Port of Otago Dredging Project: Preliminary Hydrodynamic Modelling and Scoping Further Work

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Executive Summary

Project Next Generation is an initiative by the Port Otago Ltd. to expand the capability of Port Chalmers through a substantial channel deepening capital works programme.

As part of Project Next Generation, Port Otago Ltd. (POL) commissioned NIWA to carry out a preliminary study of the hydrodynamic effects of proposed deepened channel reconfigurations. This report gives details of the modelling component of this work and provides POL and stakeholders with an initial understanding of:

- the main hydrodynamic effects of the proposed shipping channel configurations, particularly changes in velocities, tide heights and tidal phasing within Otago Harbour compared to the present situation;

- the degree of spread (dispersion) and likely concentrations of suspended-sediment plumes from the dredging operations;

- an approximate assessment of the likelihood of wave and current re-suspension of dredged material from a dredge spoil ground offshore.

DHI Environment's MIKE21 modelling package was applied to Otago Harbour and environs of the approach channel. Preliminary MIKE21 simulations for this report were undertaken on a coarser 100×100 m grid of square cells, where the nodes of the grid represents the bathymetry of the area.

The initial results reported here are based on <u>uncalibrated</u> hydrodynamic and dispersion models of Otago Harbour, using existing bathymetry (from nautical charts and soundings supplied by POL) and offshore boundary conditions derived from existing (1988) field data from Landfall Tower. An attempt is made to compare some of the results with past field measurements to provide an indication of the accuracy of these preliminary hydrodynamic model simulations. For the dispersion model, typical spreading rates (dispersion coefficients) from other New Zealand harbours have been used and a very conservative assumption was made to not allow the suspended sediment to settle anywhere. Rigorous calibration or tuning of these models will require a further set of field data to be collected during the detailed AEE investigations.

A preliminary comparison of the additional hydrodynamic effects that could occur with a deepened shipping channel was achieved by running the hydrodynamic-flow model for 18 different scenarios, varying the tide type (neap and spring), winds (calm and 20-knot SW and NE winds) and then re-running these scenarios for the two proposed deepened-channel configurations (14-m and 15-m deep). A comparison of the results to isolate the differences on the Harbour tides and currents due to dredging the main channel is complicated by a small advance (or in some wind conditions a small lag) in the timing of high and low tide with a deeper channel. This produces an "apparent" difference in

velocity or tide height at any particular time which is somewhat larger than the "actual" difference between the respective low or high tide levels or peak ebb and flood tide velocities if the tide phase shift is taken into account. It is the latter "actual" differences that are more realistic when considering changes in sediment transport and effects on ecosystems rather than also including a slight timing phase. We present results that show both the "apparent" differences and the smaller realistic "actual" differences, along with the likely magnitude of the tidal phase (timing) change.

A comparison of the dispersal effects of sediment plumes, which would originate from dredging operations, was achieved by running the dispersion model for 3 different scenarios. These covered the following situations (all assuming a continuous 6-hour dredging period over a half tide (ebb or flood) and then tracking the plume for a further 2 tidal cycles):

- sediment discharge source from dredging in Port Chalmers turning basin on flood tide, based on existing channel configuration (i.e., at commencement of dredging programme), a spring tide and a 20 knot NE wind (*this will show the furthest penetration of sediment plumes into the Upper Harbour*);

- sediment discharge source from dredging in Port Chalmers turning basin on ebb tide, based on new channel configuration, a neap tide and calm conditions (*this will show the slowest dispersal of sediment plumes in the Lower Harbour*);

- sediment discharge source from dredging in Howletts Claim (near the offshore mole) on flood tide, based on new channel configuration, a neap tide and calm conditions (*this will show dispersal of sediment plumes back into the Lower Harbour*).

The second component of the Brief was to assimilate available information on currents and waves offshore from Taiaroa Head and provide an approximate estimate of wave conditions and the frequency with which they would be sufficient to re-suspend material from an offshore dredge spoil ground, as well as the approximate directions the re-suspended fine-sand material would be transported. For demonstration purposes, a provisional spoil ground site, 3 nautical miles (5.6 km) off Taiaroa Head, was used to assess the frequency of resuspension of dredgings. The wave analysis was based on a back-prediction of wave conditions off Taiaroa Head for the 20-year period from 1979–1998 calculated using NIWA's wave model of the SW Pacific driven by analysis winds from a global weather model.

The third component of the Brief was to submit a detailed proposal to POL outlining additional field measurements and computer modelling that would be needed to support the AEE investigations and reporting. This component is still under development and discussion with POL, but overall summaries of the types of additional field and modelling investigations that may be required are provided in this report at the end of each of the relevant Sections.

The key findings

The main findings of effects of the 15-m deep dredged shipping channel, relative to the present channel regime, can be summarised as follows:

- *Ebb and flood tide duration*—for the existing situation, the main Harbour channel is flood-dominant in relation to flood-tide velocities being greater than ebb-tide velocities due to the shorter flood tide. This pattern is emphasised more on a spring tide. A 15-m deepened channel would alter flood-tide durations by no more than 0–3 minutes (mostly an increase in duration) on a spring tide, with a compensating alteration to the ebb-tide duration.

- *Tide phase timing*—small differences would occur in the timing of high or low tide with a 15-m deepened channel, mostly through a slight advance (i.e., high or low tide occurs slightly earlier), because the tidal wave travels slightly faster in deeper water. The tide phase change would be largest on spring tides. The highest change would only be an average 7-minute advance in high or low spring tide that would occur in the upper section of the Harbour (e.g., Ravensbourne and Dunedin). The average spring-tide phase advance would then gradually reduce towards the Entrance, from 5 minutes advance at Port Chalmers, 3 minutes at Harington Bend, to be negligible off the Spit Jetty.

- *Water levels*—for the 15-m channel configuration, small "apparent" differences would occur in water levels at main-channel sites throughout a tidal cycle for a given clock time of between 0.01–0.07 m compared to the situation with the existing navigation channel. The largest "apparent" differences would occur in the Upper Harbour (Dunedin, Ravensbourne) reducing to 0.01 m at the Entrance, mirroring the spatial reduction in tidal phase change down the Harbour (see above). However, the "actual" differences in low or high tide heights attained would be much less at no more than 0.01–0.02 m at selected sites along the main harbour channel when the phase shift in the timing of low and high tide is taken into account.

- *Harbour currents*—reasonably small "actual" differences would occur in the magnitude attained for peak (maximum) ebb or flood current velocity (no wind scenarios) of mostly less than ±0.02 m/s (±0.04 knots) at most channel sites, with negligible changes at Dunedin and off Spit Jetty (Entrance). The exceptions would be increases in peak-ebb speed of up to 0.06 m/s (0.12 knots) off Port Chalmers and 0.03 m/s (0.06 knots) in peak-flood speed at the Harington Bend site, all on a spring tide. These differences have only been tested at 6 selected sites along the main channel system, so maybe somewhat different over the intertidal sandflats or on the flanks of the channel. The latter uncertainties can be addressed when the hydrodynamic model is upgraded in the next phase of the investigations with more extensive intertidal bathymetry and higher model-grid resolution and subsequently calibrated against field data for the existing-channel situation.

- *Dispersion of sediment plumes*—while only indicative, the results show that reasonable dilution of suspended sediment concentrations will occur, although the rate of sediment settling is yet to be determined, and hence not allowed for at this stage. The ebb tide (Port Chalmers) and Howletts Claim simulations show that the bulk of the sediment plumes would stay within the main channel. However for the flood-tide dispersal simulation (Port Chalmers turning basin discharge) there would be considerable dispersion over the middle part of the Upper Harbour, mainly by way of the north-south channel from Kilgours Point through to Grassy Point [see Figure 1, Section 1 for locations].

For the offshore spoil ground, based on a possible site 3 nautical miles off Taiaroa Head, the preliminary findings are:

- 0.2 mm diameter sand (around the median size) in the spoil mound is expected to be resuspended by waves approximately 14% of the time in total, during an average of 23 separate resuspension events per year or approximately once per fortnight;

- the finer 0.1 mm diameter sand fraction is expected to be resuspended by waves around 23% of the time in total, during an average of 31 separate resuspension events per year;

- the finer still silt and mud fractions are not considered here, but the fate and movement of the remaining silt and mud that wasn't dispersed during descent of the dredgings, will need to be considered in the detailed phase of the AEE investigations;

- the predominant residual current (or drift) off Taiaroa Head is to the north, so during the wave resuspension events, sand will be winnowed out of the surface fabric of the spoil mound and moved mostly north to north-east by the prevailing current flow at the seabed.

<u>Next stage (summary of general requirements for modelling and field work)</u>

The hydrodynamic model of the Harbour will need to be refined at a smaller grid size (down from the present 100 m) to better represent modifications to the channel by dredging and improve current speed predictions at the channel bends (e.g., Harington Bend), between islands (e.g., Goat and Quarantine Islands) and in smaller channels. (This refined grid size will also be useful for ship-handling simulations.) Part of this refinement would need to include the assimilation of additional topography (bathymetry) of the intertidal areas from LiDAR and aerial photogrammetric surveys, which at present is poorly represented in the Harbour model.

Then the revised Harbour model will require calibration (tuning) against field measurements (tide heights and currents), then verification of its performance on a second set of field data without changing any of the model parameters. This necessary step would provide greater assurance to stakeholders and the Port Company that the model is working correctly, and is able to predict

subsequent changes in the hydrodynamics from modifications to the navigation channel. Tide-height data for this exercise would available from the existing Port gauges (Spit Jetty, Port Chalmers, Dunedin). Current velocity data for calibration would be used from a mixture of current-meter data from past harbours studies (e.g., the 1988 Harbour Board model study and University of Otago deployments), supplemented by some new velocity measurements on the flanks of the existing main channel and possibly an inter-tidal site.

For sediment-plume dispersion investigations, determining representative values for sediment characteristics (such as settling rates for different grain sizes) and plume dispersion coefficients will be the key to successfully modelling the spread and final settlement of sediments released during the dredging operation. The plume model relies on the hydrodynamic model for input current velocities and the effects of winds, so improvements in resolution of the Harbour model will flow through to improved transport and dispersion of sediment plumes. Plume-dispersion scenarios will need to be constructed to cover the expected range of environmental and dredging conditions likely to occur at different stages of the project.

To support environmental assessments in the offshore-shelf area arising from the dredged-material disposal, detailed field work offshore involving wave and current measurements and associated hydrodynamic and wave modelling will be required. Measurements of currents and waves should be undertaken concurrently at strategic sites offshore over a period of 3–6 months. An offshore-shelf model at around 200-m grid spacing would need to be developed to simulate currents in the shelf area including Blueskin Bay. Such as model would need to include predictions of the variable Southland Current and the downstream plume of the Clutha River, which would be the most expensive part of the modelling investigations.

Wave modelling on the same offshore-shelf model grid would also be used to ascertain the physical effect on inshore wave heights and directions as a result of wave passage over the extensive offshore spoil mound, particularly under swell conditions. The currents and waves from both these calibrated models can then be combined to quantify the pattern and direction of long-term movement of sediments away from the offshore spoil mound and the smaller inshore spoil grounds.

1. Introduction

1.1 Project Next Generation

Project Next Generation is an initiative by the Port Otago Ltd. to expand the capability of Port Chalmers through a substantial channel deepening capital works programme.

As part of Next Generation, Port Otago Ltd. (POL) commissioned NIWA to carry out a preliminary hydrodynamic model study of Otago Harbour to assess the degree of effects on the tides and currents of the Harbour from the proposed deepened channel reconfigurations.

This report outlines the observed hydrodynamic features of Otago Harbour in its present configuration and the preliminary modelling that was undertaken to estimate the effects of deepening the main shipping channel. The Report provides POL and various stakeholders with an initial appraisal of the degree to which the hydrodynamic characteristics of Otago Harbour could change with the proposed shipping channel configurations, focusing on changes in velocities, flows through the Harbour entrance, tide heights and the timing (phasing) of high and low tides.

DHI Environment's MIKE21 modelling package was applied to a grid of Otago Harbour and environs of the approach channel that represents the bathymetry of the area. The preliminary results reported here are based on an uncalibrated hydrodynamic model of the harbour which used existing bathymetry (from nautical charts and soundings previously supplied by POL) and offshore boundary conditions derived from existing (1988) field data from Landfall Tower.

A general location map of Otago Harbour is shown in Figure 1.

1.2 The Brief

The key priorities for the hydrodynamic component of the preliminary dredging investigations are:

- to provide an approximate understanding of the main hydrodynamic effects on Otago Harbour, such as net changes in velocities, the flows through the entrance, tide heights and the timing of high and low tide;

- where possible, comment on hydrodynamic (current and wave) conditions relating to offshore/shelf effects from dredged material disposal;

- scope out further work in the hydrodynamic field and modelling components that will be required for the detailed environmental assessment phase of the project.

The work content for the Report covers four areas:

1.2.1 Hydrodynamic modelling

Undertake a suite of preliminary (uncalibrated) hydrodynamic model simulations for Otago Harbour, using an existing 100 m model grid to simulate 18 combinations of:

- Tide type—neap and spring range (2 model runs);

- Winds—calm, persistent 20 knot SW, persistent 20 knot NE (3 runs);

- Channel configuration: i) existing channel depth at 13.0 m below CD; ii) proposed channel depth to 14.0 m below CD; and ii) proposed channel depth to 15.0 m below CD, all with relevant batter slopes as supplied by POL (3 options).

Differences between flow velocities and tide heights at selected sites in the channel and on the sand flats for the two proposed channel configurations (14.0 and 15.0 m below CD) and the existing baseline channel depth (13.0 m below CD) will be plotted for the same tide/wind combination.

1.2.2 Dispersion modelling

Undertake the following 3 preliminary (uncalibrated) sediment plume dispersal model simulations for Otago Harbour, using flows from a few selected scenarios of the hydrodynamic model outlined above. Simulations will only be carried out for a <u>“conservative tracer”</u> i.e., no settling or decay of suspended sediment (only dispersion and dilution). Three scenarios simulated would be:

Scenario 1 (penetration of upper Harbour–fast plume movement)

Existing channel configuration, spring tide, 20 knot NE wind, dredge-induced discharge source of suspended sediment in Port Chalmers turning basin for all

of flood tide (6-hr discharge), then shut off discharge and track plume for 2 tidal cycles;

Scenario 2 (effect on lower Harbour–slow, spreading dispersion)

New channel configuration, neap tide, calm, dredge-induced discharge source of suspended sediment in Port Chalmers turning basin (same discharge site as above) for all of ebb tide (6-hr discharge), then shut off discharge and track for 2 tidal cycles (although the plume may cross the offshore model boundary before then);

Scenario 3 (effect on lower Harbour–slow, spreading dispersion)

New channel configuration, neap tide, calm, dredge-induced discharge source of suspended sediment in Howletts Claim (west of Taiaroa Head) for all of a flood tide (6-hr discharge), then shut off discharge and track for 2 tidal cycles (although may run out offshore model boundary before then).

1.2.3 Offshore overview

Synthesize the available information on currents and waves in the waters offshore from Taiaroa Head and provide an approximate estimate of wave conditions and the frequency with which they would be sufficient to re-suspend material from the offshore dredge spoil ground, as well as the approximate directions the resuspended fine-sand material would be transported.

1.2.4 Scope work for AEE (Assessment of Environmental Effects)

Scope out the hydrodynamic field and modelling work required to support the development of the AEE technical reports and provide indicative prices and time-lines to POL. Note: This aspect of the project is still under development and discussion.

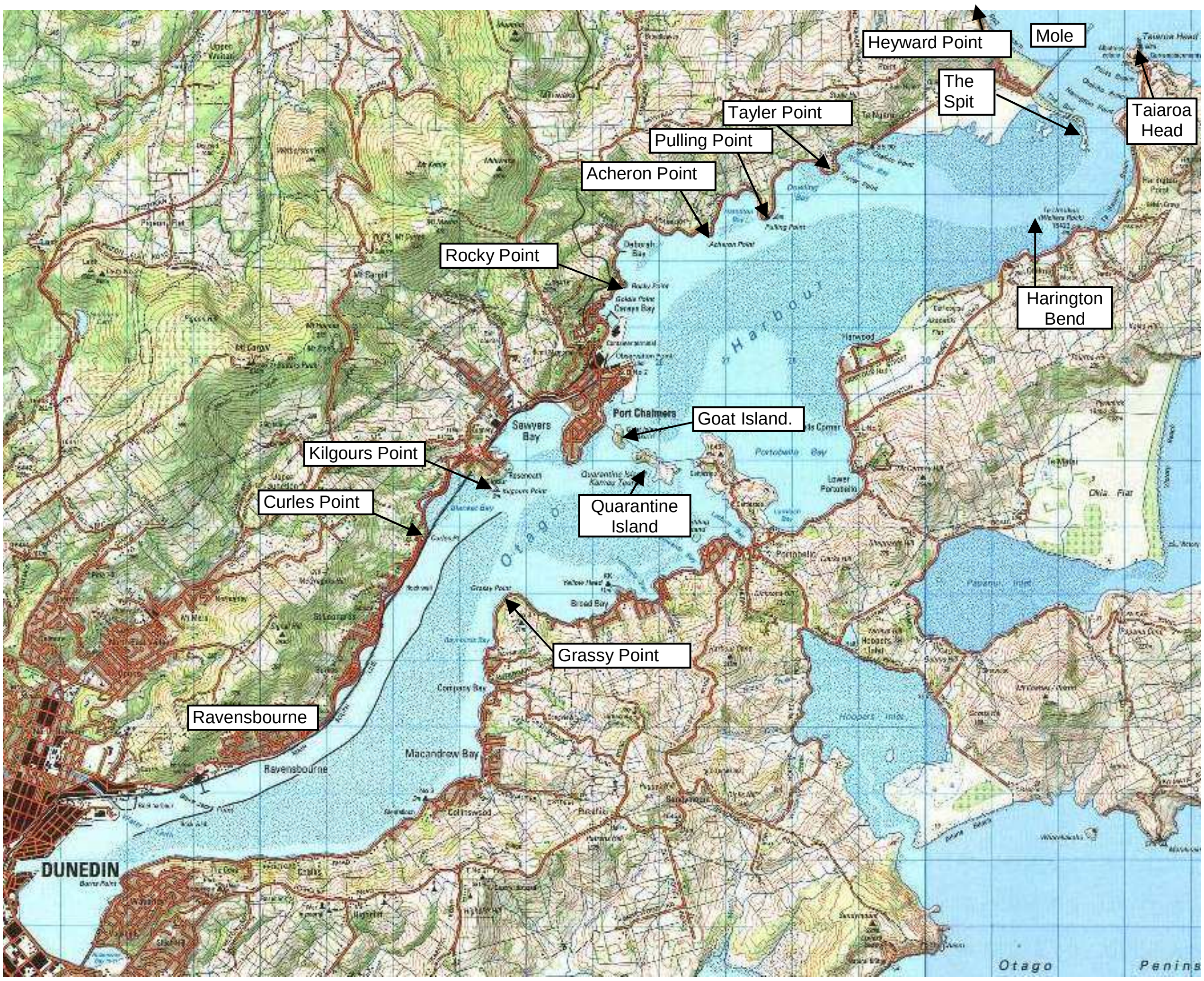


Figure 1: Geographical sites in Otago Harbour [*Source:* ©LINZ 1:50,000 topographic maps].

2. Hydrodynamic model set-up

2.1 Channel configuration

A 100 m bathymetry grid was developed for this study based on the existing channel bathymetry (previously supplied by POL) and from previously digitized data and chart soundings elsewhere in the harbour (from the study carried out in 1988). The combined bathymetry dataset is shown in Figure 2a. The 100 m grid for the existing channel bathymetry is shown in Figure 2b. At this stage, the bathymetric representation of the intertidal and shallow sand flats is only approximate due to paucity of available depth soundings.

The data shown in Table 1 gives the design depths and batter slopes used to modify the existing bathymetry grid for the two proposed channel configurations. The changes in depth associated with the two channel configurations are shown in Figure 3.

Table 1: Design depths and batter slopes for the two proposed channel configurations.

Area Name	Area Description	Design depth (m) 15 m option	Design depth (m) 14 m option	Batter slope
Entrance (Port)	LF Beacon to Hole off Mole	16.5	15.5	1:12
Howletts Claim	Mole to Harington Point	16.0	15.0	1:6
Harington	Harington Pt - Beacon 10	15.5	14.5	1:8
Cross Channel	Beacon 10 - Beacon 14	15.0	14.0	1:8
Taylers	Beacon 14 - Beacon 18	15.0	14.0	1:8
Pulling Point	150m each side of Beacon 17	15.0	14.0	1:4
Hamilton	Beacon 18 - Beacon 20	15.0	14.0	1:4
Acheron Head	150m each side of Beacon 19	15.0	14.0	1:1
Deborah (Port)	Beacon 20 - Beacon 24	15.0	14.0	1:3
Rocky Point	100m each side of Beacon 17	15.0	14.0	1:3
Basin	Beacon 24 - Beacon 28	15.0	14.0	1:3

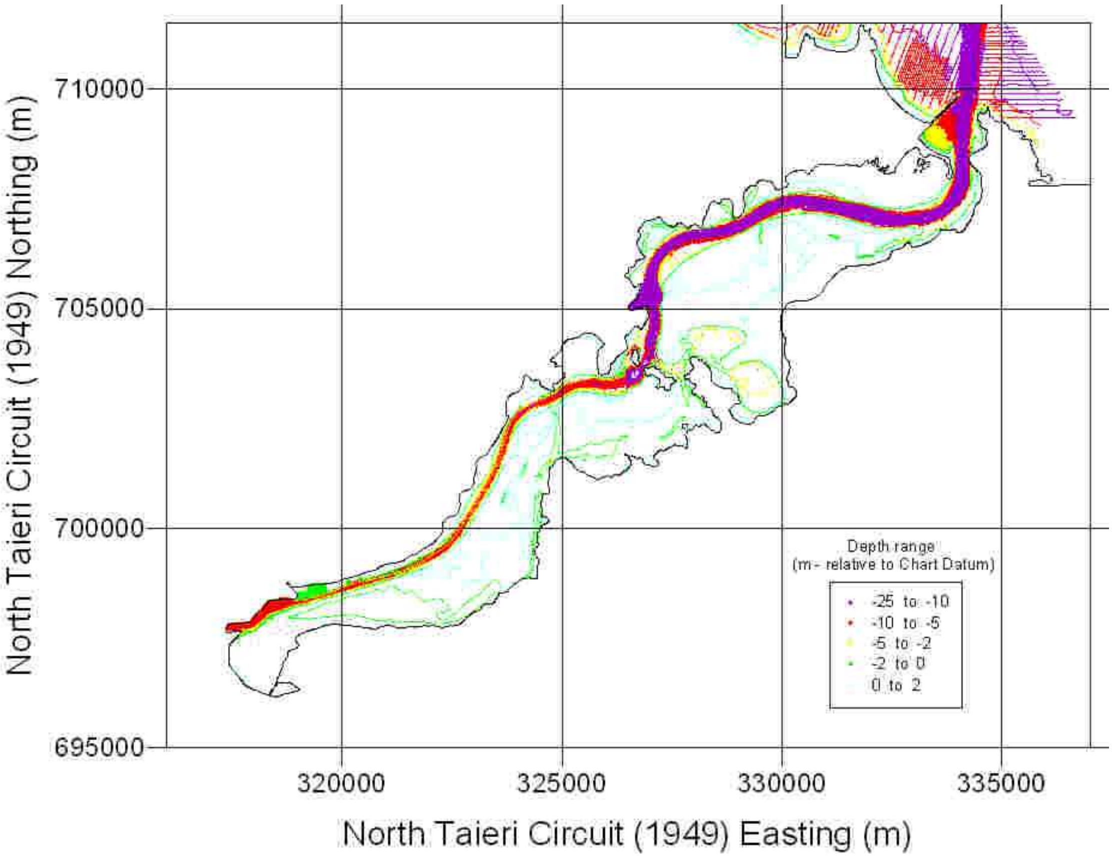


Figure 2a: Mosaic of areas where various bathymetry sounding profile runs (lines or coloured areas) or spot soundings (dots) used to establish the Otago Harbour model grid.

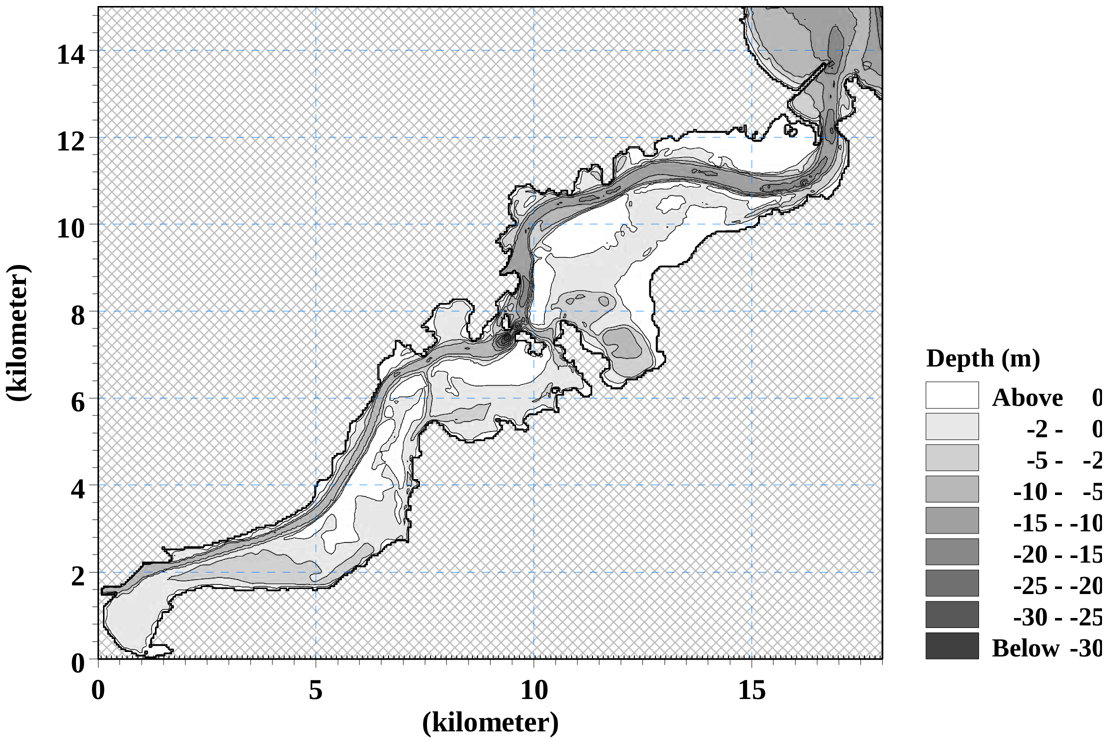


Figure 2b: Bathymetry grid for the existing channel configuration (depths relative to Chart Datum).

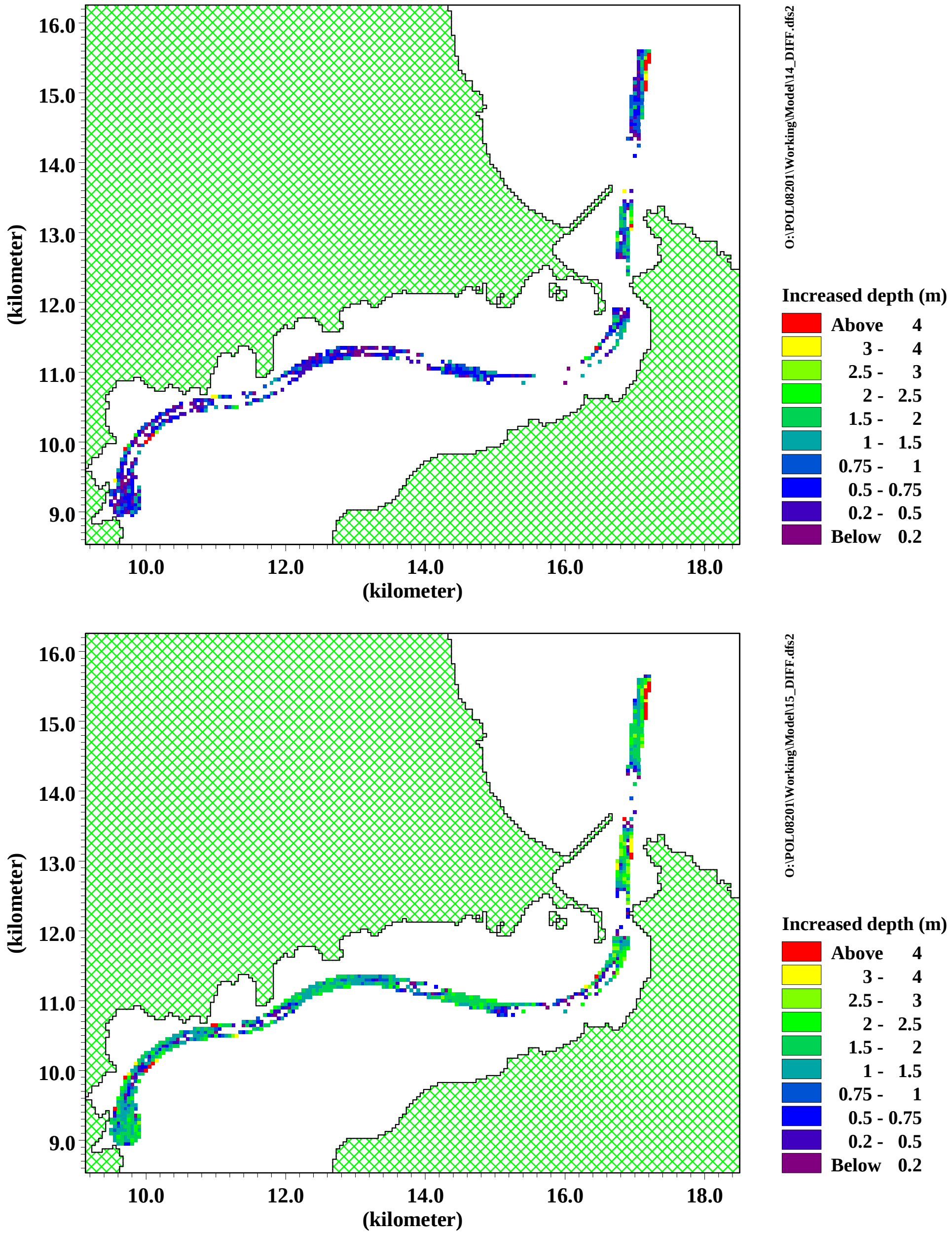


Figure 3: Increases in depth associated with the two proposed channel configurations: (TOP) 14 m deep channel (BOTTOM) 15 m deep channel and associated batter slopes.

2.2 Model setup

Data from the 1988 study at the Landfall Tower site (see Figure 19 for location) were used to define the offshore tidal boundary conditions for the preliminary model. From this data the mean spring tide range was set to 1.81 m and the mean neap tide range

was set to 1.25 m. As this preliminary work is using an uncalibrated model, both the bed roughness and eddy viscosity parameters were set to typical values that have been used to calibrate recent MIKE21 harbour models in the Auckland and Thames areas. These parameters were a Mannings bed roughness of 25 $m^{1/3}/s$ and a velocity-based eddy viscosity of 0.5 m^2/s.

3. Hydrodynamic observations

3.1 Tidal wave propagation in Otago Harbour and phase changes

Figure 4 shows a time history of measured tide levels from POL gauges at Dunedin, Port Chalmers and the Spit Jetty (near Taiaroa Head) for one tidal cycle of a larger spring tide recorded in January 2007. The combined plot illustrates the tide-wave form as it propagates up Otago Harbour. There are two key features. Firstly, the tide range increases due to friction and shallow-water effects e.g., the high water level at Dunedin of 2.25 m compares with a lower high-water level of 2.03 m at the Spit Jetty, and the tide range on this day was 2.04 m at Dunedin versus 1.73 m at the Spit Jetty (an 18% increase in range up the Harbour). Secondly there is a phase (time) lag between the high or low tides with distance up the Harbour. On this particular day, the **high tide** at Port Chalmers lags the Spit Jetty by around 15 minutes, with a further lag of around 20 minutes up to Dunedin Wharf. However **low tide** at Port Chalmers lags the Spit Jetty by around 25 minutes, with a further much longer lag of around 65 minutes up to Dunedin Wharf. The reason for the longer phase (time) lags during low tide is the tidal wave propagates at a speed proportional to the square-root of the depth h (i.e., $\sqrt{h}$), so as the average water depth in the upper harbour reduces considerably towards low tide, the wave slows down, lengthening the ebb tide and shortening the flood tide. Also, the lag or delay times are shorter for the stretch from the Spit Jetty to Port Chalmers, compared with the upper Harbour, because the main navigation channel is much deeper and the tide wave propagates faster.

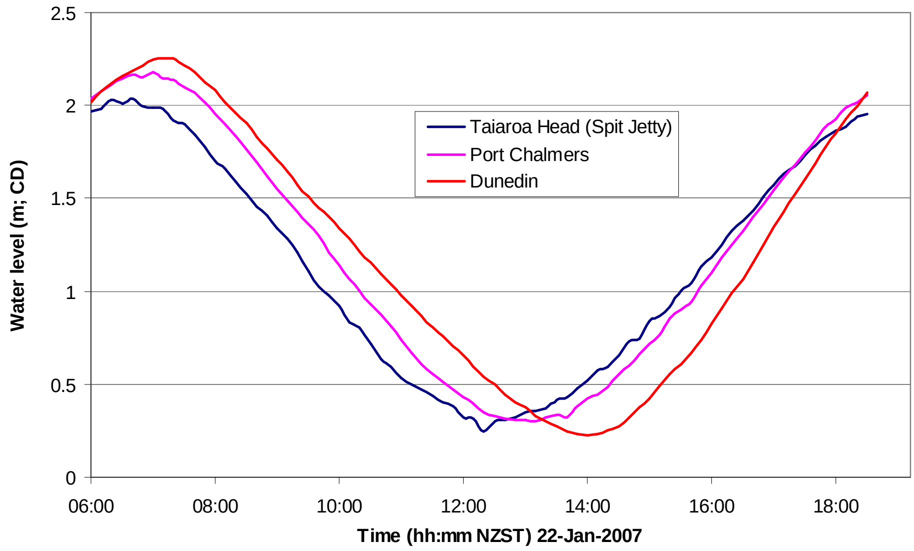


Figure 4: Measured spring tide levels (22-Jan-2007) at Spit Jetty, Port Chalmers and Dunedin showing the tidal phase lag moving up Otago Harbour and differences in tidal range.

This leads on to the implications for deepening the navigation channel—a deeper channel will generally cause a small **advance** in the time (i.e., phasing) of the low and high tides within the Harbour (considering calm wind conditions). The effect of such a change in phase on water levels (and similar for tidal currents), which shows up in the results in the next Section, is illustrated in Figure 5. Here a schematic tide curve, that has been advanced by a nominal 5 minutes (e.g., simulating the effect of a deeper channel), is plotted against the present tide curve for a particular location. At high water the effect of the phase advance is relatively small because the slope of the tide curve is quite flat (at this location anyway). Therefore, model predictions at a fixed or clock time (e.g., 7.10 hours in Fig. 5) would indicate only a small change in predicted high water due to dredging. However during the mid ebb and flood tides (when the slope of the tide curve is at its maximum), a small phase advance can show an apparent change in water level (for a given date/time) of between 0.03 and 0.05 m in this example. However, most of the "apparent" change in water level is mainly due to the phase (timing) shift in the whole tidal curve.

In terms of hydrodynamic effects on the Harbour, the key changes to watch for are actual changes in tide range, high and low tide levels and peak ebb and flood-tide currents, which must be assessed after allowing (correcting) for the phase shift at any particular location in the Harbour.

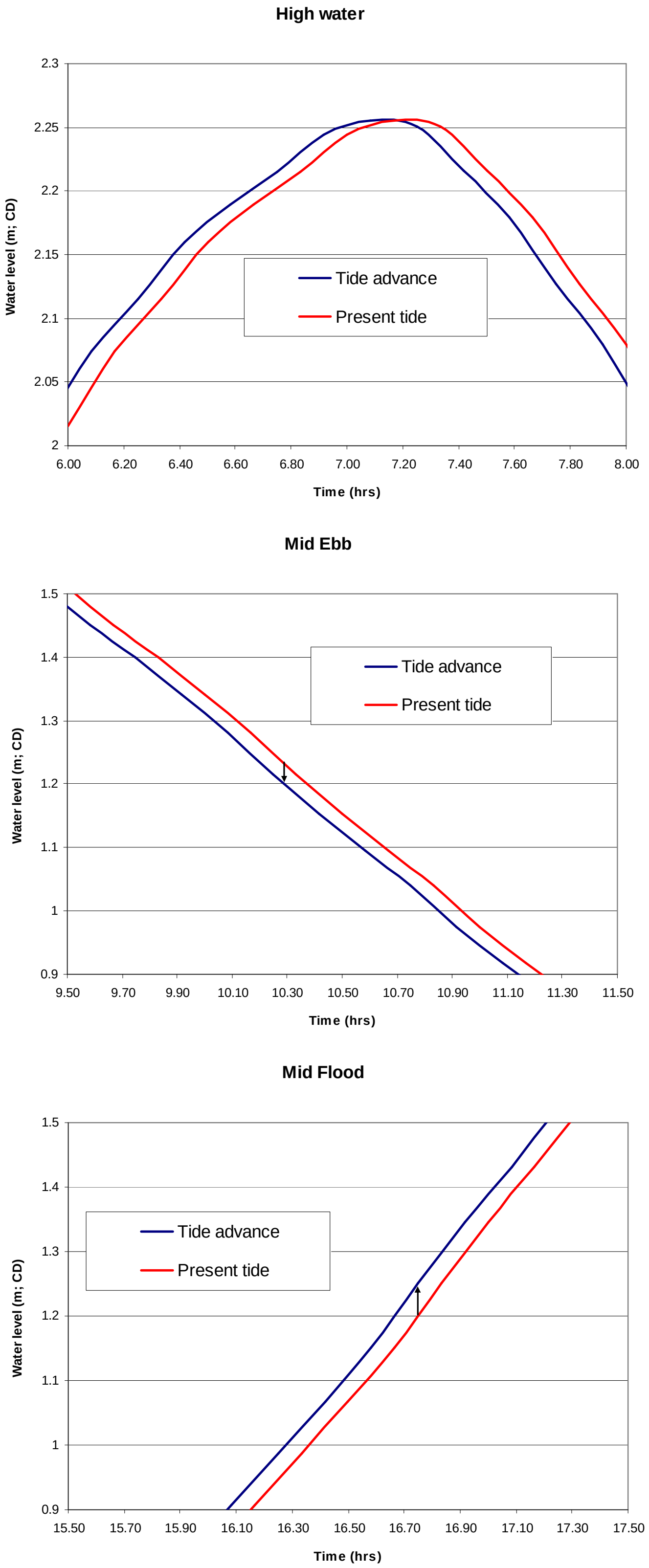


Figure 5: Schematic tide curve illustrating the effect of a 5-minute tidal phase advance on tide levels at any fixed (or clock) time.

3.2 Summary of key findings from previous studies

While it was not part of the brief for this preliminary phase to carry out a calibration of the hydrodynamic model, we used summary data from previous studies (Barnett et al. 1988; Wilson and Sutherland 1991; and Old 1998) to provide a reality check for the uncalibrated model. This will provide some degree of confidence that the preliminary findings from this work are realistic in terms of what is already known about the hydrodynamics of Otago Harbour.

Wilson and Sutherland (1991) summarised the tidal propagation process within the harbour using the tidal amplification and average phase lag between the Harbour entrance and Dunedin. They found that for larger spring tides, the amplification of the tidal range between the open coast and Dunedin was 1.178 (or ~18%) and the average phase lag was 1.08 hours (65 minutes). These values are in good agreement with the values extracted from the tide curve data in Section 3.1.

Data from beacon marker #4 just south-west of Goat Island[1] indicates peak spring tide currents are around 0.8 m/s on flood tide and 0.6 m/s on the ebb tide. At Harington Bend, recorded neap currents are around 70% of spring currents and the maximum spring ebb currents of up 0.8 m/s were recorded (Barnett et al. 1988). Within the tidal jet at the entrance to the harbour peak currents of up to 1.0 m/s have been recorded (Old, 1998).

At the Spit the ebb tide duration is longer at 6.48 hours than the flood duration that lasts 5.94 hours (Old, 1998). This difference in ebb and flood tide durations means that the Harbour is somewhat flood-dominant (i.e., dominated more by the flood tide) as a shorter duration means the peak velocity averaged across the entrance needs to be higher on the flood tide than the ebb tide to move the same amount of water in or out of the harbour. The velocity measurements from upper-harbour beacon #4 also indicate the flood dominance of the upper Harbour.

The tidal prism (total water volume) passing through the entrance, based on current velocity measurements from an ADCP field study, was 6.8×10^7 m^3 going out on the ebb tide and 6.5×10^7 m^3 coming in on the subsequent flood tide (Old, 1998). [Note: apart from measurement tolerances, differences in tidal prism will occur as the high tide seldom returns to the exact level reached on the previous high tide.]

[1] upper-harbour channel beacon #4 on Chart NZ6612, and referred to as #4UH in Barnett et al. 1988)

4. Hydrodynamic modelling results

4.1 Model comparison with observed data

In this section, comparisons of the predictions for a spring tide from the uncalibrated hydrodynamic model using the existing channel configuration are made with the summarised field data given in Section 3.

The model predicts a time of high water at Dunedin which is 1 hour after the high tide at the Spit Jetty gauge. The predicted spring tide range at Dunedin is 1.16 times the range at the Spit Jetty gauge (or 16% higher). Field data gives a phase lag of 1.08 hours and an amplification of the tidal range of 1.18 (18% increase) between the two sites. Therefore, the modelled phase lag for Dunedin is within 5 minutes of the observed values and the modelled spring tide range at Dunedin, while lower, is reasonably close to the observed tide range.

Within the entrance channel, peak currents of 1.0 m/s are predicted by the model under spring tides and no winds which is the same as the observed peak tidal jet velocities from Old (1998). At Harington Bend, the modelled peak-ebb velocity on a spring tide is 0.85 m/s while the peak-ebb velocity on a smaller neap tide is 0.61 m/s (or 72% of the spring-tide value). This compares to the maximum observed spring-tide ebb currents ranging between 0.70 and 0.76 m/s with a ratio of 70% for peak ebb velocities between neaps and springs. Thus, the uncalibrated model at Harington Bend slightly over estimates the currents but correctly estimates the ratio of spring to neap peak-ebb tidal currents. Model predictions from near Halfway Island (mid-harbour) indicate peak tidal currents of 0.79 m/s on the flood tide and 0.64 m/s on the ebb tide. This compares very well with the observed peak currents of 0.8 m/s on the flood tide and 0.6 m/s on the ebb tide.

The model prediction of tidal prism on the ebbing tide (which has a predicted duration of 6.38 hours) is 6.85 x 10^7 m^3 while the flood tide prism (which has a predicted duration of 5.87 hours) is 6.64 x 10^7 m^3. The tidal prism data are within the error bounds of the estimates of the tidal prism values from Old (1998) and the duration of the ebb and flood tide flows are to within 6 minutes of his observed values.

The predicted flood tide duration under calm (no-wind) conditions at Dunedin is 5.79 hours and the predicted ebb tide duration is 6.46 hours. This compares with the observed average flood-tide duration of 5.60 hours (±0.27 hours) and the average ebb-tide duration of 6.82 hours (±0.26 hours) based on an analysis of the Dunedin tide-gauge measurements for 2007 (Lincoln Coe; pers. comm.). The comparison shows

that the model is over predicting the flood tide duration at Dunedin by around 10 minutes and under predicting the ebb-tide duration at Dunedin by around 20 minutes.

In conclusion, it can be seen that the uncalibrated 100-m hydrodynamic model is already proving to be a reasonable predictor of tidal hydrodynamics in Otago Harbour, capturing the main tidal characteristics. Increasing the spatial resolution of the model (smaller cell size), incorporating improved bathymetric data for the intertidal areas, and a more rigorous calibration of the model (through adjustments to the friction parameters) will all ensure an even closer match of the model prediction to measurements.

For the purposes of this Report, these preliminary model predictions, while not always closely matched to field observations in absolute terms, can be relied on to provide early guidance on potential effects in relative terms through comparison of the hydrodynamic characteristics before and after dredging of the main navigation channel.

4.2 Model predictions of potential changes in the hydrodynamics of Otago Harbour

This section provides the relative comparison of the hydrodynamic characteristics between the existing Harbour bathymetry and the two reconfigured options for a deeper navigation channel up to Port Chalmers. The model simulations covered a range of tide and wind conditions.

The following Tables 2–7 summarise the hydrodynamic model results from six selected sites within the Harbour (Figure 6) for all the simulations carried out. Each Table is followed by time series plots (Figures 7–12) for the same location that show predicted water levels or current velocities (**on the left-hand axis**) for the existing bathymetry [*solid line*] compared with the proposed 15 m channel configuration [*dashed line*] and the predicted “apparent” differences (**on the right-hand axis**) relative to the existing-channel situation (without taking into account the tidal phase shift). The plots only show the “no-wind” simulations. All plots have a time axis in elapsed time relative to high water at Port Chalmers (under existing conditions for no winds), with negative times representing times in hours before high water (including the flood tide leading up to high tide).

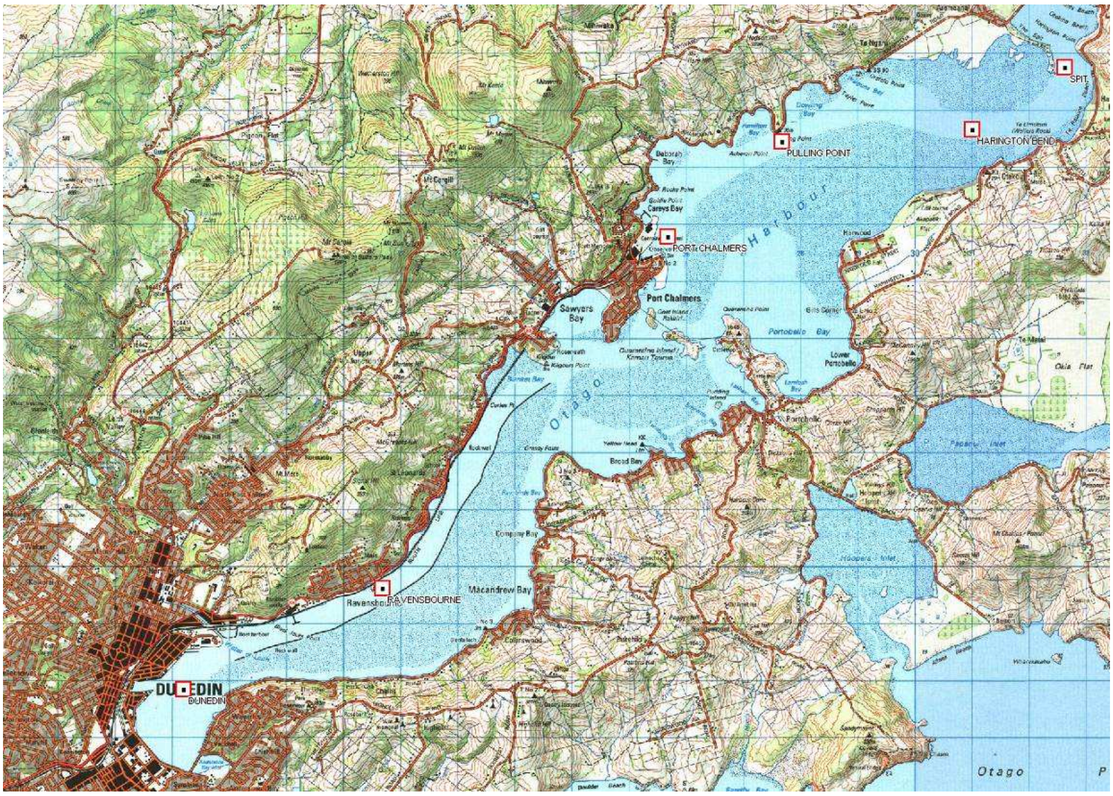


Figure 6: Six channel sites (below) selected for extracting tide level and current velocity data from the model simulations. [*Source:* ©LINZ 1:50,000 topographic maps].

4.2.1 Dunedin

Existing—Predicted velocities at the site near Dunedin are relatively low, being <0.2 m/s on a spring tide with no wind, but can rise to around 0.5 m/s during strong winds. The flood tide duration ranges from 5.7–6.0 hours and the ebb tide duration ranges from 6.32–6.83 hours, depending on the tidal range and wind condition (Table 2).

Proposed 15-m channel—There would be no substantial change in the ebb/flood tide durations or predicted velocities (within ±0.01 m/s) with the proposed 15-m channel configuration. The average tide phase would be advanced by up to 7 minutes (under no wind conditions) which leads to a maximum "apparent" change in water level at any time of up to 0.07 m on a spring tide (Fig. 7b–top panel), but the actual high and low tide heights would change by no more than 0.02 m after allowing for the tide phase change (Table 2).

4.2.2 Ravensbourne

Existing channel—Predicted velocities from the model at the Ravensbourne site during a spring tide, with different winds, peak at around 0.46 to 0.50 m/s on the flooding tide, but are lower on the ebbing tide at around 0.35 m/s.

Proposed 15-m channel—The spring flood-tide duration may increase slightly by 1–2 minutes (and a corresponding decrease on ebb-tide) while the average tide phase could be altered by up to 7 minutes earlier (under no-wind conditions) due to the proposed 15-m channel deepening (Table 3). The phase shift would cause an "apparent" change in predicted tide levels at any time of up to 0.06 m (Fig. 8b–top panel), but allowing for the tide phase change means the high and low spring-tide heights would only alter by up to 0.01 m (Table 3). The peak flood and ebb currents on a spring tide at this site would change marginally, with an increase of up to 0.01 m/s on the flood tide and decrease of 0.01 m/s on the ebb tide (Table 3)—but within the uncertainty bounds of the model estimates.

4.2.3 Port Chalmers

Existing channel—Predicted velocities from the model at the Port Chalmers channel site during a spring tide under different winds peak at around 0.55–0.60 m/s during the flood tide, but are slightly lower at 0.47–0.56 m/s on the ebb tide.

Proposed 15-m channel—The spring flood-tide duration may increase slightly by around 2–3 minutes (and a corresponding decrease on ebb-tide) while the average tide phase could be altered by up to 5 minutes earlier (under no-wind conditions) due to the proposed 15-m channel deepening (Table 4). The phase shift would cause an "apparent" change in predicted tide levels at any time of up to 0.04 m (Fig. 9b–top panel), but allowing for the tide phase change means the high and low spring-tide heights would only alter by up to 0.02 m (Table 4). The peak flood and ebb currents on a spring tide at this site would change somewhat, with a marginal increase of up to 0.01 m/s on the flood tide (no wind) and an increase of up to 0.06 m/s on the ebb tide with no wind (Table 4). However, the NE and SW wind simulations, combined with a spring tide, indicate that there would be no substantial change in the peak ebb current.

4.2.4 Pulling Point

Existing channel—For a spring tide and the two wind scenarios, the model predicts peak spring-tide velocities at the channel site off Pulling Point are around 0.86–0.91 m/s during a flood tide, but are lower at 0.76–0.82 m/s on an ebb tide. This pattern of

flood-tide dominance (i.e., higher peak flood-tide velocities) on a spring tide continues as demonstrated at the up-harbour sites.

Proposed 15-m channel—The spring flood-tide duration may decrease slightly by around 0–2 minutes (and a corresponding increase on ebb-tide) while the average tide phase could be altered by up to 4 minutes earlier (under no-wind conditions) due to the proposed 15-m channel deepening (Table 5). The phase shift would cause an "apparent" change in predicted tide levels at any time of up to 0.03 m (Fig. 10b–top panel), but allowing for the tide phase change means the high and low spring-tide heights would only alter by up to 0.02 m (Table 5). The peak flood and ebb currents on a spring tide at this site would change somewhat, with a small increase of up to 0.02 m/s on both the flood and ebb tides for no wind, but a slight decrease for the NE and SW wind combinations (Table 5).

4.2.5 Harington Bend

Existing channel—For a spring tide and the two wind scenarios, the model predicts peak spring-tide velocities at the channel site at Harington Bend are around 0.83–0.87 m/s during a flood tide, and continues to predict lower speeds on the ebb tide, peaking at 0.72–0.75 m/s on an ebb tide. These predictions show that the peak current velocities are slightly less than those off Pulling Point (previous sub-section).

Proposed 15-m channel—The spring flood-tide duration may increase slightly by around 2–3 minutes (and a corresponding decrease on ebb-tide) while the average tide phase could be altered by up to 3 minutes earlier (under no-wind conditions) due to the proposed 15-m channel deepening (Table 6). The phase shift would cause an "apparent" change in predicted tide levels at any time of up to 0.02 m (Fig. 11b–top panel), but allowing for the tide phase change means the high and low spring-tide heights would only alter marginally by up to 0.01 m (Table 6). The peak flood and ebb currents on a spring tide at this site would change somewhat, with a small increase of up to 0.03 m/s on the flood and a marginal increase of 0.01 m/s on an ebb tide for calm conditions. There would only be marginal decreases in peak ebb and flood-tide velocities (within 0.01 m/s) when strong winds combine with a spring tide (Table 6).

4.2.6 Spit Jetty (Entrance Channel)

Existing channel—For a spring tide and the two wind scenarios, the model predicts peak spring-tide velocities at the channel site off the Spit Jetty are around 0.94–0.97 m/s during a flood tide, dropping to 0.84–0.87 m/s on an ebb tide. The pattern of flood-tide dominance (i.e., higher peak flood-tide velocities) on spring tides continues

as demonstrated at all the previous up-harbour sites. However in contrast, the simulations show that for neap tides, the peak velocities are quite similar between ebb and flood tides, and at the site off the Spit Jetty, even switch to being slightly higher on the ebb tide (Fig. 12a–bottom panel). This is due to the much smaller differences in distortion of the tidal wave from bottom friction (particularly on the shallower intertidal banks) arising from the much smaller difference between low and high water on a neap tide.

Proposed 15-m channel—The spring flood- and ebb-tide durations and the average tide phase are unlikely to change much at this site (Table 7). High and low spring-tide heights would only alter marginally by up to 0.01 m–within the bounds of uncertainty of the model results (Table 7). While the average tide-phase change is likely to be negligible, there would be times during a tidal cycle when an “apparent” change in predicted tidal currents of up to 0.03 m/s occurs (Fig. 12b–top panel). However, the peak flood and ebb currents on a spring tide at this site are unlikely to change from the existing situation when winds are light (calm), but there would be a slight decrease of up to 0.04 m/s for the NE and SW wind combinations with a spring tide (Table 7).

Table 2: Predicted flood-tide and ebb-tide duration, high-water and low-water level, peak-flood and peak-ebb tide velocity at a site within the main channel near Dunedin for the different tide and wind conditions and channel depth. The last three columns give the high-water tide phase change (negative= phase advance) and the largest "apparent" increases and decreases in speed induced by deepening the navigation channel at any time of the tide cycle (but without correcting for phase shift).

TIDE	WIND	SITE	CASE	Flood-tide duration (hrs)	Ebb-tide duration (hrs)	Height of high tide (m)	Height of low tide (m)	Peak-flood velocity (m/s)	Peak-ebb velocity (m/s)	Average phase shift (min)	Largest "apparent" *increase* in speed (m/s)	Largest "apparent" *decrease* in speed (m/s)
Neap	NO	Dunedin	13m	5.85	6.47	1.85	0.42	0.11	0.08			
Neap	SW	Dunedin	13m	6.00	6.32	1.71	0.28	0.47	0.43			
Neap	NE	Dunedin	13m	5.87	6.45	1.99	0.52	0.44	0.44			
Spring	NO	Dunedin	13m	5.72	6.82	2.20	0.23	0.18	0.11			
Spring	SW	Dunedin	13m	5.78	6.77	2.07	0.09	0.54	0.44			
Spring	NE	Dunedin	13m	5.70	6.83	2.35	0.32	0.46	0.45			
Neap	NO	Dunedin	14m	5.87	6.45	1.86	0.39	0.12	0.09	-6	<0.01	<-0.01
Neap	SW	Dunedin	14m	6.02	6.30	1.72	0.28	0.48	0.43	-1	<0.01	<-0.01
Neap	NE	Dunedin	14m	5.83	6.48	1.99	0.52	0.44	0.44	-2	<0.01	<-0.01
Spring	NO	Dunedin	14m	5.72	6.82	2.22	0.2	0.19	0.12	-7	0.01	<-0.01
Spring	SW	Dunedin	14m	5.78	6.77	2.07	0.09	0.54	0.44	-3	<0.01	<-0.01
Spring	NE	Dunedin	14m	5.70	6.83	2.35	0.32	0.46	0.45	-3	<0.01	<-0.01
Neap	NO	Dunedin	15m	5.88	6.43	1.86	0.39	0.12	0.09	-5	<0.01	<-0.01
Neap	SW	Dunedin	15m	6.02	6.30	1.72	0.28	0.48	0.43	-1	<0.01	<-0.01
Neap	NE	Dunedin	15m	5.83	6.47	1.99	0.52	0.44	0.44	-1	<0.01	<-0.01
Spring	NO	Dunedin	15m	5.73	6.80	2.22	0.19	0.19	0.12	-7	0.01	<-0.01
Spring	SW	Dunedin	15m	5.80	6.73	2.08	0.08	0.54	0.44	-3	<0.01	<-0.01
Spring	NE	Dunedin	15m	5.70	6.83	2.36	0.31	0.46	0.45	-3	<0.01	<-0.01

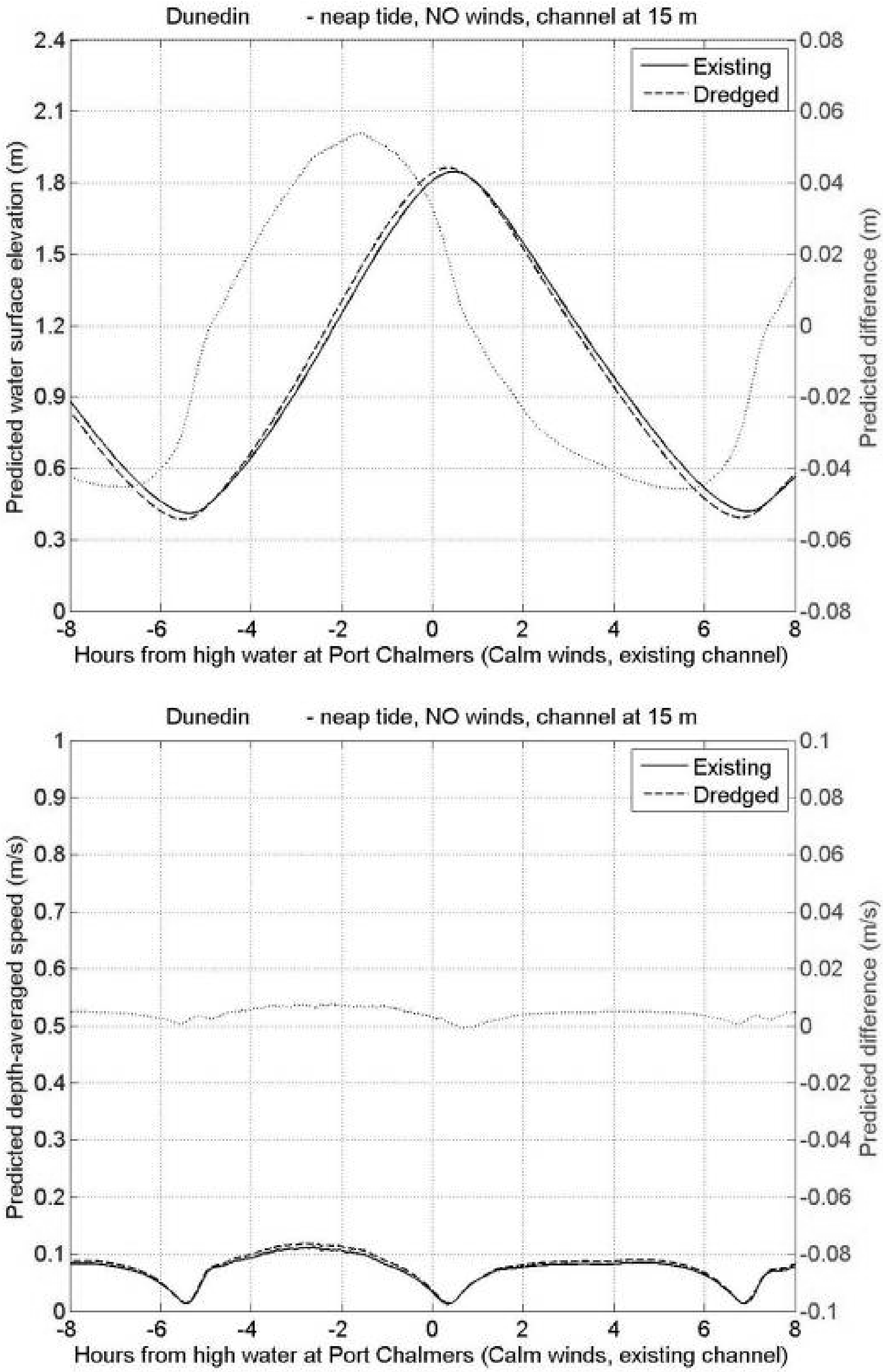


Figure 7a: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a neap tide at Dunedin.

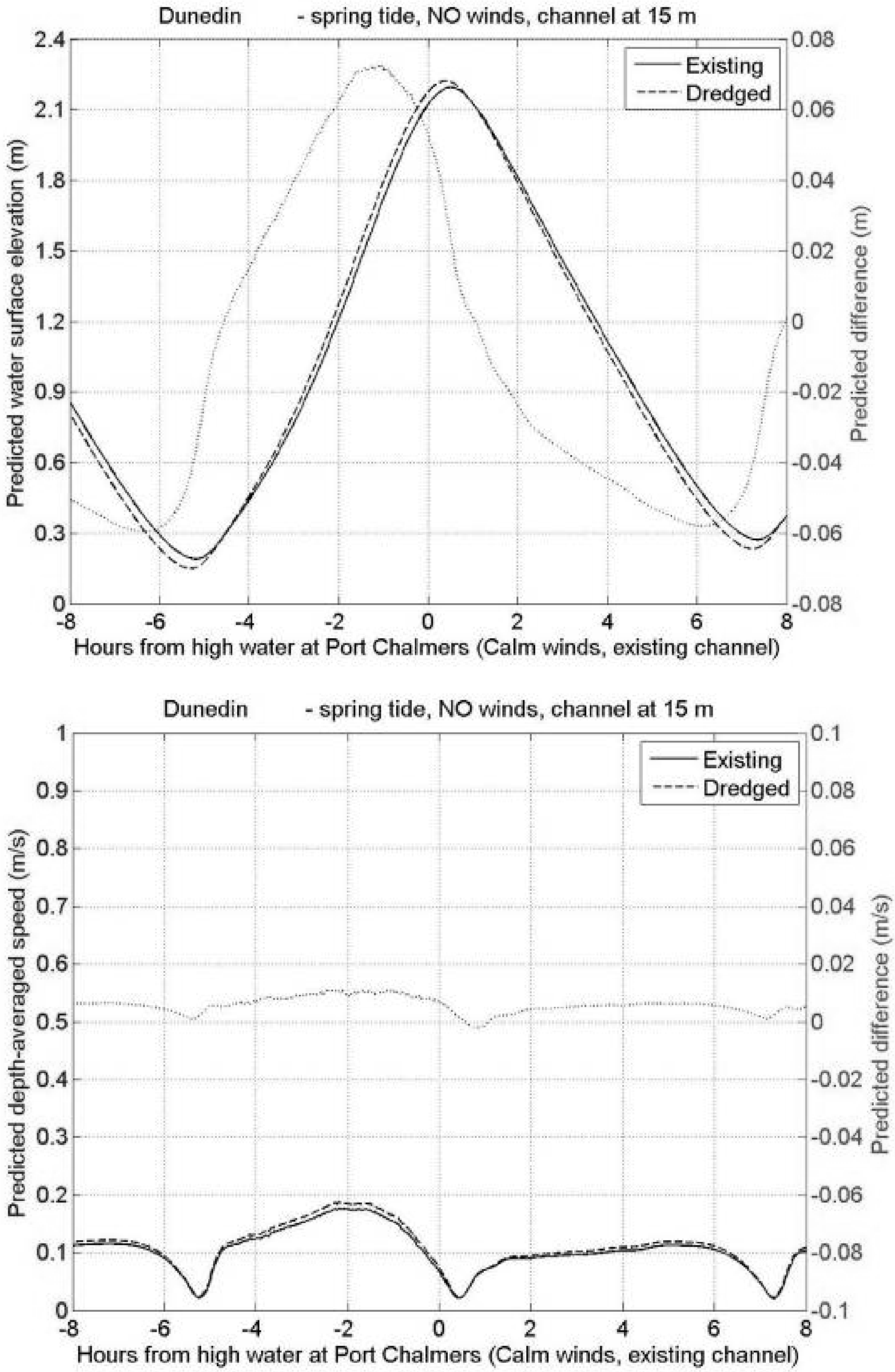
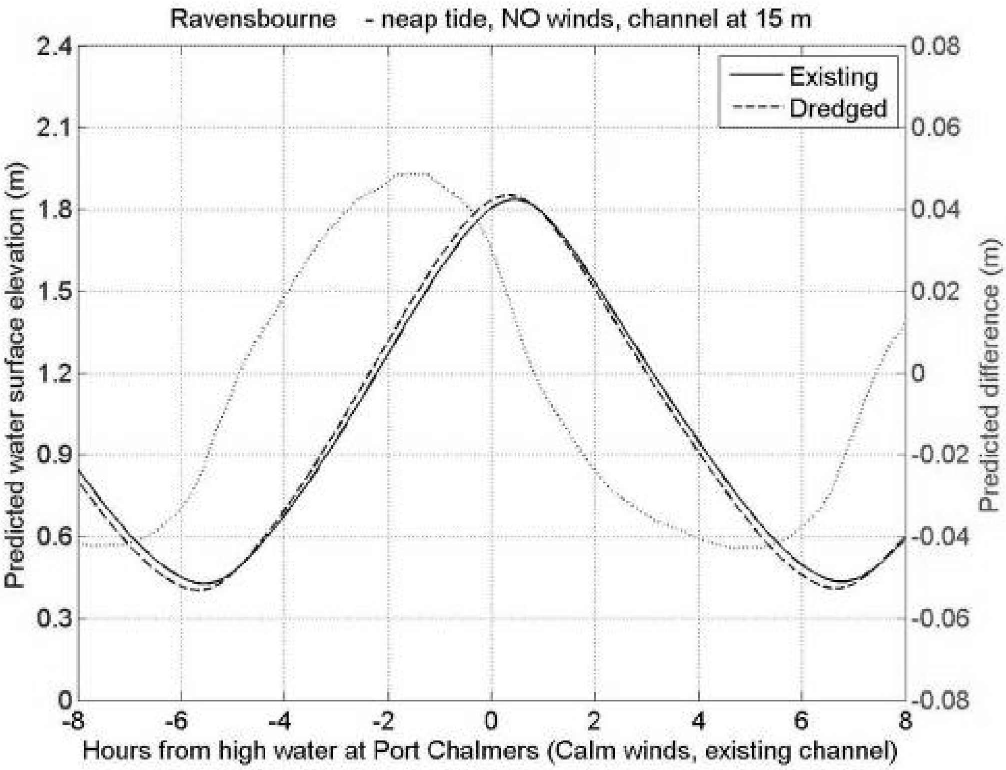


Figure 7b: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a spring tide at Dunedin.

Table 3: Predicted flood-tide and ebb-tide duration, high-water and low-water level, peak-flood and peak-ebb tide velocity at a site within the main channel near Ravensbourne for the different tide and wind conditions and channel depth. The last three columns give the high-water tide phase change (negative= phase advance) and the largest "apparent" increases and decreases in speed induced by deepening the navigation channel at any time of the tide cycle (but without correcting for phase shift).

TIDE	WIND	SITE	CASE	Flood-tide duration (hrs)	Ebb-tide duration (hrs)	Height of high tide (m)	Height of low tide (m)	Peak-flood velocity (m/s)	Peak-ebb velocity (m/s)	Average phase shift (min)	Largest "apparent" *increase* in speed (m/s)	Largest "apparent" *decrease* in speed (m/s)
Neap	NO	Ravensbourne	13m	5.95	6.35	1.84	0.43	0.35	0.28			
Neap	SW	Ravensbourne	13m	6.13	6.17	1.73	0.33	0.38	0.30			
Neap	NE	Ravensbourne	13m	5.95	6.37	1.95	0.50	0.34	0.29			
Spring	NO	Ravensbourne	13m	5.88	6.65	2.18	0.25	0.48	0.35			
Spring	SW	Ravensbourne	13m	5.90	6.63	2.08	0.15	0.51	0.34			
Spring	NE	Ravensbourne	13m	5.83	6.70	2.30	0.31	0.47	0.35			
Neap	NO	Ravensbourne	14m	5.93	6.38	1.85	0.41	0.36	0.28	-5	0.04	-0.03
Neap	SW	Ravensbourne	14m	6.12	6.23	1.74	0.33	0.38	0.30	-1	<0.01	<-0.01
Neap	NE	Ravensbourne	14m	5.97	6.33	1.95	0.50	0.34	0.29	-2	<0.01	<-0.01
Spring	NO	Ravensbourne	14m	5.87	6.67	2.2	0.22	0.49	0.33	-7	0.05	-0.04
Spring	SW	Ravensbourne	14m	5.98	6.55	2.09	0.14	0.51	0.34	-3	0.01	<-0.01
Spring	NE	Ravensbourne	14m	5.85	6.68	2.31	0.31	0.47	0.35	-3	<0.01	<-0.01
Neap	NO	Ravensbourne	15m	5.93	6.38	1.85	0.41	0.36	0.28	-4	0.05	-0.04
Neap	SW	Ravensbourne	15m	6.07	6.27	1.74	0.33	0.39	0.30	-1	0.02	-0.01
Neap	NE	Ravensbourne	15m	6.00	6.33	1.95	0.50	0.34	0.29	-2	0.02	-0.01
Spring	NO	Ravensbourne	15m	5.92	6.63	2.21	0.22	0.49	0.34	-6	0.06	-0.04
Spring	SW	Ravensbourne	15m	5.95	6.57	2.09	0.14	0.51	0.34	-3	0.02	-0.01
Spring	NE	Ravensbourne	15m	5.85	6.68	2.31	0.30	0.47	0.35	-3	0.02	-0.02



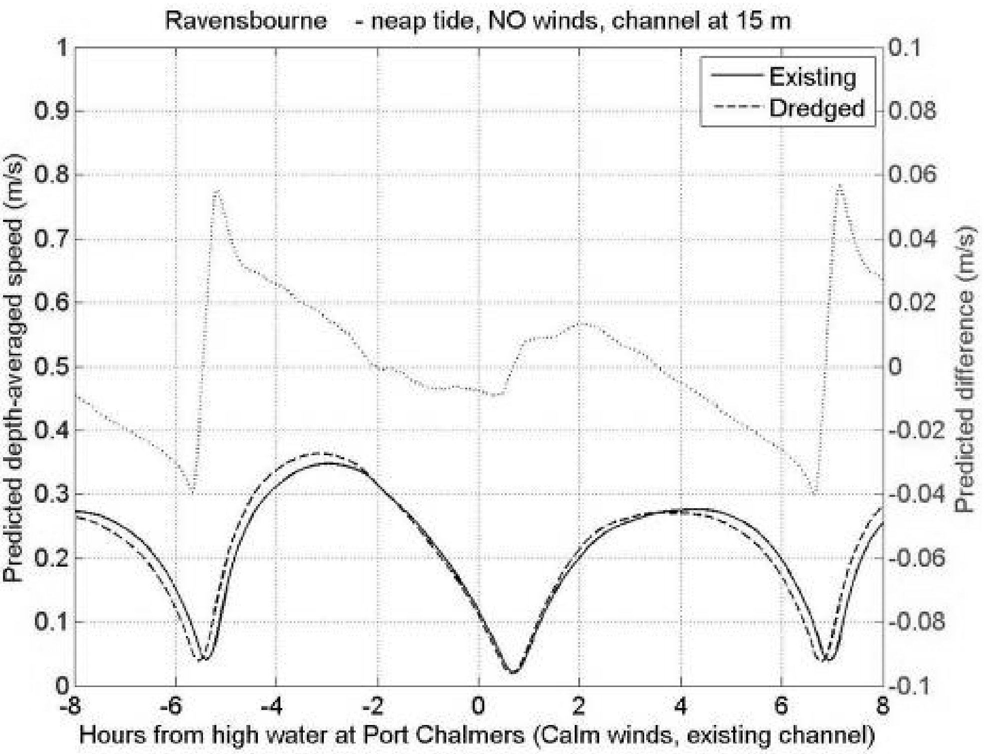


Figure 8a: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a neap tide at Ravensbourne.

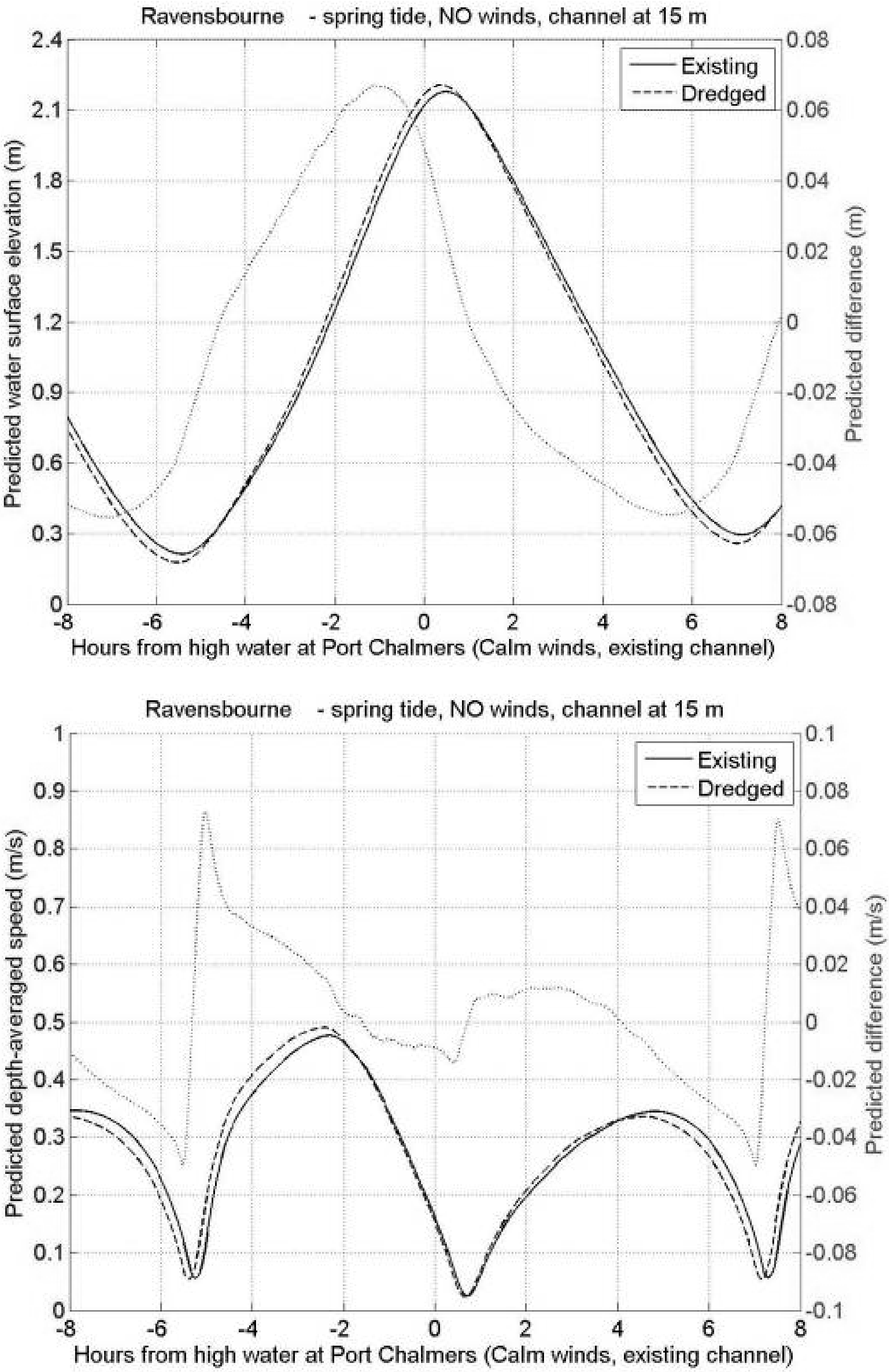


Figure 8b: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a spring tide at Ravensbourne.

Table 4: Predicted flood-tide and ebb-tide duration, high-water and low-water level, peak-flood and peak-ebb tide velocity at a site within the main channel at Port Chalmers for the different tide and wind conditions and channel depth. The last three columns give the high-water tide phase change (negative= phase advance) and the largest "apparent" increases and decreases in speed induced by deepening the navigation channel at any time of the tide cycle (but without correcting for phase shift).

TIDE	WIND	SITE	CASE	Flood-tide duration (hrs)	Ebb-tide duration (hrs)	Height of high tide (m)	Height of low tide (m)	Peak-flood velocity (m/s)	Peak-ebb velocity (m/s)	Average phase shift (min)	Largest "apparent" increase in speed (m/s)	Largest "apparent" decrease in speed (m/s)
Neap	NO	Port Chalmers	13m	6.47	5.82	1.78	0.46	0.38	0.37			
Neap	SW	Port Chalmers	13m	6.45	5.82	1.74	0.41	0.44	0.4			
Neap	NE	Port Chalmers	13m	6.45	5.83	1.84	0.48	0.4	0.45			
Spring	NO	Port Chalmers	13m	6.63	5.90	2.10	0.24	0.54	0.47			
Spring	SW	Port Chalmers	13m	6.48	5.98	2.06	0.19	0.60	0.52			
Spring	NE	Port Chalmers	13m	6.62	5.93	2.16	0.26	0.56	0.56			
Neap	NO	Port Chalmers	14m	6.47	5.85	1.79	0.45	0.40	0.41	-3	0.05	<-0.01
Neap	SW	Port Chalmers	14m	6.47	5.83	1.74	0.41	0.43	0.4	-1	<0.01	<-0.01
Neap	NE	Port Chalmers	14m	6.45	5.83	1.84	0.48	0.39	0.44	-1	<0.01	<-0.01
Spring	NO	Port Chalmers	14m	6.58	5.92	2.12	0.22	0.57	0.53	-4	0.06	<-0.01
Spring	SW	Port Chalmers	14m	6.50	5.97	2.07	0.19	0.59	0.52	-2	<0.01	-0.01
Spring	NE	Port Chalmers	14m	6.58	5.98	2.16	0.26	0.55	0.56	-3	<0.01	-0.01
Neap	NO	Port Chalmers	15m	6.47	5.82	1.79	0.44	0.39	0.41	-3	0.04	<-0.01
Neap	SW	Port Chalmers	15m	6.50	5.80	1.75	0.41	0.42	0.39	-1	<0.01	-0.02
Neap	NE	Port Chalmers	15m	6.47	5.80	1.84	0.48	0.38	0.44	-1	<0.01	-0.02
Spring	NO	Port Chalmers	15m	6.57	5.93	2.12	0.22	0.55	0.53	-5	0.06	<-0.01
Spring	SW	Port Chalmers	15m	6.48	6.00	2.07	0.18	0.58	0.51	-2	<0.01	-0.03
Spring	NE	Port Chalmers	15m	6.60	5.93	2.17	0.25	0.53	0.56	-3	0.01	-0.03

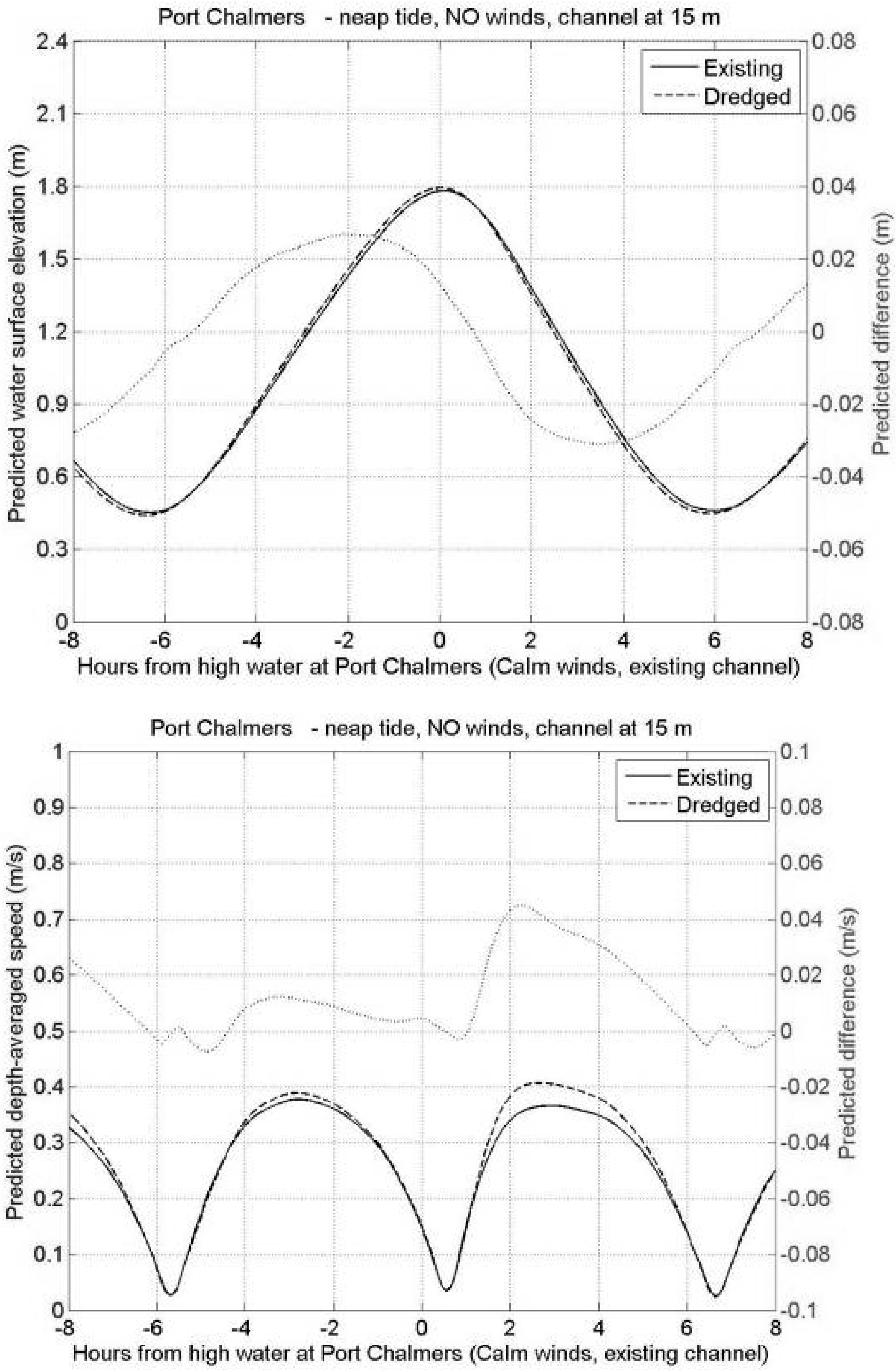


Figure 9a: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a neap tide at Port Chalmers.

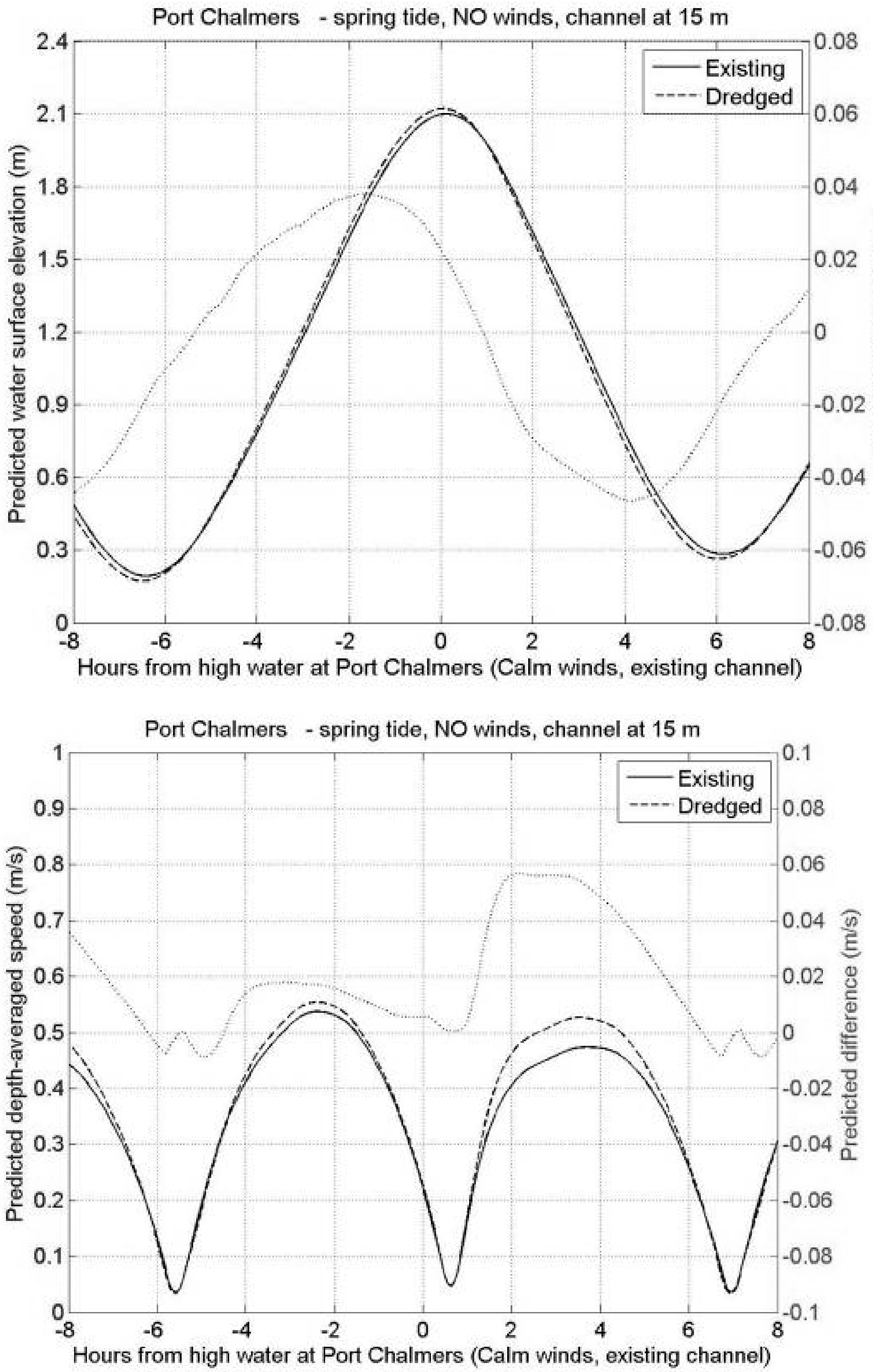


Figure 9b: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a spring tide at Port Chalmers.

Table 5: Predicted flood-tide and ebb-tide duration, high-water and low-water level, peak-flood and peak-ebb tide velocity at a site within the main channel near Pulling Point for the different tide and wind conditions and channel depth. The last three columns give the high-water tide phase change (negative= phase advance) and the largest "apparent" increases and decreases in speed induced by deepening the navigation channel at any time of the tide cycle (but without correcting for phase shift).

TIDE	WIND	SITE	CASE	Flood-tide duration (hrs)	Ebb-tide duration (hrs)	Height of high tide (m)	Height of low tide (m)	Peak-flood velocity (m/s)	Peak-ebb velocity (m/s)	Average phase shift (min)	Largest "apparent" *increase* in speed (m/s)	Largest "apparent" *decrease* in speed (m/s)
Neap	NO	Pulling Point	13m	6.43	5.90	1.77	0.46	0.61	0.6			
Neap	SW	Pulling Point	13m	6.45	5.85	1.74	0.43	0.66	0.6			
Neap	NE	Pulling Point	13m	6.38	5.93	1.80	0.48	0.62	0.67			
Spring	NO	Pulling Point	13m	6.53	6.02	2.08	0.24	0.86	0.76			
Spring	SW	Pulling Point	13m	6.58	5.93	2.06	0.2	0.91	0.77			
Spring	NE	Pulling Point	13m	6.55	6.00	2.12	0.25	0.88	0.82			
Neap	NO	Pulling Point	14m	6.42	5.90	1.78	0.46	0.63	0.62	-3	0.03	-0.01
Neap	SW	Pulling Point	14m	6.45	5.80	1.74	0.43	0.65	0.6	0	<0.01	-0.01
Neap	NE	Pulling Point	14m	6.45	5.83	1.8	0.48	0.61	0.67	-1	<0.01	-0.01
Spring	NO	Pulling Point	14m	6.53	6.03	2.09	0.23	0.88	0.79	-4	0.04	-0.01
Spring	SW	Pulling Point	14m	6.58	5.95	2.06	0.20	0.90	0.76	-1	0.01	-0.02
Spring	NE	Pulling Point	14m	6.53	6.05	2.13	0.25	0.87	0.81	-2	0.02	-0.02
Neap	NO	Pulling Point	15m	6.43	5.88	1.78	0.45	0.62	0.62	-2	0.04	-0.02
Neap	SW	Pulling Point	15m	6.42	5.85	1.74	0.43	0.65	0.59	0	0.02	-0.03
Neap	NE	Pulling Point	15m	6.40	5.90	1.81	0.48	0.60	0.66	-1	0.02	-0.03
Spring	NO	Pulling Point	15m	6.52	6.05	2.10	0.22	0.88	0.78	-4	0.05	-0.03
Spring	SW	Pulling Point	15m	6.60	5.93	2.06	0.20	0.90	0.75	-3	0.03	-0.04
Spring	NE	Pulling Point	15m	6.52	6.03	2.13	0.25	0.86	0.81	-2	0.04	-0.04

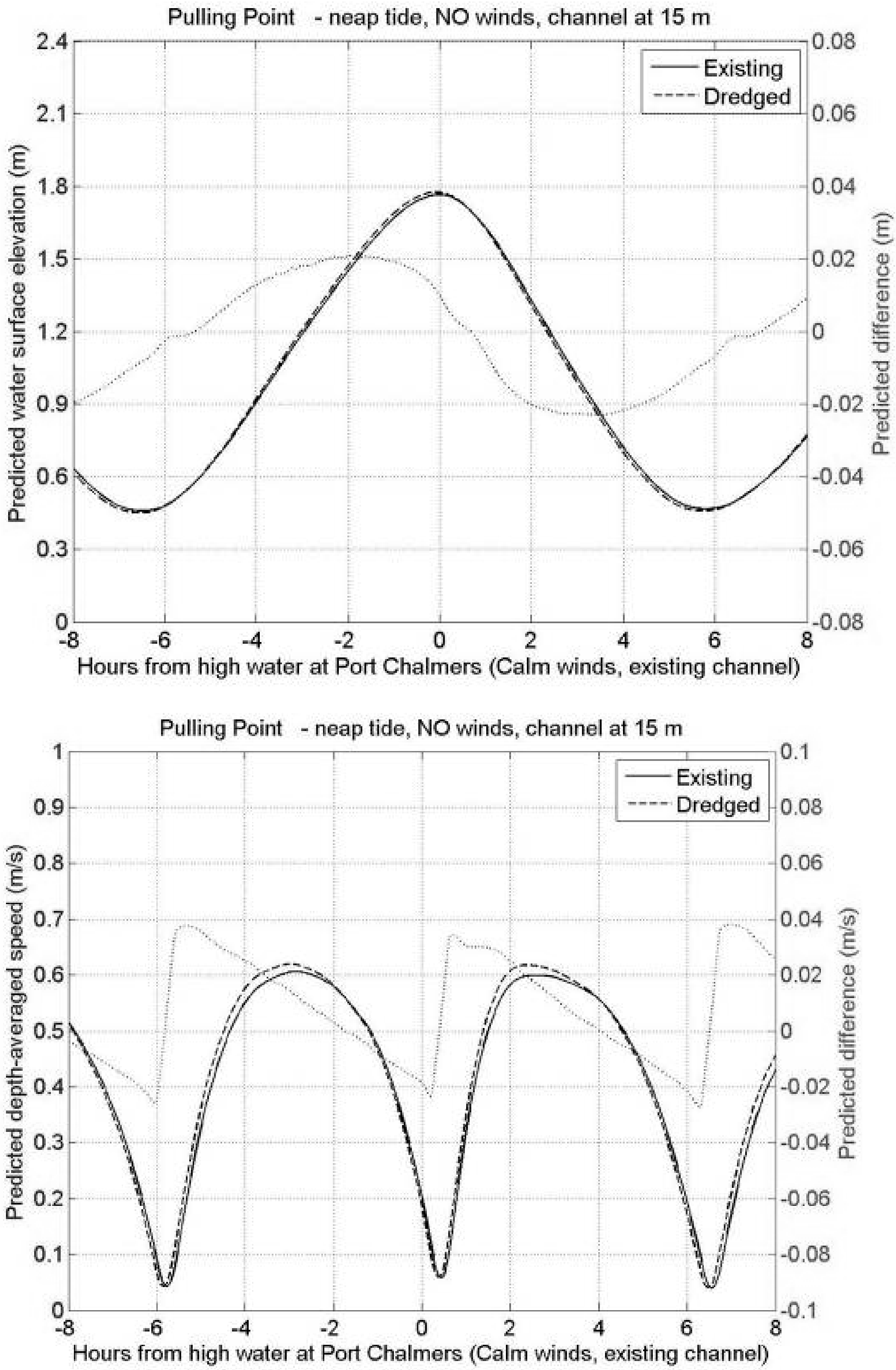


Figure 10a: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a neap tide at Pulling Point.

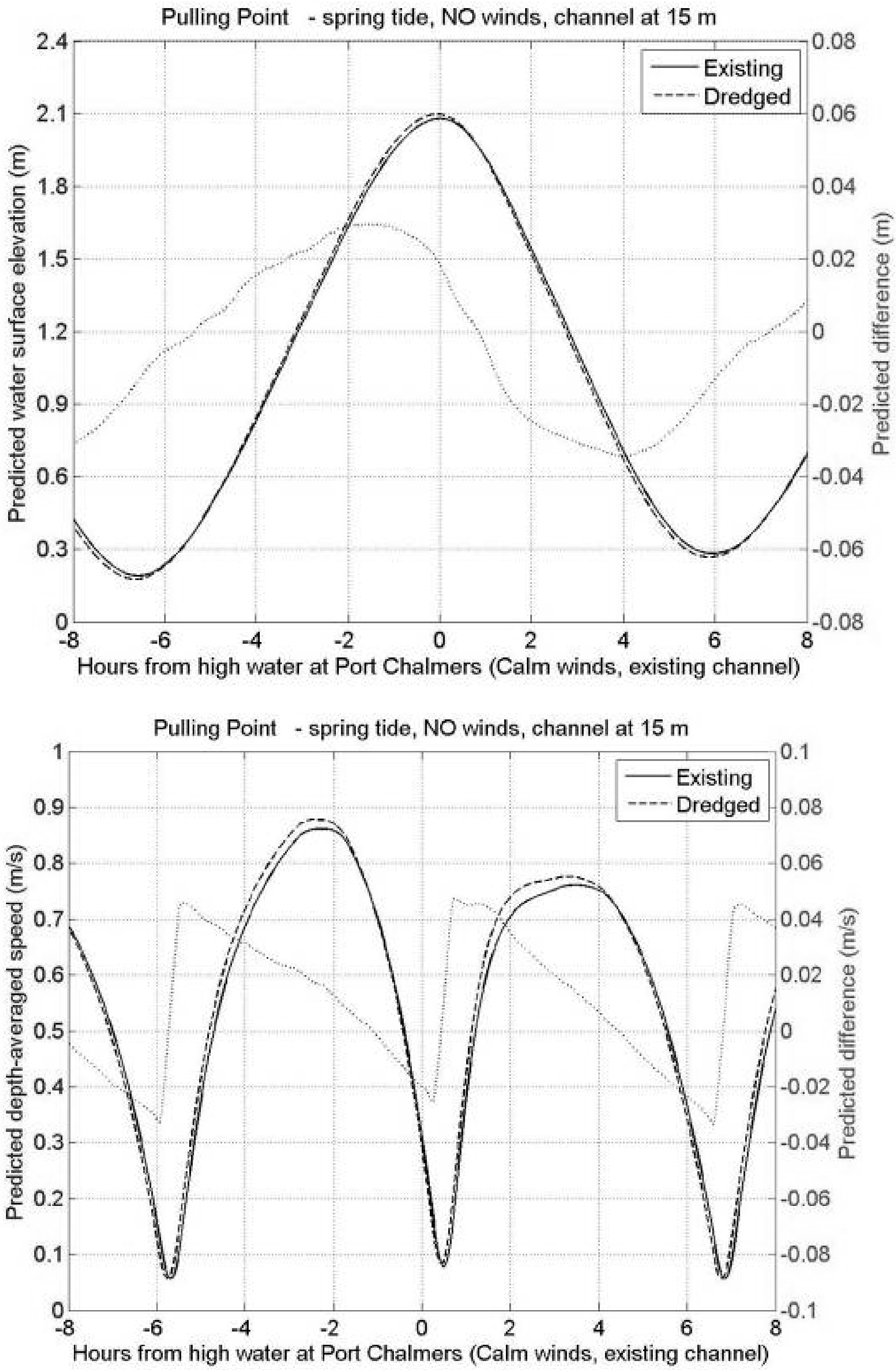


Figure 10b: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a spring tide at Pulling Point.

Table 6: Predicted flood-tide and ebb-tide duration, high-water and low-water level, peak-flood and peak-ebb tide velocity at a site within the main channel near Harington Bend for the different tide and wind conditions and channel depth. The last three columns give the high-water tide phase change (negative= phase advance) and the largest "apparent" increases and decreases in speed induced by deepening the navigation channel at any time of the tide cycle (but without correcting for phase shift).

TIDE	WIND	SITE	CASE	Flood-tide duration (hrs)	Ebb-tide duration (hrs)	Height of high tide (m)	Height of low tide (m)	Peak-flood velocity (m/s)	Peak-ebb velocity (m/s)	Average phase shift (min)	Largest "apparent" *increase* in speed (m/s)	Largest "apparent" *decrease* in speed (m/s)
Neap	NO	Harington Bend	13m	6.47	5.80	1.74	0.47	0.56	0.57			
Neap	SW	Harington Bend	13m	6.45	5.82	1.73	0.45	0.59	0.58			
Neap	NE	Harington Bend	13m	6.47	5.78	1.76	0.49	0.60	0.60			
Spring	NO	Harington Bend	13m	6.47	6.03	2.06	0.24	0.83	0.72			
Spring	SW	Harington Bend	13m	6.52	5.95	2.05	0.22	0.86	0.73			
Spring	NE	Harington Bend	13m	6.47	6.05	2.08	0.25	0.87	0.75			
Neap	NO	Harington Bend	14m	6.45	5.82	1.75	0.47	0.59	0.59	-2	0.04	<-0.01
Neap	SW	Harington Bend	14m	6.40	5.83	1.73	0.45	0.59	0.58	-1	<0.01	<-0.01
Neap	NE	Harington Bend	14m	6.50	5.75	1.77	0.49	0.60	0.60	-1	<0.01	<-0.01
Spring	NO	Harington Bend	14m	6.50	5.93	2.07	0.23	0.87	0.74	-3	0.04	<-0.01
Spring	SW	Harington Bend	14m	6.43	6.03	2.05	0.21	0.86	0.73	-1	0.01	-0.01
Spring	NE	Harington Bend	14m	6.53	6.00	2.08	0.25	0.87	0.75	-2	0.01	-0.01
Neap	NO	Harington Bend	15m	6.50	5.77	1.75	0.47	0.58	0.58	-1	0.03	-0.02
Neap	SW	Harington Bend	15m	6.38	5.83	1.73	0.45	0.58	0.58	-1	0.01	-0.02
Neap	NE	Harington Bend	15m	6.48	5.77	1.77	0.49	0.59	0.59	-1	0.02	-0.02
Spring	NO	Harington Bend	15m	6.50	5.97	2.07	0.23	0.86	0.73	-2	0.04	-0.02
Spring	SW	Harington Bend	15m	6.50	5.98	2.06	0.21	0.85	0.72	-2	0.02	-0.03
Spring	NE	Harington Bend	15m	6.48	5.98	2.09	0.25	0.86	0.74	-2	0.03	-0.03

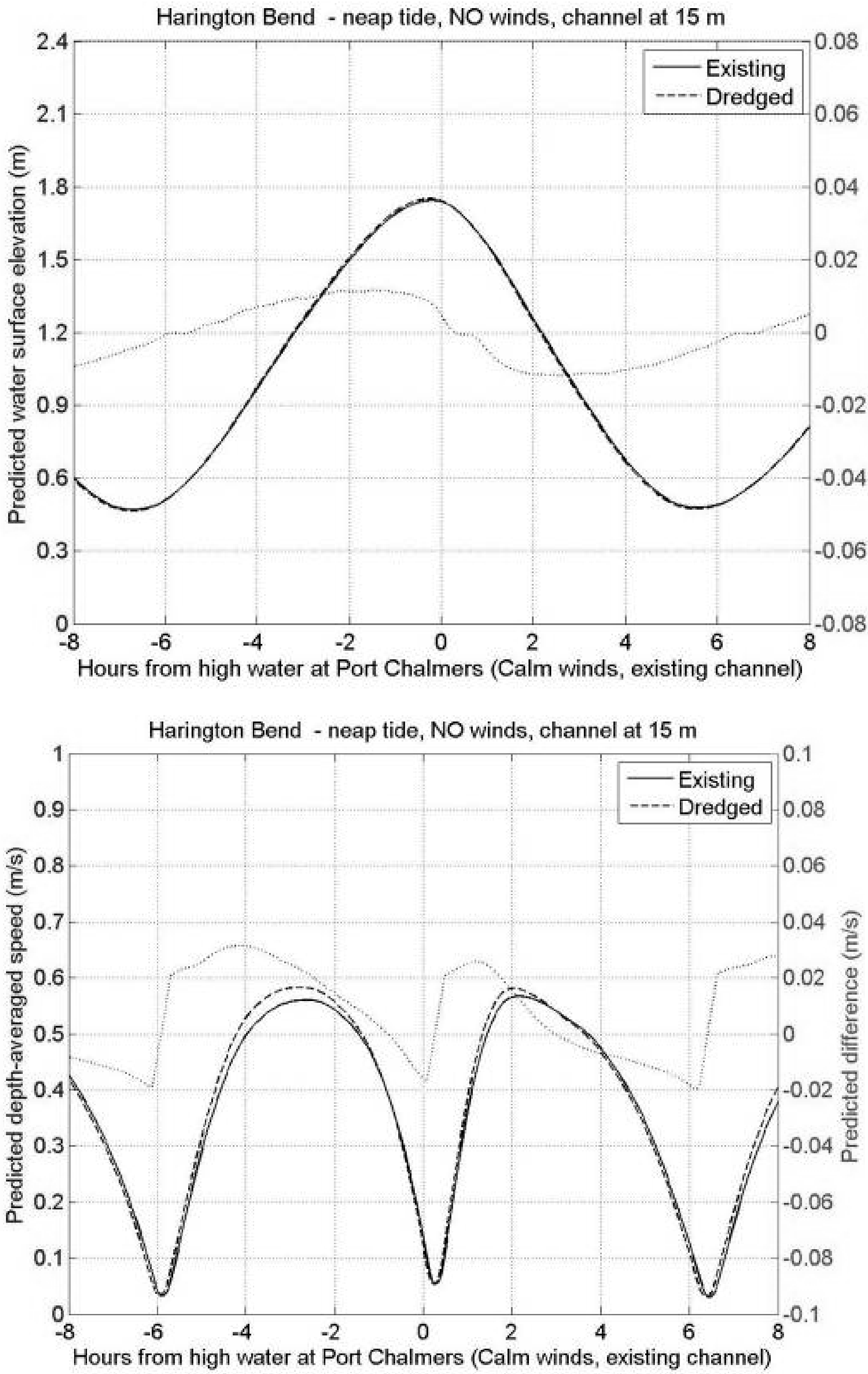


Figure 11a: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a neap tide at Harington Bend.

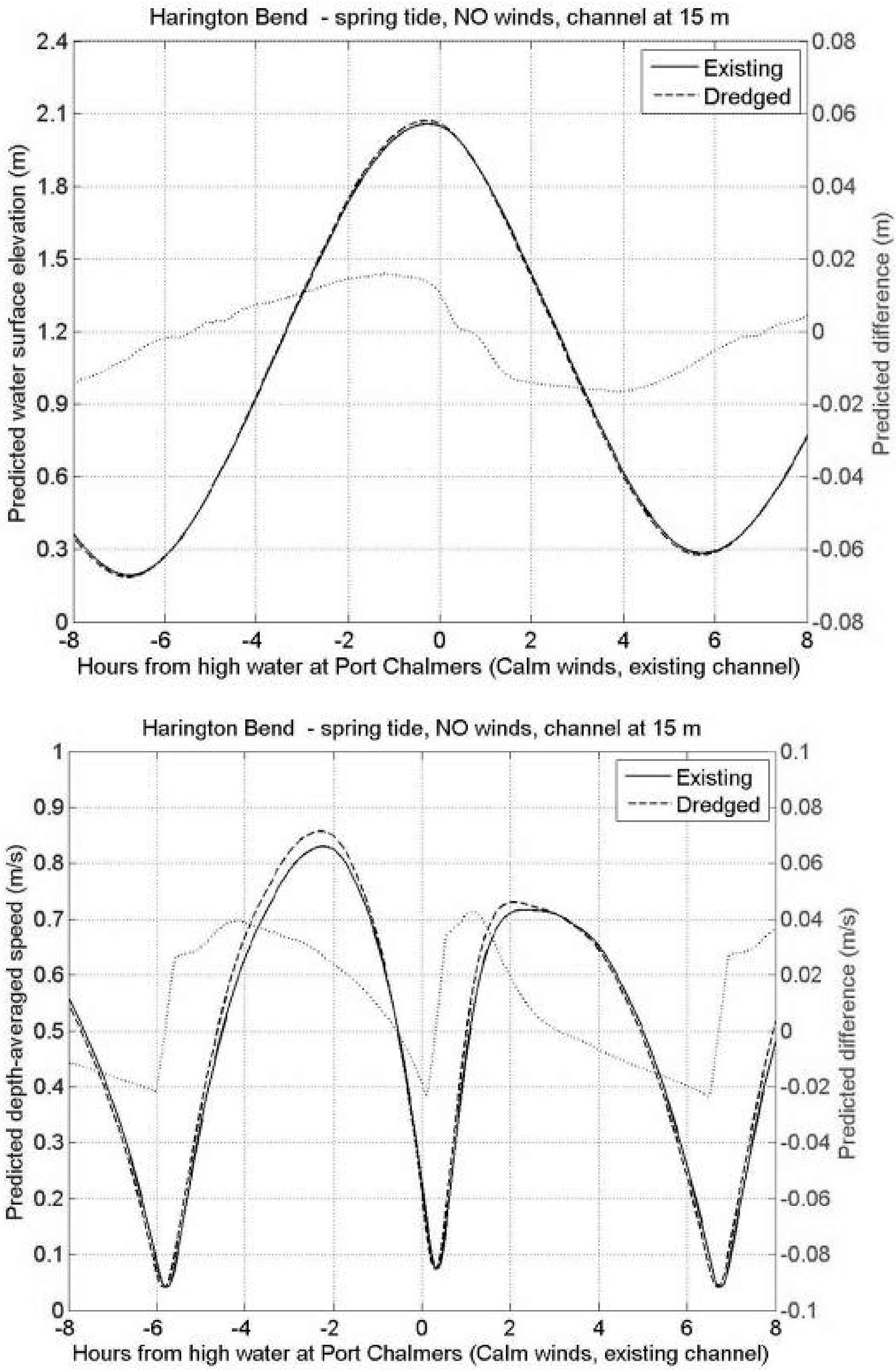


Figure 11b: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a spring tide at Harington Bend.

Table 7: Predicted flood-tide and ebb-tide duration, high-water and low-water level, peak-flood and peak-ebb tide velocity at a site within the main channel at the Spit Jetty tide gauge for the different tide and wind conditions and channel depth. Last three columns give the high-water tide phase change (negative= phase advance) and the largest "apparent" increases and decreases in speed induced by deepening the navigation channel at any time of the tide cycle (but without correcting for phase shift).

TIDE	WIND	SITE	CASE	Flood-tide duration (hrs)	Ebb-tide duration (hrs)	Height of high tide (m)	Height of low tide (m)	Peak-flood velocity (m/s)	Peak-ebb velocity (m/s)	Average phase shift (min)	Largest "apparent" *increase* in speed (m/s)	Largest "apparent" *decrease* in speed (m/s)
Neap	NO	Spit Tide Gauge	13m	6.45	5.80	1.73	0.48	0.64	0.66			
Neap	SW	Spit Tide Gauge	13m	6.42	5.85	1.72	0.47	0.64	0.67			
Neap	NE	Spit Tide Gauge	13m	6.47	5.80	1.74	0.49	0.66	0.70			
Spring	NO	Spit Tide Gauge	13m	6.42	6.05	2.05	0.23	0.94	0.84			
Spring	SW	Spit Tide Gauge	13m	6.42	6.07	2.04	0.22	0.94	0.86			
Spring	NE	Spit Tide Gauge	13m	6.42	6.05	2.06	0.25	0.97	0.87			
Neap	NO	Spit Tide Gauge	14m	6.47	5.80	1.73	0.48	0.64	0.67	0	0.02	-0.01
Neap	SW	Spit Tide Gauge	14m	6.42	5.85	1.72	0.47	0.63	0.66	0	<0.01	-0.02
Neap	NE	Spit Tide Gauge	14m	6.45	5.80	1.74	0.49	0.65	0.68	0	<0.01	-0.02
Spring	NO	Spit Tide Gauge	14m	6.42	6.05	2.05	0.23	0.95	0.85	0	0.03	<-0.01
Spring	SW	Spit Tide Gauge	14m	6.40	6.07	2.05	0.22	0.94	0.84	0	<0.01	-0.02
Spring	NE	Spit Tide Gauge	14m	6.42	6.07	2.06	0.24	0.96	0.86	0	<0.01	-0.02
Neap	NO	Spit Tide Gauge	15m	6.45	5.82	1.74	0.48	0.63	0.66	0	0.02	-0.03
Neap	SW	Spit Tide Gauge	15m	6.40	5.85	1.72	0.47	0.62	0.64	0	0.01	-0.03
Neap	NE	Spit Tide Gauge	15m	6.45	5.80	1.74	0.49	0.64	0.67	0	<0.01	-0.03
Spring	NO	Spit Tide Gauge	15m	6.42	6.05	2.06	0.23	0.94	0.83	0	0.03	-0.03
Spring	SW	Spit Tide Gauge	15m	6.40	6.07	2.05	0.22	0.93	0.82	0	0.01	-0.04
Spring	NE	Spit Tide Gauge	15m	6.42	6.07	2.06	0.24	0.95	0.84	0	0.02	-0.04

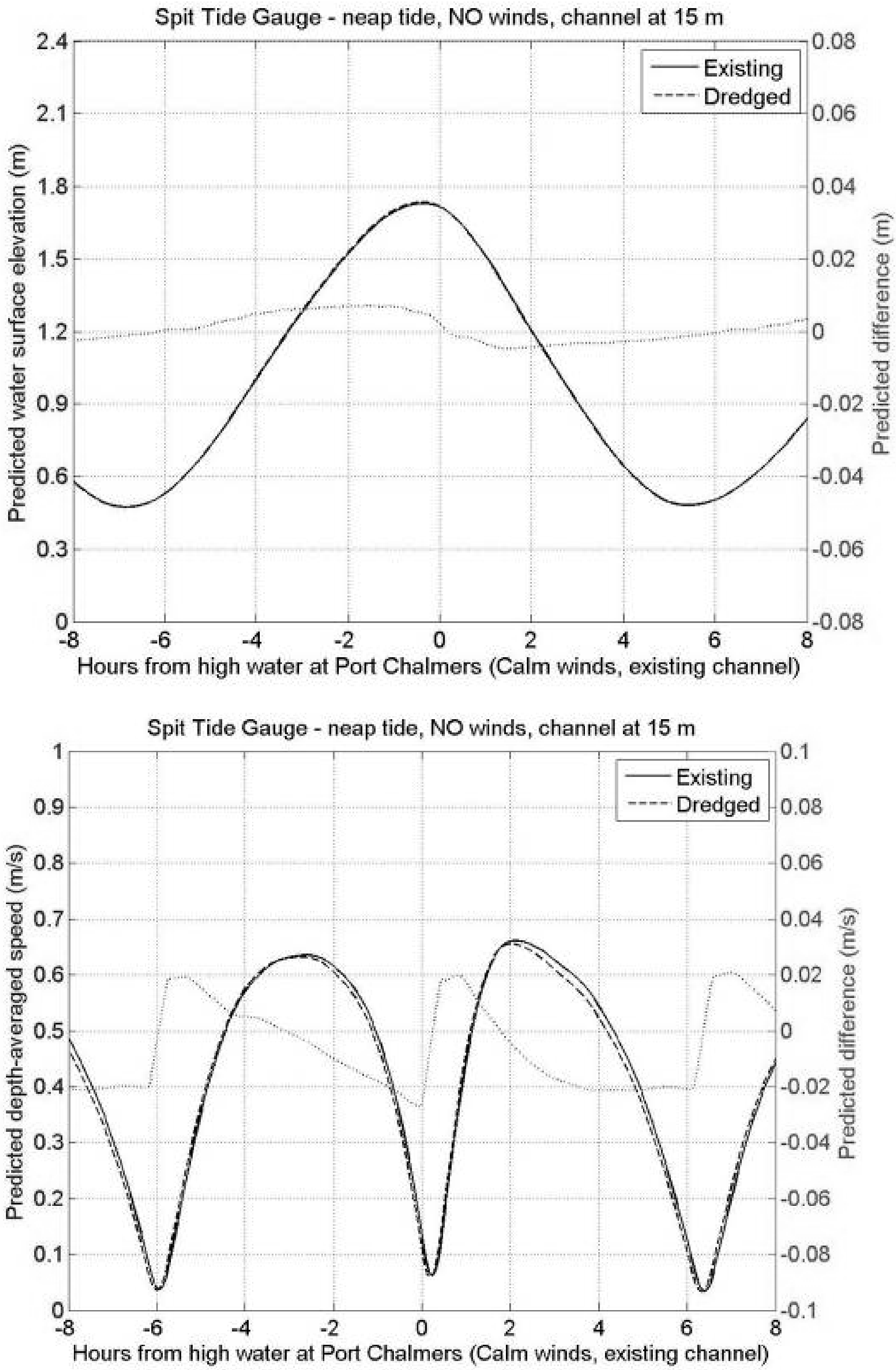


Figure 12a: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a neap tide off Spit Jetty.

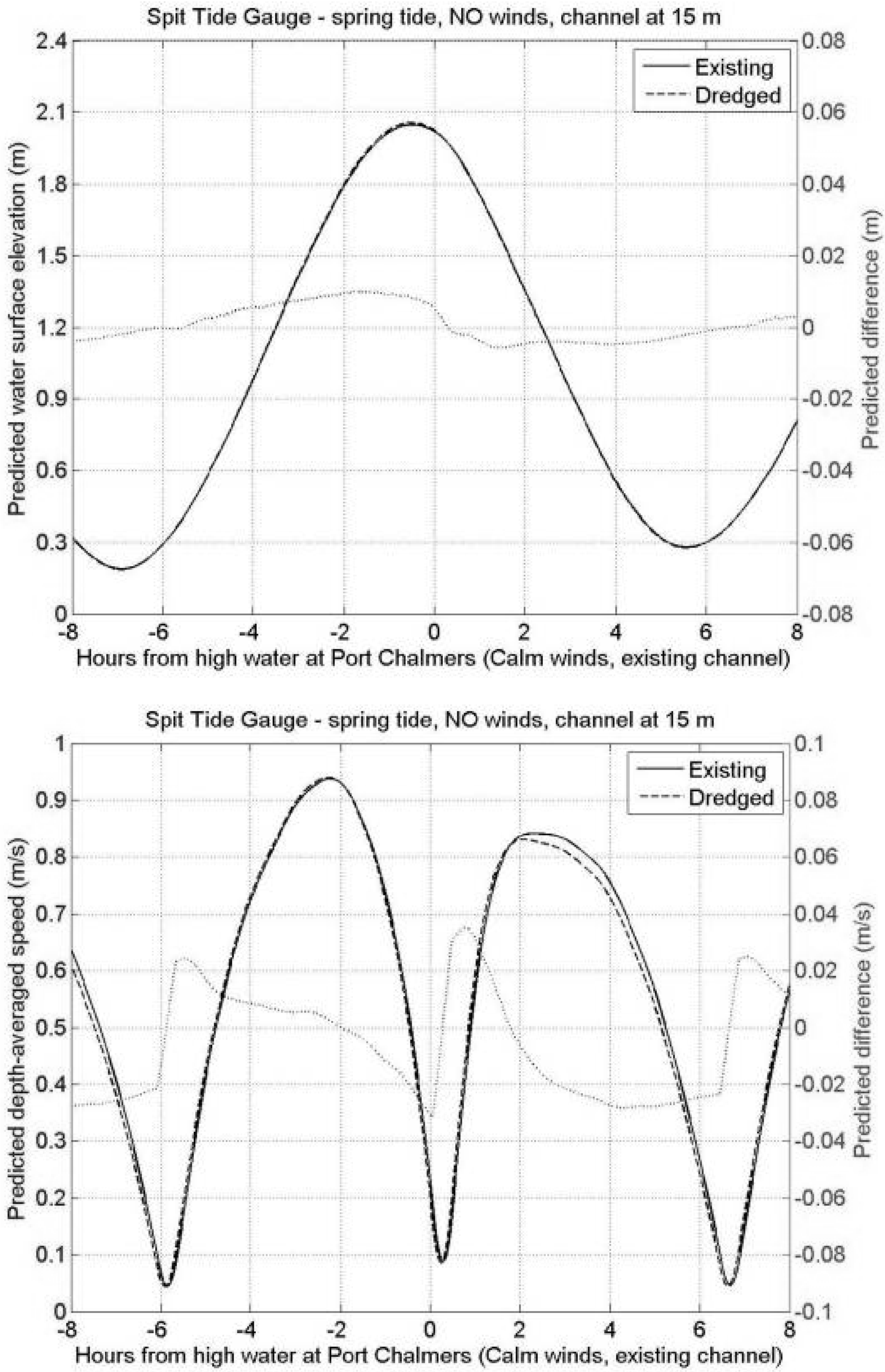


Figure 12b: Comparison of predicted tide levels (top panel) and velocities (bottom panel) between the existing and 15-m dredged channel option for a spring tide off Spit Jetty.

4.3 Future work (Harbour hydrodynamics)

Refinement of the existing 100-m hydrodynamic model to a higher-resolution grid with improved bathymetry coverage (e.g., intertidal flats) will be required to better represent modifications to the channel by dredging and to improve current speed predictions at the channel bends (e.g., Harington Bend), channels between islands, and particularly on the intertidal flats.

The refined hydrodynamic model will then require more rigorous calibration (tuning) against measured tide heights and currents. Current-velocity measurements can be a mixture of current-meter data from past investigations (e.g., the 1988 Harbour Board model study and University of Otago deployments), supplemented by some new velocity measurements from the flanks of the existing main channel and possibly an inter-tidal site. Improved model resolution coupled with a more robust calibration will provide further assurance to stakeholders that the Harbour flow model is working correctly, and can be confidently used to predict subsequent changes in the Harbour hydrodynamics from modifications to the navigation channel and to drive the sediment-plume model.

5. Sediment plume dispersal

5.1 Results from preliminary scenarios

Particle-tracking dispersion model runs were carried out for the 3 scenarios outlined in Section 1.2.2. In this type of dispersion model, the discharge of contaminants or sediment is represented by thousands of small "particles", which are each tracked by the model as the current transports them downstream. As they "go with the flow", the particles also disperse (move wider apart) as they encounter turbulence and shearing in the current velocity (horizontal and vertical). This dispersive process is simulated by a "random-walk" process, where particles are free to wander and disperse within limits imposed by the dispersion coefficients. At this stage, not only is the flow model (MIKE21) uncalibrated, but so is the dispersion model, which is based on using typical values of dispersion coefficients NIWA has used in several other harbours.

The predicted concentrations are the depth-averaged values normalised so that a relative concentration of 1.0 (or 100% of the initial concentration) occurs at the sediment-release site during the initial part of the simulation. That is, the maximum predicted concentration predicted by the model during the simulation is a value of 1.0. Also for example, a relative concentration of 0.4 means a concentration that is 0.4× the initial concentration. A major assumption (although conservative in terms of area affected) is that particles were assigned neutral buoyancy (i.e., no fall velocity) and were not allowed to either settle onto the bed or be resuspended from the bed. The model output therefore gives an indication of the likely maximum possible extent of suspended-sediment plumes and dilution values that may occur after two and a half tidal cycles.

The first simulation consisted of a 6-hour release on the flooding tide from the Port Chalmers turning circle with the existing channel configuration under spring tides and strong north easterly winds. Figure 13 shows the predicted relative concentration at the end of a 6-hour release and Figure 14 the predicted relative concentration after a further two tidal cycles. At the end of the simulation, the majority of the plume sits between Ravensbourne and Tayler Point with concentrations mostly in the range of 0.05–0.10 (5–10% of the initial concentration).

The second simulation consisted of a 6-hour release on the ebbing from the Port Chalmers turning circle with the 15-m channel configuration under neap tides and calm wind conditions. Figure 15 shows the predicted concentration at the end of the 6-hour release and Figure 16 the predicted concentration after a further two tidal cycles. At the end of the simulation, the majority of the plume sits between Curles Point and

Tayler Point with relative concentrations mostly in the range of 0.05–0.10 (5–10% of the initial concentration).

The third simulation consisted of a 6-hour release on the flooding tide from the Howletts Claim with the 15 m channel configuration under neap tides and calm wind conditions. Figure 17 shows the predicted relative concentration at the end of the 6-hour release and Figure 18 the predicted relative concentration after a further two tidal cycles. At the end of the simulation, the majority of the plume sits seaward of Goat Island (with relative concentrations mostly in the range of 0.05–0.10) with some of the plume moving out into the deeper waters beyond Heyward Point.

5.2 Next stage (plume dispersal)

The above three scenarios illustrate the type of plume dispersal modelling that can be undertaken, although no sediment settling was included. In the detailed investigation phase, determining representative values for sediment characteristics (such as settling rates for different grain sizes) and plume dispersion coefficients will be the key to successfully modelling the spread and final settlement of sediments released during the dredging operation. The plume model relies on the hydrodynamic model for input current velocities and the effects of winds, so improvements in resolution of the Harbour model will flow through to improved transport and dispersion of sediment plumes, particularly over the intertidal flats. Plume-dispersion scenarios will need to be constructed to cover the expected range of environmental and dredging conditions likely to occur at different stages of the project.

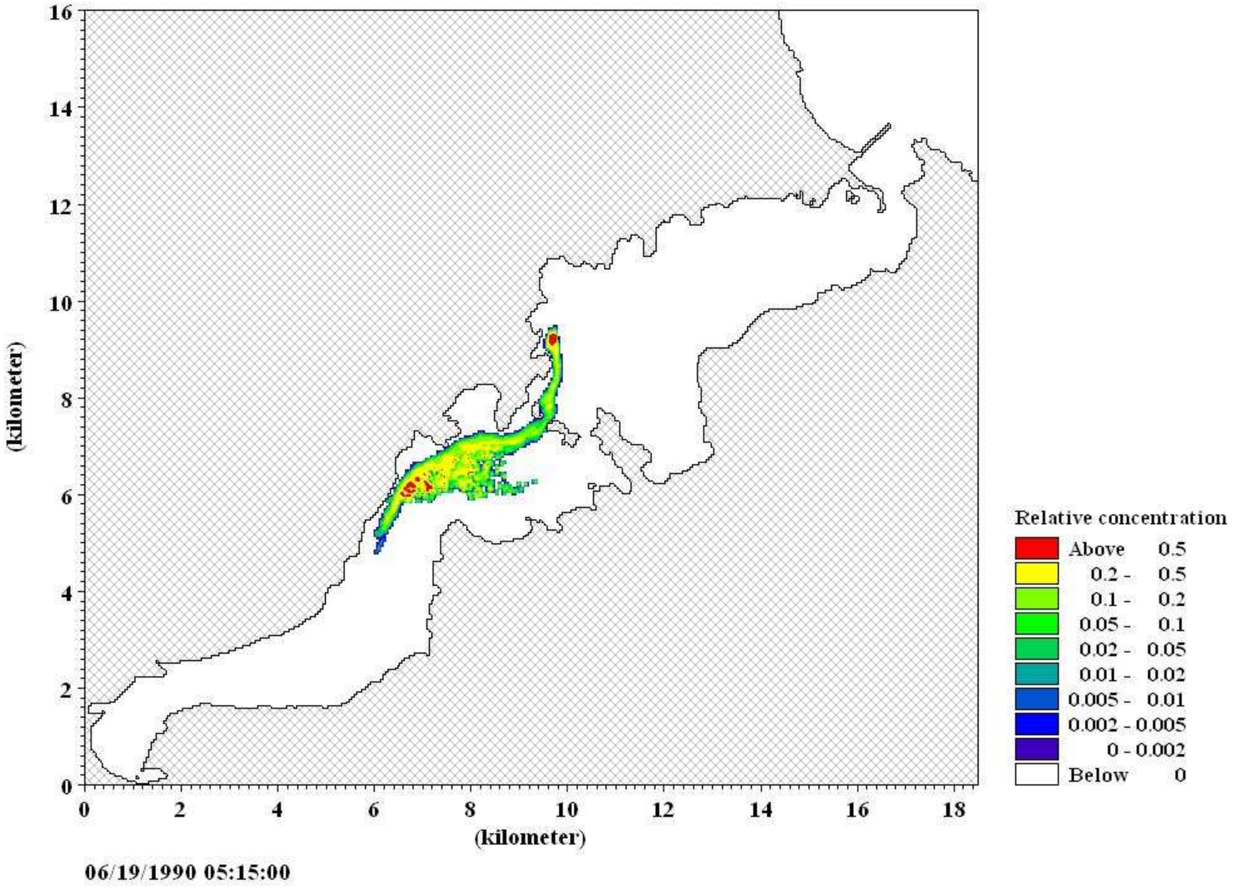


Figure 13: Depth averaged concentration at the end of a 6-hour sediment release for the existing channel configuration, spring tide, 20 knot NE wind. Release point for the dredge-induced discharge in Port Chalmers turning basin for all of flood tide. Colour scale to the right of the plot shows the relative concentration with a value of 1.0 being assigned to the peak concentration that occurred at the release site at slack water.

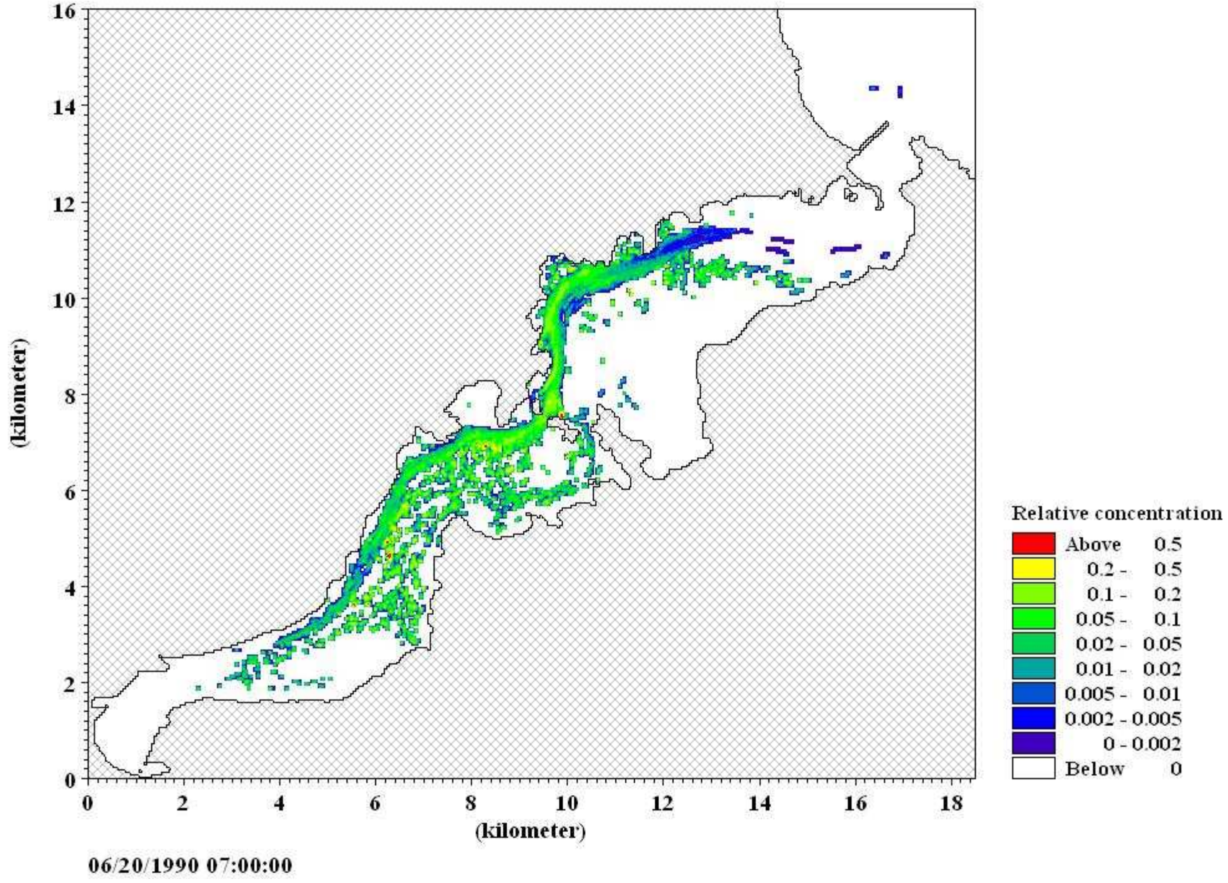


Figure 14: Depth averaged concentration after a 6-hour sediment release and a further two tidal cycles for the existing channel configuration, spring tide, 20 knot NE wind. Release point for the dredge-induced discharge in Port Chalmers turning basin for all of flood tide. Colour scale to the right of the plot shows the relative concentration with a value of one being assigned to the concentration that occurred at the release site at slack water.

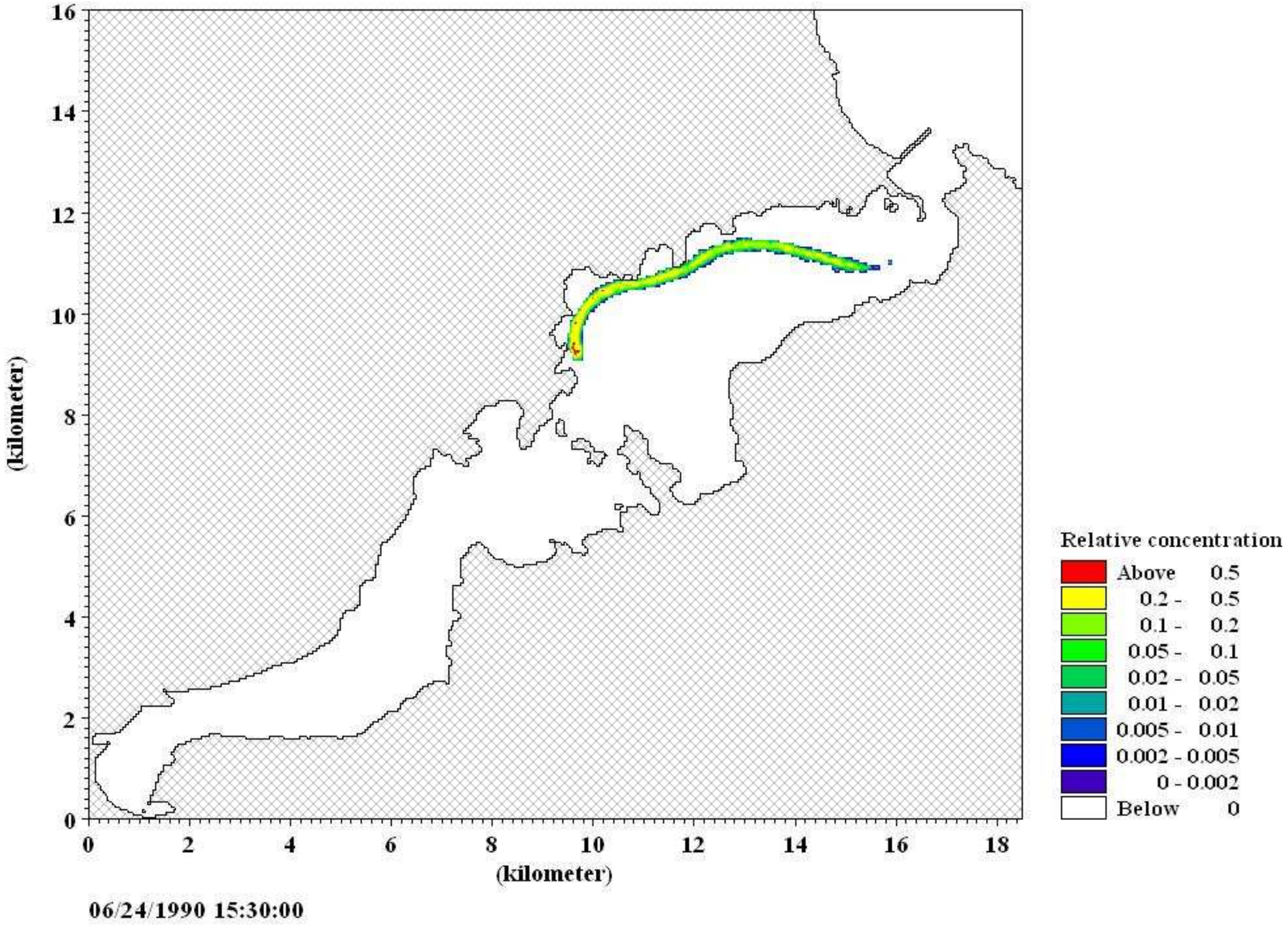


Figure 15: Depth averaged concentration at the end of a 6-hour sediment release for the 15 m channel configuration, neap tide, calm wind conditions. Release point for the dredge-induced discharge in Port Chalmers turning basin for all of ebb tide. Colour scale to the right of the plot shows the relative concentration with a value of one being assigned to the concentration that occurred at the release site at slack water.

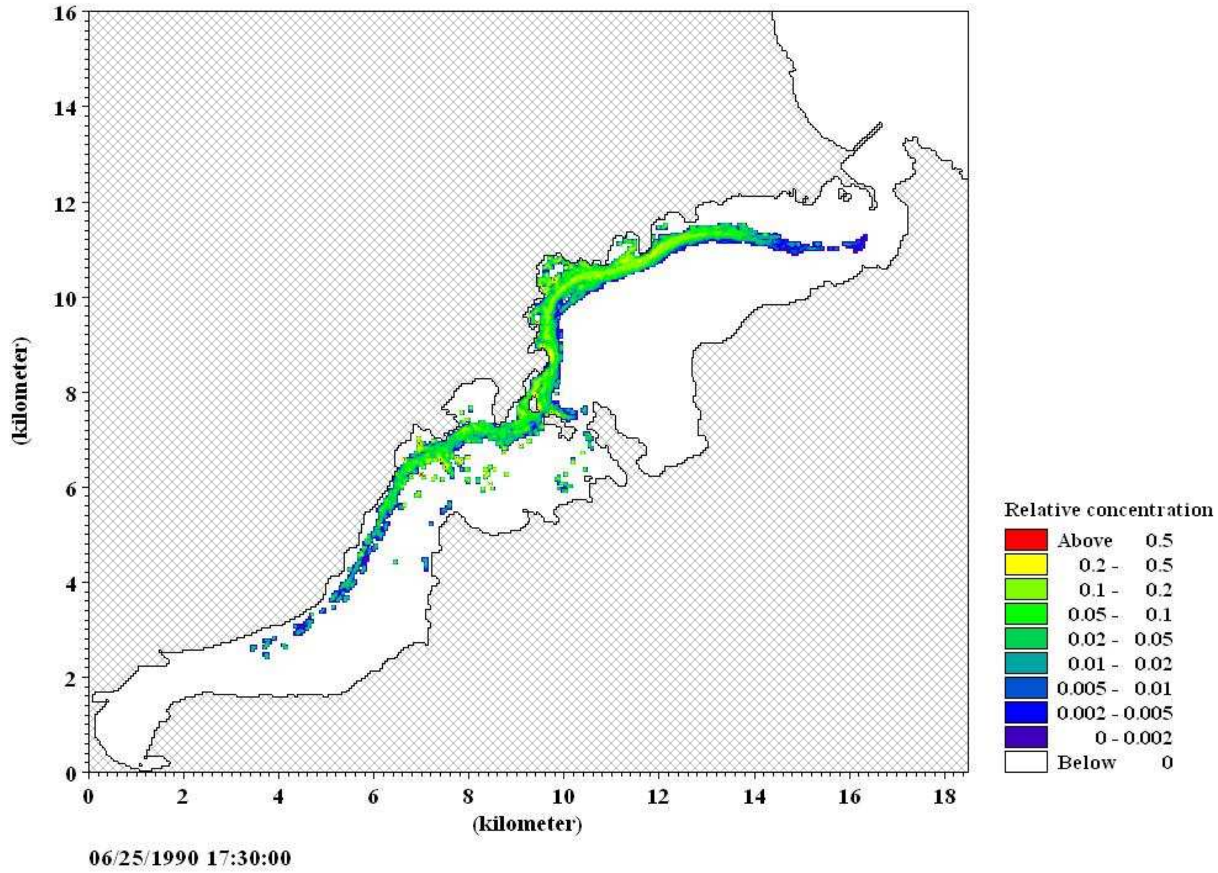


Figure 16: Depth averaged concentration after a 6-hour sediment release and a further two tidal cycles for the 15 m channel configuration, neap tide, calm wind conditions. Release point for the dredge-induced discharge in Port Chalmers turning basin for all of ebb tide. Colour scale to the right of the plot shows the relative concentration with a value of one being assigned to the concentration that occurred at the release site at slack water.

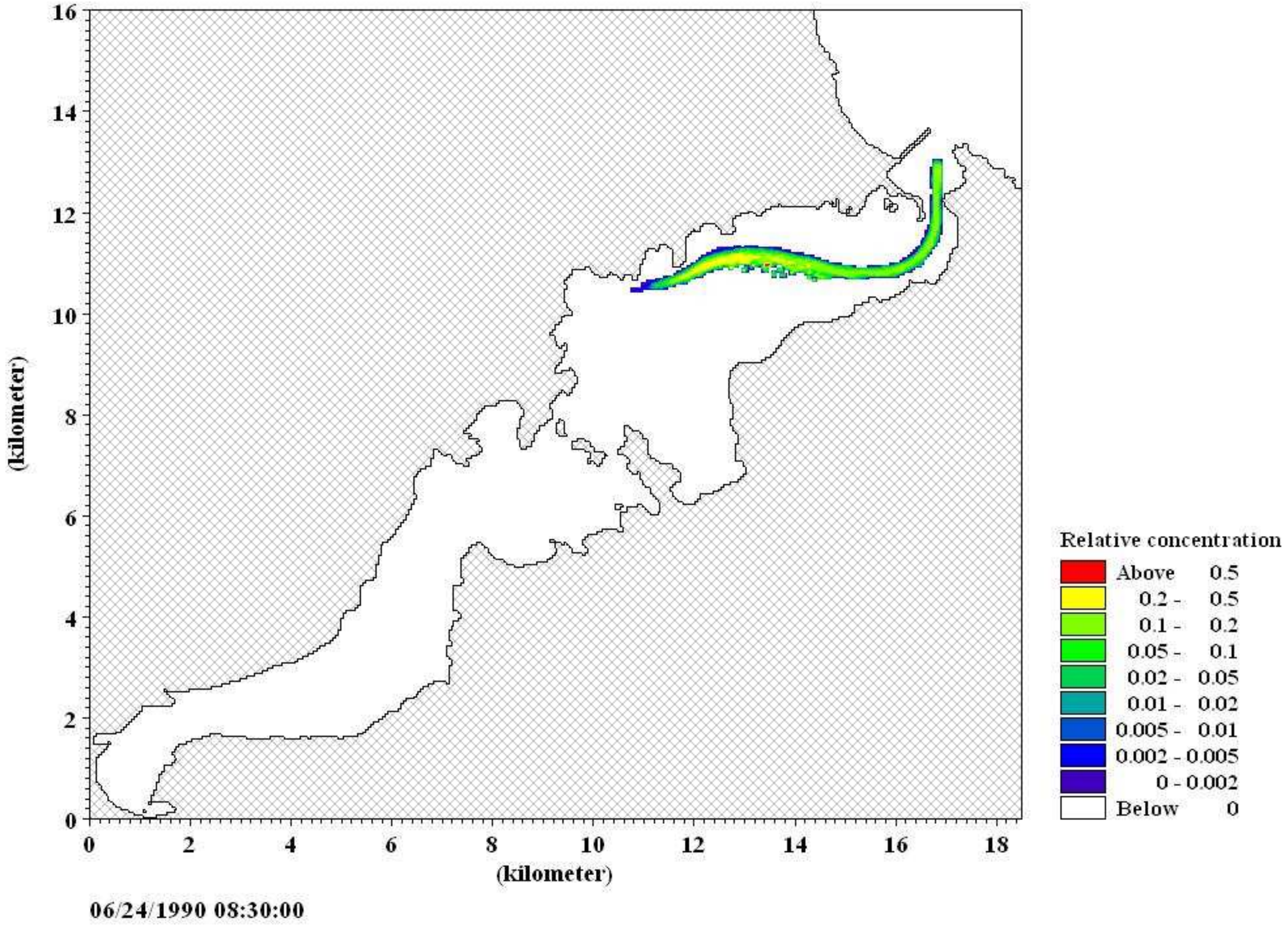


Figure 17: Depth averaged concentration at the end of a 6-hour sediment release for the 15 m channel configuration, neap tide, calm wind conditions. Release point for the dredge-induced discharge source in Howletts Claim (west of Taiaroa Head) for all of a flood tide. Colour scale to the right of the plot shows the relative concentration with a value of one being assigned to the concentration that occurred at the release site at slack water.

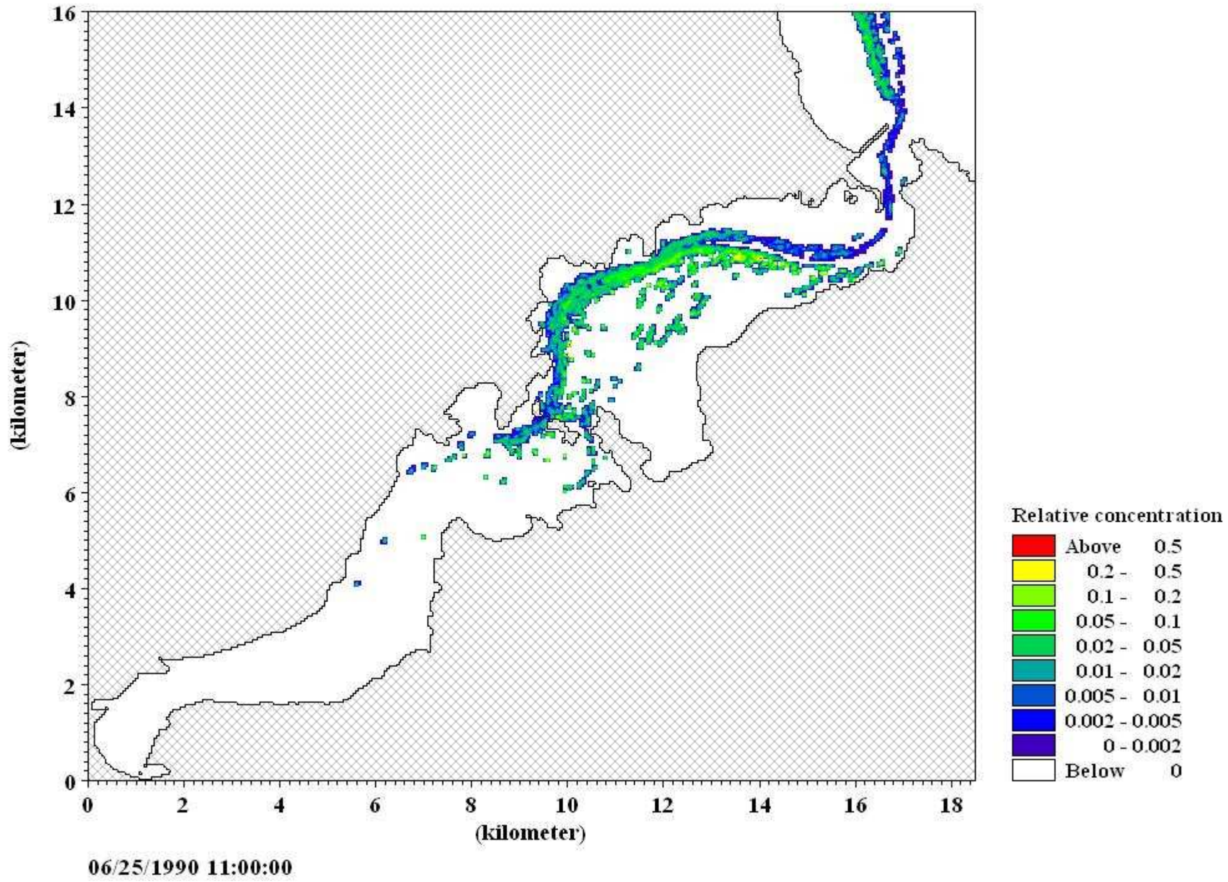


Figure 18: Depth averaged concentration after a 6-hour sediment release and a further two tidal cycles for the 15 m channel configuration, neap tide, calm wind conditions. Release point for the dredge-induced discharge source in Howletts Claim (west of Taiaroa Head) for all of a flood tide. Colour scale to the right of the plot shows the relative concentration with a value of one being assigned to the concentration that occurred at the release site at slack water.

6. Offshore spoil ground mobility

6.1 Introduction

This feasibility study is limited to two aspects of the potential mobility of dredged sediment from the larger offshore spoil ground. These aspects are:

- synthesize the available information on waves in the waters offshore from Taiaroa Head and provide an approximate estimate of wave conditions and the frequency with which they would be sufficient re-suspend material from the offshore dredge spoil ground; and

- the approximate directions the resuspended fine-sand material would be transported.

6.2 Offshore Waves

Historically, wave data coverage of New Zealand’s coast has been poor, particularly for directional records. With very few data sets available of more than one year’s duration, it has been difficult to establish an accurate wave climatology at most sites. To help fill in the gaps in our wave records, the WAM wave generation model has been implemented over a domain covering the Southwest Pacific (Australia) and the Southern Ocean south of New Zealand and Australia (to capture all the potential swell sources). The model has been used to hindcast (back-predict) the generation and propagation of deep-water waves incident on the New Zealand coast over a 20-year period (1979–98). The wave model is driven by winds supplied from the European Centre for Medium Range Weather Forecasting (ECMWF). The 20-year wave hindcast product therefore opens up the ability to generate a synthetic wave climatology near the New Zealand coast where no wave measurements have been made (Gorman et al. 2003). However, for the hindcast to be used with confidence, it needs to be verified and tuned by local wave measurements for a period of several months to capture several storms.

For this study, the 20-year WAM wave hindcast was extracted for one possible spoil site on the underwater bank located 3 nautical miles due east of Taiaroa Head at approximately 170.778°E, –45.774°S (Figure 19). The depth at this site is approximately 27 m relative to Chart Datum or around 28 m depth for the average sea level that waves would encounter. Subtracting a possible 1.25–1.5 m for height of spoil mound means the waves at an average sea level would encounter a 26.5 m depth over the mound (taking the higher mound height to be conservative).

Figure 19: Locations of the two NIWA current meter sites: Landfall Tower (78-day record), Aanderaa current meter (4 days); and a possible spoil ground location used for the purposes of estimating the mobility of dredged sand. [*Image source: Google Earth*].

Based on the 58440 sets of 3-hourly wave statistics in the hindcast, the mean significant wave height H_s (average of the highest 1/3rd of waves) was 1.1 m, mean wave approach direction D (coming from) was 125° (i.e., from the south-east) and the mean wave period T_m (using second-moment method) was 6.4 seconds. The distribution of significant wave height (H_s) and mean wave period (T_m) are shown in Figures 20 and 21 respectively. The directional distribution of the waves at this site is shown in Figure 22. Linear wave theory was used to calculate the horizontal wave orbital velocity from the timeseries of H_s and T_m. The distribution of wave orbital velocities is shown in Figure 23.

Komar and Miller (1975) showed that the critical erosion threshold for wave-resuspended sand depends on the grain size and the wave period (e.g., Table 8). Particle size analyses of four Port Otago samples of dredged sediment show a D_{50} sand diameter of ~0.2 mm and a D_{10} sand diameter of ~0.1 mm, classified as fine sand, with a smaller coarser medium-sand fraction. The critical erosion threshold was evaluated

for the 20-year hindcast of wave periods, for both sediment sizes. This was compared to the calculated wave orbital velocity at the seabed, to determine times of expected sand resuspension (e.g., Figure 24). The resuspension occurrences for the example mound height (26.5 m water depth) are summarised in Table 9.

Table 8: Example of critical erosion thresholds (U_{c50}) in m/s for sand of 0.2 mm and 0.1 mm diameter, for various mean wave periods (T_m).

Mean wave period T_m **(s)**	**6**	**8**	**10**	**12**	**14**
U_{c50} (m/s) for d = 0.2 mm	0.16	0.18	0.19	0.21	0.22
U_{c10} (m/s) for d = 0.1 mm	0.13	0.14	0.15	0.16	0.17

Table 9: Summary of resuspension occurrence for fine sands of 0.2 mm and 0.1 mm diameter.

Sand size	**% of time of active resuspension**	**No. of resuspension events in 20-yr period (1979–98)**	**Average No. of resuspension events per year**
d = 0.2 mm	14%	469	23
d = 0.1 mm	21%	621	31

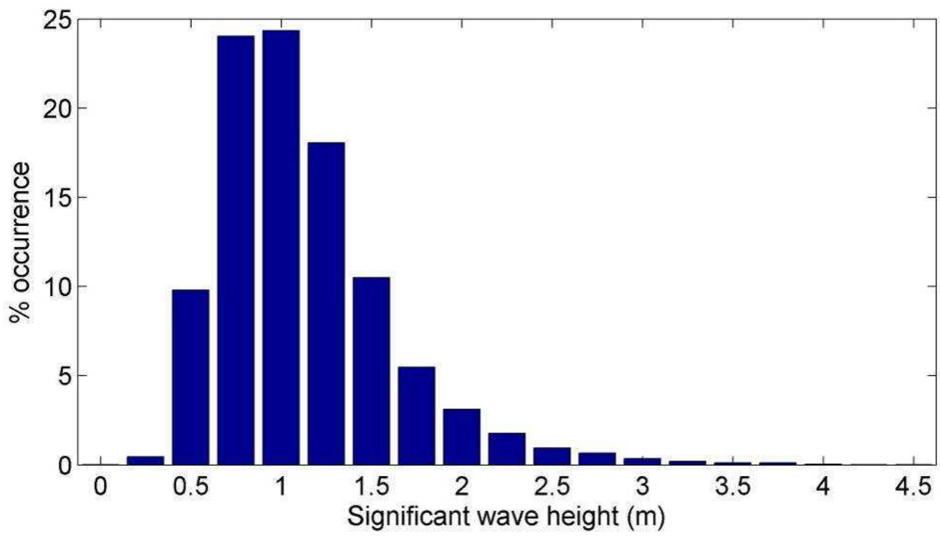


Figure 20: Distribution of significant wave height from the 20-year (1979–98) wave hindcast model at a site located 3 nautical miles due east of Taiaroa Head.

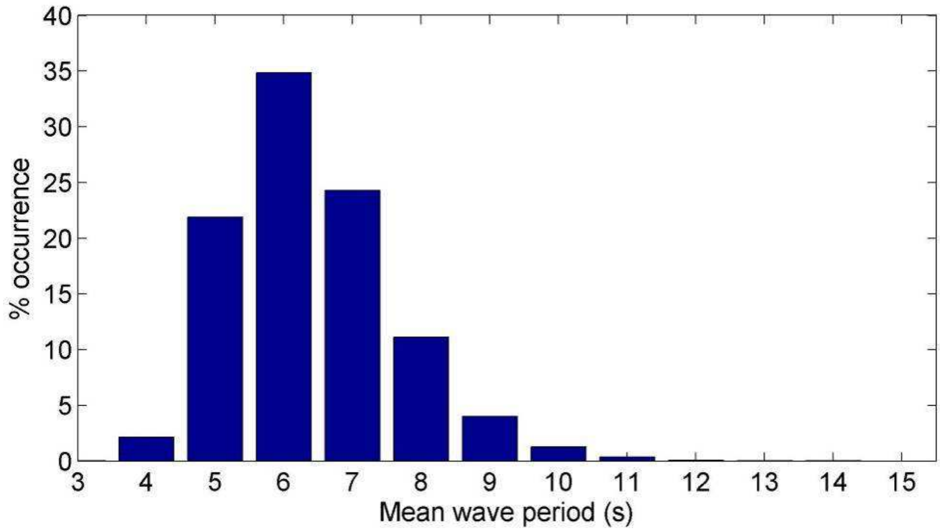


Figure 21: Distribution of mean wave period from the 20-year (1979–98) wave hindcast model at a site located 3 nautical miles due east of Taiaroa Head.

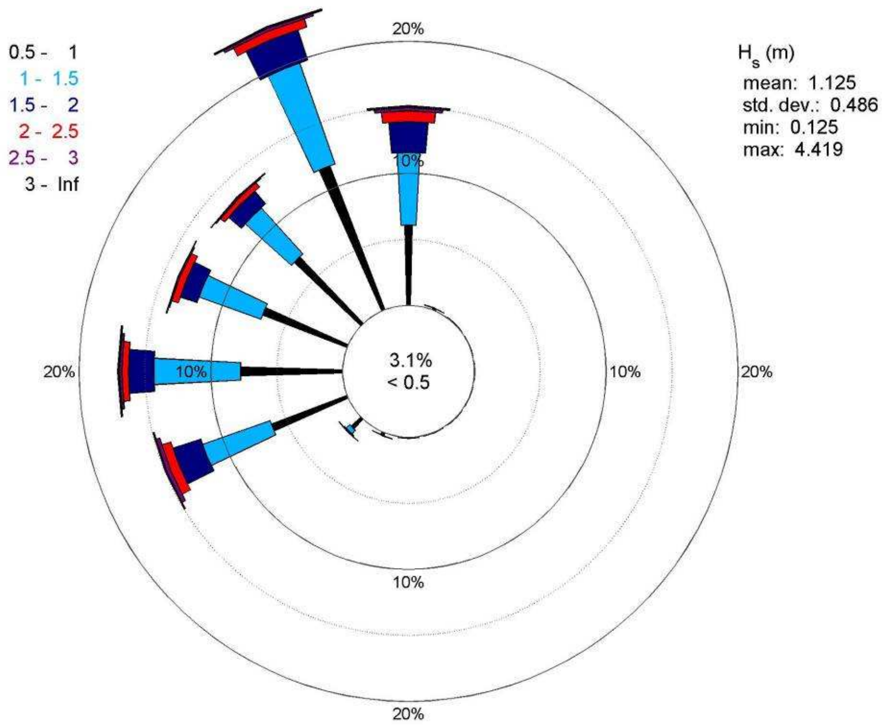


Figure 22: Wave rose from the 20-year (1979–98) wave hindcast model at a site located 3 nautical miles due east of Taiaroa Head. Directions are shown in the direction to where the waves are travelling.

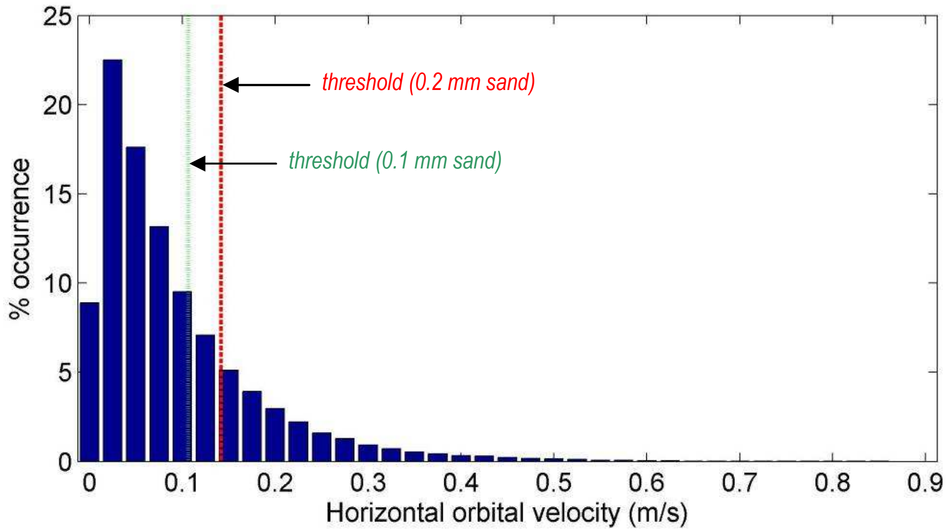


Figure 23: Distribution of horizontal wave orbital velocity at the seabed on top of a theoretical spoil mound at a site located 3 nautical miles due east of Taiaroa Head, calculated using linear wave theory and H_s, T_m statistics from the 20-year (1979–98) wave hindcast model. The vertical dashed lines mark the minimum erosion threshold for sand (no sand eroded at orbital velocities to the left of these lines): green LHS line = 0.1 mm diameter sand; red RHS line = 0.2 mm diameter sand.

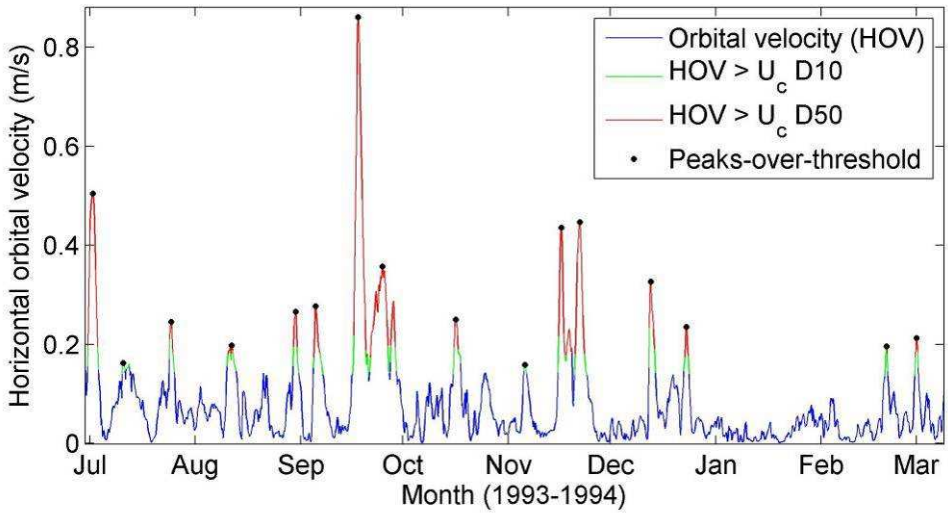


Figure 24: Example timeseries of wave horizontal orbital velocities (HOV) at the seabed (26.5 m depth) calculated from the 20-year wave hindcast using linear wave theory. The calculated orbital velocities are plotted in blue. The orbital velocities that exceed the threshold for D_{10} (0.1 mm diameter) fine sand are over-plotted in green and those that exceed the threshold for D_{50} (0.2 mm diameter) fine sand are over-plotted again in red. The black dots mark local maxima that are separated in time by at least 3 days, indicating separate peaks of resuspension events.

In summary, from Table 9, 0.2 mm diameter sand is expected to be resuspended 14% of the time in total, during an average of 23 separate resuspension events per year or approximately once per fortnight. The finer 0.1 mm diameter sand fraction is expected to be resuspended 23% of the time in total, during an average of 31 separate resuspension events per year.

Finer silt fractions are not considered here, but remaining silt that wasn’t dispersed during descent of the dredgings, will subsequently winnow out of the surface fabric of the mound under lower wave conditions than the fine-sand threshold. These processes will need to be considered in the detailed phase of the AEE investigations.

6.3 Offshore currents and potential dredged-sediment drift

Once resuspended, the fine sand from the spoil mound would be transported by the near-bed current flow at the time. However, this process usually occurs in a series of small hops, where sand grains are mobilised, carried for a time by the near-bed current, then re-deposited, before being re-mobilised again when conditions exceed the threshold wave orbital velocity. The sand can also slide along the bed surface.

Field measurements of offshore currents have been undertaken by the Marine Sciences Dept (University of Otago) using a downward-looking ADCP from a vessel. One such study reported by Old and Vennell (2001), who described the ebb-tide jet flow through the approach channel adjacent to the north-south oriented bar. The residual current at the northern end of the bar was shown to be in the northerly direction. A previous deployment of an InterOcean S4 current meter at Landfall Tower (Figure 19), at the northern end of the bar, during the 1988 model study by the Harbour Board (Barnett, 1988) also showed a consistent northerly residual current. The average residual (or drift) velocity was 4.5 km per day to the north based on the S4 current-meter record for a 78-day period from the 18-March to 7-June 1988. The only other known current-meter in the area is a short 4-day deployment in February 1983 of an Aanderaa current meter at the location shown in Figure 19. The currents from this deployment were consistently flowing in a NNE to NE direction.

Further offshore in the region of the underwater bank (identifiable by the 20 m depth contour – see Fig. 1 of Carter et al. (1985)), the tidal residual current will be much slower. However, the Clutha Plume and the Southland Current signatures become more prominent, both of which move in a north to north-east direction, as shown in Figure 25.

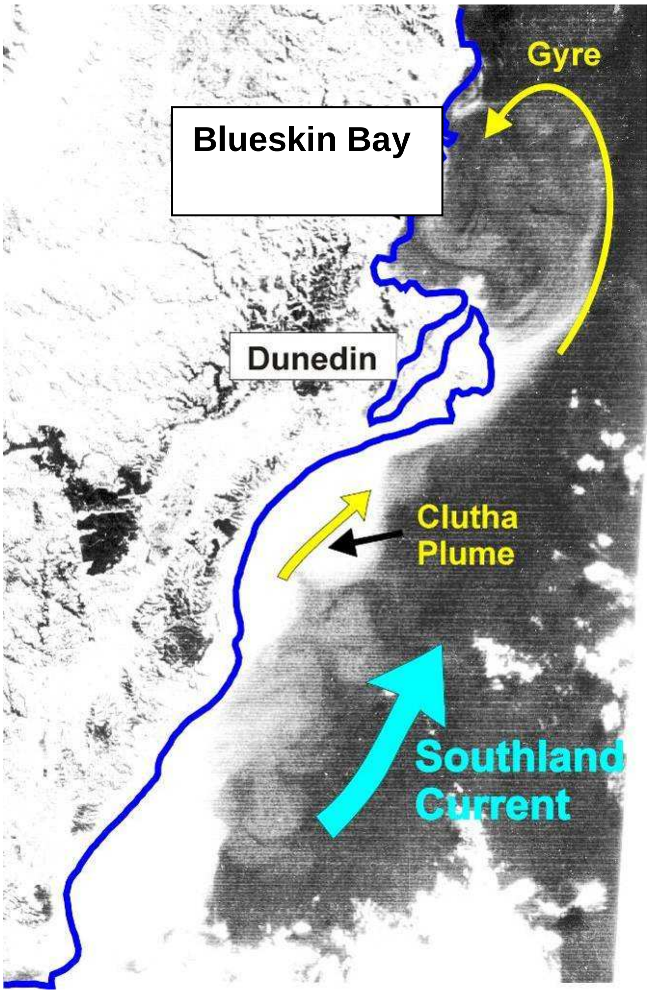


Figure 25: Landsat II image showing the flow paths of the predominantly Clutha River-derived suspended sediment along the Otago continental shelf. Note the complex eddy (gyre) of suspended sediment in Blueskin Bay, immediately north of Otago Peninsula (modified after Carter et al. 1985 and Murdoch et al. 1990). The approximate position of the Southland current is also marked.

In summary, the predominant residual current (or drift) off Taiaroa Head is to the north or north-east, so during the wave resuspension events, sand will be winnowed from the spoil mound and moved mostly north to north-east by the current flow at the seabed, but generally in short steps during storm-wave periods.

6.4 Future work (offshore area)

To support environmental assessments in the offshore-shelf area arising from the dredged-material disposal, detailed field work offshore involving wave and current measurements and associated hydrodynamic and wave modelling will be required.

Measurements of currents and waves should be undertaken concurrently at strategic sites offshore over a period of 3–6 months. An offshore-shelf model at around 200-m grid spacing would need to be developed to simulate currents in the shelf area including Blueskin Bay. Such as model would need to include predictions of the variable Southland Current and the downstream plume of the Clutha River, which would be the most expensive part of the modelling investigations.

Wave modelling on the same offshore-shelf model grid would also be used to ascertain the physical effect on inshore wave heights and directions as a result of wave passage over the extensive offshore spoil mound, particularly under swell conditions. The currents and waves from both these calibrated models can then be combined to quantify the pattern and direction of long-term movement of sediments away from the offshore spoil mound and the smaller inshore spoil grounds.

7. References

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