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NUMERICAL MODEL STUDIES TO SUPPORT THE SUSTAINABLE MANAGEMENT OF DREDGE SPOIL DEPOSITION IN A COMPLEX NEARSHORE ENVIRONMENT

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Abstract: The numerical modelling approach used to inform and guide the sustainable management of maintenance dredge spoil within a nearshore environment is presented. Port Otago is one of New Zealand's primary commercial ports and has a recent annual maintenance dredging history of approximately 150,000 m^3. Long term disposal options for these sediments need to consider the sediment budgets for adjacent beaches as well as the quality of surfing conditions at nationally-significant breaks nearby. The port is set within a natural harbour that features strong tidal flows and complex entrance morphology, with a wave climate that is frequently energetic. A multi-scale, multi-model approach, combined with an input-reduction framework, is presented. The modelling effort is supported by an extensive field dataset, including hydrodynamic measurements and historical bathymetries - used to calibrate the suite of models which are subsequently used to characterize the contemporary morphodynamics. The model suite is being used for the planning of future disposal activities that sustain the valued surfing wave conditions as well as providing adequate sediment bypassing.

Context

The site

The Otago Harbour is an elongated shallow inlet opening to the Pacific Ocean, located on the southeast coast of the South Island of New Zealand (Figure 1). This natural harbour hosts a nationally significant port, with an entrance channel that truncates an ebb tide delta. The exposed section of the shipping channel is bounded by a large submerged bar system that extends some 2 km offshore along its eastern side and by a training mole to the west. The entrance region is subject to strong tidal flows. Topographical sheltering from the predominant weather typically results in a moderate wave energy climate at the entrance, but the region remains highly exposed to sea and swell from the Pacific Ocean as well as an influence from far-field long period energy from the Southern Ocean. In the region of the entrance, the complex bathymetry has a profound influence on the local wave transformations and the resultant wave climate at the shore.

The shipping channel has been subject to ongoing maintenance dredging over the last century, and in recent decades the spoil has been placed at three disposal grounds relatively close to the entrance (Heyward's Point, Aramoana and Shelly Beach; Figure 1). This disposal practice has in turn created bathymetric features that have further interacted with the ambient wave fields. A unique aspect of the contemporary harbour entrance dynamics is the combination of specific bathymetric features that produce high quality surfing waves at two sites on the adjacent coastline. These sites have been recognized as being of "national significance", and therefore have a degree of protection under the law.

The project

The aim of the present research was to model and characterize the existing morphodynamics at the existing disposal grounds and adjacent coastal areas and investigate solutions for managing the future disposal activities. The project was based on the implementation of a multi-scale and multi model framework which was supported by an extensive field dataset including wave and current measurements (see Figure 1) as well as historical bathymetries for morphodynamic model validation.

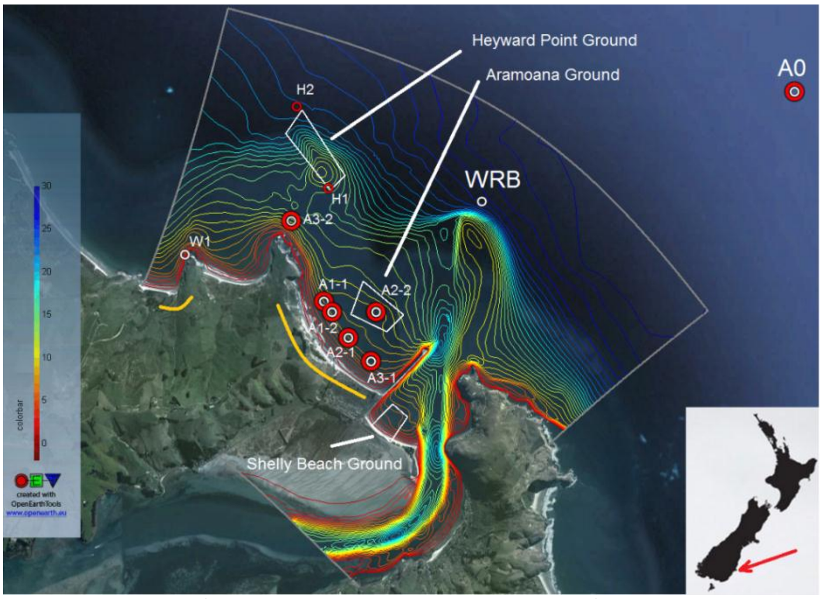


Figure 1. Bathymetry of the Otago Harbour Entrance (South Island of New Zealand). The white polygons are the existing disposal grounds. Note the significant morphological features including the entrance channel, ebb delta bar, and sediment mounds in the disposal grounds. White and red circles indicate positions of wave and current measurements. The gray lines indicate the Delft3D grid extents, and the orange curves indicate the position of high quality surfing zones.

Numerical modelling approach

Characterization of the local-scale coastal processes generally requires detailed information on the regional oceanographic forcings. The base of the model framework consisted of 20-year hindcasts of the waves and currents undertaken at regional and nested to local scale. These long-term datasets allowed a detailed characterization of the large-scale behaviour and the major event forcing. The regional wave modelling was undertaken with SWAN (Holthuijsen, 2007) and an implementation of the Princeton Ocean Model (Blumberg and Mellor, 1987) was used to replicate the depth –averaged coastal currents. High resolution tidal hydrodynamics of the harbour were determined using the finite element model SELFE (Zhang, 2008). These model datasets provided a robust basis for the implementation of a high-resolution morphodynamic model of the harbour entrance and adjacent coasts. The open-source version of Delft3D (Lesser et al., 2004) was used, which allows coupling of wave, hydrodynamics, sediment transport and sea-bed evolution models. The regional wave and current models used regular grids with resolution of ~ 400 m, and the local morphodynamic model used a curvilinear grid over the extent shown in Figure 1. Local model resolution ranged from 50 to 15 m with high resolution in areas of shallower or complex features.

Field dataset

An extensive field measurement program was undertaken, specifically designed to provide the necessary validation basis for the implemented models. Waves and currents were measured at positions throughout the study site (see Figure 1), with a particular interest on the wave transformation process and the resultant nearshore wave-driven circulation. In addition, a set of annual historical bathymetries of the existing disposal grounds from 2002 to 2010 allowed quantitative analysis of sediment dispersion and therefore a rare opportunity to quantitatively calibrate the morphodynamic model.

Input reduction for morphological modelling

The main challenge with applying process-based models to predict morphological evolution is that the morphological behaviour of a coastal system generally develops over time scales several orders of magnitude larger than the time scale of the hydrodynamic fluctuations driving the sediment transport (i.e. hours to days versus months to years). This potentially implies long-term simulation of instantaneous hydrodynamics and sediment transport which is often too computationally expensive. Instead several strategies are commonly applied to simplify and accelerate the modelling of medium to long term morphological evolution (i.e. de Vriend et al., 1993, Roelvink, 2006). The approach employed in this study combined the reduction of the input forcing (i.e. wave and tides) with the use of morphological factors, which is one of the most commonly applied methods (e.g. Dastgheib, 2012; Grunnet et al., 2004; Lesser, 2009).

The basis for tidal input reduction is to find a *representative* tide that most closely reproduce the net and gross sediment transport as the naturally varying tides over the region of interest and for the time period considered. In the present study, the *representative* tide was determined following the approach of Latteux (1995), which consists in matching the long term net tidal transport with a single tide. Here, sediment transport was considered as a simple power law (e.g. Engelund and Hansen, 1967, p=5) to capture its strong non-linearity. The analysis was undertaken for several control sites throughout the harbour entrance area where the underlying tidal sediment transport is expected to be the most significant. The comparison process yielded a *representative* tide consisting of an M2 signal (~12.5 h. period) with an elevation range 9% larger than the mean range, which is consistent with expected values (5-20 %, e.g. Grunnet et al., 2004; Lesser, 2009). The tidal forcing was applied at the open model boundaries as water level to the northeast and southwest and as gradient type boundaries (i.e. Neumann) along the cross-shore limits.

The approach employed for reduction of the wave forcing followed the guidance provided in Lesser (2009) and Walstra et al. (2013). A set of representative wave classes is defined by distributing the discrete wave data points into a finite number of height and direction bins, and computing a *representative* value for each bin. Here the classification was applied on wave time series extracted a site on the offshore wave model boundary for the entire 20 year hindcast, or for individual years depending on the application.

The basic method to determine a representative value within a bin is to use a weighted average of the data points by their frequency of occurrence:

$$F_{rep,j} = \frac{\sum_{i=1}^{n} f_i . F}{\sum_{i=1}^{n} f_i} \tag{1}$$

where F represents the wave height, period or direction, f is the frequency of occurrence of the wave condition i and n is the number of data points within a bin.

To account for the non-linear dependence of sediment transport on wave height, an additional weighting can be applied for the computation of the representative height:

$$H_{s,rep,j} = \left(\frac{\sum_{i=1}^{n} f_i \,.H_{s,i}^{p}}{\sum_{i=1}^{n} f_i} \right)^{1/p} \tag{2}$$

where p is the power to which the sediment transports are assumed to be related to the wave height (typically p=2 to 3). The exponent p ensures that larger waves will have a relatively greater contribution in the computation of the representative wave height. Here Equation (2) was used with a value of p = 2.5 which corresponds with the CERC formula for longshore transport (CERC, 1984) and is frequently used to estimate the morphological impact of waves. Associated representative periods and directions were determined using the same weighting as the wave height.

The initial choice for wave data binning is typically arbitrary and can be equidistant or non-equidistant (i.e. varying bin size). Here, non-equidistant wave height and directions delimitations were defined so that the relative "morphological impact of waves" (Lesser, 2009) was constant in each bin. The indicator, which is also referred to as "potential sediment transport" in Dastgheib (2012) was computed as:

$$M_j = p_j \,. H_{s,rep,j}^{2.5} \tag{3}$$

where p_j is the probability of occurrence of the bin j, and $H_{s,rep,j}$ the representative wave height of that bin.

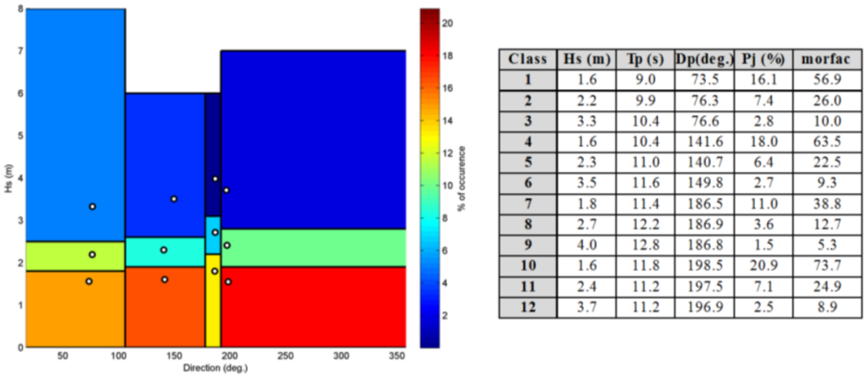
To bridge the gap between hydrodynamic and morphological timescales while conserving reasonable computing times, the reduction approach was combined with the use of morphological acceleration factors ("morfac" hereafter) (Lesser et al., 2004). The technique consists in multiplying the calculated depth changes over a hydrodynamic time step dt hydrodynamic by a constant factor f_{MOR}, effectively predicting morphological changes over a period $t = f_{MOR} \,.dt$. Such an approach has obviously limits and involves many implicit assumptions (including linearity of changes) but it has been found to provide a useful method to estimate medium-term morphological evolutions of tidal (e.g. Van der Wegen and Roelvink, 2008) and mixed tide and wave environments (e.g. Grunnet et al., 2004; Lesser, 2009; Reniers et al., 2004).

Each of the representative wave conditions were simulated for the duration of one complete tidal cycle to account for the naturally random phasing between waves and tides. A morphological acceleration factor specific to each wave class was defined so that the morphological duration of the wave class matches its probability of occurrence within the period considered. The morphological factor is computed following:

$$f_{MOR} = \frac{p_j \, . \, Period\ Duration}{T_{morph\ tide}} \tag{4}$$

where p_j is the probability of occurrence of wave conditions falling in the wave class (or bin) j, “Period Duration” is the total duration to be simulated, and $T_{\text{morph tide}}$ is the duration of the representative morphological tide (M2 period ~ 12.5 hours).

The approach was applied to simulate the morphological behaviour of the existing disposal sites over a 6-month period. An example of wave classification determined from the 20 year time series is illustrated in Figure 2. Note it was decided to model a 6-month period rather than a full year to keep morfacs much smaller than 100 which is the suggested safe limits given the available experience (e.g. Lesser, 2009, Ranasinghe et al., 2011).



Class	Hs (m)	Tp (s)	Dp(deg.)	Pj (%)	morfac
1	1.6	9.0	73.5	16.1	56.9
2	2.2	9.9	76.3	7.4	26.0
3	3.3	10.4	76.6	2.8	10.0
4	1.6	10.4	141.6	18.0	63.5
5	2.3	11.0	140.7	6.4	22.5
6	3.5	11.6	149.8	2.7	9.3
7	1.8	11.4	186.5	11.0	38.8
8	2.7	12.2	186.9	3.6	12.7
9	4.0	12.8	186.8	1.5	5.3
10	1.6	11.8	198.5	20.9	73.7
11	2.4	11.2	197.5	7.1	24.9
12	3.7	11.2	196.9	2.5	8.9

Figure 2. Example of wave climate classification based on the 20 year hindcast, and associated morfacs. White dots on the left figure are the representative wave parameters of each bin.

Results

An initial validation step was undertaken on the wave and current hindcasts to ensure the information used for input reduction and morphological simulations at the local scales were valid. Both hindcasts were validated using the data from site A0 and were found to faithfully replicate the measured wave and current events (not reproduced here). Interestingly, the current regime at the site was found to be highly variable with frequent reversals which contrast with the large-scale northward flow which is expected further offshore due to the geostrophic Southland Current flowing up the southeastern coast of New Zealand (Brodie, 1960). Model predictions suggest that this is due to an anticlockwise meso-scale eddy developing in the bay north of the peninsula including the A0 site.

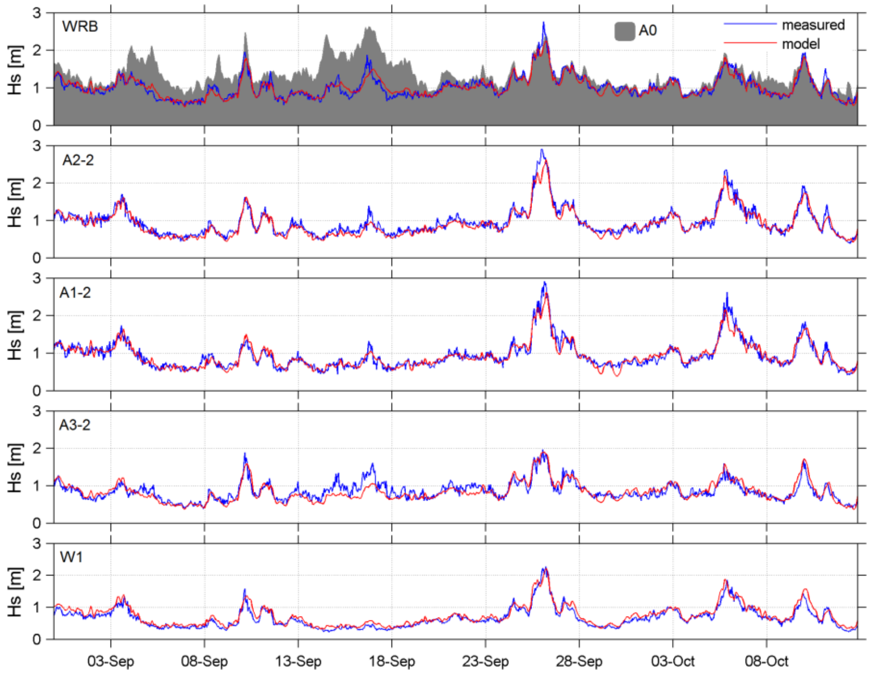


Figure 3. Measured and modelled significant wave heights at sites shown in Figure 1. The model correctly reproduces wave transformation along the axes WRB/A3-2/W1 and WRB/A2-2/-A1-2.

The residual current magnitudes at the harbor entrance were relatively small so no residual current were included in the morphological simulations. The complex bathymetry has a significant effect on the incoming wave field at the local scale, notably with intense wave refraction and focusing developing over the submerged delta bar and dredged mounds (see Figure 6 for example). These wave focusing zones are key features of the wave field pre-conditioning that eventually creates high quality surfing waves along the coast. The two instruments transects from the offshore to the coast in the lee of the existing disposal grounds (A0/WRB/A3-2/W1, and A0/WRB/A2-2/A1-2) were used to further verify that the local wave transformation was correctly reproduced by the Delft3D wave module (SWAN). The deployment period captured several energetic events with Hs>2 m (Figure 3, top) with various offshore direction. The differences in resulting wave energy at the WRB position for similar wave height at A0 are indeed explained by contrasting offshore direction (southerly versus northeasterly) and resulting sheltering effect from the adjacent Otago Peninsula. The wave conditions measured at A0 were directly applied as boundary conditions to a larger scale wave grid inside which the Delft3D grid was nested. Measured and predicted significant wave heights are in good agreement indicating that the model correctly reproduces the wave height gradients developing as the wave field propagates over the complex bathymetry towards the shore.

The bathymetric dataset covering the existing disposal grounds provided some valuable empirical information on the morphological behaviour of the disposal ground. The bathymetry sequence and associated seabed level changes are provided in Figures 4 and 5. The bathymetries clearly indicate the disposed sediment is mobilized, with an onshore migration at the Aramaona ground and a westward movement at the Heyward ground. The successive bathymetries were analyzed to provide volumetric changes of the grounds over the different periods. The net annual volumetric ground changes were estimated by subtracting the recorded disposed volumes from the raw ground volume changes, and converting to an annual time base pro-rata of the period duration (Table 1). These volumes provided validation targets which were used to sensitivty-test and tune the morphodynamic model. Note the progressive reduction in sediment dispersion form the Aramoana ground is due to a significant reduction of disposed volumes from 2007 onwards (Table 1) which resulted in a smoothing of the mound (Figure 4) and reduction of its dispersal potential.

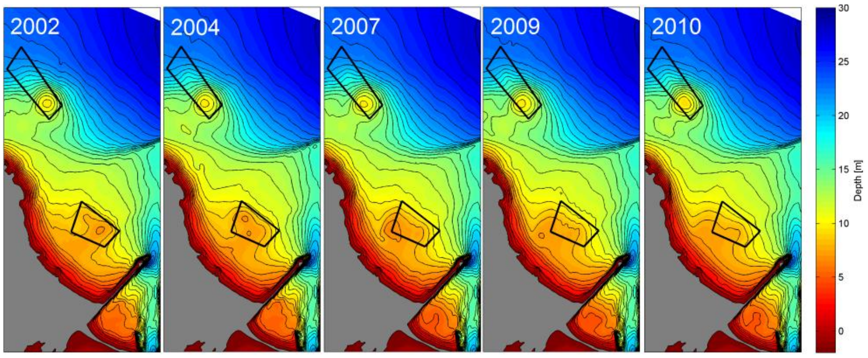


Figure 4. Historical bathymetries of the existing disposal ground from 2002 to 2010. Disposal grounds are shown in black.

Table 1. Volumetric changes of the Aramoana and Heyward disposal grounds. A negative volume means a net sediment loss from the ground.

	Volumetric change Aramoana [m^3/yr]	**Volumetric change Heyward Pt [m^3/yr]**	**Disposed Aramoana [m^3/yr]**	**Disposed Heyward Pt [m^3/yr]**
Sept. 2002 - Sept. 2004	-87241.3	-11095.7	95378.8	39459.2
Sept. 2004 - Aug. 2007	-118779.9	-29488.9	88996.5	23445.3
Aug. 2007 - Jan. 2009	-121014.1	-48740.4	39665.6	54878.1
Jan. 2009 - May 2010	-53479.5	-15795.8	23861.3	76436.3
May 2010 - Oct. 2013	-55096.7	-47504.5	14068.4	134282.0

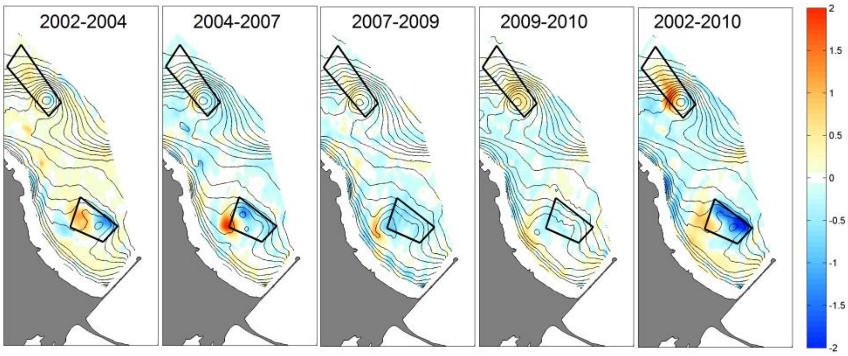


Figure 5. Measured sea bed level changes over several intervals from 2002 to 2010.

The morphodynamic model includes several modules that each has a set of parameters that can potentially be adjusted to tune model prediction. Here, the sensitivity testing focused primarily on the effects of the sediment transport formulations used to compute the sediment transport fluxes based on the instantaneous hydrodynamic forcing, which is often the most significant. Different formulations often use different sub-process parametrizations and assumptions to predict transport fluxes which, in practice, can result in different transport fields and bathymetries. Correct transport fields are critical since they directly govern the morphological adjustments, even to greater extents when used in combination with morfacs. The sensitivity testing focused on 3 formulations appropriate in situations with tides and waves, namely van Rijn (2007 a,b) (VR07) that is used as default in Delft3D, Bijker (1971) (BJK), with wave asymmetry effects included following the approach of Bailard (1981), and Soulsby-van Rijn (Soulsby, 1997) (SVR). Model parameters were set to default or recommended values and a median grain size d_{50} of 250 µm was used. Note that only the VR07 and BJK formulation include wave asymmetry effects which are expected to be significant for the study site given measured morphological adjustements (Figure 5). Sensitivity testing was undertaken for a 6 month period between 2007 and 2009 for which measured bathymetries and quantitative volumetric dispersal were available. An average wave climate representative of that period was used.

Predicted patterns of bathymetric changes were relatively consistent for the three formulations (Figure 7) but some variations in magnitudes of changes were present. Predicted volumetric changes of the mounds converted to an annual basis are provided in Table 2. Sediments are mobilized on the exposed slopes of the submerged delta bar east of the harbour entrance and deposit on the lee-side bar slopes. This process is likely enhanced by the ebb tidal jet which disrupts and helps locally counter the ambient westwards transport to sustain the bar. Sediment erosion is predicted over the end lobe of the delta bar (Figure 6),

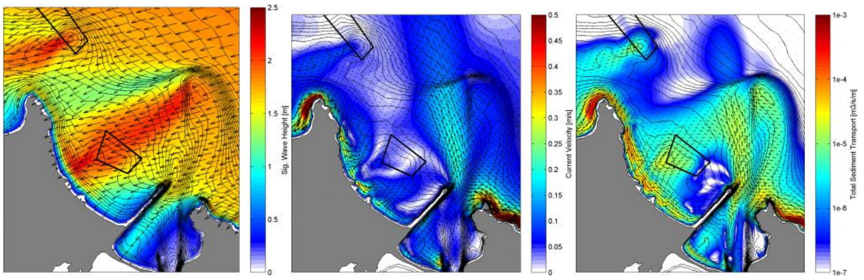


Figure 6. Predicted mean wave, circulation and sediment transport fields for event 2 (see Figure 2) of a 6-month accelerated simulations using the VR07 formulation.

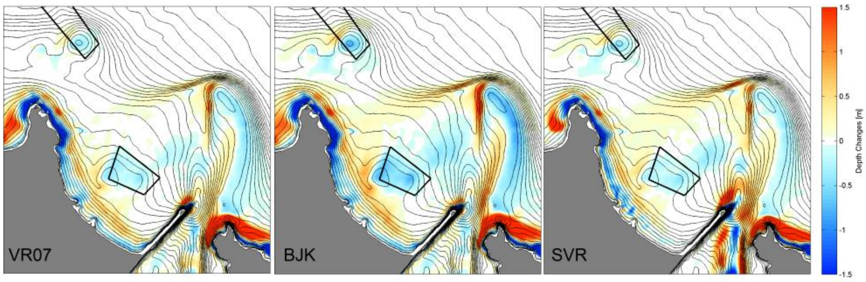


Figure 7. Predicted morphological changes after an accelerated 6 month-simulation using the VR07, BJK, and SVR formulations.

Table 2. Predicted volumetric changes over the disposal grounds for the different transport formulations. Note the 6-month resulted were converted to an annual basis.

Transport Formulation	Wave Climate Period	Initial Bathymetry	Volumetric change Aramoana [m^3/yr]	Volumetric change Heyward [m^3/yr]
VR07	2007-2009	2007	-100834.0	-21966.0
BJK	2007-2009	2007	-212480.0	-38858.0
SVR	2007-2009	2007	-93568.0	-11410.0

and is associated with significant deposition along the channel eastern edge, which is where most of the maintenance dredging is undertaken. Important bathymetric changes were predicted within the channel for the SVR simulation but not reproduced by the others. The erosion consistently observed throughout the Aramoana ground (Figure 5) was reproduced by the models with the largest bathymetric changes being predicted over the shallowest parts of the mound, where the wave entrainment of sediments is enhanced. Both the VR07 and SVR formulations yielded volumetric changes in good agreement with the measured targets while BJK predicted volumes twice as large. Along the shore, model consistently predicted sediment erosion along the northwest end of the beach with an associated accretion past the point which is a likely westwards transport pathway out of the Aramoana beach system. At the Heyward ground, the model consistently predicts erosion of the well-defined circular mound, with the mobilized sediment migrating southwestward. The disposal of dredged sediment throughout the ground complicates the direct comparison with the measured bathymetric changes over that period (Figure 5, ~70k m^3 disposed over the period), however, it is clear from the longer term bathymetric changes from 2002 to 2010 that such westward sediment migration is occurring at the site. A volumetric loss of ~20k m^3 /year was predicted using the VR07 which is smaller than estimated from bathymetries (~50 k m^3). BJK predicts again volumes twice as large as VR07, while SVR volumes are twice as small, which can likely be attributed to the absence of wave asymmetry scheme.

Here, the apparent under-prediction of the sediment dispersal using the VR07 formulation may be related to limits in the method employed to estimate volumetric targets. Exact dumping records were not kept, but the anecdotal evidence is that material was preferentially placed in the shallow southeast end of the ground thus creating an elevated mound that will more effectively erode and become transported out of the ground as sediment is progressively disposed. This process is not accounted for in the model which is initialized from a pre-dumped bathymetry and therefore likely produces results that are conservative. It is interesting to note that the SVR formulation that accounts for wave effects in a relatively simple way was still able to reproduce morphological changes that are in qualitative agreement with both measured evolutions and predictions using the more sophisticated BJK or VR07 schemes. This suggests that the spatial gradient in wave orbital velocity magnitudes, which matches wave patterns, is an important process in the development of the site morphology. Subsequent testing efforts mostly focused on the VR07 formulation given the correct agreement with measurements and available options to tune the formulation. Additional tests were undertaken to assess model sensitivity to a range of parameters including balance of wave-current / bed-suspended transport fractions, slope correction, available mass of sediment, net tidal flows in and out of the harbour. These are not presented here reasons of constraint.

As a final validation test, several simulations were undertaken initializing the model with different historical bathymetries. The reduced wave climate applied was either defined from the actual period when possible or the mean wave climate defined from the 20 year hindcast. Results are summarized in Table 3. The predicted volumes for the entire Heyward ground consistently remains in the 20-30k m^3 range which is in generally smaller than measured estimations, likely due for the absence of an active mound (i.e. subject to continuous disposal) as mentioned above. That being, further analysis of the historical bathymetric datasets suggested that the long-term dispersal potential of the shallower part of Heyward ground (depth< 15 m i.e. circular mound) which is where most of the transport occurs in the model was typically in the 20-30k m^3/year range. Importantly, the model correctly reproduces the significant dispersal reduction estimated from measurement from 2009 onwards (down to ~50k m^3). The model suggests a further dispersal reduction for the most recent morphology of 2013 with a highly-smoothed deposition mound at Aramoana.

Table 3. Predicted volumetric changes for different model initializations using the VR07 formulation.

Transport Formulation	Wave Climate Period	Initial Bathymetry	Volumetric change Aramoana [m^3/yr]	Volumetric change Heyward [m^3/yr]
VR07	2007-2009	2007	-100834.0	-21966.0
VR07	2009-2010	2009	-56500.0	-23700.0
VR07	Long Term (20 y.)	2010	-43014.0	-25338.0
VR07	Long Term (20 y.)	2013	-20807.0	-24452.0

Conclusion

The numerical modelling approach employed to implement and validate a morphodynamic model of the existing disposal grounds in the Otago Harbour Entrance region has been presented. The aim was to provide a robust tool to characterize the existing wave, circulation and sediment dynamics and to plan future disposal activities. Regional wave and current hindcasts of 20-years duration provided quality information on the relevant system forcing and an input-reduction framework was used to simulate the morphological behavior of the disposal grounds over a 6-month period. The model validation process was supported by an extensive field dataset. Wave and hydrodynamic measurements were used to verify the regional hindcasts, as well as validating the local wave model, and historical bathymetries provided a rare opportunity to sensitivity test the morphological model, including effects of various sediment transport formulations (VR07, BJK, SVR). The sensitivity testing indicated the importance of spatial gradients in wave orbital velocity magnitude due to the complex underlying bathymetry. The comparison process yielded a relative consistency in predicted morphological patterns but revealed possibly large variations of quantitative results. The final model implementation, using the VR07 formulation, was able to correctly reproduce the qualitative and quantitative aspects of the measured sediment transport, thereby providing a valuable tool for assessing the future disposal activities following channel deepening.

Acknowledgements

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