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Sand Shoal Dynamics of a Tide-Dominated Estuarine Embayment: Comparison of a Numerical Sediment Transport Model against Field Observations

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ABSTRACT

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This paper presents an innovative and detailed dataset of currents and sediment transport observations over a sand shoal system responsable for focussing wave energy on eroding coastline. The data are used to measure the performance of a detailed numerical sediment transport model of the sand shoal system . The predictive skill of the model is $\geq$0.96 for tidal elevations within Port Phillip Bay, 0.75 for tidal currents over the shoals, and 0.80 for bedload transport. Analysis of available bathymetric data suggests the sand shoal system exhibits large-scale mobility over unexpectedly short timescales, which must be driven by exceptionally strong tidal currents. Simulated residual bedload estimates are of the order of 5,000 m3/ m / annum over the crest of the bank and are highly ebb-dominant. The data and calibrated model system will be used as a tool to informing the efficacy of various coastal managment options at Portsea.

ADDITIONAL INDEX WORDS:,*Tidal Sand Banks, Sediment Transport, Morphological Modelling*

INTRODUCTION

Tidal sand banks, and their associated mobile sand shoals, are important coastal features within shelf seas and estuarine environments. Where shallow or of sufficient dimension they can modulate wave energy delivered to the shoreline through wave refraction, govern the speed and distribution of tidal currents, and act as a source or sink of sediment to the associated coastal zone. They are also frequently exploited as a source of beach nourishment material. If the bank or shoal is mobile then a change in its shape or position can have implications for the management of adjacent shorelines

In this paper we describe the performance of a numerical model (Delft3D) against a robust and innovative dataset of hydrodynamic and sediment transport observations occurring over such a sand shoal system within an area of the Great Sands of Port Phillip Bay (Figure 1) during spring tidal conditions.

The calibrated model, which provides the first time a quantifiable, published estimate of bedload transport rates for the Great Sands región of Portsea, is being employed to quantify sediment transport pathways and magnitudes occurring around the shoal system over a range of spatial and temporal scales.

PHYSIOGRAPHY

The Great Sands region is a relict geological feature forming a series of sand shoals within the entrance of Port Phillip Bay, which took on its present shape some time between the Last Glacial Maximum (LGM) and the end of the Holocene period about 8,000 years ago.

Figure 1. Location of the Great Sands within Port Phillip Bay, Victoria. Tide gauges used during calibration of the hydrodynamic model (Figure 5) also shown.

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The major features of the channels and shallow banks in the Great Sands have been relatively stable over time. Analysis of available vibrocore data suggests the sandbars form a veneer of variable thickness resting on indurated Pleistocene aeolianites (Holdgate et al., 2001). At “The Rip”, a narrow opening maintains oceanic exchange between Port Phillip and Bass Strait. Although the The Rip is dredged periodically to maintain a declared depth of 17m, typically depths exceed 20m and is reported anecdotally to have maximum depths extending to 100 m within “The Deep”, which is a submarine canyon scoured by fluvial actiuvity duirng the LGM and forms an extensión of Point Nepean.

Tidal flow through the constricted entrance is highly turbulent due to the rapidly changing water depths; peak tidal currents reach 3m/s (Cardno, 2010), effectively blocking swell wave energy from propagating through Port Phillip Heads during ebb tide (Water Technology, 2013). During flood tide wave energy is ‘pushed’ in to the bay.

The incident swell wave climate is highly directional, with approximately 80% of swell wave energy incident between 195° and 215°. The dominant swell wave period is 12 seconds, with approximately 90% of the incident swell wave climate occurring between 10 and 15 seconds. The mean wave height is 1.5m, although wave heights of 6.5m are observed. The larger waves are associated with wave periods in excess of 10 seconds.

The deep channel running through Port Phillip Heads strongly refracts wave energy around Point Nepean. Wave energy directed towards South Channel tends to be ‘captured’ *via* internal reflection off deep channels and focused along a system of shallow sand banks separating the deeper water areas of South Channel and Sorrento Channel (Figure 2).

The presence of a large, shallow, linear bank (“Nicholson Knoll) located approximately 1.5 km north-west of Portsea Pier appears to effectively focus wave energy on to the shore at Portsea, which influences littoral processes in the area.

OBSERVED MORPHOLOGICAL BEHAVIOUR

Detailed bathymetric information on the Great Sands area and adjacent coastline is provided by a Laser Airborne Depth Sounding (LADS) surveys undertaken by Port of Melbourne Corporation (PoMC) in January 2010 and January 2012. LADS data is captured by aerial survey in a similar manner to LiDAR, with the difference that the laser signal can generate reliable returns from the sea floor down to depths of about 30 m, depending on water clarity and ambient current field.

Recent changes in the overal morphology of the sand shoal system has been significant over a two year period (Figure 3). This timeframe is short compared to the expected morphological timescale of sand banks similar dimensions, which are typically meaasured over decadal scales. The predominant mode of chnage is via migration of large sand waves with a typical wave length of 200m and amplitide of 5m. This is of sufficient dimensión to significantly influence refraction of swell wave energy at the dominant period (12s) in water depths associated with the bank crest (depth order of 9m). Aggregating net bed level change over spatial scales much greater than the individual sand waves showed that the bank is exhibiting large scale behaviour over two dimensions.

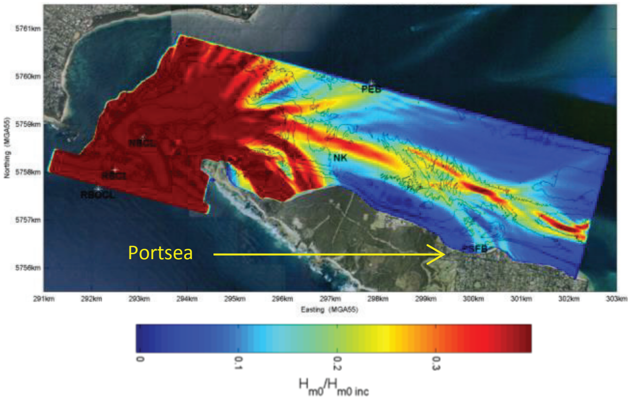


Figure 2. Refraction of wave energy through Port Phillip Heads and trapping along the crests of sand shoals lining the south boundary of South Channel. Boussinesq simulation of swell waves, Tp = 12s.

The mobility of the bank, coupled with its demonatated ability to control incident swell wave energy, has significnat implications for the management of underlying coastline changes presently occuring at Portsea.

FIELD OBSERVATIONS OF SEDIMENT TRANSPORT

To better understand the dynamics of the sand shoal system, a field campaign was designed by the authors to measure key physical parameters at various locations around the sand shoal (Advisian, 2015; WRL, 2015). The data were collected for the purposes of numerical model calibration and to constraint estimates of sediment transport around the sand shoal system.

Specifically, the targeted data collection campaign focussed on obtaining measurements of tidal currents at various locations throughout the water column; Measurements of sand in suspension above the bed (i.e. bed load transport); Obtain grab samples for determination of particle size distribution of bed sediments; and assess currents and acoustic backscatter over multiple transects across main axis of the bank.

Water column velocity/direction and backscatter were measured using a RDI 600kHz ADCP. Precise vessel position was obtained using a Trimble R10 RTK GPS with real time co-ordinate corrections provided via the AusPOS cors network.

Bed velocity measurements were obtained by comparing boat movement and position as calculated using the ADCP bottom tracking reference, with the actual boat position as provided by the RTK GPS.

Water column current velocities were adjusted to account for the bed tracking velocities. Backscatter was converted to suspended sediment concentrations (obtained from pump samples at multiple levels above the sea floor and over multiple tidal cycles), and multiplied by the ADCP velocity readings to provide a measurement of suspended sediment flux.

Seabed sediment samples were collected at various locations over the sand shoals (Figure 4) and analysed for grain size, sorting and fall velocity using a Rapid Sediment Analyser (Table 1). Results were converted to an equivalent grain-size distribution using the relatinship between fall velicity and sediment diameter given by Van Rijn (1993).Currents measured by ADCP were depth-averaged and convolved using a simple 30-second moving avaerage filter. Bedload transport rates were estimated indirectly using by two independant methods:

(a) **QBVR:** Applying Van Rijn (1993) bedload transport formula with depth-averaged velocity as measured by ADCP and D50 as obtained from the fall velocities.

(b) **QBDW:** Multiplying the bottom-tracking velocity measurements by a multiple of the local D50, as described by Williams (2008). This approach assumes that the corrected bed velocity measurements correspond to movement of the saltating layer.

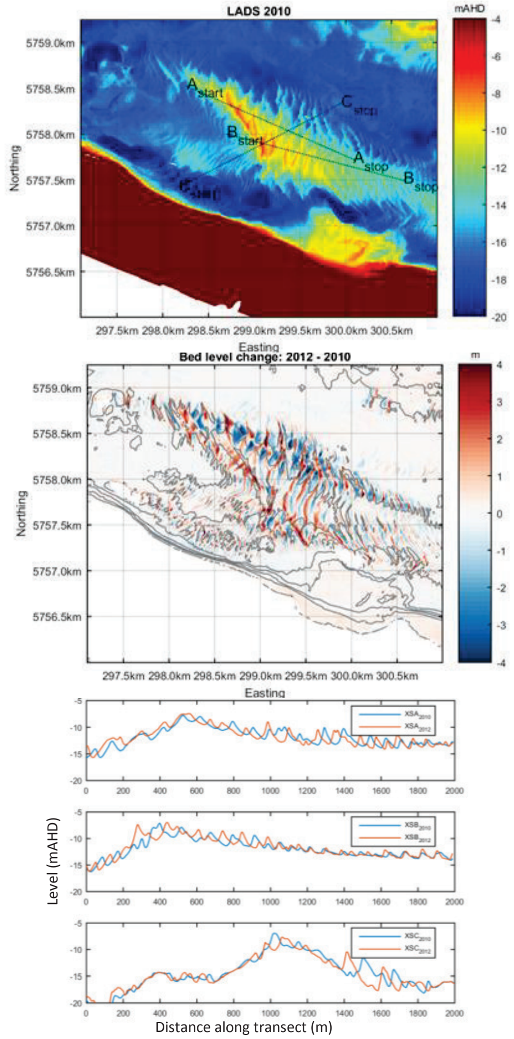


Figure 3. Observed changed in morphology and bedforms at Nicholson Knoll, 2010 - 2012. Calibration locations 'ADCP-1' and 'ADCP-2' are also shown.

NUMERICAL MODEL

Depth-averaged simulations of tidal hydraulics and sediment transport were undertaken employing Delf3D with a rectilinear grid system. Boundary conditions were driven by tidal elevation constituents obtained from the TPXO8 global tide inversión model. A domain decomposition approach was used to dynamically downscale the horizontal resolution of the model from 270m at the boundary and within Port Phillip Bay, to 90m through Port Phillip Heads and The Great Sands Region, to 30m at Portsea and Nicholson Knoll. The sediment transport module used the Van Rin (2007) algorithm for suspended load and bed load transport. The bedload calculations in the presence of a depth-averaged current are consistent with Van Rijn (1993).

Initial calibration occured using predicted tidal elevations within Port Phillip Bay at multiple tide gauges maintained by PoMC. Bed roughness (Chezy coeffcient) was varied uniformly within the model domain as a calibration parameter. The predictive skill of the model was almost linearly correlated to the selected bed friction coefficeint, which suggests water levels within Port Phillip Bay are to a large extent controlled by the friction associated with the water flowing past the constricted entrance. The best calibration is obtained for a uniform chezy coefficeint of 68 (Figure 5), which gave a Skill Score of 0.96 when averaged across all available tide gauges.

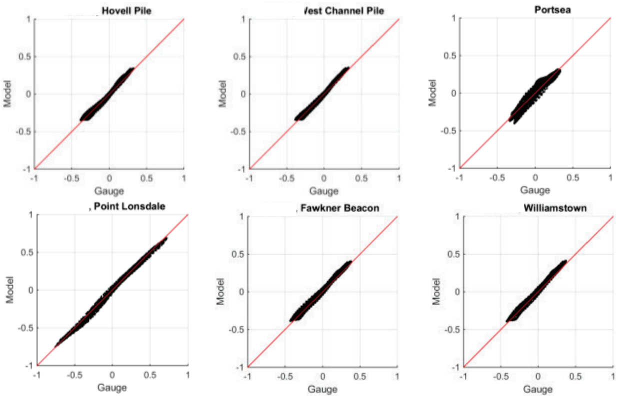


Figure 5. Validation of hydrodynamic model against tide gauges operated by Port of Melbourne Corporation. Locations of tide gauges shown in Figure 1.

Tidal current data was collected in the form of AWAC deployments at Portsea betweeen July 2014 and February 201, and two further ADCP observation sites over tidal cycles established during sediment transport fieldwork in April 2015. Bed friction was again used as a calibration parameter, which was varied only within the 30m domain encompassing Portsea and Nicholson Knoll. Varying the bed friction for ths domain did not degrade the models predictive skill of water levels within the wider Port Phillip Bay región, but did successfully increase depth-averaged currents over the shoals.

Figure 6 (second panel) shows the depth-averaged currents measured at one location over the shoals. When the compared to 10-minute ensemble averages of the ADCP data for both locations over the shoals, the overall predictive skill of the model is 0.75 with a Mean Average Error (MAE) of 0.15 m/s and a bias of+ 0.1m/s. The magnitude of the MAE corresponds to an error of about 10% of the ensemble-averaged peak tidal current speeds. A further validation was undertaken against depth-averaged current data measured during two AWAC deployments (not shown) adjacent to Portsea, for the period July 2014 to February 2015. The predictive skill of the model averaged across both AWAC deployments is 0.45. The MAE is 0.1m/s and the bias is +0.04m/s.

Figure 6 (third and fourth panels) show a time series of simulated bedload transport from the calibrated model against bedload estimated from the field data [QBVR and QBDW] at calibration location 'ADCP-2'.

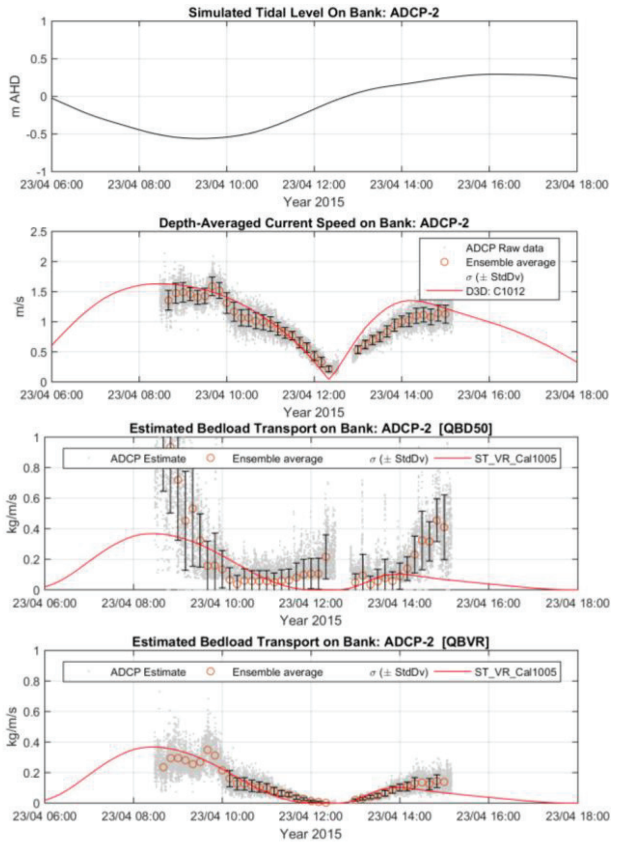


Figure 6. Bedload of calibrated model against field data over the shoal system., location 'ADCP-2'.

Figure 7 shows the correlation of the calibrated model against ensemble-averaged sediment transport estimates at location 'ADCP-2'. Calibration occured by iteratively adjsuting a scaling factor controlling the magnitude of bedload transport obtained by the sediment transport module. Various sensitivity tests adjusting parameterrs such as the bed sediment geometric deviation did not influence the quality of the calibration. The model was calibrated to QBVR, with QBQW used as an independant verification of the estimated sediment transport magnitude. The predictive skill of the sediment transport model against QBVR at ADCP-2 is 0.8 (Van Rijn classification = 'Excellent'), with no bias. The MAE is 0.03kg/s/m. Bedload transport estimated from the bottom tracking information (QBDW) at ADCP-2 is higher than that estimated from QBVR and with a significantly higher level of variability (Figure 6, third panel). Nevertheless, the predicive skill of the model against bedload trasnsport estimated from bottom tracking data is 0.29 (Van Rijn classification = 'reasonable'). The bias against QBDW is -0.1 kg/s/m, which is due to the generally higher transport magnitudes obtained from the bottom tracking data compared to QBVR. The MAE is 0.14 kg/s/m, which reflects the higher level of variability in the sediment transport estimates from the bottom tracking data.

The calibrated sediment transport model was validated against sediment transport estimates obtained over a tidal cycle at a second site on the shoals (site 'ADCP-1', results not shown). The predictive skill of the model was 0.69 against QBVR (Van Rijn classification = 'good'), with 0.0 kg/m/s bias and 0.02 kg/s/m MAE. The MAE against QBDW at ADCP-1 was 0.31 kg/m/s and the bias was -0.31 kg/m/s.

Figure 8 shows residual bedload transport vectors and magnitudes around Portsea and Nicholson Knoll, calculated by simulating a whole number of tides over a 29 day lunar cycle and then scaling the transport to that expected to occur over a year. The results show the spatial variability of the residual transport magnitude and regions of flood and ebb domainance.

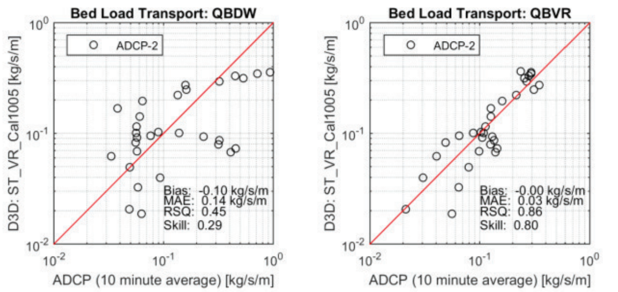
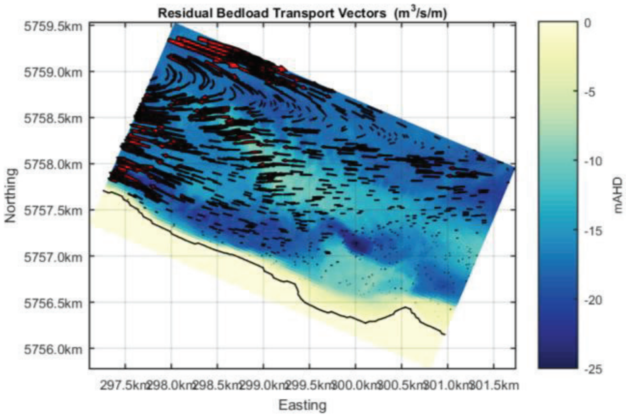


Figure 7. Error of calibrated sediment transport model compared to measured bedload transport estimates.



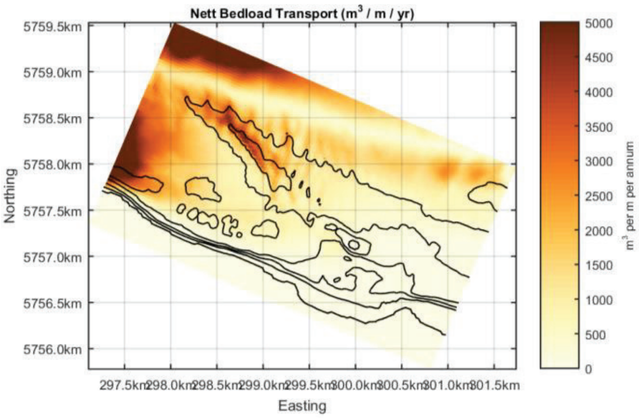


Figure 8. Simulated residual bedload transport pathways (upper panel) and magnitudes (lower panel) over the shoal system .

DUSUSSION AND CONCLUSIONS

This study makes several important and novel contributions to coastal process understanding within the Point Nepean and Portsea región of Port Phillip Bay:

1) We have collected an innovative and robust datase of hydrodynamic and sediment transport observations over a sand shoal system of importance to coastline processes at Portsea. The field data will be maintained by DELWP Victoria for validating numerical models of the Portsea región of Port Phillip Bay.

2) We have measured the performance of a detailed numerical sediment transport system against detailed hydrodynamic and sediment transport observations over the sand shoal. The predictive skill of the model is ≥ 0.96 for water levels within Port Philliip Bay, 0.75 for tidal currents over the shoals, and 0.29 to 0.80 for sediment transport (depending on the measurement method used). Given the difficulties associated with measuring sediment transport in the field, this is considered highly successful.

3) We have shown that the sand bank system comprising Nicholson Knoll exhbits large-scale mobility over unexpectedly short timescales. This rapid morphological response must be driven by the exceptionally strong tidal currents experienced in the región. Until now it had been assumed that although sediment mobility was high, the geometry and position of the banks were relavtively stable. Comparison of bed level changees shows that the relict Calcarenite core of the bank is overlain by a mobile sand layer up to 5m thick.

4) The calibrated model suggests net bedload rates are of the order of 5,000 m^3/ m / annum over the crest of the bank. This implies that individual sand waves will have migrated over distances much further than thier wavelength between LADS surveys presently undertaken bi-annually. This has implications for any prior sediment transport studies of the región that may have been interpeted on the basis of apparent beform migration between bathymetric surveys.

The calibrated model system presented herein is presently being used by the first two authors as a tool to quantify the effects of various potential engineering options for Portsea. The results are informing the efficacy of various coastal managment options in the face of recent coastal change along the shoreline at Portsea.

ACKNOWLEDGMENTS

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