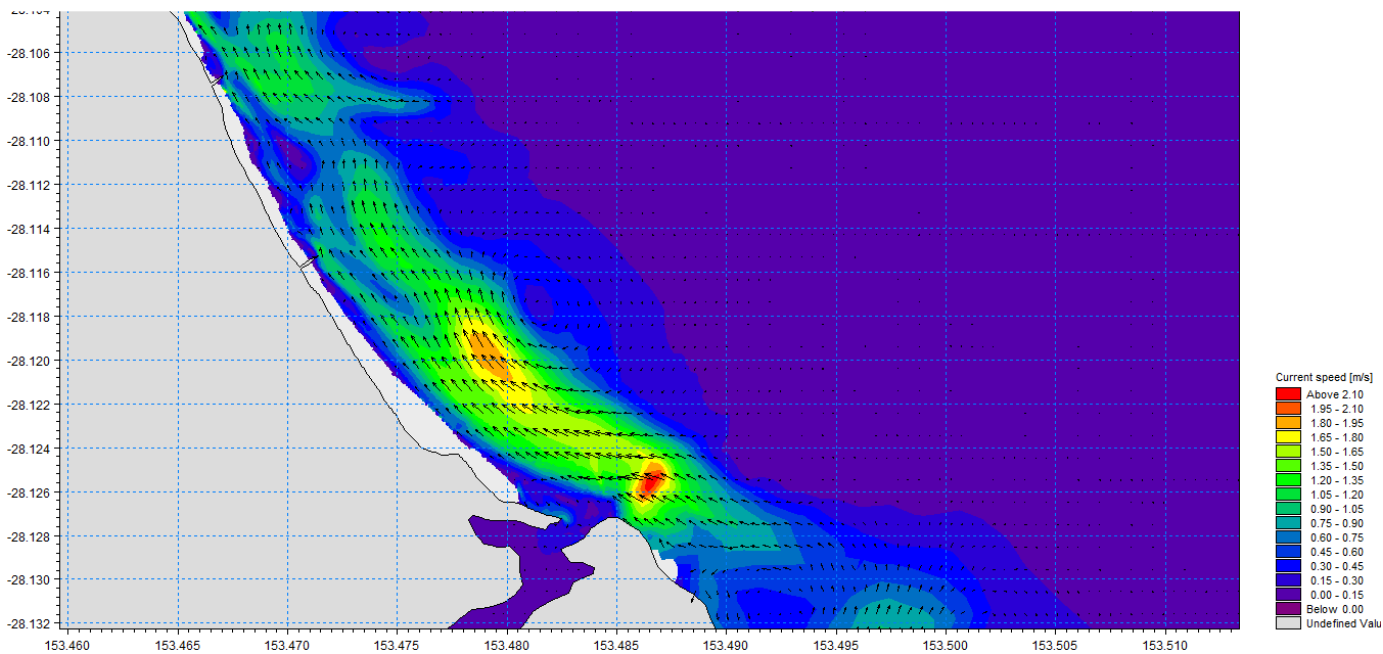


Figure12b: Current profile of the southern end of Palm Beach, (May 2009).

Comparing model-predicted to measured beach width changes across the domain yields a fair agreement with respect to spatial variability (**Figure13a**).

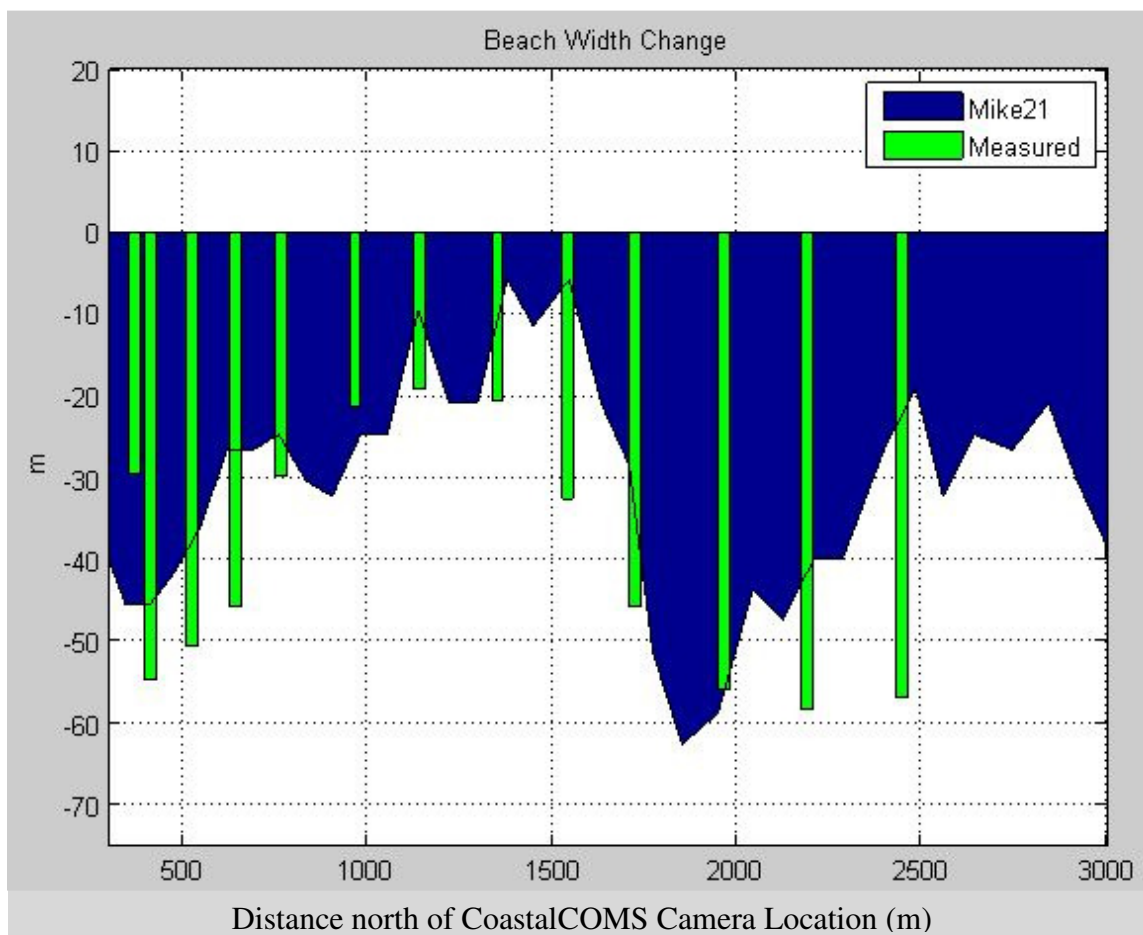


Figure13a: Comparison of shoreline regression along the length of Palm Beach for The East Coast Low, May 2009.

The comparison of mean beach width recession demonstrates a good agreement with both the numerical model and the measured data exhibiting a mean shore line recession of approximately 40 m during the three month period (**Figure14b**).

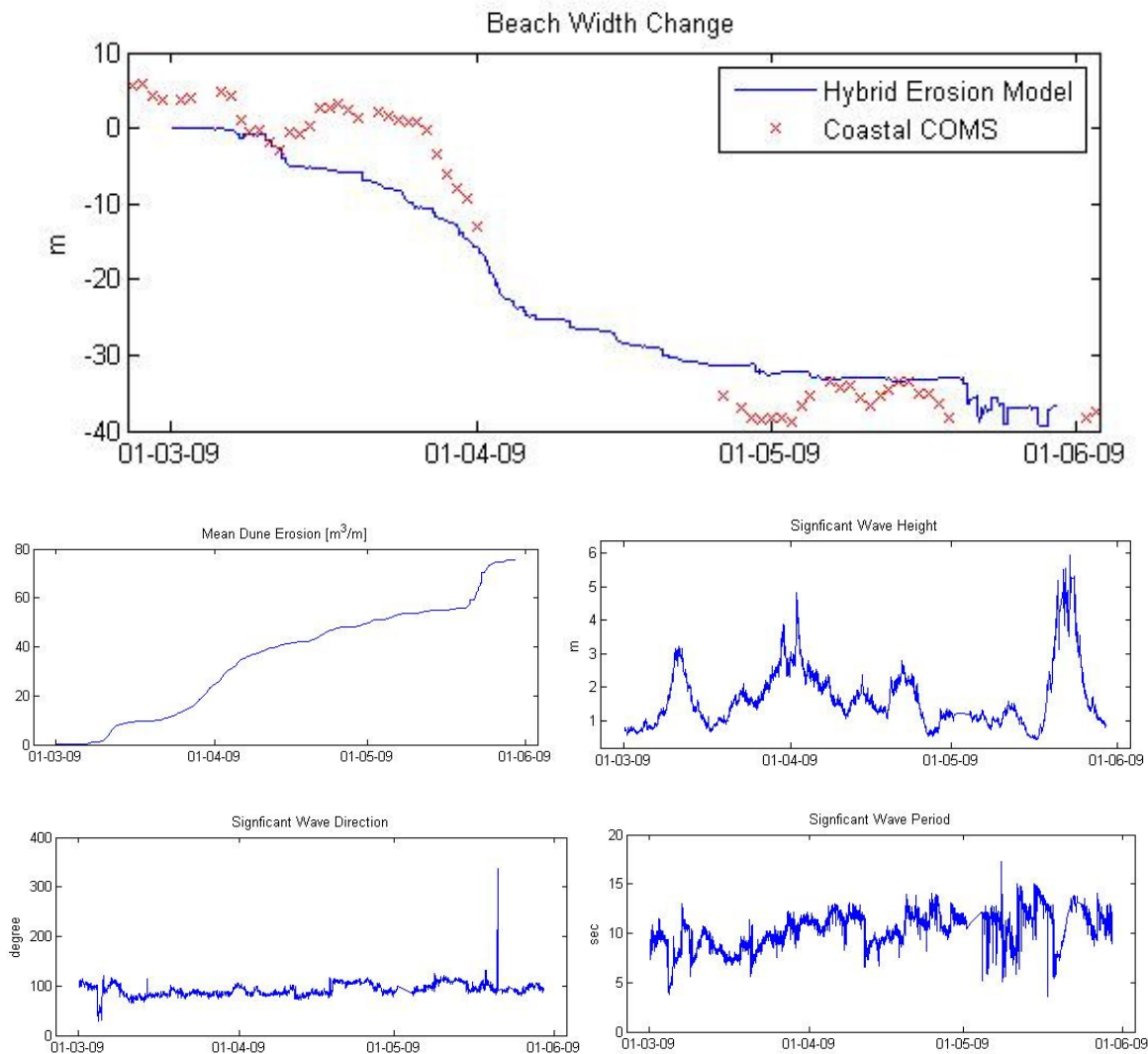


Figure14b: Mean Beach Width Change and modelled dune erosion volume in response to the wave conditions recorded between March 1st to May 30th 2009.

Conclusion

A hybrid shoreline evolution model for Palm Beach has been developed to capture the detailed shoreline response to a period of successive highly energetic wave events causing significant erosion and damage to coastal property. The modelling framework consists of a coupled state-of-the-art 2D sediment transport MIKE21 model and an empirical dune erosion formulation model to provide a quantification of the combined longshore and cross-shore sediment transport processes governing the beach evolution across Palm Beach.

The comparison of mean beach width recession demonstrates a good agreement between the numerical model and the measured data with a mean shoreline recession of approximately 40 m during the three month period (**Figure 14b**). When comparing the measured and predicted variation in beach width across Palm Beach the agreement is best along the southern end while some disparity is noticed towards the northern end.

With regards to obtaining the maximum model accuracy, one of the key constraints were that the detailed bathymetric survey of Palm Beach used was taken 1 year after (April 2010) the East Coast Low erosion events of 2009, which could potentially influence the calculated coastal processes. Resolution of the measured bathymetry around the Palm Beach reef is also limited with only one recorded bathymetry transect for the entirety of the reef. Interpolation of the aforementioned dated data to this single transect could result in imprecision causing an alteration of the modelled wave driven current field for this region.

In spite of the limited data available for validation, comparison of modelled results with field measurements of shoreline evolution was encouraging. This demonstrated the capability of the developed hybrid model, which incorporates a simplistic representation of the upper beach and dune erosion processes with a detailed 2D sediment transport model. Consequently, in using this approach it is possible to arrive at an applicable estimate of the detailed spatially-varying shoreline response to an extended period of successive large wave events.

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Biography

James received his bachelor degree from Griffith University Gold Coast in Civil Engineering with a major in Coastal Engineering in 2004. He has been involved in the water and wastewater industry for five years before specializing in coastal and marine work in his current role with DHI Water & Environment.