APPENDIX 13

EFFECTS ON WAVES AND TIDAL CURRENTS

Implications of the Lyttelton Port Recovery Plan on Waves and Tidal Currents in Lyttelton Harbour

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EXECUTIVE SUMMARY

From modelling of the waves and hydrodynamics in Lyttelton Harbour for a suite of proposed reclamation scenarios a number of conclusions can be drawn.

Waves

- Wave heights are a maximum at the harbour entrance and fall off rapidly to 6 km from the entrance. Thereafter, the drop in wave height is small. This is a natural process associated with shoaling and friction as waves propagate into a harbour whose depth is decreasing.
- Mean wave periods fall from 9s to 7s over the length of the harbour as swell waves dissipate.
- As a result of any of the reclamation and channel scenarios, there will be a change in the wave climate at some places in the harbour. Close to the reclamation (within a few hundred m), the wave heights will decrease as a result of the blockage to the flow caused by the reclamation and the deepening of the swing basin. Along the northern and southern bays on the flanks of the deepened shipping channel, wave heights will increase as a result of refraction. Most of these changes will be small in absolute terms. In the Upper Harbour and in Port Levy, the changes will be insignificant.
- The differences between the various scenarios are generally small and this illustrates that the effects are not particularly sensitive to the overall scale of the reclamation.
- Waves in the Inner Harbour will more than double under Scenario 4 (removal of Z-Berth) and Scenario 5 (oil/cruise berth), though they will still be small (less than 6 cm).
- Waves stir up the sediment making it available for transport by currents.
- Reclamation will affect swell waves more than sea waves.
    - In the Upper Harbour, the swell waves are already small, so the reduction will have no significant effect; however,
    - In the vicinity of the reclamation (Diamond Harbour, for example), where swell waves are a significant proportion of the wave climate, the reduction in these as a result of the reclamation and channel deepening will reduce the amount of time the sediment is disturbed by waves.

Tidal Currents

- For all of the scenarios, tidal currents will decrease in the vicinity of the reclamation and increase along the northwestern shorelines (Cass to Governors Bays). Elsewhere, there will be no significant change.
- Under Scenario 3 (full reclamation with breakwater), the currents in the vicinity of the breakwater will decrease to less than half of existing.
- Under Scenarios 4 (removal of Z-Berth) or 5 (removal of Z-Berth and excavation of a cruise/oil berth), the tidal currents in the Inner Harbour will more than double, though they will still be small.
- The effect on sediment transport of changes in the tidal currents will be small, even in Diamond Harbour where a decrease of 9% in the flood-tide currents will occur.

- Under all of the scenarios, sediment transported in and out of Charteris Bay on the tide will be slightly different from the present in that it will reach the northern side of Quail Island sooner than it does at present.
- Reclamation causes a narrowing of the harbour width, which results in increases in the tidal currents, but deepening of the navigation channel and swing basin will offset this effect, meaning the overall change in tidal currents will be small.

Table of Contents

1 INTRODUCTION

This report describes work carried out as part of the Lyttelton Port Recovery Plan to assess the environmental effects of various reclamation scenarios. The project involved modelling the waves and tidal currents under the various scenarios, comparing the results, and assessing the effects of the changes.

The Port Lyttelton Plan sets out LPC's 30 year vision for the repair, rebuild, enhancement and reconfiguration of the port. A large number of construction projects are required as part of the vision, and these are expected to occur over a period of approximately 12-15 years. These construction projects will enable the port to continue to reconfigure to meet the growing freight demands for the next 30 years as well as providing community access to the waterfront.

The purpose of the Lyttelton Port Recovery Plan is to address the recovery of the port. This includes the repair, rebuild and reconfiguration needs of the port, and its restoration and enhancement, to ensure the safe, efficient and effective operation of Lyttelton Port and supporting transport networks.

The ultimate outcome of this repair, rebuilding and reconfiguration work is the moving east of port operations in a timely manner, which will result in:

- The container terminal being established with up to 37 ha of reclaimed land in Te Awaparahi Bay;
- The shifting of some types of general cargo from the Inner Harbour to Cashin Quay; and
- The development of public access to the Inner Harbour in two stages (Dampier Bay and potentially the Dampier Bay Extension) to provide a commercial marina and associate activities, with public access and connectivity between Lyttelton and other parts of Naval Point.

Some of the repaired or rebuilt berths at Cashin Quay, Naval Point, and the new berths at Te Awaparahi Bay will be designed to handle larger vessels with deeper draught. The deepening and widening of the current navigation channel to enable access by these larger vessels is therefore inextricably linked to and forms an important part of the Port's Recovery.

This report examines the potential changes to existing tidal current and wave regimes in Lyttelton Harbour and Port Levy caused by the 37 ha reclamation, combined with the proposed deepening of the navigation channel.

The design of the reclamation (including the exact area requirements) and configuration of the port are still being progressed. Therefore, a number of scenarios were modelled. This has provided a way to understand how different sizes and layouts of reclamation affect the waves and tidal currents. Please note that these scenarios were produced for the purpose of this modelling exercise and do not represent a design. They were a means to test the harbour's sensitivity to different reclamation sizes and different widths of navigation channel.

Specifically, five scenarios (described below) were developed to compare with the existing environment (Scenario 0). Scenario 2, for example, equals the 37 ha reclamation envelope, Scenario 1 is inside the envelope, while Scenario 3 extends Scenario 2 with a breakwater which is outside the project envelope. Scenario 3 is not part of the recovery proposal, but was considered as part of a test each side of the 37 ha reclamation. This was done in order to provide a better understanding of how the waves and tidal currents respond.

Contour maps of depth showing the various scenarios are attached in Appendix I.

- Baseline Scenario 0:
  Present port layout (existing bathymetry) with a 180 m navigation channel of 13.5 m depth[1] below MSL.

- Scenario 1:
  A 33 ha reclamation out to 50 m from the end of the existing Cashin Quay breakwater (750 m wide) with a 180 m navigation channel dredged to a depth of 17.5 m below MSL;
- Scenario 2:
  A 37 ha reclamation that extends out to the end of the existing Cashin Quay breakwater (750 m wide) and a 220 m wide navigation channel dredged to a depth of 17.5 m below MSL;
- Scenario 3: Scenario 2 with breakwater:
  A 37 ha reclamation that extends out to the end of the existing Cashin Quay breakwater (750 m wide), with a 200 m long breakwater and a 220 m wide navigation channel dredged to a depth of 17.5 m below MSL;
- Scenario 4: Scenario 2 with Z-Berth removed:
  This option includes the removal of Z-Berth in the Inner Harbour in order for cruise ships to berth at Gladstone Quay in the Inner Harbour.
- Scenario 5: Scenario 4 with outer harbour berth:
  This option adds a dredged berth pocket and swing basin to serve a new outer berth (originally considered for a cruise berth and an oil berth) located off the southern end of Naval Point.

In some of the figures in the report, the scenarios listed above are referred to as “schemes”. For the purpose of this report, “scheme” is synonymous with scenario.

As the aim of this work is to model the final scenarios and include the potential cumulative effects, all the reclamation scenarios assume that a deeper navigational channel exists.

The report has 5 sections. The next section describes the models that were used by MetOcean Solutions Ltd in their Raglan office and how they applied those models to Lyttelton Harbour. Section 3 presents the model results for waves, tidal currents and sediment transport and compares the effects of the different scenarios. In Section 4, more detailed scientific analysis is presented on the effects of waves on sediment and the effect of the dredged channel and swing basin on waves and tides is examined. Finally, Section 5 has some conclusions that can be drawn from the work.

[1] The depth datum used in the modelling was mean sea level (MSL) which is 1.4 m above Chart Datum.

An important aspect of modelling is validation of the models to ensure they are giving realistic results. This validation was carried out by Mulgor Consulting Ltd on the MetOcean Solutions Ltd models and effectively constitutes a peer review and 'ground truth' of the model. Reports on validation of the hydrodynamic and wave models are provided as Annexes to this report.

2 DATA AND METHODS

2.1 Hydrodynamic Model

The hydrodynamics (tidal currents in the harbour) were modelled using SELFE[2], a state-of-the-art, open-source model that solves the shallow-water equations on an unstructured grid. This type of model is considered best practice and is the most advanced and accurate model available to simulate tidal currents.

In general terms the model works by applying a set of tidal flow conditions to the seaward edge of the created Lyttelton model grid (the semi-circular boundary of the domain) and using Newton's Laws of Conservation of Mass and Momentum to propagate the tide into the harbour. The tidal conditions that drive the model were developed from global and national tidal models. A brief description of how this works is as follows:

The first stage uses the global tide model TPXOv7[3] to provide boundary conditions at the edge of a New Zealand scale model. The global model was developed by Oregon State University and is based upon altimeter data from the TOPEX/Poseidon oceanographic satellite.

The global information is used to drive a model MetOcean Solutions created for New Zealand tides at a national scale, providing significantly more detail than the global model. Data from this model are regularly used for a range of hydrodynamics applications and are considered to be the most accurate available.

The national level tidal data are then applied to the edge of the Lyttelton model to drive the tidal calculations. Essentially the model takes this information and using Newton's Laws of Motion calculates how the tidal flow interacts with the shorelines and sea-bed.

All of these models have been validated using measurements and are the most accurate data available at present. Validation of the SELFE model used in this project is presented in Annex I.

The model domain (area that the model covers) is shown in Figure 2.1.1. It comprises a set of 238,178 triangles with 123,616 nodes. At each of these triangles (elements), at each time step, Newton's Laws are applied to resolve the flow into and out of the element (Conservation of Mass) and the forces acting on the sides and the bottom (Conservation of

[2] SELFE is Semi-implicit, Eulerian-Lagrangian Finite Element model, see: http://www.stccmop.org/knowledge_transfer/software/selfe
[3] See: http://volkov.oce.orst.edu/tides/global.html

Momentum), then these results are accumulated over the whole domain; time is advanced by one step, and the process is repeated for 220 days of model time.

The triangles are scaled so that their area is proportional to *gh*, where *g* is the acceleration of gravity and *h* is the depth. Since shallow water waves like the tide propagate with a speed of $\sqrt{gh}$, this means that waves take the same time to travel across an element in deep water as they do to travel across an element in shallow water. This makes the model numerically stable, but also results in smaller triangles and more detailed information in the shallow parts of the harbour and near the shorelines as is illustrated in Figure 2.2, which shows the elements around Quail Island. The model can also be manually manipulated to provide smaller triangles and more detail in areas of interest. This has been applied in this model (and can be seen in Figure 2.1) around the navigation channel where a greater level of detail was desired.

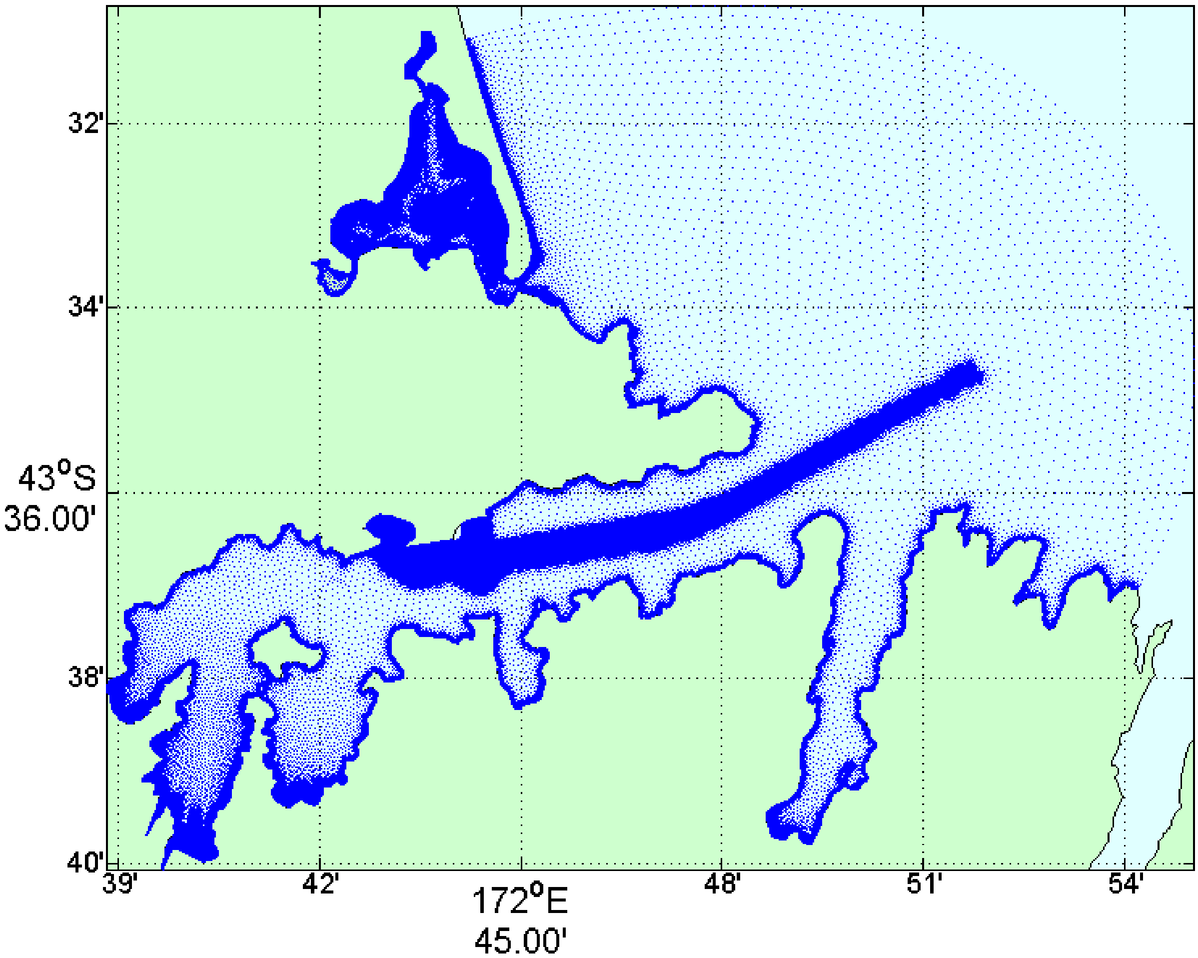

Figure 2.1 Domain for SELFE model showing the grid of 123,616 nodes.

At each of the nodes in the grid, the model produces the amplitude and phase of tidal height, eastward velocity and northward velocity for 25 tidal constituents, including the primary semidiurnal components: M_2, N_2, S_2, and K_2; the primary diurnal components: K_1, O_1, P_1, Q_1; and 17 other minor components including 8 shallow water components. With these constituents, we are able to accurately forecast the tide anytime in the past or future.

Essentially, the model output is equivalent to having 123,616 tide gauges (measuring tide height and velocity) throughout the model domain shown in Figure 2.1.

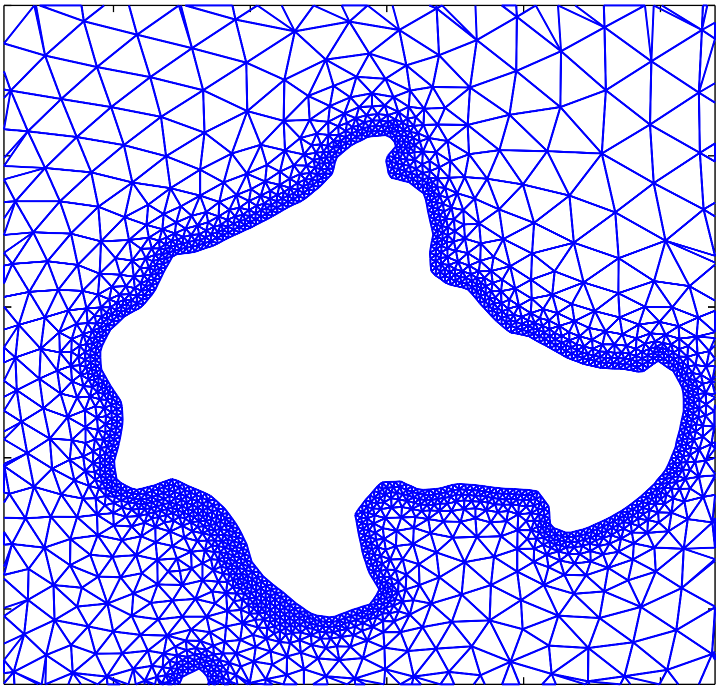

Figure 2.2 The finite element grid around Quail Island.

2.2 Wave Model

Waves were modelled using SWAN[4] which is a 3rd generation wave model developed by Delft University of Technology. It is the most widely used computer model to compute irregular waves in coastal environments, based on deep water boundary conditions, wind, bottom topography, currents and tides. SWAN explicitly accounts for all relevant processes of propagation, generation by wind, interactions between the waves and decay by breaking and bottom friction.

For this study, the model domain (area) was the same as for the tide model, but with a rectangular grid as shown in Figure 2.3. The interval between nodes is 0.29 s in longitude (65 m) and 0.18 s in latitude (56 m), and the grid is 250x160, resulting in 40,000 nodes. At each of these nodes, the model gives significant wave height[5], period and direction as well as other wave parameters at 3-hourly intervals for the decade from 2004 to 2014.

The model was driven using boundary conditions from the MetOcean Solutions Ltd's wind and wave models of the NZ region. Like the tide model, this model comes from several nested models, starting with a global wave model called NOAA[6] WaveWatch III which provides data for a New Zealand wide model. A report on the validation of the model against wave measurements at Parson Rock is presented in the Annex II.

[4] SWAN: **S**imulating **WA**ves **N**earshore, see: http://www.swan.tudelft.nl/

[5] Significant wave height is the height that would be estimated by a ship's master from the bridge of a large vessel. Mathematically, it is $H_s = 4\sqrt{M_0}$ where M_0 is the area under the wave spectrum.

[6] NOAA = National Oceanic and Atmospheric Administration, an agency of the US Dept of Commerce.

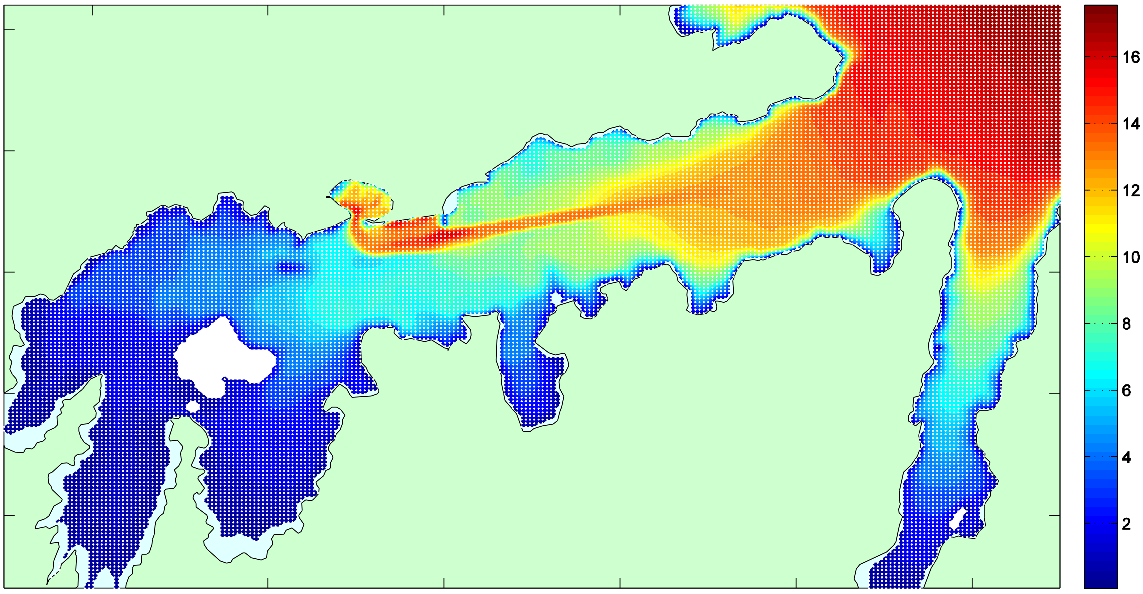

Figure 2.3 Grid for SWAN model showing the nodes as white dots over the depths (m).

The bathymetry data for the harbour come from the LINZ chart NZ6321, supplemented by the March 2014 hydrographic survey of the navigation channel.

3 RESULTS

3.1 Waves

In this section, the effect the reclamation, combined with a deeper and in some cases wider navigation channel, will have on waves is presented. First, the present wave climate is described both in terms of the overall statistics and for wave events; then the change that will occur under the various proposed reclamation scenarios are examined.

3.1.1 Present Wave Climate

3.1.1.1 Wave Heights

The present wave climate in Lyttelton Harbour and Port Levy is presented in Figure 3.1.1, which shows a contour map of the mean significant wave height. At both harbour entrances, the wave heights are maximum and the heights attenuate as we go into the harbours. The attenuation with distance in Lyttelton Harbour is shown more clearly in Figure 3.1.2 which shows the variation in various wave height statistics along the thalweg[7], which is shown in Figure 3.1.3. The 95% and 99% statistics represent the wave heights that are only exceeded for 5% and 1% of the time respectively.

Figure 3.1.2 shows that for all wave height statistics, there is rapid attenuation in wave height between 1 and 6 km from the harbour entrance, but thereafter the attenuation is much slower. The attenuation is caused by the effects of shoaling and friction, and by refraction from the

[7] The thalweg is the line of maximum depth.

centre of the harbour to the northern and southern beaches where the waves break. All of these effects result in a reduction in the wave energy that has entered the harbour.

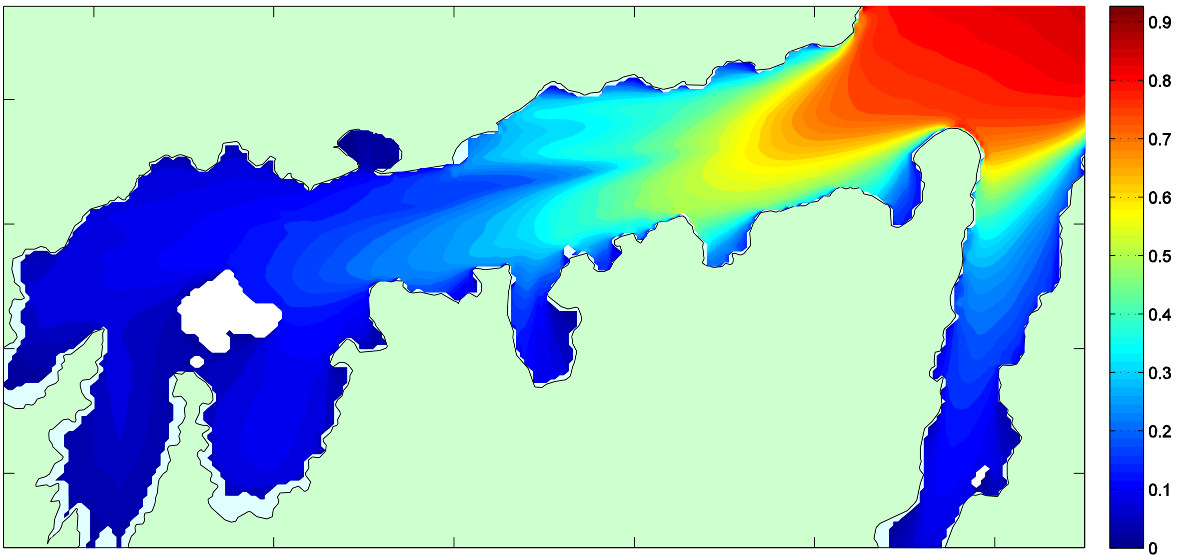

Figure 3.1.1. Distribution of mean significant wave height in Lyttelton Harbour and Port Levy.

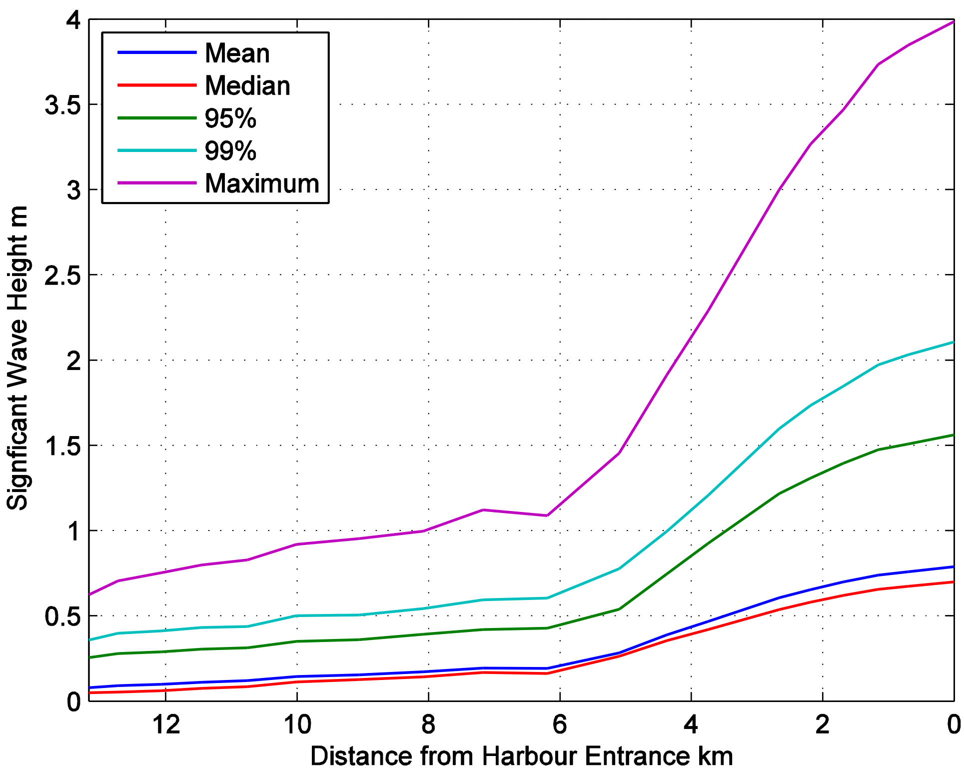

Figure 3.1.2. Dissipation in wave heights up the harbour.

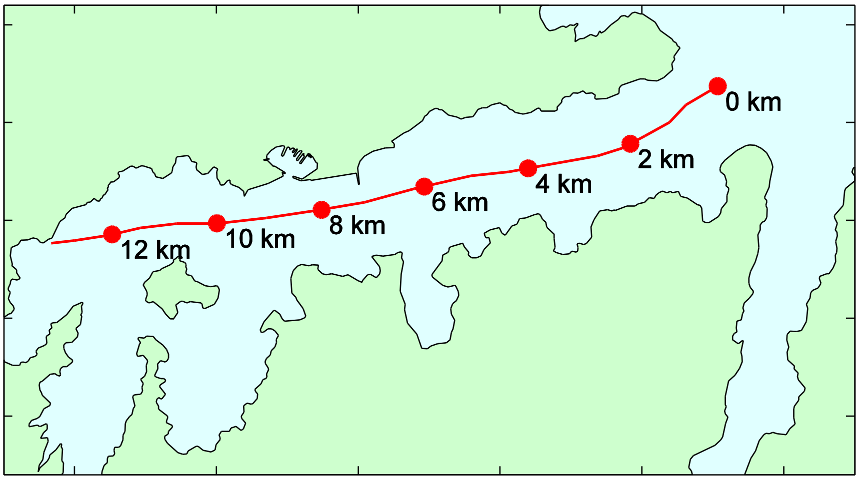

Figure 3.1.3. The thalweg in Lyttelton Harbour and distances from the entrance.

3.1.1.2 Wave Periods

Wave period is the time between crests. The waves at a particular location and at a particular time will have a whole range of periods from a second or two (chop or sea waves) to 13 s (swell). The distribution of energy with period is called the wave spectrum. The period of the dominant waves is called the "peak period" because that is the period of maximum energy (for details, see Appendix III). The distribution of mean peak periods is presented in Figure 3.1.4. At the harbour entrance, wave periods are about 9 seconds (s) and as we pass into the harbour they reduce, dropping to about 7 s at Governors Bay. This reduction in period corresponds to long-period waves dissipating due to shoaling and friction as they propagate into the shallow water of the harbour, while the short-period, locally-generated waves are affected less. This matter is discussed in more detail in Section 4.

In the vicinity of the Cashin Quay breakwater, the periods are very short. This indicates the breakwater is effectively doing its job, which is to reduce the long-period waves that cause large ships at berth to strain their mooring lines.

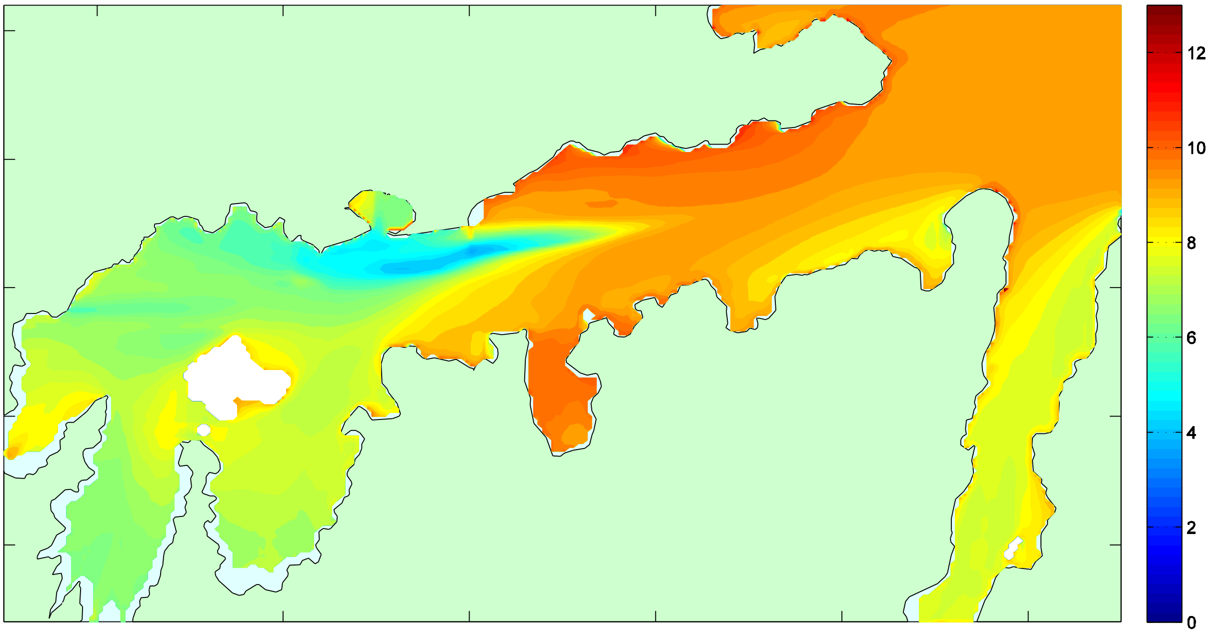

Figure 3.1.4 Distribution of mean peak period (s) throughout the harbour.

3.1.2 Effect of Reclamation and Dredged Channel

In this section, the wave height and period of each scenario is compared to Scenario 0 (present day bathymetry). For wave height, this is done by taking differences between the wave height at each node in each scenario and Scenario 0.

3.1.2.1 Overall Wave Height Statistics

Contour maps of the differences in mean significant wave height from the present bathymetry for the various scenarios are presented in Figures 3.1.5a to d. Contour maps of the wave heights for each scenario are given in Appendix II. All of the scenarios show a similar pattern, as follows:

- Along the dredged shipping channel, the wave heights are reduced because of the extra depth.
- The deeper channel causes refraction of the waves, thus increasing the wave heights along the northern and southern bays.
- In the vicinity of the reclamation and deepened swinging basin, wave heights are generally reduced except for Scenario 3 where the breakwater causes an increase in wave heights upstream of the breakwater.
- In the upper harbours of both Lyttelton and Port Levy, the change in wave heights is small.

To examine these differences in more detail and compare the effects of the various scenarios, data have been extracted for several points as shown in Figure 3.1.6. The mean wave heights at these locations before and after reclamation are presented in Tables 3.1.1a (for differences in m) and 3.1.1b (for percentage differences).

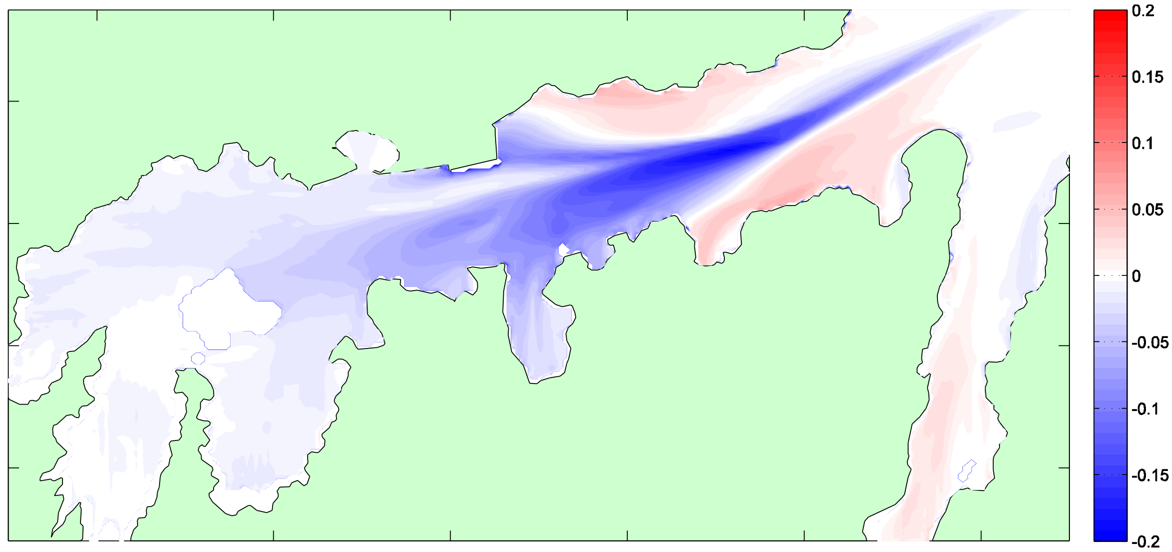

Figure 3.1.5a. Difference in mean wave height (m) for Scenario 1.

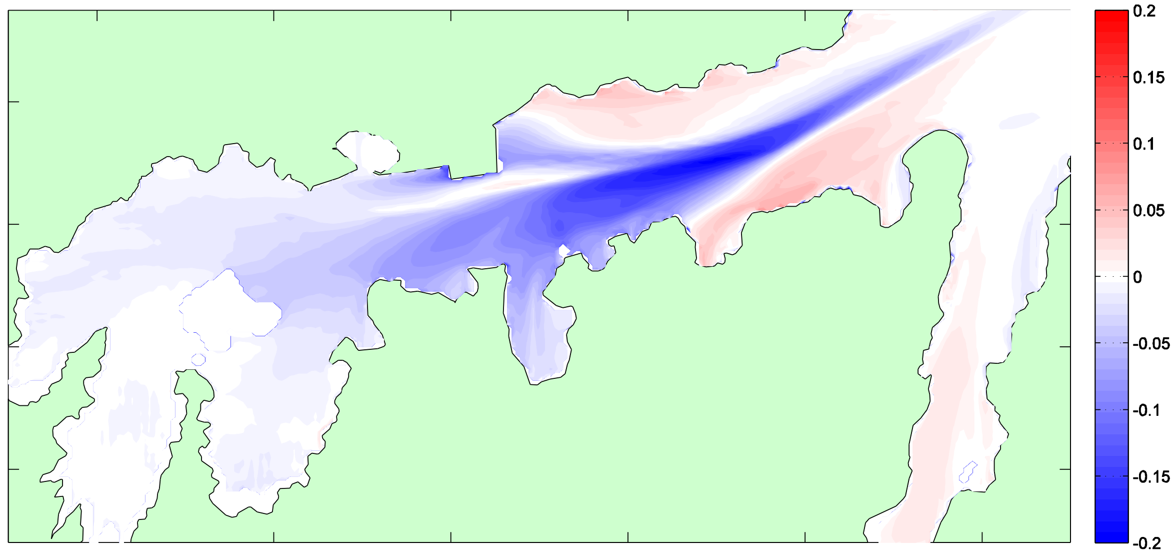

Figure3.1.5b. Difference in mean wave height (m) for Scenario 2.

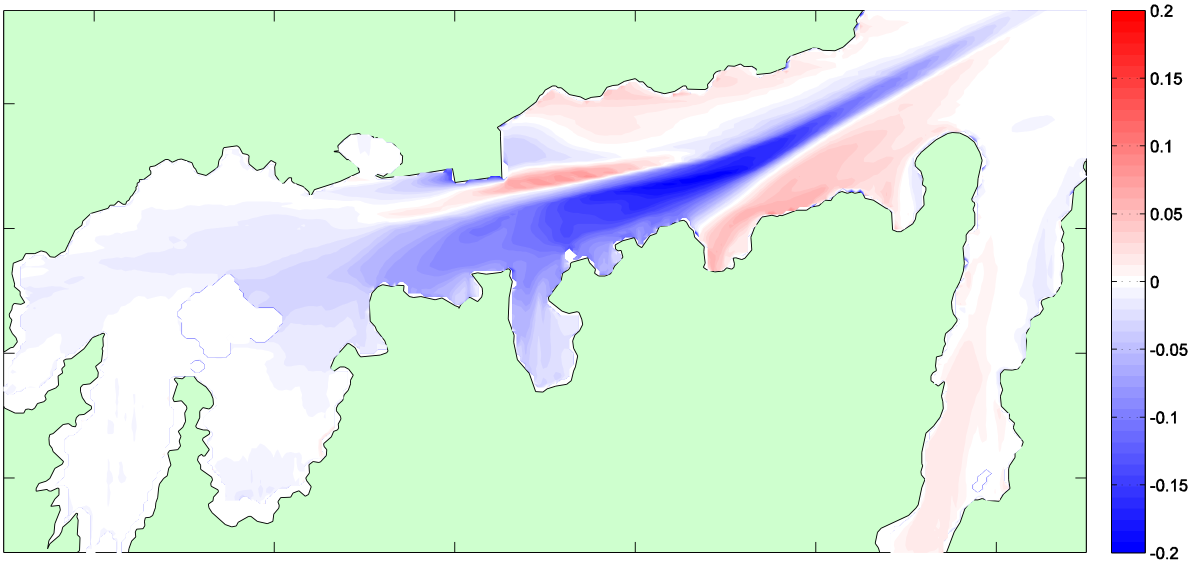

Figure 3.1.5c. Difference in mean wave height (m) for Scenario 3.

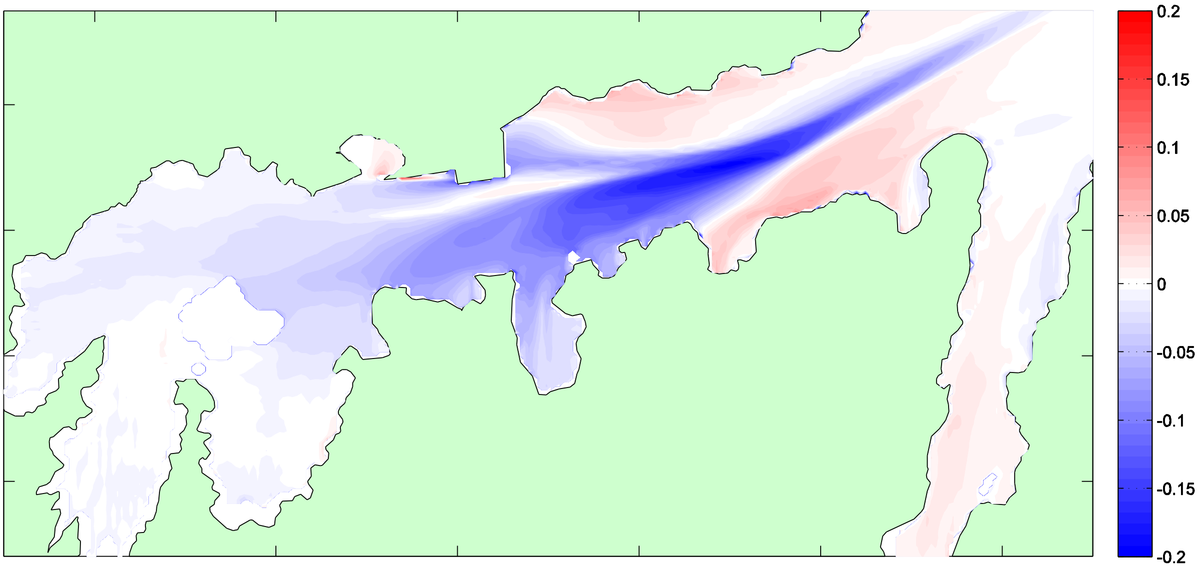

Figure 3.1.5d. Difference in mean wave height (m) for Scenario 4.

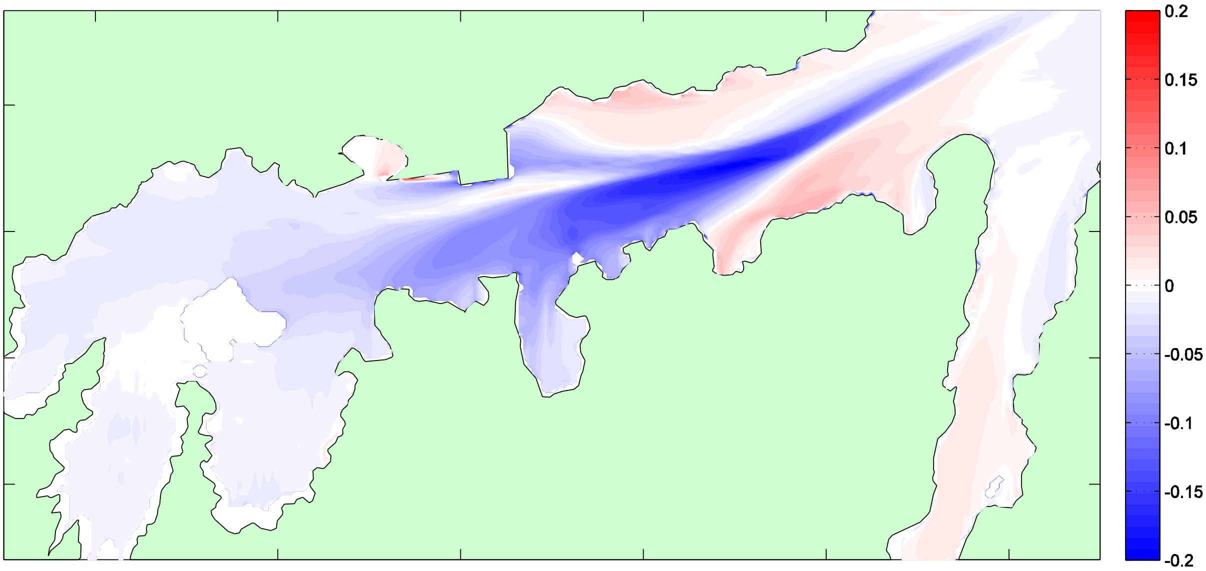

Figure 3.1.5d. Difference in mean wave height (m) for Scenario 5.

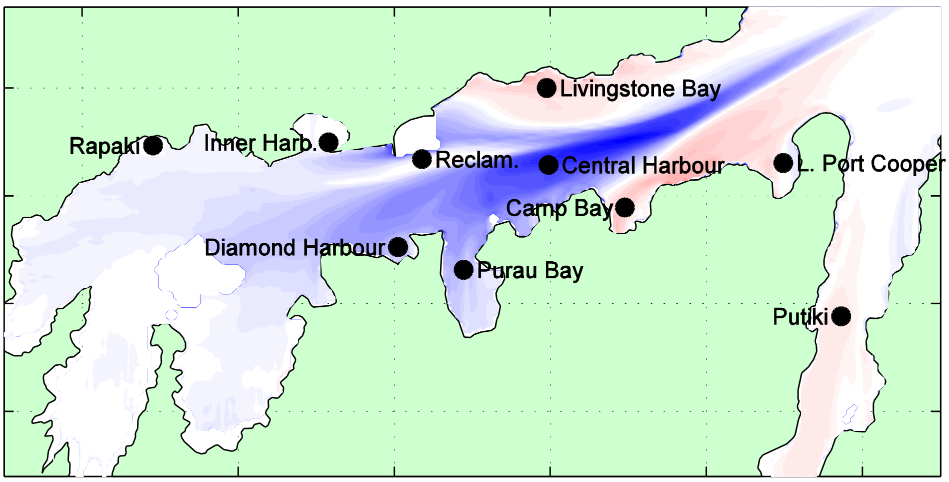

Figure 3.1.6. Locations of points where statistics have been extracted (Tables 3.1.1a and b).

Table 3.1.1a. For the sites shown in Figure 3.1.6, mean wave heights (Hs m) for the present bathymetry and differences for the various scenarios (positive means an increase, negative means a decrease from present).

Location	Hs m	Difference from Present m				
	Present	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Central Harbour	0.446	-0.137	-0.156	-0.173	-0.155	-0.154
Camp Bay	0.323	0.041	0.043	0.051	0.043	0.043
L. Port Cooper	0.239	0.008	0.008	0.010	0.009	0.008
Putiki	0.174	0.018	0.018	0.017	0.018	0.019
Livingstone Bay	0.344	0.044	0.039	0.027	0.039	0.039
Reclam.	0.181	-0.009	-0.008	0.015	-0.009	-0.007
Inner Harb.	0.024	-0.001	0.000	0.001	0.038	0.039
Rapaki	0.074	-0.002	-0.001	0.004	0.002	0.001
Diamond Harbour	0.154	-0.032	-0.036	-0.043	-0.036	-0.038
Purau Bay	0.157	-0.045	-0.049	-0.053	-0.049	-0.048

Table 3.1.1b. For the sites shown in Figure 3.1.6, mean wave heights (Hs m) for the present bathymetry and percentage differences for the various scenarios (positive means an increase, negative means a decrease from present).

Location	Hs m	Difference from Present %				
	Present	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Central Harbour	0.446	-31	-35	-39	-35	-35
Camp Bay	0.323	13	13	16	13	13
L. Port Cooper	0.239	3	3	4	4	3
Putiki	0.174	10	10	10	10	11
Livingstone Bay	0.344	13	11	8	11	11
Reclam.	0.181	-5	-4	8	-5	-4
Inner Harb.	0.024	-4	0	4	158	163
Rapaki	0.074	-3	-1	5	3	1
Diamond Harbour	0.154	-21	-23	-28	-23	-25
Purau Bay	0.157	-29	-31	-34	-31	-31

From examination of Tables 3.1.1a and b, the following points arise:

1) Under any of the proposed scenarios:
    a) Waves in the central harbour will decrease by up to 39%;
    b) Waves at Livingstone and Camp Bays will increase by 13%;
    c) Waves in Little Port Cooper will increase by a small amount;
    d) Waves at Putiki in Port Levy will increase by 10%;
    e) At Purau Bay and Diamond Harbour the waves will decrease by up to 34%.
2) At Rapaki the waves will decrease by a small amount for Scenarios 1 and 2, but increase slightly for Scenarios 3, 4 and 5.
3) For Scenario 4 (removal of Z-Berth) and 5 (oil/cruise berth), the wave heights in the Inner Harbour will more than double from 0.024 m to 0.062 m, though they will still be small.
4) The effect of the breakwater (Scenario 3) is to exaggerate the changes, whether positive or negative, but only in the immediate vicinity of the reclamation.

For completeness, the 99% wave heights are presented in Table 3.1.2. The pattern is similar to Table 3.1.1 and the comments on that table (listed above) apply for these data also, except for Rapaki where the 99% wave height increases by up to 5% under any of the scenarios, and by 10% for Scenario 5.

The implications of these changes in wave height are discussed in Section 4.1, along with more detailed mathematical analysis of the changes

Table 3.1.2a. For the sites shown in Figure 3.1.6, wave heights that are exceeded for 1% of the time for the present bathymetry and differences for the various scenarios (positive means an increase, negative means a decrease from present).

Location	Hs m	Difference from Present m				
	Present	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Central Harbour	1.154	-0.285	-0.314	-0.355	-0.314	-0.314
Camp Bay	0.982	0.031	0.030	0.042	0.030	0.029
L. Port Cooper	0.823	0.022	0.024	0.023	0.024	0.024
Putiki	0.710	0.049	0.049	0.048	0.049	0.050
Livingstone Bay	0.855	0.151	0.133	0.085	0.133	0.133
Reclam.	0.590	-0.025	-0.041	-0.011	-0.041	-0.041
Inner Harb.	0.188	-0.010	-0.001	-0.006	0.174	0.174
Rapaki	0.310	0.016	0.016	0.007	0.016	0.033
Diamond Harbour	0.420	-0.020	-0.023	-0.025	-0.021	-0.021
Purau Bay	0.440	-0.045	-0.044	-0.037	-0.044	-0.042

Table 3.1.2b. For the sites shown in Figure 3.1.6, wave heights that are exceeded for 1% of the time for the present bathymetry and the percentage differences for the various scenarios (positive means an increase, negative means a decrease from present).

Location	Hs m	Difference from Present %				
	Present	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Central Harbour	1.154	-25	-27	-31	-27	-27
Camp Bay	0.982	3	3	4	3	3
L. Port Cooper	0.823	3	3	3	3	3
Putiki	0.710	7	7	7	7	7
Livingstone Bay	0.855	18	16	10	16	16
Reclam.	0.590	-4	-7	-2	-7	-7
Inner Harb.	0.188	-5	-1	-3	93	93
Rapaki	0.310	5	5	2	5	11
Diamond Harbour	0.420	-5	-5	-6	-5	-5
Purau Bay	0.440	-10	-10	-8	-10	-10

3.1.2.2 Wave Periods

The effect of the scenarios on wave period is illustrated in Figure 3.1.7, which compares Scenario 0 (top) and Scenario 2 (bottom) — the other scenarios are shown in Appendix II.

The most obvious change to wave period as a result of reclamation and dredging the channel is that the periods of the waves in the deepened channel and in the mid to upper harbour are reduced. This occurs because the swell waves do not penetrate as far into the harbour — .the technical reasons for this are addressed in Section 4. These reductions are quantified for the locations shown in Figure 3.1.6 in Table 3.1.3.

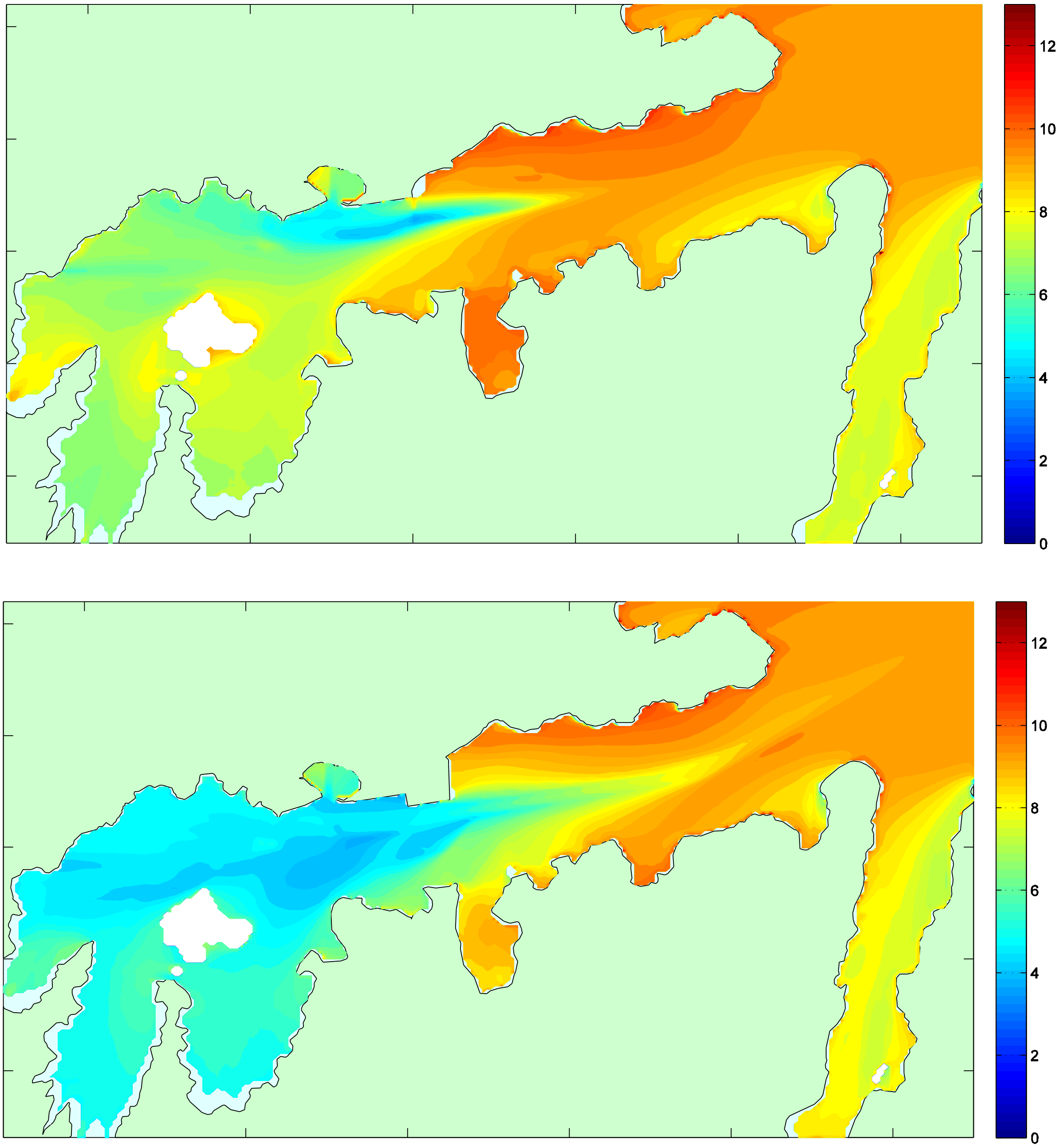

Figure 3.1.7 Distribution of mean peak period (s) for Scenario 0 (top) and Scenario 2(bottom).

Table 3.1.3. Mean peak periods for the sites shown in Figure 3.1.6.

Location	**Mean Peak Period seconds for Scenario:**					
	0	**1**	**2**	**3**	**4**	**5**
Central Harbour	9.5	7.9	7.4	6.7	7.3	7.4
Camp Bay	8.9	9.5	9.5	9.6	9.5	9.5
L. Port Cooper	8.0	8.4	8.4	8.4	8.4	8.4
Putiki	7.8	8.0	8.0	8.0	8.0	8.0
Livingstone Bay	10.3	9.8	9.9	9.9	9.9	9.8
Reclam.	4.4	3.9	4.8	6.5	4.8	4.7
Inner Harb.	6.4	6.2	5.6	6.0	4.6	4.5
Rapaki	6.1	4.5	4.8	5.2	4.7	4.6
Diamond Harbour	8.7	7.4	6.8	6.1	6.8	6.8
Purau Bay	10.1	9.2	8.9	8.6	8.9	8.9

Table 3.1.3 shows that for all scenarios:

1. There is a slight increase in wave period in the outer harbour and Port Levy – this is most likely an effect of the deeper shipping channel, which will reduce the effects of shoaling and friction on long-period waves, and allow them to penetrate further into the harbour.
2. There is a reduction in wave period in the Upper Harbour – this is most likely the result of reclamation reducing the penetration of long-period waves into the Upper Harbour.
3. There is a reduction in wave period in Diamond Harbour and Purau Bay as a result of the reclamation and deepening for the swing basin.

Removal of Z-Berth (Scenarios 4 and 5) will result in a reduction in period in the Inner Harbour as more short-period energy enters the wider entrance.

The effects of changes in period are pursued in more detail in Section 4.

3.1.2.3 Events

The results presented so far have been for overall statistics, i.e. the average wave conditions across a period of 10 years. In this section, we examine the differences during specific events.

Figure 3.1.8 shows the two largest events at Rapaki. The weather conditions that led to the first of these are shown in Figure 3.1.9. The figure shows a set of synoptic maps 12 hours apart in which atmospheric pressure is shown as coloured contours (blue is low pressure, red is high pressure), and wind as vectors whose length indicates the speed. The weather pattern that led to the event shown in the upper panel of Figure 3.1.8 was a low pressure system to the northwest of the North Island that propagated to the southeast across central New Zealand. At midnight on 31-Jul, the cyclonic winds to the northeast of Banks Peninsula were directed into Pegasus Bay and generated the large waves at Rapaki. This weather pattern is typical of the weather that produces the largest waves in the harbour and the other events described in this section had similar patterns.

Comparing the waves for the various scenarios in Figure 3.1.8, we see there is an increase in wave height from Scenario 0 (the present bathymetry) for all reclamation scenarios, but the changes between scenarios are indistinguishable. The increase in wave height for all scenarios occurs because the deepened swing basin beside the reclamation causes reduced effects of friction on the swell waves. The lack of difference between Scenario 2 (without a breakwater) and Scenario 3 (with a breakwater) was a surprise. We expected the breakwater would reduce the waves in the upper harbour. That it does not for these large events indicates how localised the effects of the breakwater are.

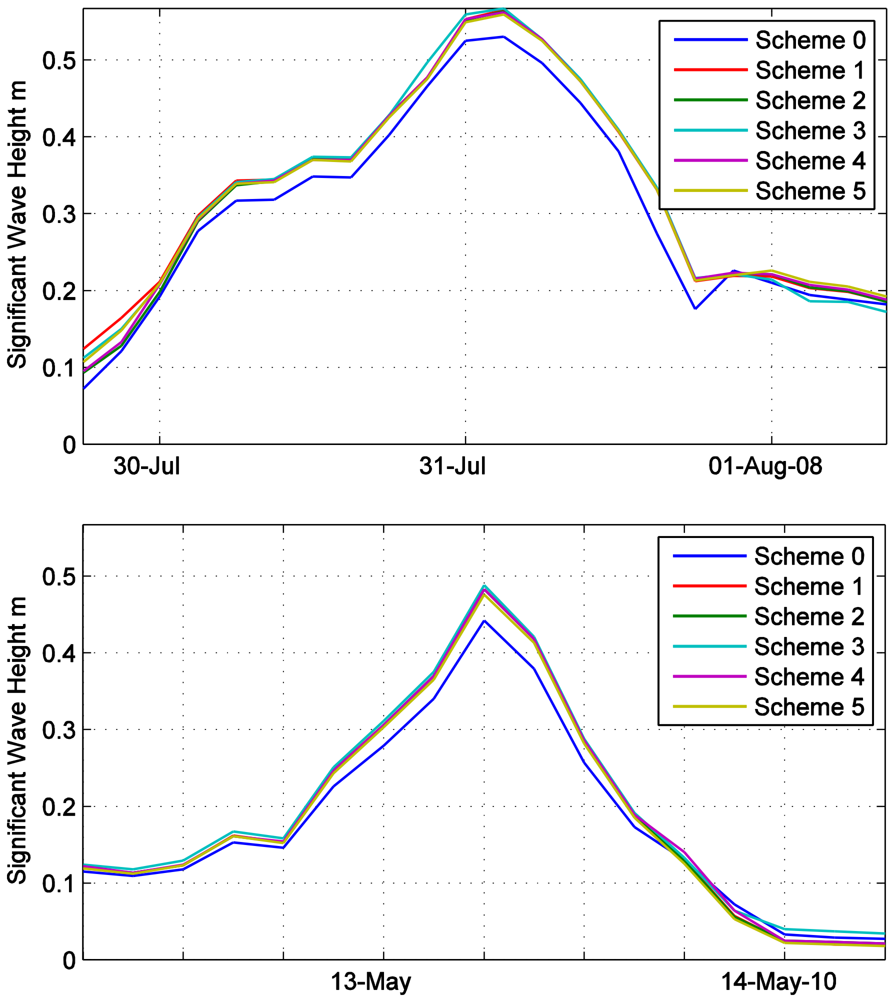

Figure 3.1.8. Comparison of wave heights for the various scenarios for the two largest events at Rapaki.

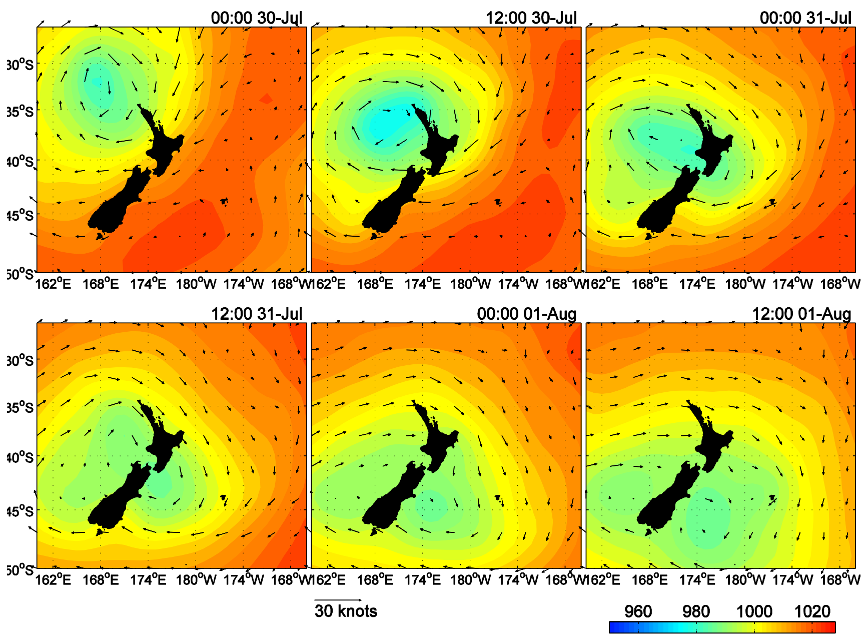

Figure 3.1.9. Weather system that led to the waves in the upper panel of Figure 3.1.8.

Figure 3.1.9 for Diamond Harbour shows there is reduction in wave height from Scenario 0 and slight differences between the scenarios, with Scenario 3 (full reclamation with breakwater) having the smallest wave heights. The signal for Scenario 2and 4 are completely obscured by the signal for Scenario 5, indicating that removal of Z-Berth and dredging of a cruise/oil basin have no effect on the waves at Diamond Harbour.

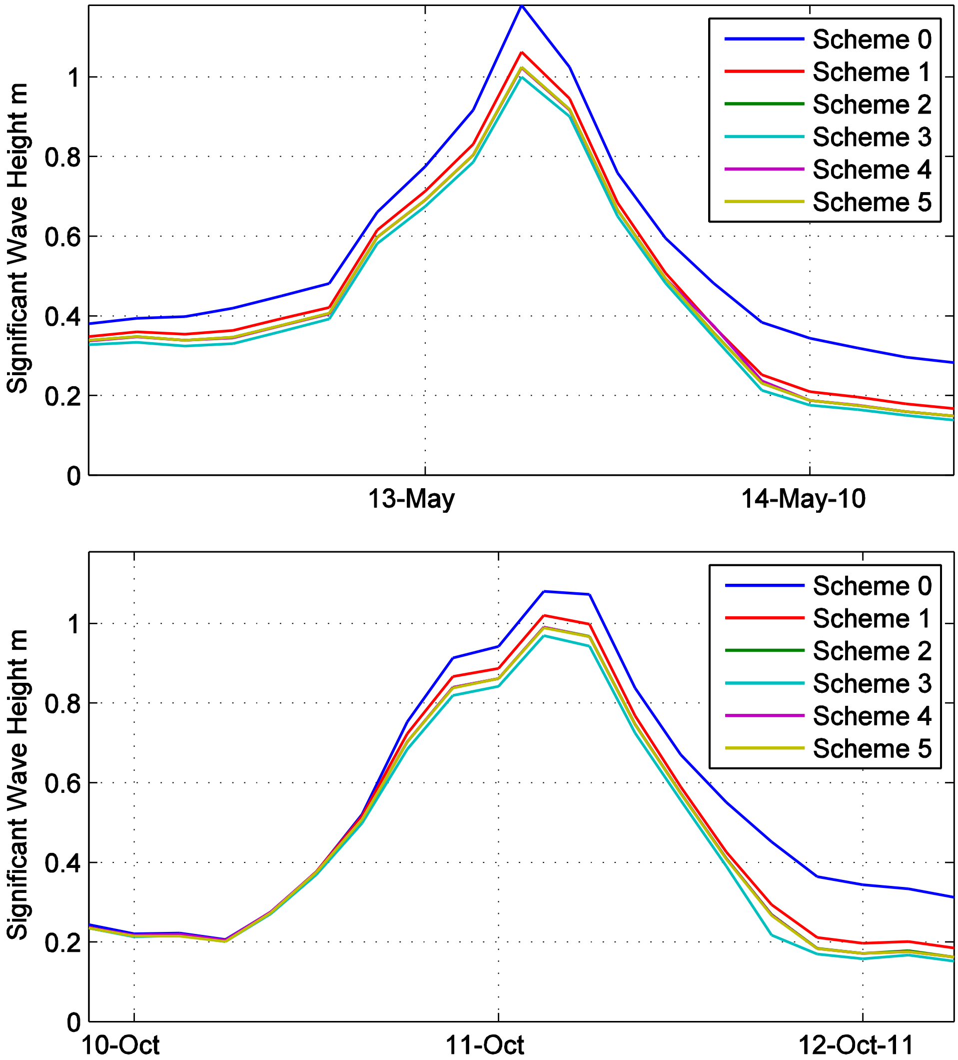

Figure 3.1.10. Comparison of wave heights for the various scenarios for the two largest events at Diamond Harbour.

3.2 Tidal Currents

The model results have been synthesized have been used to forecast the tide for a perigean spring tide (aka "king tide"). These occur every 7 months when lunar perigee[8] coincides with a Full or New Moon. In Lyttelton Harbour, high tide heights at perigean spring tides are 2.51 m above Chart Datum and are exceeded by only 6.5% of all high tides.

3.2.1 Present Tidal Currents

Figures 3.2.1a and b show contour maps of the current speeds at mid-ebb (flow out of the harbour) and mid-flood (flow into the harbour) perigean spring tides for the existing configuration. The largest currents speeds occur around the ends of the Cashin Quay and Naval Point breakwaters and in the Head of the Bay where the water is quite shallow (~ 1.5 m). Relatively large currents also occur at various places around Quail Island. This occurs because the island displaces the tidal flow, causing the flow to speed up as it passes around the obstruction. The effect is most pronounced around points or features that protrude into main tidal flow.

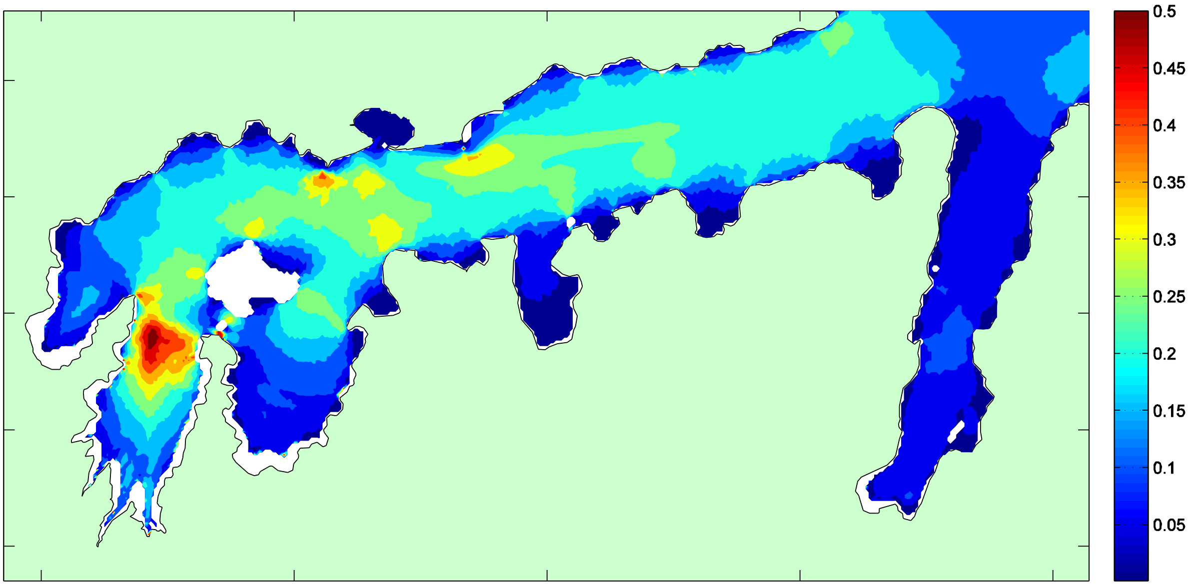

Figure 3.2.1a Speed (m/s) of currents at mid-ebb tide for a perigean spring tide.

[8] Lunar perigee occurs each month when the Moon on its elliptical orbit is closest to Earth.

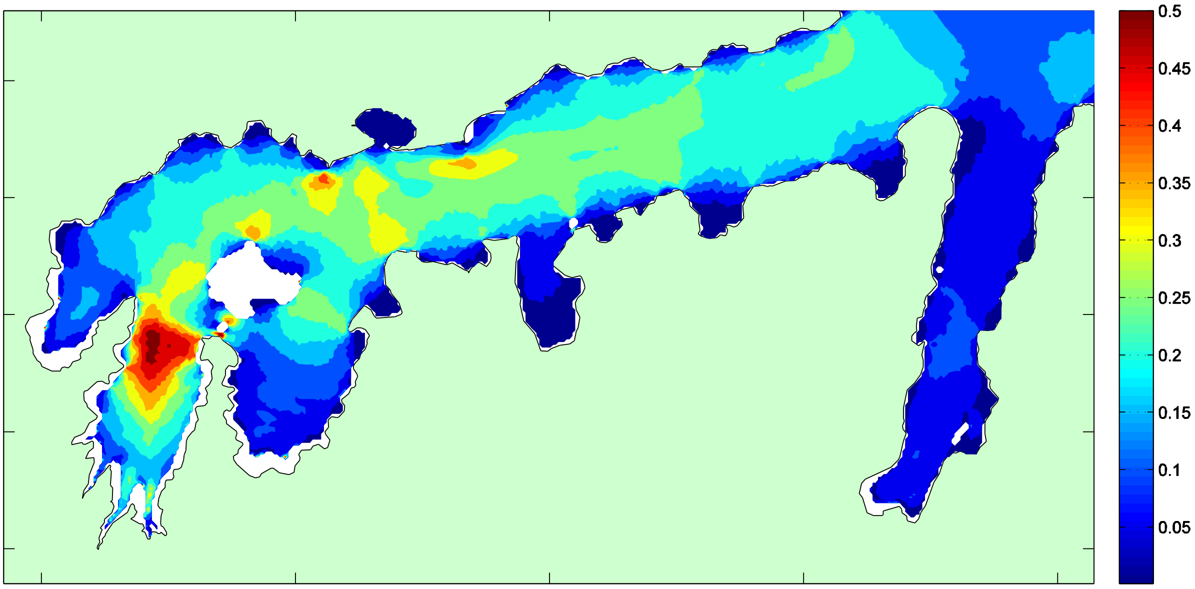

Figure 3.2.1b Speed (m/s) of currents at mid-flood tide for a perigean spring tide.

3.2.2 Effect of Reclamation and Dredged Channel

Figures 3.2.2a to d show contour maps of the differences in speed at mid-ebb tide as a result of the various scenarios. The maps for flood tide are essentially the same and have not been included.

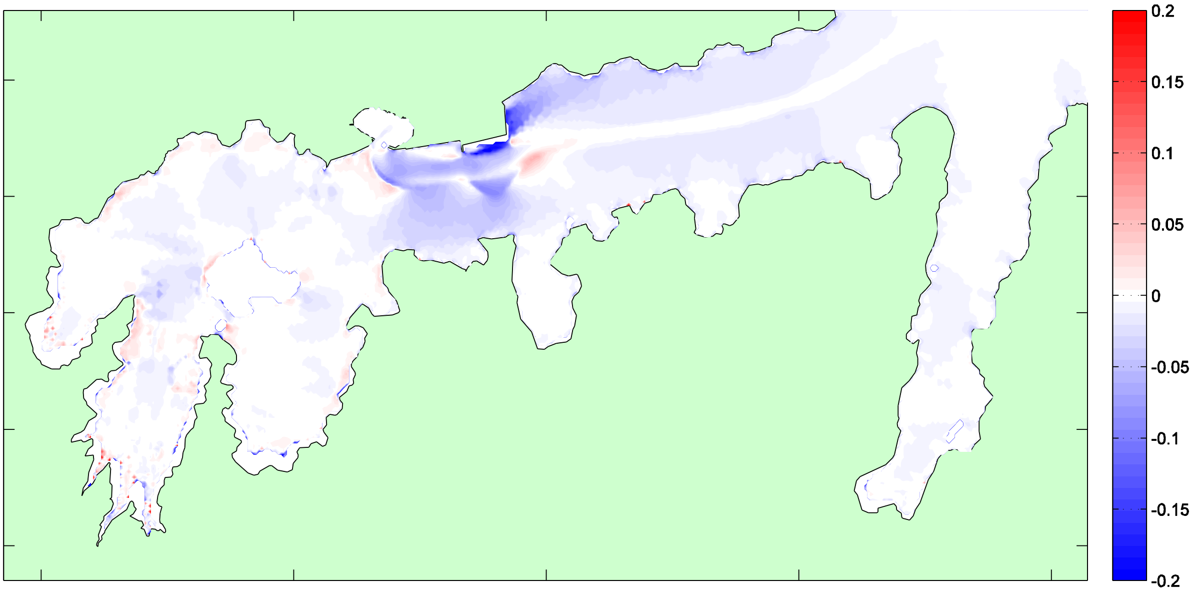

Figure 3.2.2a Difference in speed in m/s at mid-ebb tide between Scenario 0 (present) and Scenario 1 — positive means the scenario will result in an increase in speed.

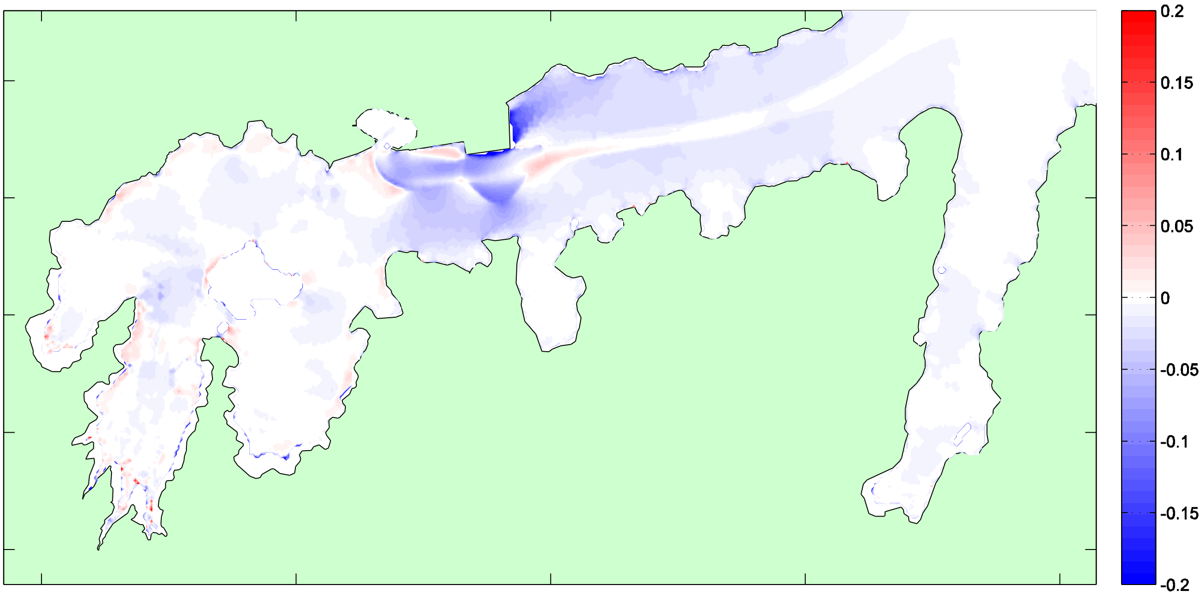

Figure 3.2.2b Difference in speed in m/s at mid-ebb tide between Scenario 0 (present) and Scenario 2 — positive means the scenario will result in an increase in speed.

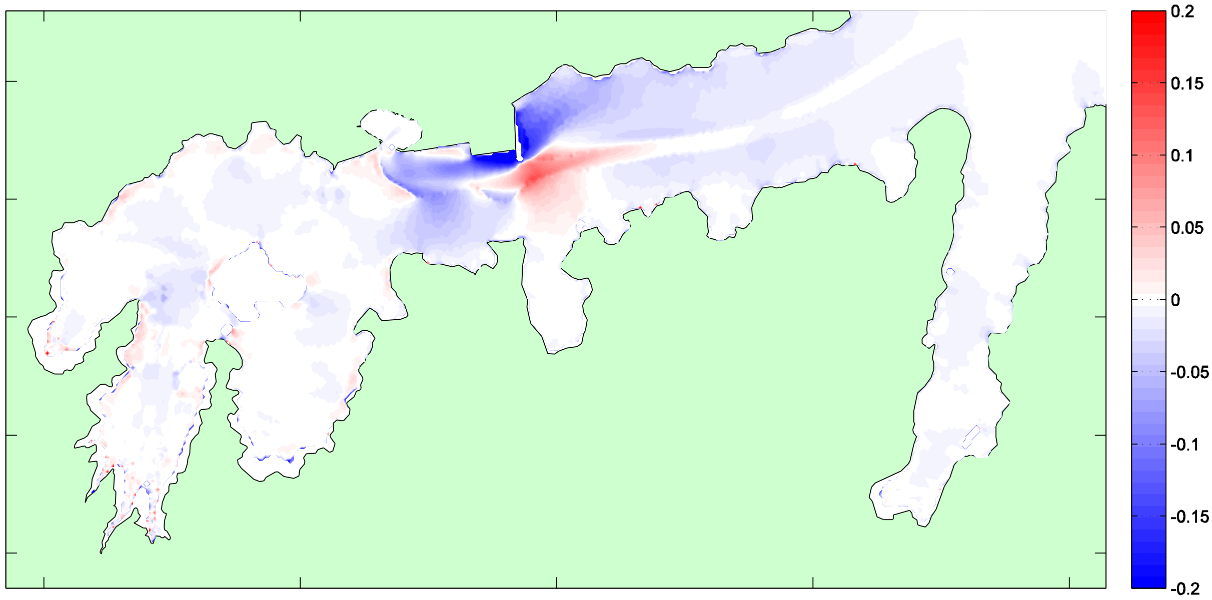

Figure 3.2.2c Difference in speed in m/s at mid-ebb tide between Scenario 0 (present) and Scenario 3 — positive means the scenario will result in an increase in speed.

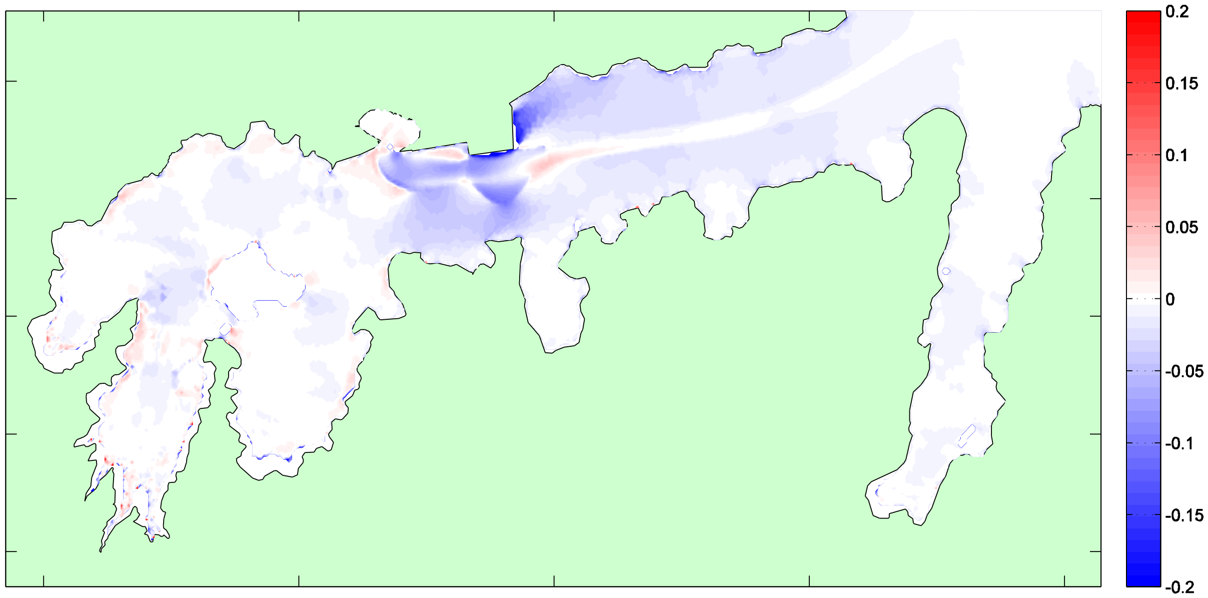

Figure 3.2.2d Difference in speed in m/s at mid-ebb tide between Scenario 0 (present) and Scenario 4 — positive means the scenario will result in an increase in speed.

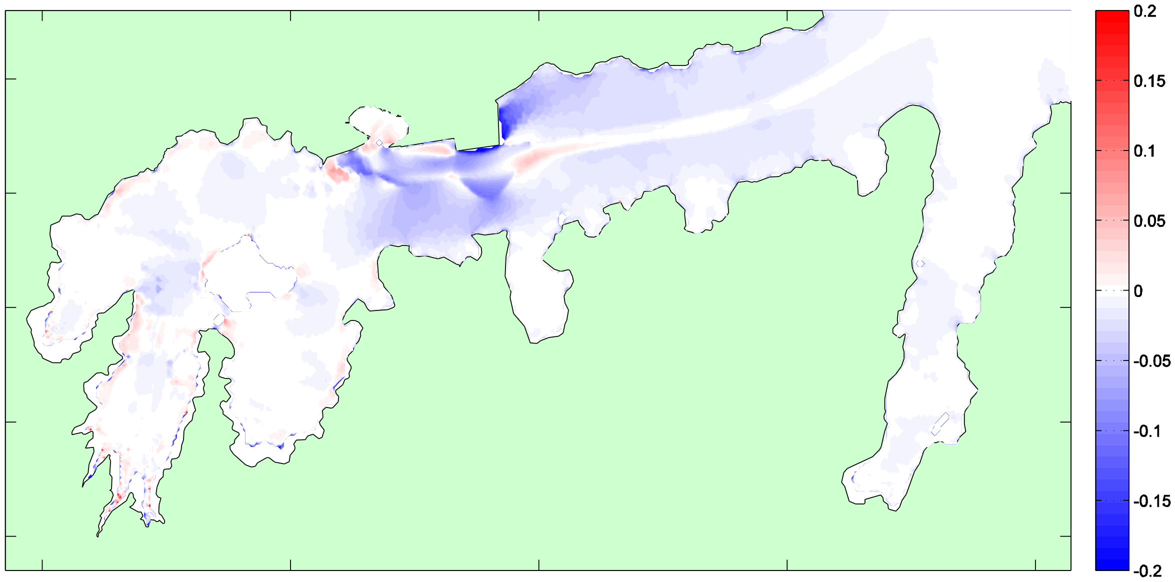

Figure 3.2.2e Difference in speed in m/s at mid-ebb tide between Scenario 0 (present) and Scenario 5 — positive means the scenario will result in an increase in speed.

For Scenarios 1 and 2 (Figures 3.2.2a and b), the differences appear similar, namely:

- Tidal currents either side of the shipping channel are reduced, but in the channel itself there is no significant change in spite of the increase in width from 180 to 220 m between Scenario 1 and 2.
- Currents in the vicinity of the reclamation (Figure 3.2.3) are changed by up to ±0.2 m/s from Scenario 0, indicating that increasing the reclamation by 50 m has no significant additional effect.

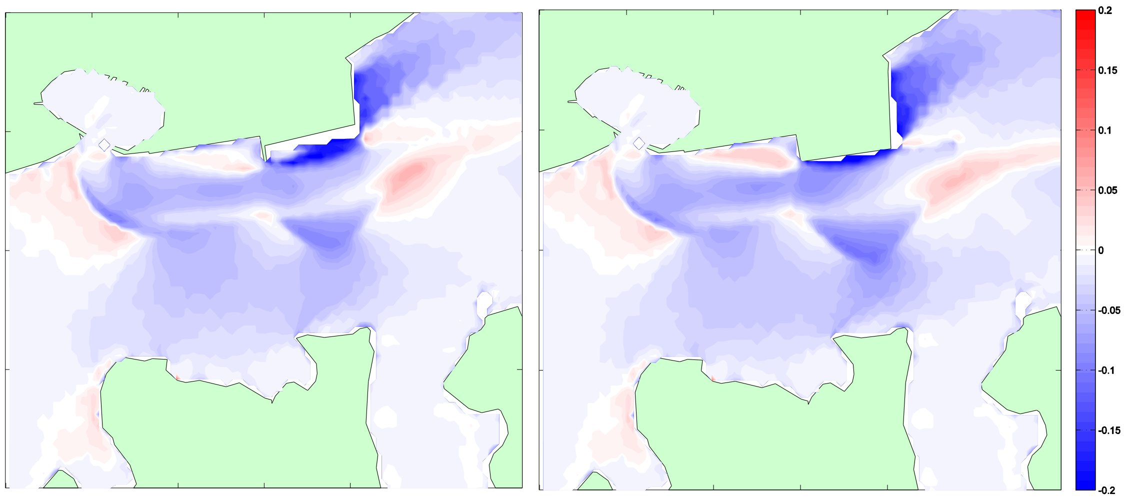

Figure 3.2.3 Difference in speed in m/s at mid-ebb tide between Scenario 0 and Scenario 1(left) and Scenario 2 (right) in the vicinity of the reclamation.

For Scenario 3 (Figure 3.2.2c), the breakwater increases the current speeds in the vicinity of the breakwater and reduces the currents in the lee of the breakwater, as shown in Figure 3.2.4.

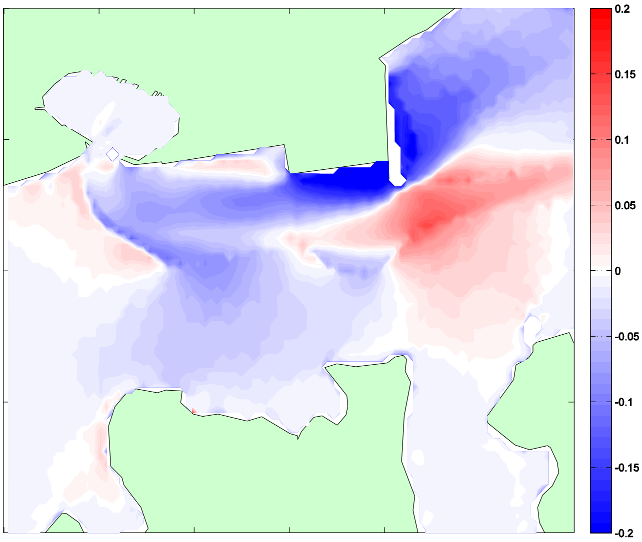

Figure 3.2.4 Difference in speed in m/s at mid-ebb tide between Scenario 0 and Scenario 3in the vicinity of the reclamation

For Scenario 4 and 5 (Figure 3.2.2.d and e), the currents in the Inner Harbour are increased because the opening has increased in size allowing more tidal flow in and out (the effect of this on sediment transport is addressed in Section 3.3). Figure 3.2.5 shows the changes in speed in the vicinity of the reclamation and Inner Harbour entrance in more detail. The only discernible differences between these two scenarios is at the oil/cruise berth to the west of the entrance (Scenario 5, right panel of Figure 3.2.5), where the speed is decreased and to the west where the speed is increased to compensate.

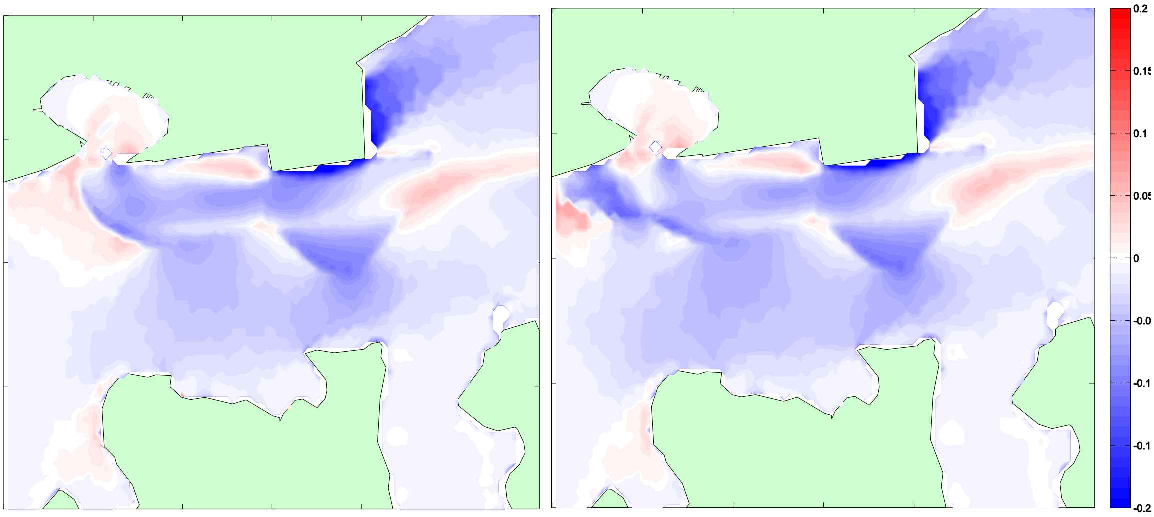

Figure 3.2.5 Difference in speed in m/s at mid-ebb tide between Scenario 0 and Scenario 4 (left) and Scenario 5 (right) in the vicinity of the reclamation.

To examine these changes in more detail and make it easier to compare the different scenarios, the data for a set of points as shown in Figure 3.2.6 have been extracted.

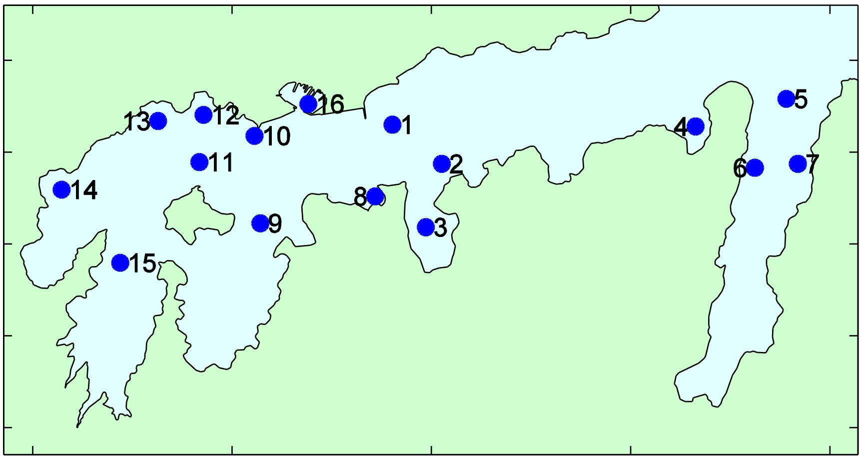

Figure 3.2.6 Location of sites for detailed examination.

Tables 3.2.1a to d have been prepared to show the difference in currents speeds at the different locations. The first two tables show the difference in m/s from Scenario 0 for ebb and flood tides respectively, and the second two show the percentage difference from Scenario 0. The following points arise:

1. For all scenarios, the following points apply:
   a. Current speeds at Cass Bay, Rapaki, and Governors Bay will increase by up to 9.6%;
   b. Current speeds in Purau Bay, Parson Rock, Diamond Harbour, Charteris Bay, Quail I North and the Head of the Bay will decrease, the largest being in Diamond Harbour where the flood-tide speeds will decrease by 9.3% (though this will be by only 4 mm/s and will be indiscernible);
   c. Current speeds in Port Levy and Little Port Cooper will change by up to 2 mm/s which is not significant (it is at the limit of accuracy of the model);
2. The largest differences will occur at the Reclamation and for Scenario 3 where the speeds will be more than halved - .
3. In the Inner Harbour the speeds will increase by between 108 and 192% under Scenarios 4 and 5, though they are still small (less than 3 cm/s).
4. At the Naval Point Breakwater, under Scenario 5, flood flows will be increased by 4% and ebb flows by 1% as a result of the flow out of the dredged berth; whereas under the other scenarios the flows will reduce slightly.
5. Apart from Scenario 5 at the Naval Point Breakwater, there is no significant difference in the results between ebb and flood tides indicating symmetry in the flow patterns.

The significance of the differences in current speed is not readily apparent. For example, what will be the effect of a 9% decrease in the mid-flood and mid-ebb tide speeds in

Diamond Harbour? In the next section, this issue is addressed for sediment particles suspended in the water column.

Table 3.2.1a Comparison of mid-ebb tide speeds (m/s) between various scenarios for the sites shown in Figure 3.2.6.

		Present	Difference from Present m/s				
	Scenario	**0**	**1**	**2**	**3**	**4**	**5**
1	Reclamation	0.317	-0.040	-0.041	-0.174	-0.041	-0.041
2	Parson Rock	0.221	-0.012	-0.018	0.019	-0.018	-0.018
3	Purau Bay	0.060	-0.002	-0.002	-0.002	-0.002	-0.002
4	Little Port Cooper	0.035	0.000	0.000	0.000	0.000	0.000
5	Mouth Port Levy	0.076	0.000	0.000	0.000	0.000	0.000
6	W Mussel Farm	0.062	-0.001	-0.001	-0.001	-0.001	-0.001
7	E Mussel Farm	0.070	0.000	0.000	0.000	0.000	0.000
8	Diamond Harbour	0.037	-0.002	-0.001	-0.001	-0.001	-0.002
9	Charteris Bay	0.233	-0.005	-0.005	-0.005	-0.005	-0.005
10	Naval Point B/W	0.412	-0.009	-0.010	-0.009	-0.009	0.005
11	Quail I North	0.273	-0.012	-0.012	-0.012	-0.012	-0.010
12	Cass Bay	0.125	0.012	0.012	0.012	0.012	0.010
13	Rapaki	0.148	0.005	0.006	0.006	0.006	0.005
14	Governors Bay	0.091	0.001	0.001	0.001	0.001	0.001
15	Head of the Bay	0.553	-0.004	-0.005	-0.005	-0.002	-0.003
16	Inner Harbour	0.012	0.000	0.000	0.000	0.016	0.023

Table 3.2.1b Comparison of mid-flood tide speeds (m/s) between various scenarios for the sites shown in Figure 3.2.6.

		Present	Difference from Present m/s				
	Scheme	**0**	**1**	**2**	**3**	**4**	**5**
1	Reclamation	0.323	-0.020	-0.025	-0.147	-0.025	-0.025
2	Parson Rock	0.235	-0.014	-0.019	0.023	-0.019	-0.018
3	Purau Bay	0.059	-0.003	-0.003	-0.003	-0.003	-0.003
4	Little Port Cooper	0.037	0.001	0.001	0.001	0.001	0.001
5	Mouth Port Levy	0.081	-0.001	-0.001	-0.001	-0.001	-0.001
6	W Mussel Farm	0.062	-0.002	-0.002	-0.002	-0.002	-0.002
7	E Mussel Farm	0.072	0.001	0.001	0.001	0.001	0.001
8	Diamond Harbour	0.043	-0.003	-0.004	-0.004	-0.004	-0.004
9	Charteris Bay	0.236	-0.004	-0.004	-0.004	-0.004	-0.004
10	Naval Point B/W	0.430	-0.002	-0.002	-0.002	-0.003	0.018
11	Quail I North	0.290	-0.012	-0.012	-0.012	-0.012	-0.010
12	Cass Bay	0.132	0.012	0.012	0.012	0.012	0.010
13	Rapaki	0.156	0.006	0.006	0.006	0.006	0.006
14	Governors Bay	0.098	0.001	0.001	0.001	0.001	0.001
15	Head of the Bay	0.555	0.002	0.001	0.000	0.001	0.003
16	Inner Harbour	0.012	0.000	0.000	-0.001	0.013	0.019

Table 3.2.1c Percentage change in mid-ebb tide speeds (m/s) between various scenarios for the sites shown in Figure 3.2.6.

		Present	Difference from Present %				
	Scheme	**0**	**1**	**2**	**3**	**4**	**5**
1	Reclamation	0.317	-12.6	-12.9	-54.9	-12.9	-12.9
2	Parson Rock	0.221	-5.4	-8.1	8.6	-8.1	-8.1
3	Purau Bay	0.060	-3.3	-3.3	-3.3	-3.3	-3.3
4	Little Port Cooper	0.035	0.0	0.0	0.0	0.0	0.0
5	Mouth Port Levy	0.076	0.0	0.0	0.0	0.0	0.0
6	W Mussel Farm	0.062	-1.6	-1.6	-1.6	-1.6	-1.6
7	E Mussel Farm	0.070	0.0	0.0	0.0	0.0	0.0
8	Diamond Harbour	0.037	-5.4	-2.7	-2.7	-2.7	-5.4
9	Charteris Bay	0.233	-2.1	-2.1	-2.1	-2.1	-2.1
10	Naval Point B/W	0.412	-2.2	-2.4	-2.2	-2.2	1.2
11	Quail I North	0.273	-4.4	-4.4	-4.4	-4.4	-3.7
12	Cass Bay	0.125	9.6	9.6	9.6	9.6	8.0
13	Rapaki	0.148	3.4	4.1	4.1	4.1	3.4
14	Governors Bay	0.091	1.1	1.1	1.1	1.1	1.1
15	Head of the Bay	0.553	-0.7	-0.9	-0.9	-0.4	-0.5
16	Inner Harbour	0.012	0.0	0.0	0.0	133.3	191.7

Table 3.2.1d Percentage change in mid-flood tide speeds (m/s) between various scenarios for the sites shown in Figure 3.2.6.

		Present	Difference from Present %				
	Scheme	**0**	**1**	**2**	**3**	**4**	**5**
1	Reclamation	0.323	-6.2	-7.7	-45.5	-7.7	-7.7
2	Parson Rock	0.235	-6.0	-8.1	9.8	-8.1	-7.7
3	Purau Bay	0.059	-5.1	-5.1	-5.1	-5.1	-5.1
4	Little Port Cooper	0.037	2.7	2.7	2.7	2.7	2.7
5	Mouth Port Levy	0.081	-1.2	-1.2	-1.2	-1.2	-1.2
6	W Mussel Farm	0.062	-3.2	-3.2	-3.2	-3.2	-3.2
7	E Mussel Farm	0.072	1.4	1.4	1.4	1.4	1.4
8	Diamond Harbour	0.043	-7.0	-9.3	-9.3	-9.3	-9.3
9	Charteris Bay	0.236	-1.7	-1.7	-1.7	-1.7	-1.7
10	Naval Point B/W	0.430	-0.5	-0.5	-0.5	-0.7	4.2
11	Quail I North	0.290	-4.1	-4.1	-4.1	-4.1	-3.4
12	Cass Bay	0.132	9.1	9.1	9.1	9.1	7.6
13	Rapaki	0.156	3.8	3.8	3.8	3.8	3.8
14	Governors Bay	0.098	1.0	1.0	1.0	1.0	1.0
15	Head of the Bay	0.555	0.4	0.2	0.0	0.2	0.5
16	Inner Harbour	0.012	0.0	0.0	-8.3	108.3	158.3

3.3 Sediment Transport

The SELFE model produces at each node a full set of tidal constituents that can be used to establish the tidal velocity over the whole model area for anytime in the past or future. If we take a set of neutrally-buoyant particles, i.e., particles that neither rise to the surface nor sink to the bottom, and drop them into the flow field, we can use the flow velocities from the model to estimate their trajectories. In reality, most particles are either positively buoyant (e.g., organic material), in which case they will rise to the surface and be moved about by wind and waves, or negatively buoyant (such as sediment), in which case they will fall to the sea bed and their motion will stop. However, using neutrally-buoyant particles allows us to see the pattern of movement under tidal currents alone. For sediment this is a conservative approach as in reality the sediment particle will sink to the bottom at some stage in the estimated trajectory.

3.3.1 Present Bathymetry

Concern has been expressed about the effect development will have on sediment transport in the Upper Harbour and whether the development will cause additional sedimentation. Figure

3.3.1 shows the trajectories that neutrally-buoyant particles take when released from various locations in the Upper Harbour at mid-ebb in a perigean spring tide. The trajectories are for 2 tidal cycles (further tidal cycles are available in the animations on the DVD). Except for the particle released in Charteris Bay, there is remarkably little variation in the trajectories between one tidal cycle and another. Further analysis of the Charteris Bay trajectory has shown that it is not sensitive to the exact position where the particle is released; the trajectories always drift towards Quail Island like this.

The extent of the trajectories is quite variable, with the longest being 4 km for the particle released to the north of Quail Island to 2 km for the particle released in Governors Bay.

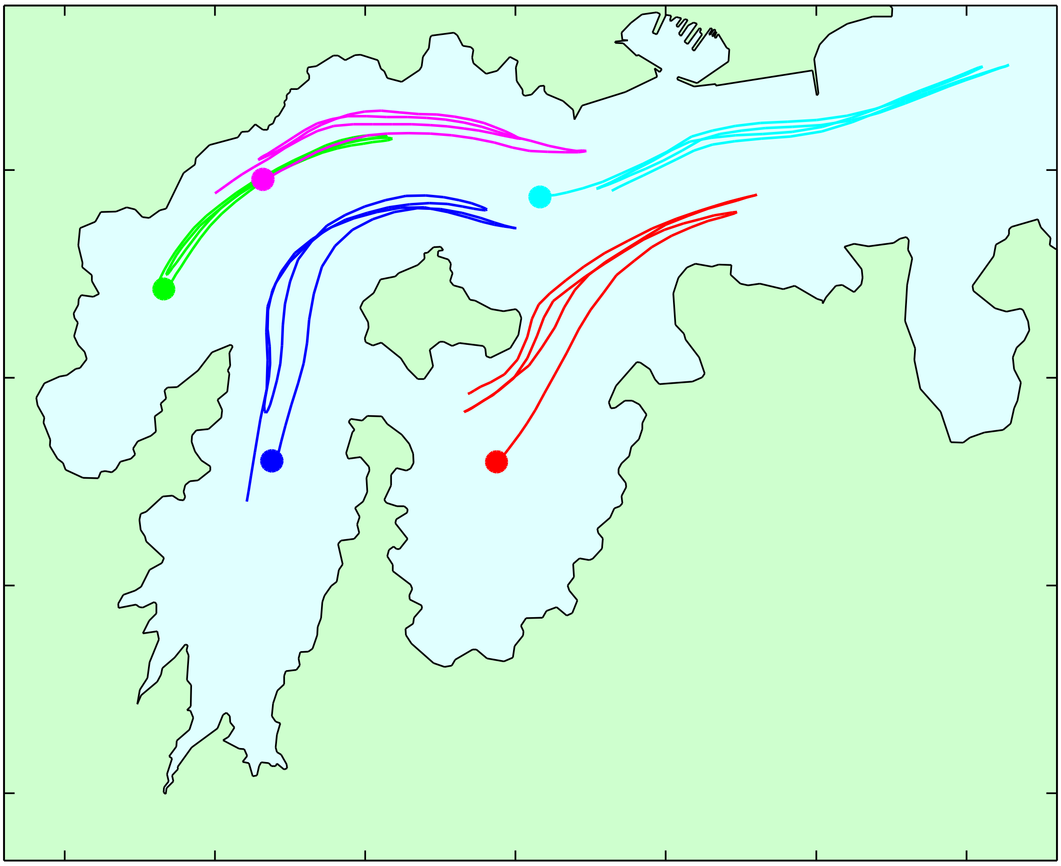

Figure 3.3.1 Trajectories of neutrally-buoyant particles released in the Upper Harbour for the present scenario. The blobs are at the point of release.

Diamond Harbour is another area of interest because it is close to the reclamation, and both waves and tidal currents are likely to be reduced, so the effect of this on sediment transport is important. The trajectories of particles released at mid-ebb and mid-flood tides at Diamond Harbour are shown in Figure 3.3.2. A particle released at ebb tide will travel towards the open sea, but return to close to the same spot and oscillate back and forth. On the other hand, a particle released at flood tide will travel around into Charteris Bay and with each tidal cycle will drift slowly towards Quail Island.

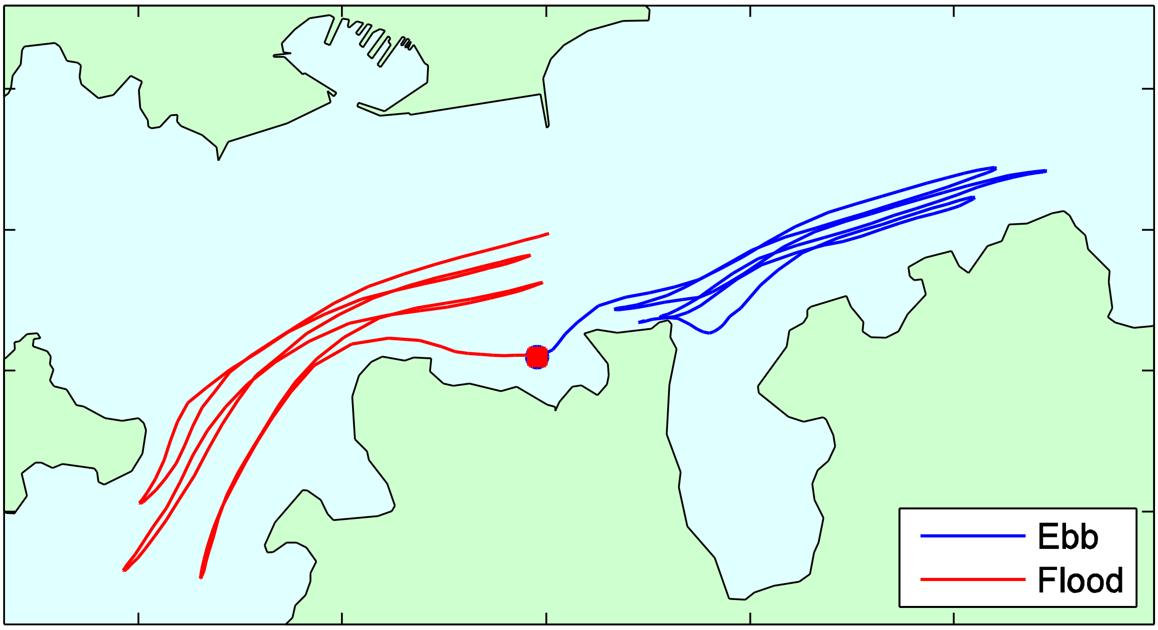

Figure 3.3.2 Trajectories of neutrally buoyant particles released at mid-ebb and mid-flood tide at Diamond Harbour.

3.3.2 Effect of Reclamation and Dredged Channel

The simulations shown in Figures 3.3.1 and 3.3.2 were repeated for the various scenarios and the results are presented in Figures 3.3.3a to e for particles released in the Upper Harbour and 3.3.4a to e for particles released at Diamond Harbour. In these figures, Scenario 0 (present bathymetry) is shown as the grey lines.

For release sites in the western Upper Harbour, the trajectories of all of the scenarios show essentially no difference from the present bathymetry. For the site to the northeast of Quail Island, the trajectories are essentially the same, except for Scenario 3 where the breakwater pushes the trajectory offline because of the shift in flow required to skirt the breakwater. For a particle released in Charteris Bay, the drift towards Quail Island is faster than for the present bathymetry and eventually the particles swing to the north of the island. This also happens with the present bathymetry, but it takes many more tidal cycles to occur.

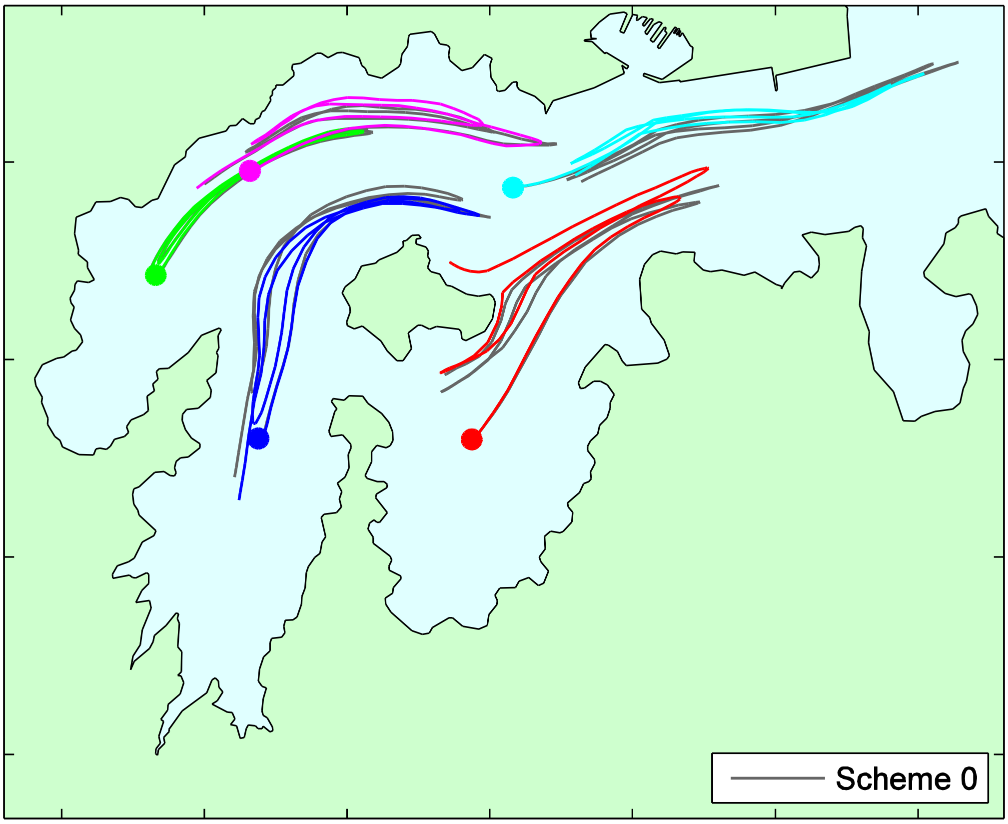

Figure 3.3.3a Trajectories of neutrally buoyant particles for Scenario 1.

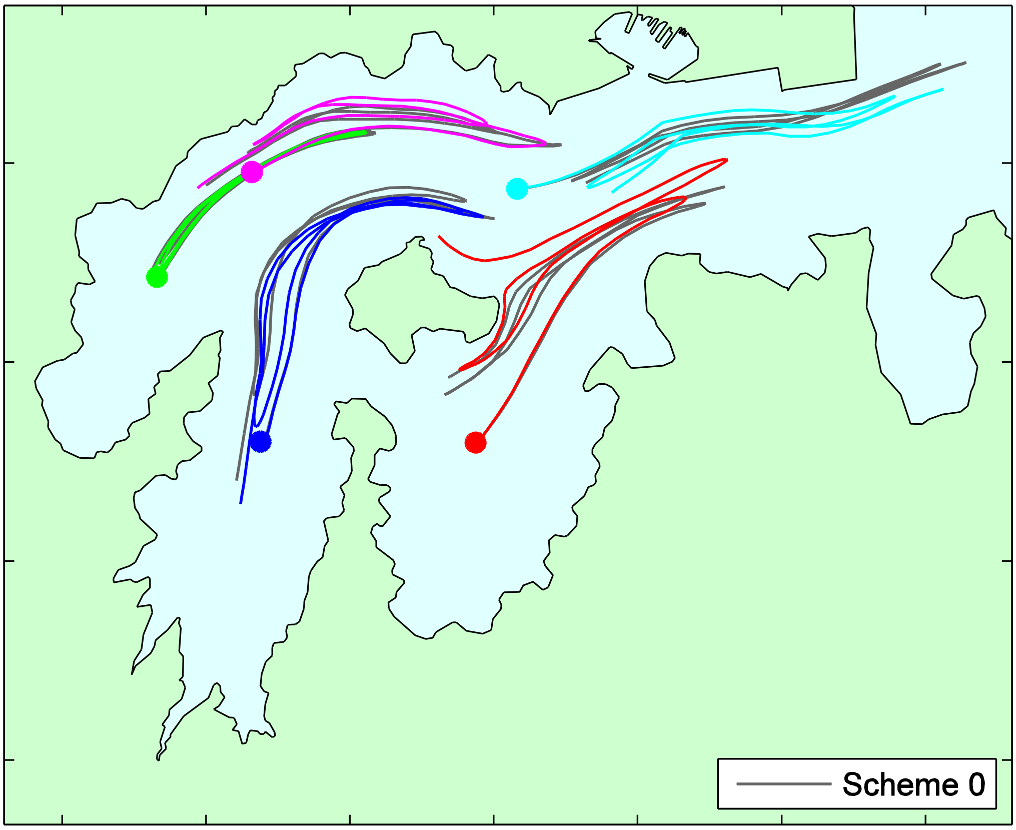

Figure 3.3.3b Trajectories of neutrally buoyant particles for Scenario 2.

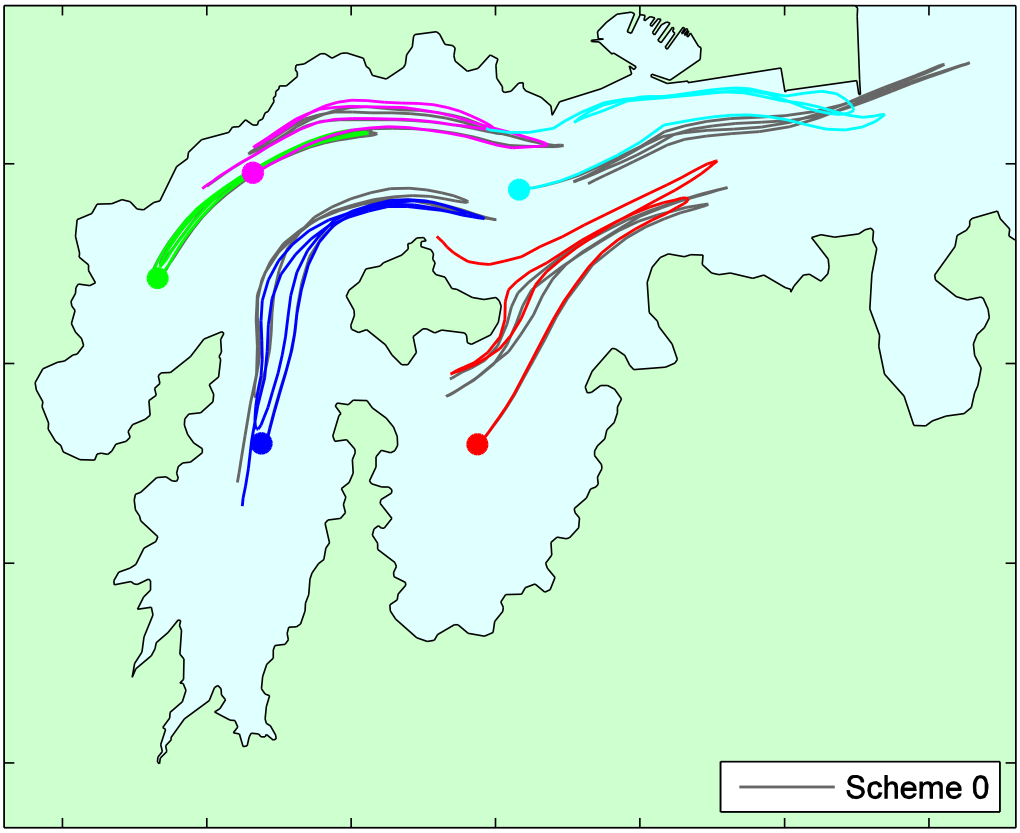

Figure 3.3.3c Trajectories of neutrally buoyant particles for Scenario 3.

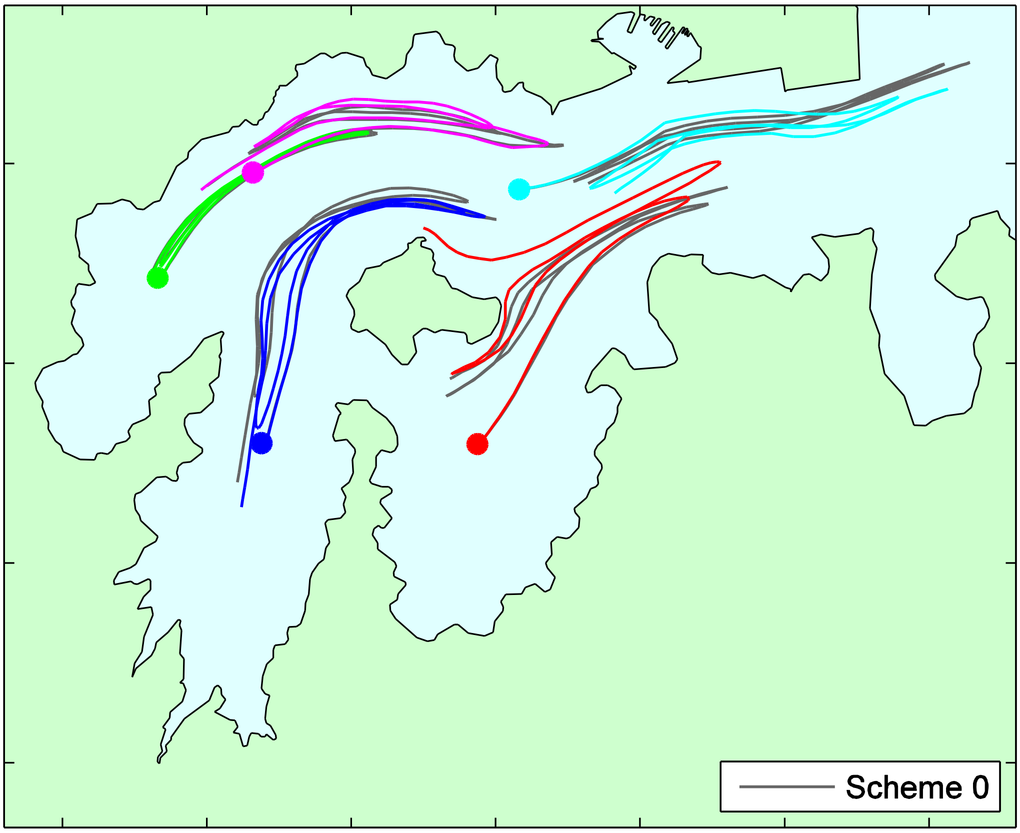

Figure 3.3.3d Trajectories of neutrally buoyant particles for Scenario 4.

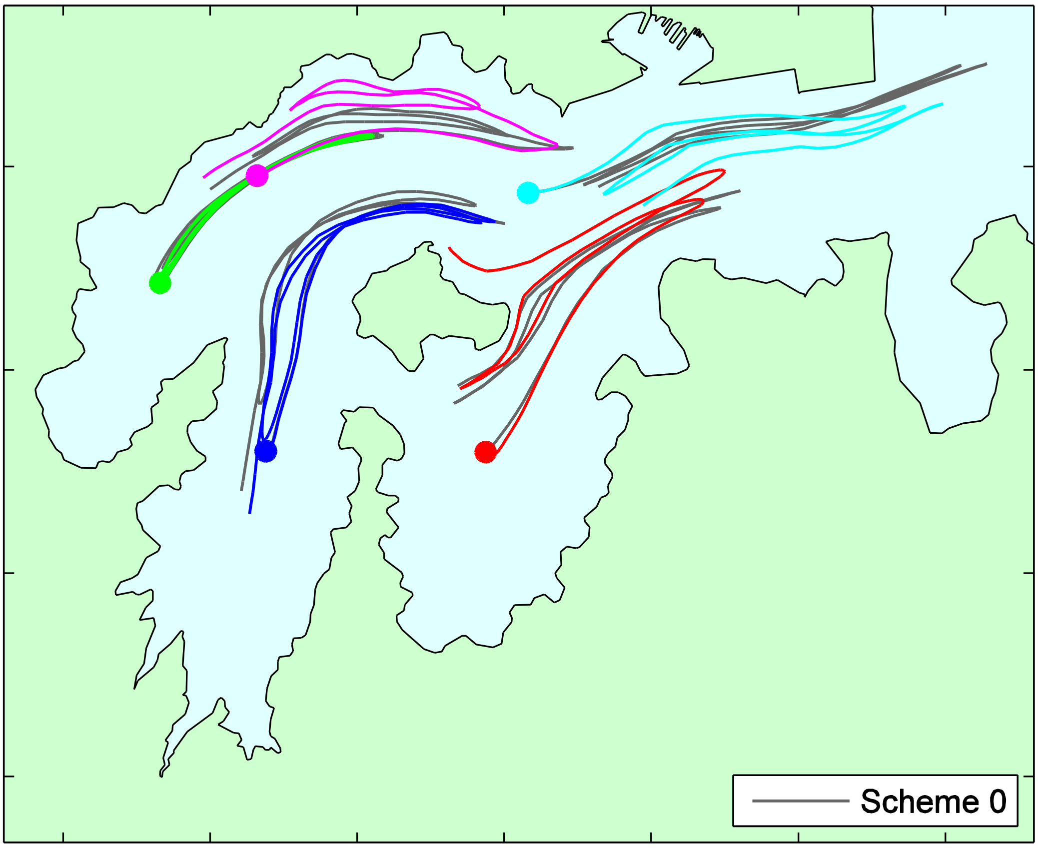

Figure 3.3.3e Trajectories of neutrally buoyant particles for Scenario 5.

For a particle released at Diamond Harbour at ebb tide, the trajectories for all scenarios follow the trajectory for Scenario 0 and there is only a very minor difference between them. The flood tide trajectories are slightly different, especially in the vicinity of Quail Island.

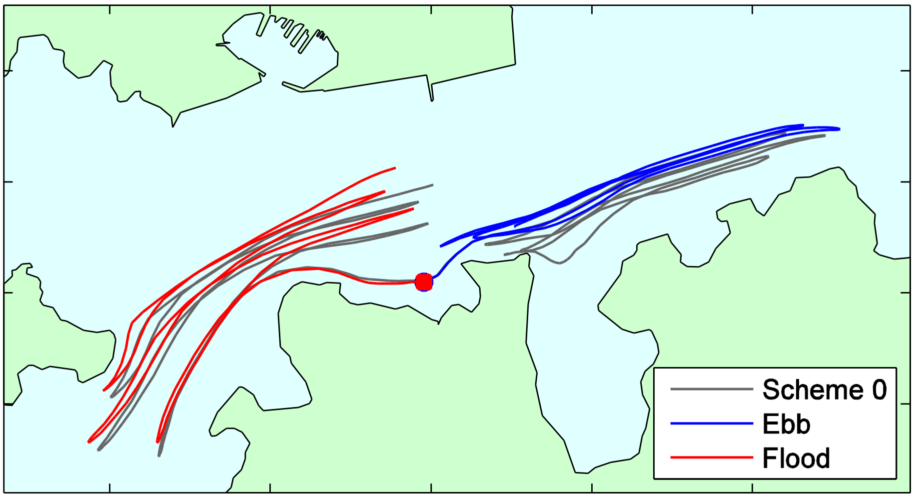

Figure 3.3.4a Trajectories for neutrally buoyant particles for Scenario 1.

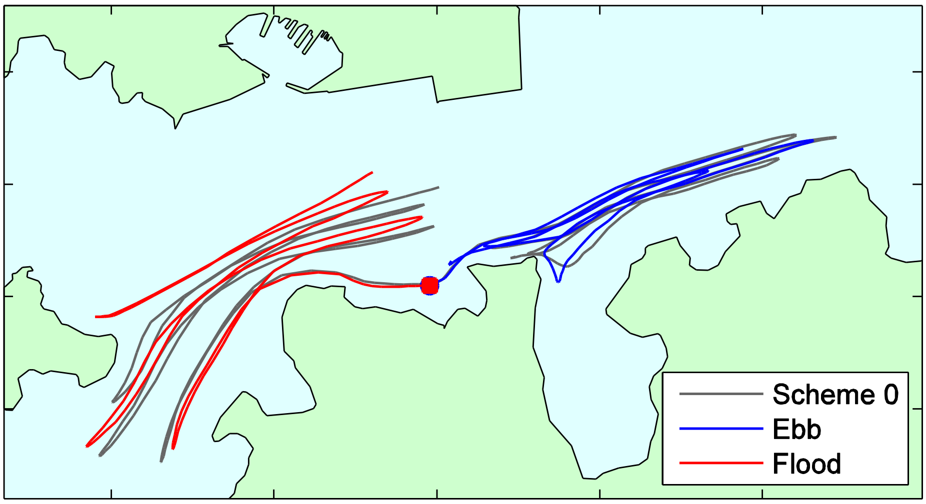

Figure 3.3.4b Trajectories for neutrally buoyant particles for Scenario 2.

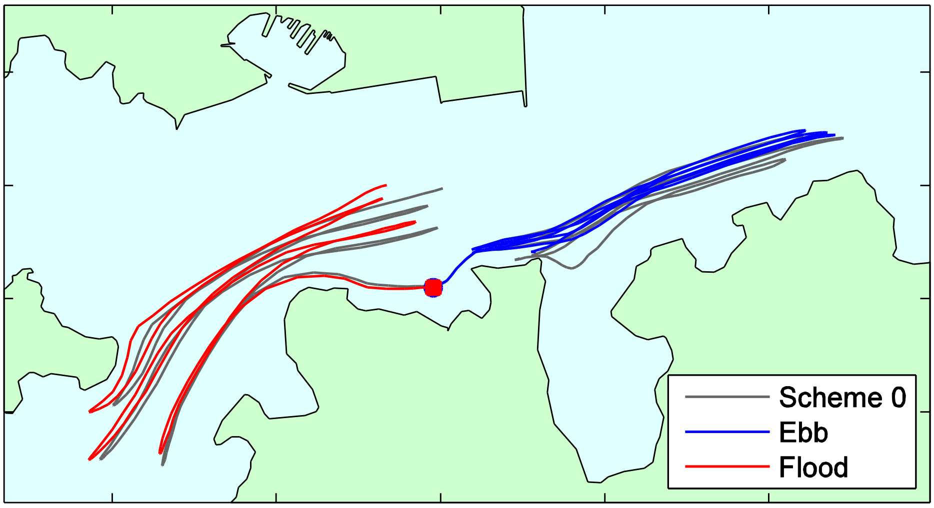

Figure 3.3.4c Trajectories for neutrally buoyant particles for Scenario 3

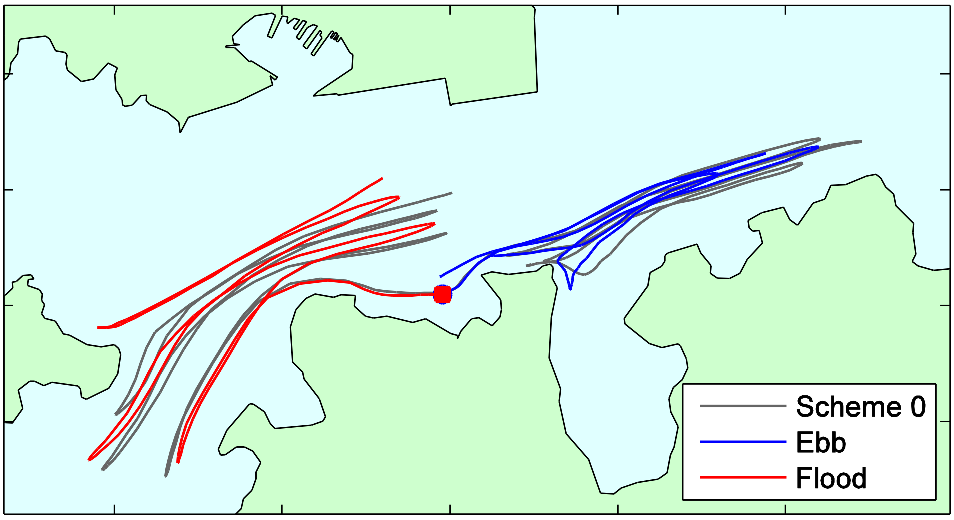

Figure 3.3.4d Trajectories for neutrally buoyant particles for Scenario 4.

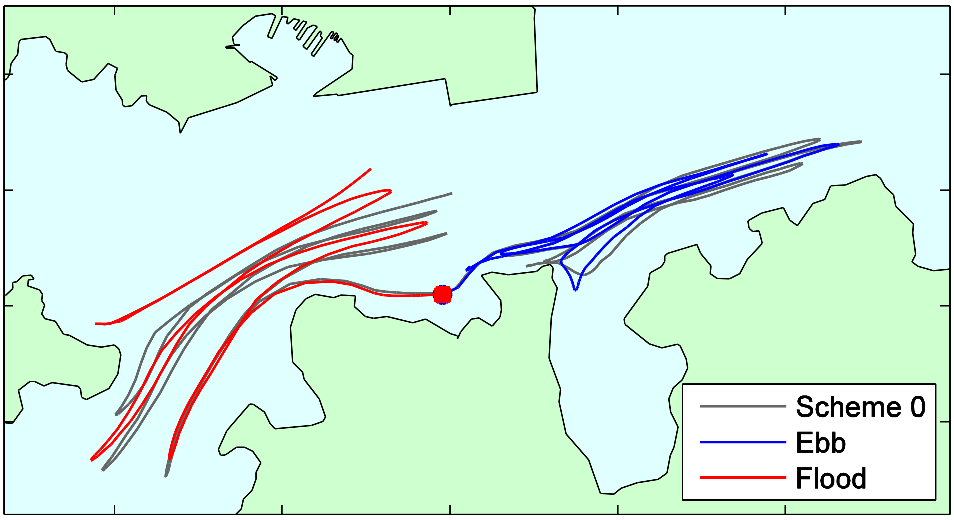

Figure 3.3.4e Trajectories for neutrally buoyant particles for Scenario 5.

4 DISCUSSION

4.1 Waves

4.1.1 Waves and Sediment Transport

In Section 3.1.2 (Effect of Reclamation and Navigational Channel on Waves) we showed the differences in wave height and period that will occur as result of the various reclamation and channel scenarios. In some locations such as Diamond Harbour and Purau Bay there will be reductions of up to 5 cm in the mean wave height. In this section, we address the significance of such changes in wave heights on sediment transport.

Because of their oscillatory nature, waves are not effective at producing net transport of sediment – the sediment moves back and forth by a metre or two over the same spot. An exception is in shallow water where the height of the waves is the same order as the depth and waves break, producing net drift of sand along a beach, for example. In deeper water, where the wave height is much smaller than the depth, waves stir up the bottom and bring the sediment into suspension, then tidal and other currents transport it.

To examine this in more detail, we need to consider some wave mechanics.

Figure 4.1 shows a typical wave-producing weather event at a location in the outer harbour. The upper panel indicates the wind at the site increased from 10 knots to 30 knots over 24 hours, before dying away. The wind direction was W to SW.

The resulting waves are shown in the lower panel. There are two components to the total waves at the site: sea waves and swell waves. The mathematical relationship between these and the total wave height is:

$$H_{total} = \sqrt{H_{sea}^2 + H_{swell}^2}$$

Sea waves have periods up to 7 s and are generated by local winds. These are the small closely spaced waves which are seen on a typically windy day on the harbour.

Swell waves have periods longer than 7 s and are generated by storms far away, they are seen as long rolling swells.

In Figure 4.1, the sea waves follow the increase in wind and when the wind dies away, the sea waves follow it. On the other hand, the swell waves rise later than the sea waves because these waves have been generated elsewhere and have propagated into the region. In this instance they are likely to have been generated from the same weather event but out in the ocean to the south of Banks Peninsula.

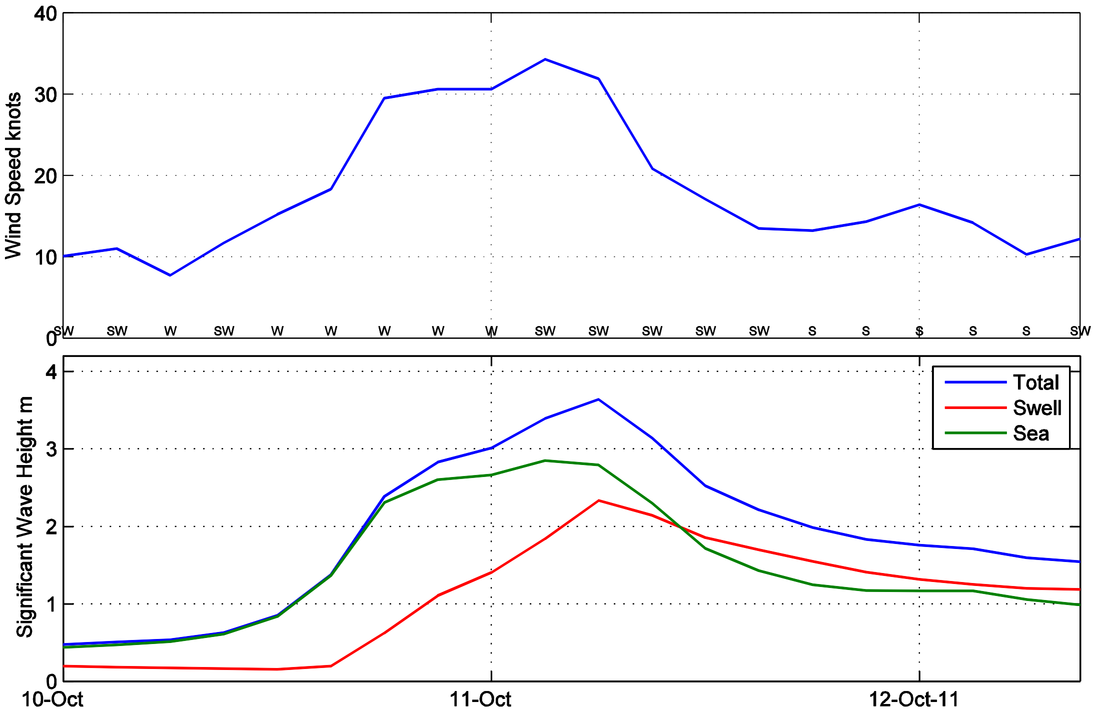

Figure 4.1. Typical event in the outer harbour showing local winds (upper panel) and waves (lower panel).

Figures 4.2 and 4.3 are generic diagrams that show the velocities under typical sea and swell waves in the outer and upper harbour respectively. The plots also indicate the minimum velocity which would cause sediment movement. At velocities below this, sediment does not move.

In the outer harbour (Figure 4.2), where the depth is 12 m, the velocity under the short period sea waves (upper plot) reduces through the depth and at the sea bed it is only slightly above zero; whereas the velocity under longer period swell waves reaches down to the sea bed almost unchanged. Thus in deep water (such as in the outer harbour) the sea waves do not mobilise the sediment but the swell waves do.

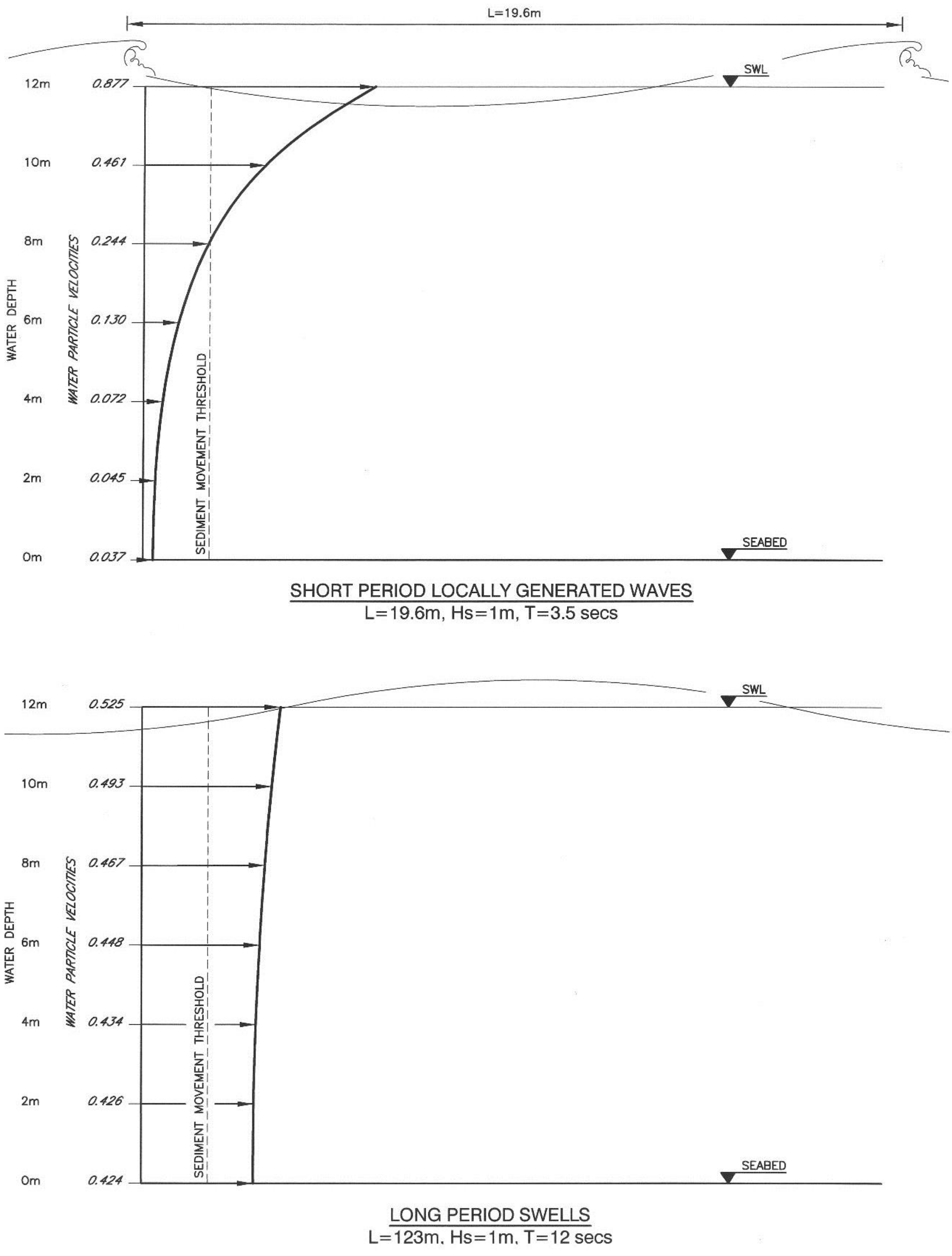

Figure 4.2. Wave effects in outer harbour.

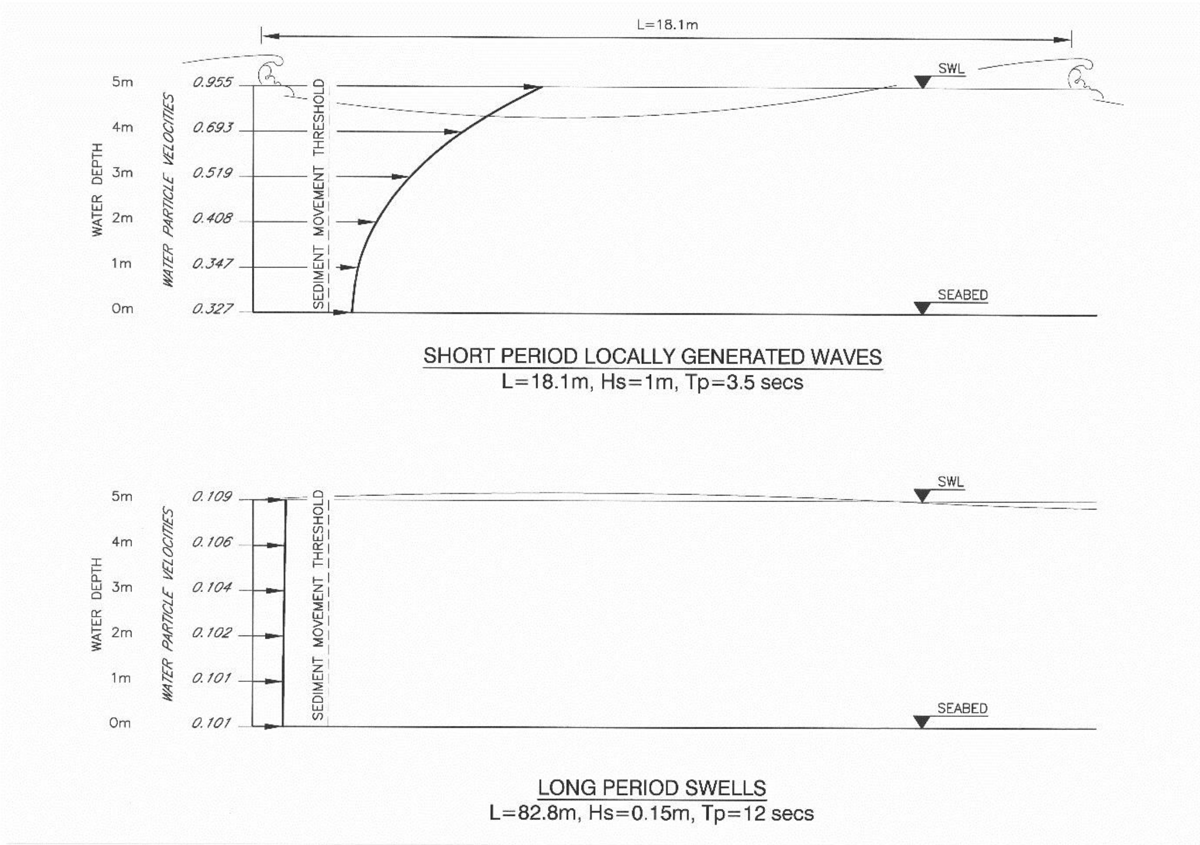

Figure 4.3. Wave effects in the upper harbour.

In the shallow water of the upper harbour, such as Rapaki Bay (Figure 4.4), which is an area of particular interest to local people, the situation is opposite. Here, sea waves generated by wind over the harbour predominate and the induced velocities at the bed are large enough to initiate sediment transport. On the other hand, swell waves in Rapaki Bay are much smaller and the velocities do not reach the threshold for sediment transport. Thus, for the upper harbour the sea waves are the more important factor for sediment suspension, not swell waves.

Figure 4.5 shows how the sea and swell waves vary for the different scenarios. For sea waves, there will be a small increase (4.1 cm) for all of the scenarios (because the propagation of the waves is altered by the reclamation), but there are no distinguishable differences between them. For swell waves (note the scale of this plot is a tenth of the scale for sea waves), there will be a reduction for all but Scenario 3; however, these waves are already below the level to initiate sediment transport, so the reduction in height is not important for sediment transport.

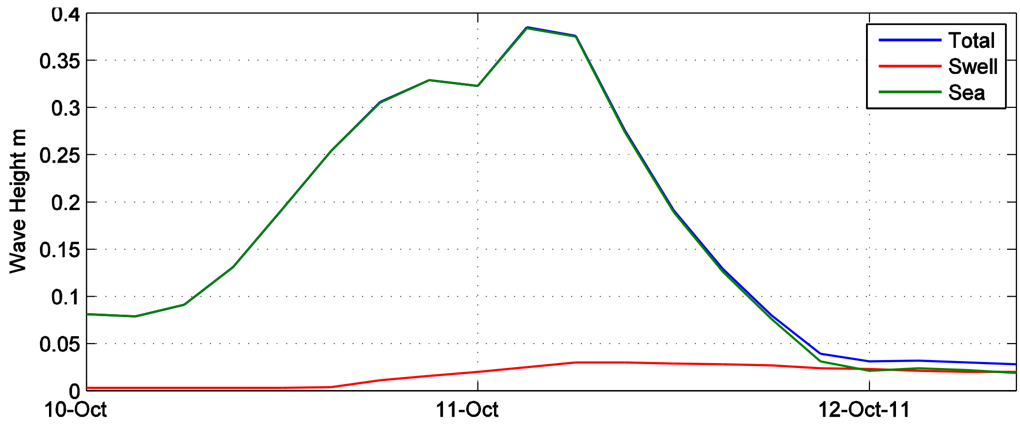

Figure 4.4 Waves at Rapaki for the event shown in Figure 4.1

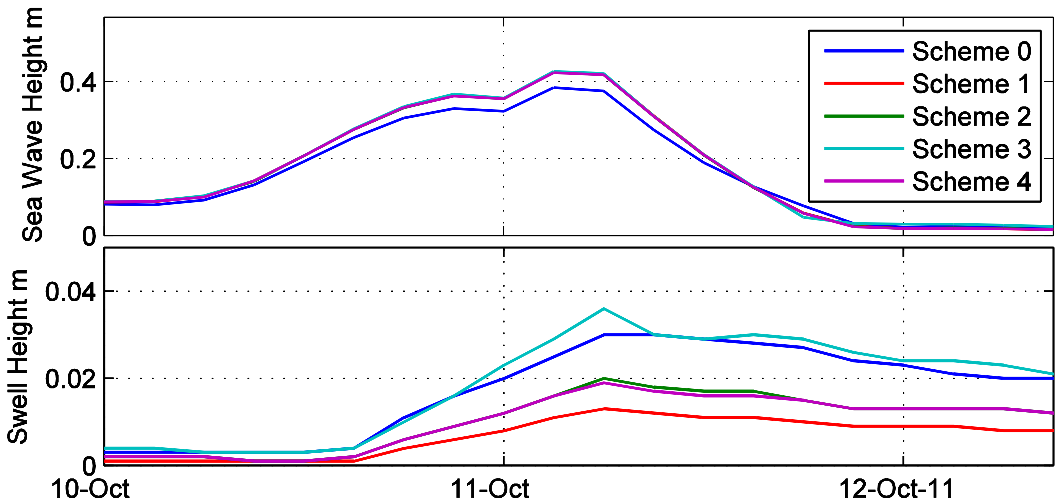

Figure 4.5 Sea waves (upper) and swell (lower) at Rapaki for various scenarios for the event in Figure 4.1 (note the difference in scale between sea and swell waves).

At Diamond Harbour, where the depth is 5 m, sea waves also predominate (Figure 4.6), but swell waves contribute a significant proportion to the peak. The sea and swell waves under various scenarios are shown in Figure 4.7. The reduction in sea waves is quite small (from 1.07 m to 0.97 m for Scenario 3), but the reduction in swell waves is more than 50%. This reduction in swell waves is most likely caused by the swell waves refracting from the shipping channel towards the northern and southern shorelines, thus reducing the wave energy reaching Diamond Harbour, as well as the blockage of the reclamation and the deepening of the swing basin.

The effect of the longer waves being reduced in height is to move the peak period of the waves from 8 s to 4s. As a result of this, the significant particle velocity at the bed decreases from 0.669 m/s to 0.392 m/s. However, in terms of mobilising the sediment by the waves, this reduction is partly offset by the fact that there are twice as many waves per hour for 4 s periods as for 8 s period.

This means the length of time each hour that the velocity at the bed exceeds the threshold for motion (i.e., a velocity of 0.25 m/s) is reduced from 2722 s to 2015 s[9], a 26% reduction, although this specific analysis applies only to the peak of the event shown in Figure 4.1. Table 3.1.3 indicates that on average, over the 10 years of record, the reduction in wave period will be much smaller than this. Nevertheless, as a result of the development scenarios (reclamation plus channel enlargement) there is a potential change in the initiation of sediment transport by waves in Diamond Harbour. Whether this will have any effect on sedimentation is not clear. Anecdotal evidence suggests that the sediment on the bed of Diamond Harbour is hard-packed mud, not the loose mud present elsewhere in the harbour. If this is the case, then the small decrease in the wave climate is unlikely to have any effect. However, any development should include monitoring of this part of the harbour.

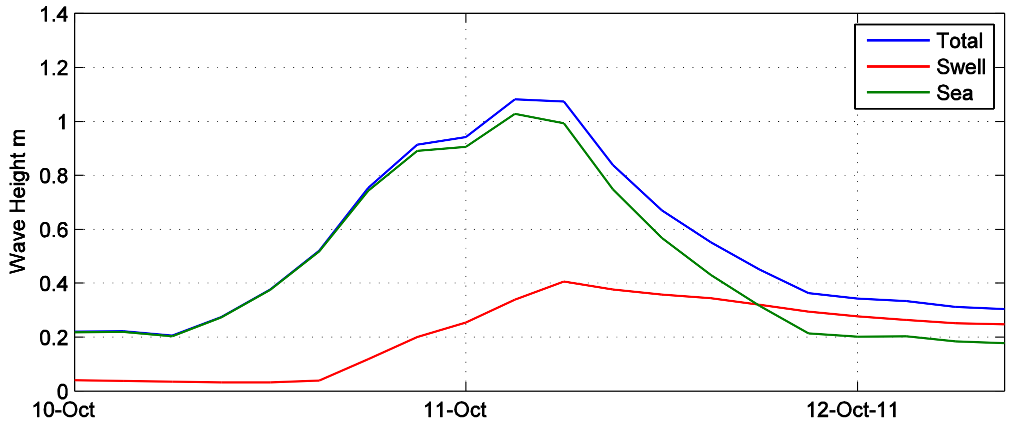

Figure 4.6 Waves at Diamond Harbour for the event shown in Figure 4.1.

[9] The calculations used for this analysis are presented in Appendix III.

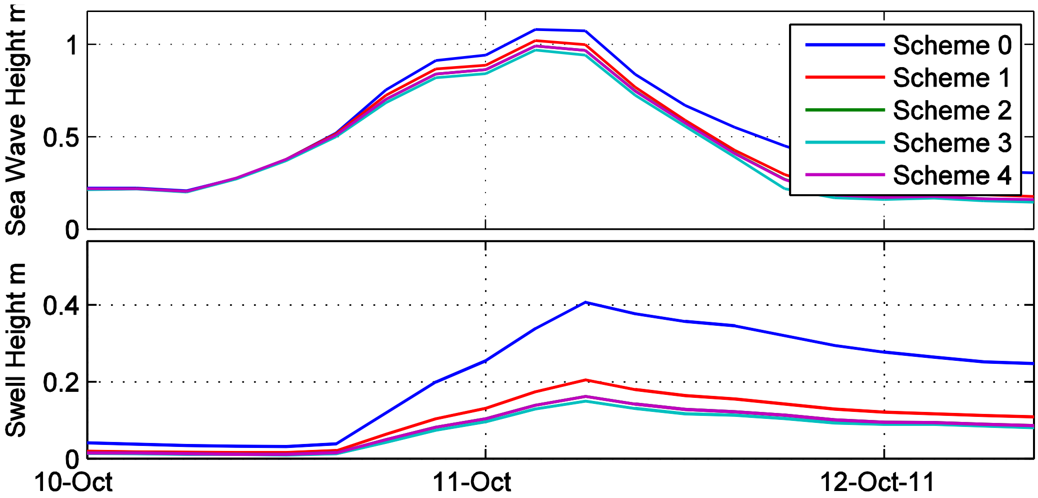

Figure 4.7 Sea waves (upper) and swell (lower) at Diamond Harbour for various scenarios for the event in Figure 4.1 (note the difference in scale between sea and swell waves).

4.1.2 Beach Erosion

A concern has been raised that increased wave activity along the northern and southern bays east of the reclamation resulting from wave refraction from the deepened channel may cause increased beach erosion.

Beach erosion by waves is caused by large waves approaching the beach at an angle and breaking, with resultant net transport of sediment along the beach[10]. The important parameter in this process is wave energy which is proportional to the square of the significant wave height. Erosion mainly occurs in the highest waves, so the most appropriate wave height to use to compare the effect of development on beach erosion is the 1% exceedance values in Table 3.1.2a. For Livingstone Bay (which is typical of the shorelines affected by dredging of the deeper shipping channel), these have been converted to wave energy in Table 4.1.

Table 4.1 Wave energy at Livingstone Bay for 1% exceedance waves

Parameter	Scheme 0	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Wave Height m	0.855	1.006	0.988	0.940	0.988	0.988
Wave Energy m^2	0.731	1.012	0.976	0.884	0.976	0.976
%age change	-	38	34	21	34	34

For a sandy beach, increases in wave energy of more than 30% would be expected to have a significant effect on the transport of sediment along the beach. However, for the rocky beaches along the northern and southern bays of the middle to outer harbour, such an increase is unlikely to cause significant erosion, though finer sediment (sand) if there is any may become more mobile.

[10] US Corps of Army Engineers Coastal Engineering Manual, Part III, Chapter 2: Longshore Sediment Transport

4.2 Tidal Currents and Sediment Transport

The trajectories of sediment particles shown in Figures 3.3.1 to 3.3.4 indicate that the tidal currents carry sediment only for 2 to 4 km over a half-tidal cycle, then they return to roughly the same point (except for particles propagating into and out of Charteris Bay). The implication of this cyclical pattern is that there is no direct mechanism for such particles to exit from their location of origin. Thus, particles that start in the Upper Harbour will remain there. Of course, this is not quite the way things work in practice for a particular sediment particle, because the actual mechanism will be for a particle to be brought into suspension by waves, then to be transported by tidal currents until it falls to the bottom, whence it will be picked again in the next wave event and depending on the state of the tide (ebb or flood) will be carried forward or backwards. Thus, the trajectories in Figures 3.3.1 to 3.3.4 show the behaviour of a particle on average. The pattern is consistent with the compartmentalisation hypothesis of OCEL(2014)[11], who used drogue studies to show that the harbour consists of 3 tidal compartments: outer, middle and upper, and there is indirect communication between them.

4.3 Effect of Deepened Channel and Swing Basin on Waves and Tidal Currents

Scenarios 1 to 5 comprise a reclamation with various configurations with a deepened shipping channel and swing basin. For Scenario 1, the existing channel is deepened from 13.5 to 17.5 m below MSL in the existing width (180 m). For the other schemes, the channel is deepened to 17.5 m and its width is increased to 220 m, as shown in Figure 4.8a, where for Scenario 2 and others, the channel needed to be shifted south to accommodate the extra width of reclamation. The scenarios also involve an enlarged and deepened swing basin, as shown in Figure 4.8b.

A question that arises is: to what extent are the changes in wave climate and tidal currents caused by the deepened shipping channel and swing basin and to what extent by the reclamation?

To answer this question, a further model scenario was run with Scenario 2 (full reclamation to the end of the existing Cashin Quay breakwater), but with the existing shipping channel and swing basin. In this section, the results of this scenario are compared with the results of the present configuration (Scenario 0).

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[11] Implications of Lyttelton Port Recovery Plan on Sedimentation and Turbidity in Lyttelton Harbour, OCEL Consultants Ltd., (Oct. 2014).

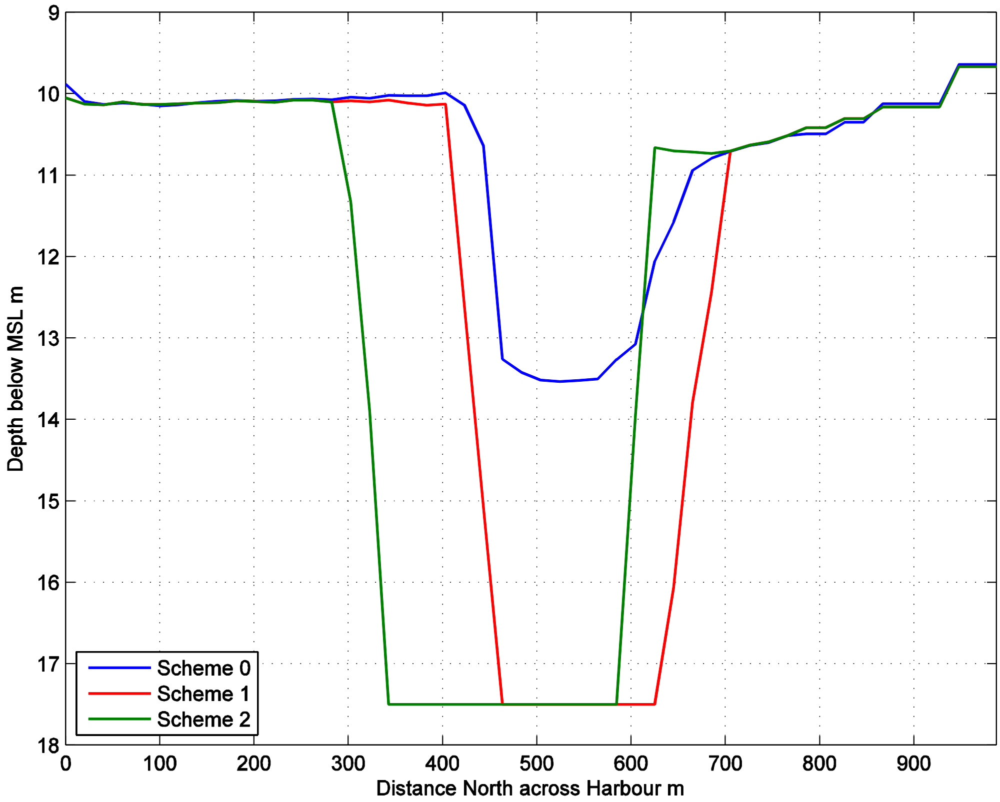


Figure 4.8a Cross sections through the navigation channel.

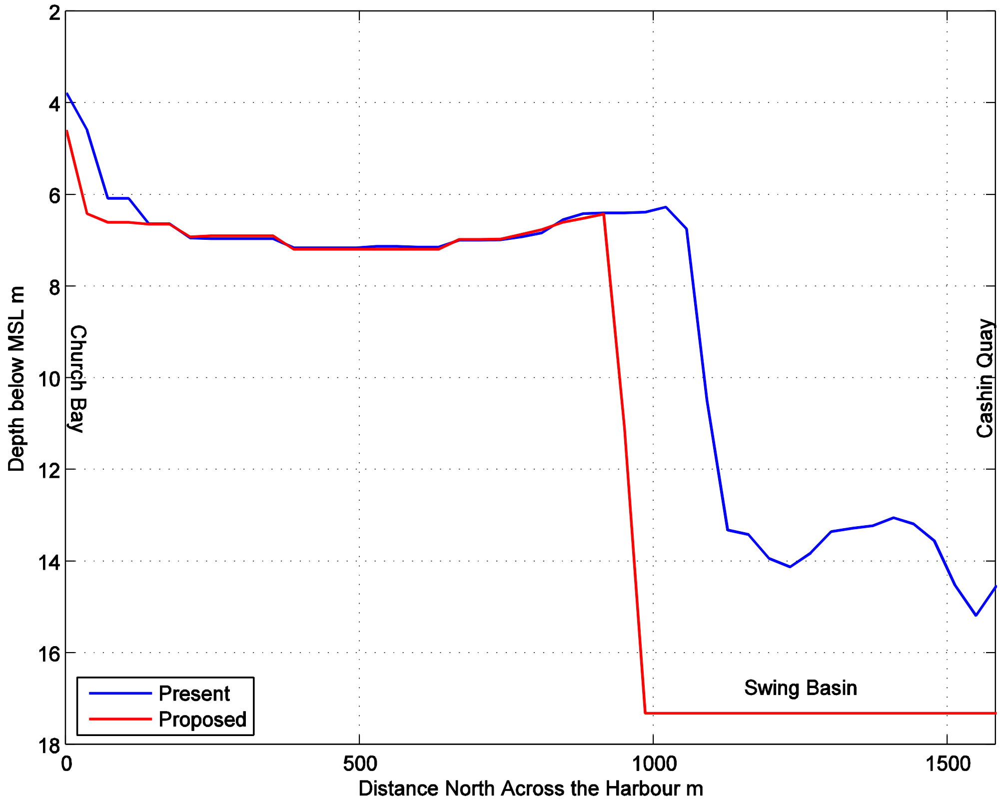


Figure 4.8b Cross sections between Church Bay and Cashin Quay showing swing basin.

4.3.1 Waves

The results of running the SWAN model on reclamation only are shown in Figure 4.9 and the difference from the present is shown in Figure 4.10. The changes in wave height at particular locations are presented in Table 4.2.

The figures and table show clearly that the reclamation has an effect only in the vicinity of the reclamation and the effect elsewhere is essentially zero. This means that the changes observed earlier and shown in Table 4.2 are almost entirely due to the deepening of the shipping channel, which has the effect of refracting the waves towards the northern and southern shorelines of the mid- and outer-harbour, thus reducing the wave energy reaching the Upper Harbour.

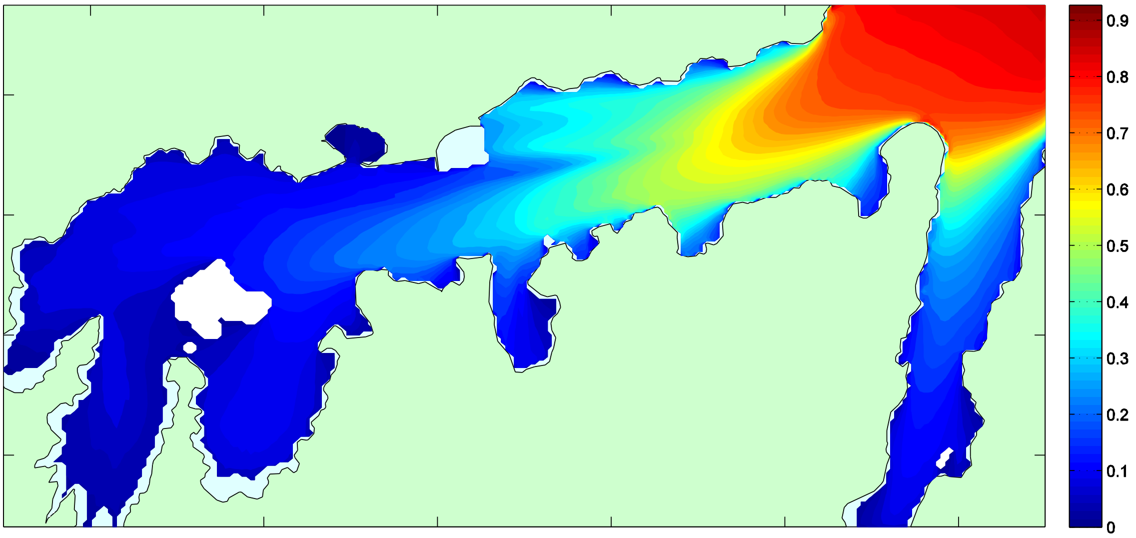


Figure 4.9 Distribution of significant wave height (m) for reclamation only.

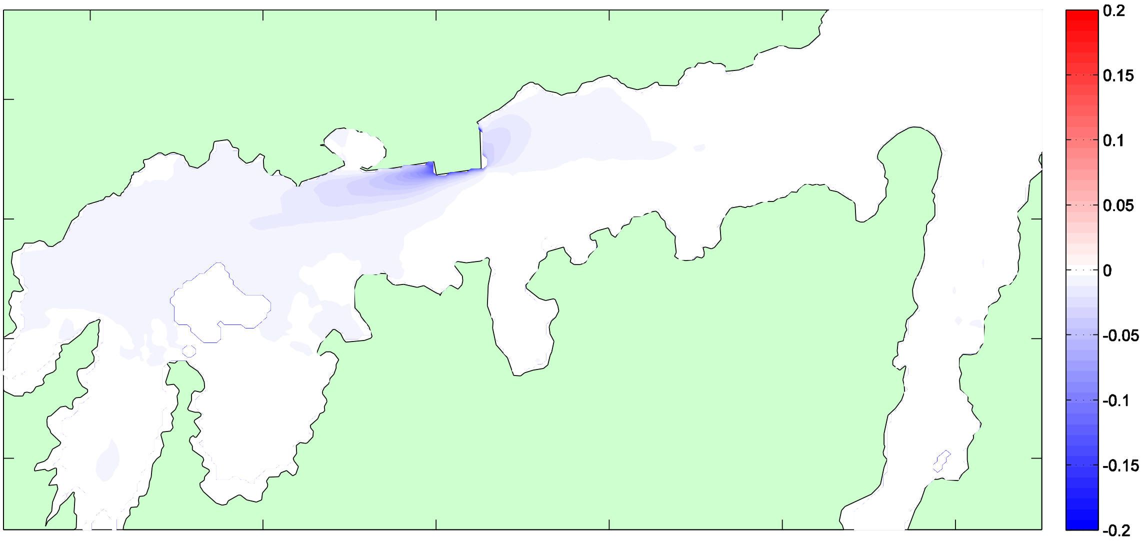


Figure 4.10 Difference in significant wave height (m) between reclamation only and the present configuration.

Table 4.2 Change in significant wave height at the locations shown in Figure 3.1.6

	Present	Change in Hs m		%age Change in Hs	
	m	Rec Only	Rec + Deep	Rec Only	Rec + Deep
Central Harbour	0.446	-0.000	-0.156	-0.1	-35.0
Camp Bay	0.323	-0.000	0.043	-0.1	13.2
L. Port Cooper	0.239	-0.000	0.008	-0.2	3.5
Putiki	0.174	0.000	0.018	0.1	10.6
Livingstone Bay	0.344	-0.002	0.039	-0.7	11.3
Reclamation	0.181	-0.016	-0.008	-8.8	-4.2
Inner Harbour	0.024	0.000	0.000	1.5	2.0
Rapaki	0.074	-0.001	-0.001	-0.9	-1.6
Diamond Harbour	0.154	-0.000	-0.036	-0.3	-23.4
Purau Bay	0.157	-0.001	-0.049	-0.4	-31.1

4.3.2 Tidal Currents

The results of running the model with reclamation only and with reclamation + a deepened channel and swing basin are presented in Figures 4.11 and 4.12 for mid-ebb tide (mid-flood tide results are similar).

The change from present configuration to reclamation without deepened channel and swing basin shows quite marked increases in flow beside the reclamation, at Naval Point, and in the high-flow region southwest of Quail Island. Indeed, the plot of differences (Figure 4.12) indicates that there is a general increase in current speed throughout the harbour. However, when the deepened channel and swing basin are included, the changes are reduced substantially. This is borne out by Tables 4.3a and b which have a comparison of speeds at various points in the harbour. Thus, the changes induced by the reclamation are offset by the dredging of a deepened channel and swing basin.

To examine this in more detail, the tidal ellipses in the mid- to outer-harbour were extracted for the M_2 tide (which accounts for 95% of the energy) and are presented in Figures 4.13a and b. A tidal ellipse shows the locus of a current vector with its base at the centre and the distance to the circumference representing the speed. An ellipse that is thin denotes unidirectional flow, whereas an ellipse that has some width denotes flow with a transverse component. In the open ocean, far from land, tidal ellipses are usually almost circular, whereas near land, where the tidal flow is directed along a shoreline, they can be straight lines.

With reclamation only (Figure 4.13a), at the entrance there is a stronger transverse component to the flow, especially towards the middle and this is also evident to a lesser extent in the inner two cross sections. At the cross section just east of the reclamation, the flow is substantially changed, with the alignment of the ellipses changing by up to 14° as the flow accelerates and deflects around the reclamation, while cross-harbour flows are induced. At the cross section between the reclamation and the Diamond Harbour headland, the tidal ellipses are very thin indicating (unidirectional flow) and the velocities are substantially increased as the flow is squeezed through the chute between the reclamation and the Diamond Harbour headland, and all of this results in increased tidal currents in the Upper Harbour (Figure 4.12).

With reclamation and deepening (Figure 4.13b), to the east of the reclamation, the tidal ellipses are essentially unchanged indicating that the deepened shipping channel is offsetting the effect of the reclamation. In the vicinity of the reclamation and deepened swing basin, the orientation of the ellipses is changed, but the current speed (indicated by the length of the ellipse) is generally reduced.

Thus, the effect of the reclamation is to increase tidal currents, but the deepening of the navigation channel and swing basin offsets this increase, resulting in only small changes to the tidal currents away from the immediate vicinity of the reclamation.

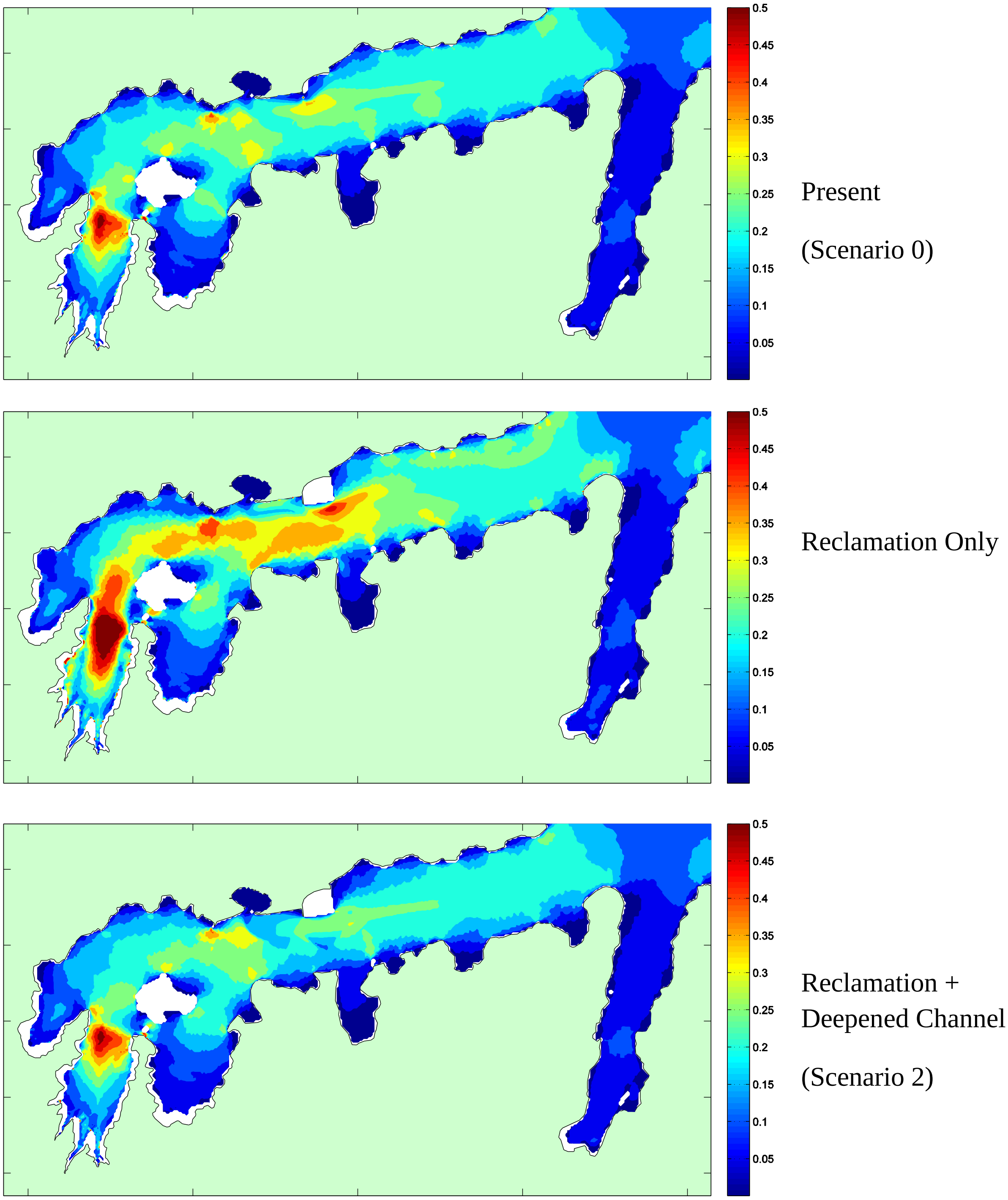


Figure 4.11. Speeds at mid-ebb tide for present (top), reclamation only (middle) and reclamation with channel deepening (bottom).

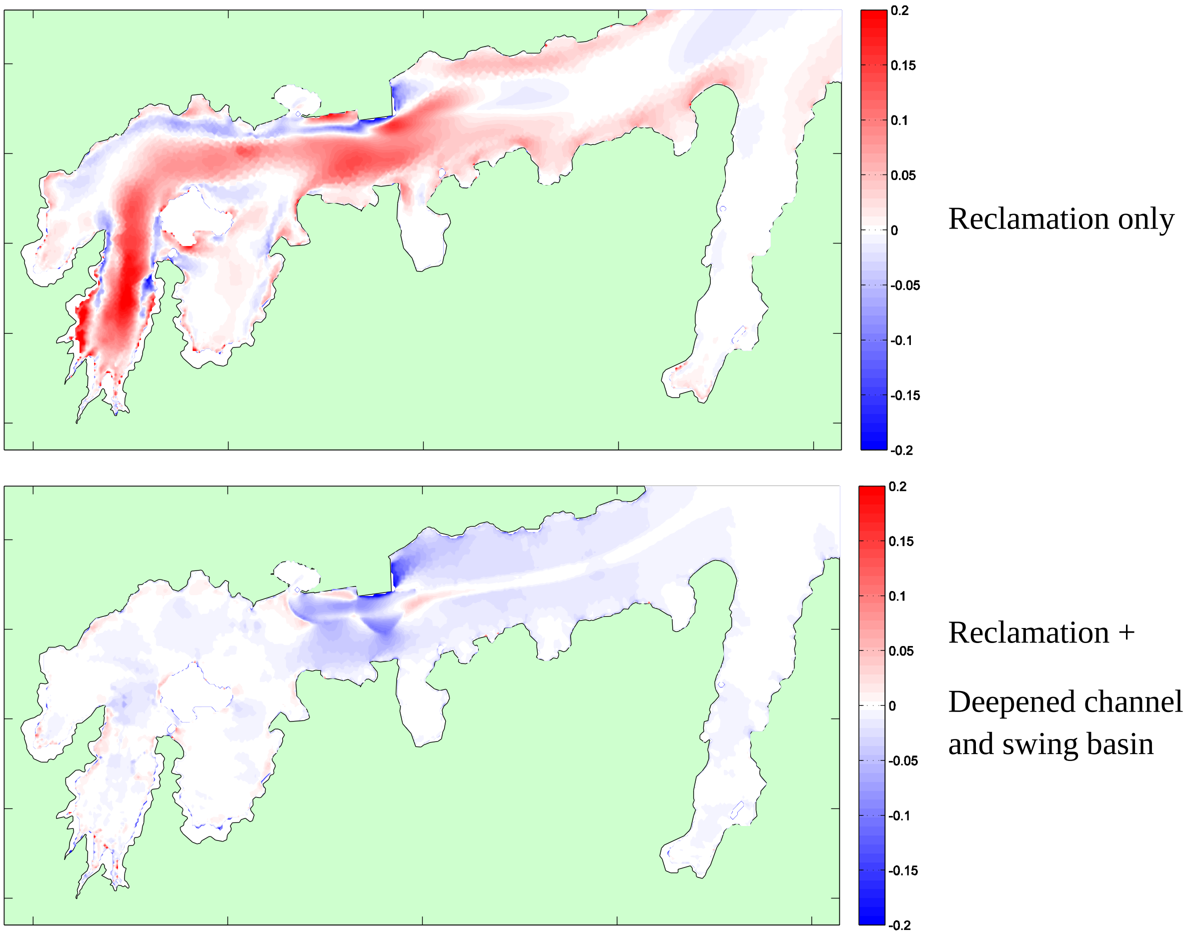


Figure 4.12. Difference from present in speeds (m/s) at mid-ebb tide for reclamation only (top) and reclamation with channel deepening (bottom).

Table 4.3a Change in speed in mid-ebb tide speeds at the locations shown in Figure 3.2.6

Location	Present	Speed Change m/s		Speed Change %	
	m/s	Rec. Only	Rec + Deep	Rec Only	Rec + Deep
Reclamation	0.317	0.135	-0.041	42.5	-12.9
Parson Rock	0.221	0.039	-0.018	17.5	-8.0
Purau Bay	0.060	0.003	-0.002	5.7	-4.0
Little Port Cooper	0.035	0.014	-0.000	41.2	-0.6
Mouth Port Levy	0.076	0.003	-0.000	4.0	-0.5
West Mussel Farm	0.062	-0.001	-0.001	-1.7	-2.1
East Mussel Farm	0.070	0.006	-0.000	9.1	-0.6
Diamond Harbour	0.037	0.013	-0.001	34.5	-3.8
Charteris Bay	0.233	0.021	-0.005	8.8	-2.2
Naval Point B/water	0.412	0.000	-0.010	0.1	-2.3
Quail I North	0.273	0.084	-0.012	30.8	-4.3
Cass Bay	0.125	0.005	0.012	4.2	9.6
Rapaki	0.148	-0.019	0.006	-13.1	3.7
Governors Bay	0.091	-0.007	0.001	-7.4	0.6
Head of the Bay	0.553	0.058	-0.005	10.4	-0.9
Inner Harbour	0.012	0.016	-0.000	132.2	-2.8

Table 4.3b Change in speed in mid-flood tide speeds at the locations shown in Figure 3.2.6

Location	Present	Speed Change m/s		Speed Change %	
	m/s	Rec. Only	Rec + Deep	Rec Only	Rec + Deep
Reclamation	0.323	0.193	-0.025	59.8	-7.8
Parson Rock	0.235	0.044	-0.019	18.6	-7.9
Purau Bay	0.059	0.003	-0.003	5.5	-4.9
Little Port Cooper	0.037	0.012	0.001	30.9	2.9
Mouth Port Levy	0.081	0.002	-0.001	3.0	-0.8
West Mussel Farm	0.062	-0.003	-0.002	-4.0	-3.5
East Mussel Farm	0.072	0.005	0.001	7.7	1.7
Diamond Harbour	0.043	0.025	-0.004	58.4	-9.3
Charteris Bay	0.236	0.016	-0.004	6.7	-1.6
Naval Point B/water	0.430	-0.014	-0.002	-3.3	-0.5
Quail I North	0.290	0.068	-0.012	23.5	-4.2
Cass Bay	0.132	0.029	0.012	22.2	9.2
Rapaki	0.156	-0.014	0.006	-9.3	4.0
Governors Bay	0.098	0.006	0.001	5.8	1.2
Head of the Bay	0.555	0.059	0.001	10.6	0.1
Inner Harbour	0.012	0.005	-0.000	39.7	-2.5

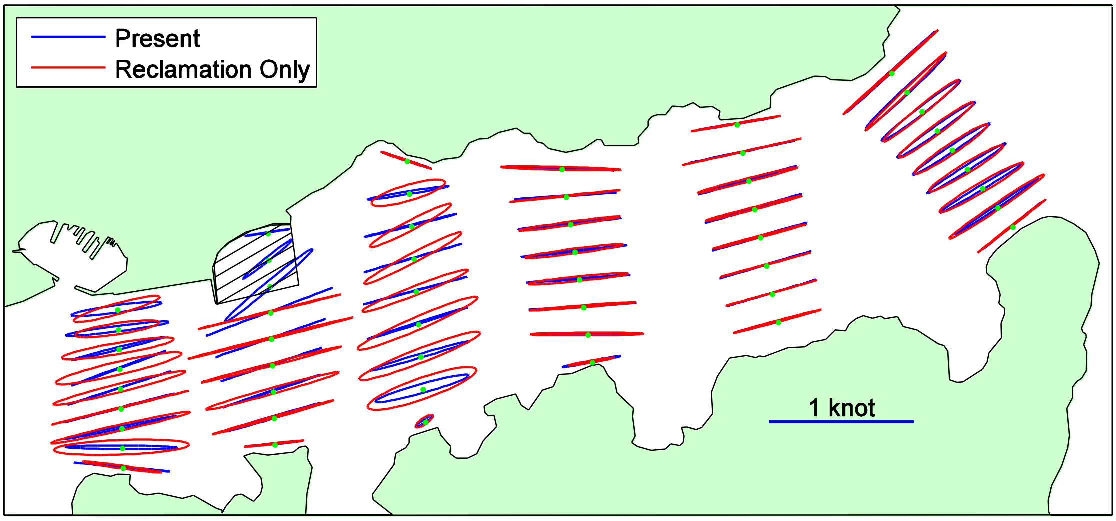


Figure 4.13a. Effect of reclamation on tidal ellipses in the mid- and outer-harbour.

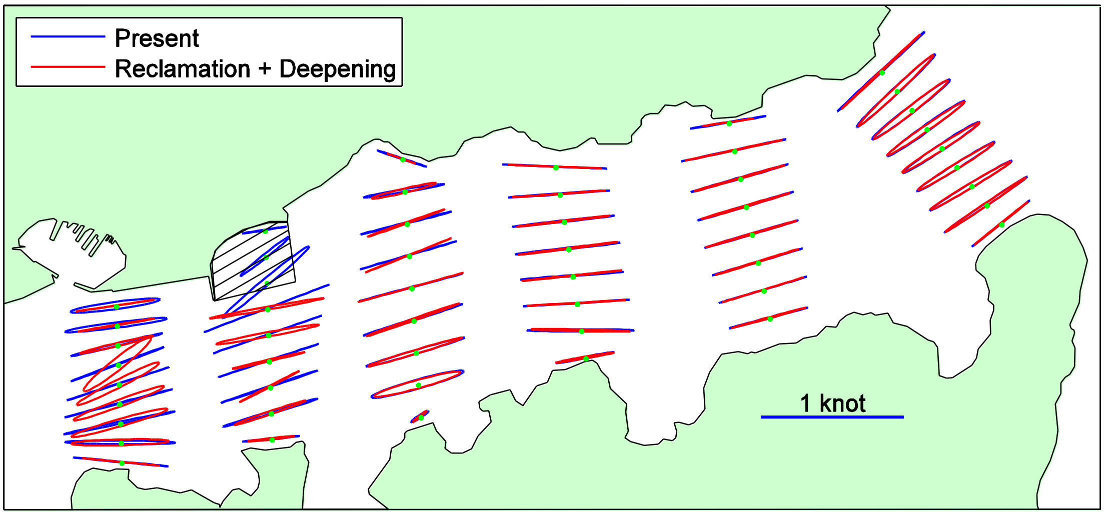


Figure 4.13b. Effect of reclamation and deepening on tidal ellipses in the mid- and outer-harbour.

5 CONCLUSIONS

From modelling of the waves and hydrodynamics in Lyttelton Harbour for a suite of proposed reclamation scenarios (including associated channel enlargement) a number of conclusions can be drawn.

5.1 Waves

- Wave heights are a maximum at the harbour entrance and fall off rapidly to 6 km from the entrance. Thereafter, the drop in wave height is small. This is a natural process associated with shoaling and friction as waves propagate into a harbour whose depth is decreasing.

- Mean wave periods fall from 9s to 7s over the length of the harbour as swell waves dissipate.
- As a result of any of the reclamation and channel scenarios, there will be a change in the wave climate at some places in the harbour. Close to the reclamation (within a few hundred m), the wave heights will decrease as a result of the blockage to the flow caused by the reclamation and the deepening of the swing basin. Along the northern and southern bays on the flanks of the deepened shipping channel, wave heights will increase as a result of refraction. Most of these changes will be small in absolute terms. In the Upper Harbour and in Port Levy, the changes will be insignificant.
- The differences between the various scenarios are generally small and this illustrates that the effects are not particularly sensitive to the overall scale of the reclamation.
- Waves in the Inner Harbour will more than double under Scenario 4 (removal of Z-Berth) and Scenario 5 (oil/cruise berth), though they will still be small (less than 6 cm).
- Waves stir up the sediment making it available for transport by currents.
- Reclamation will affect swell waves more than sea waves.
    - In the Upper Harbour, the swell waves are already small, so the reduction will have no significant effect; however,
    - In the vicinity of the reclamation (Diamond Harbour, for example), where swell waves are a significant proportion of the wave climate, the reduction in these as a result of the reclamation and channel deepening will reduce the amount of time the sediment is disturbed by waves.

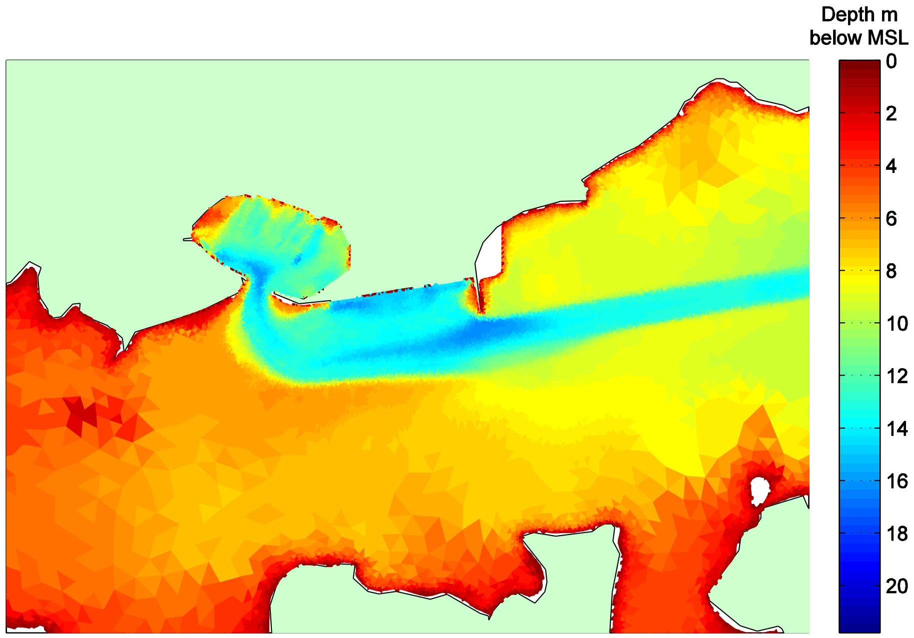
5.2 Tidal Currents

- For all of the scenarios, tidal currents will decrease in the vicinity of the reclamation and increase along the northwestern shorelines (Cass to Governors Bays). Elsewhere, there will be no significant change.
- Under Scenario 3 (full reclamation with breakwater), the currents in the vicinity of the breakwater will decrease to less than half of existing.
- Under Scenarios 4 (removal of Z-Berth) or 5 (removal of Z-Berth and excavation of a cruise/oil berth), the tidal currents in the Inner Harbour will more than double, though they will still be small.
- The effect on sediment transport of changes in the tidal currents will be small, even in Diamond Harbour where a decrease of 9% in the flood-tide currents will occur.
- Under all of the scenarios, sediment transported in and out of Charteris Bay on the tide will be slightly different from the present in that it will reach the northern side of Quail Island sooner than it does at present.
- Reclamation causes a narrowing of the harbour width, which results in increases in the tidal currents, but deepening of the navigation channel and swing basin will offset this effect, meaning the overall change in tidal currents will be small.

Derek Garard Goring **6-Nov-2014**

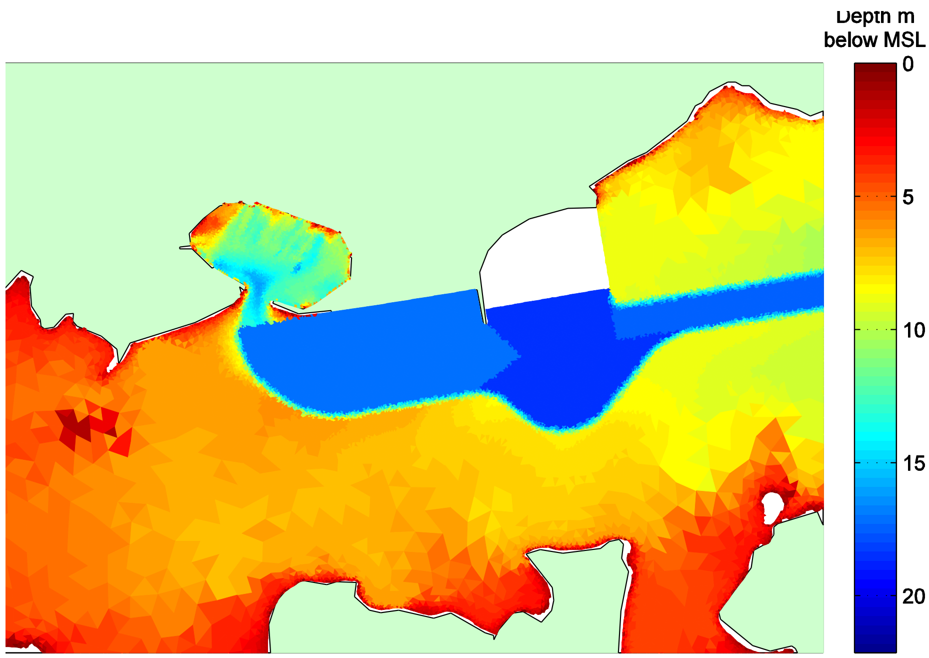
6 Appendix I: Depth Contours for the Various Scenarios

The contour maps that follow show the bathymetry that was used for modelling (both waves and tidal currents). The reclamation is shown in white.



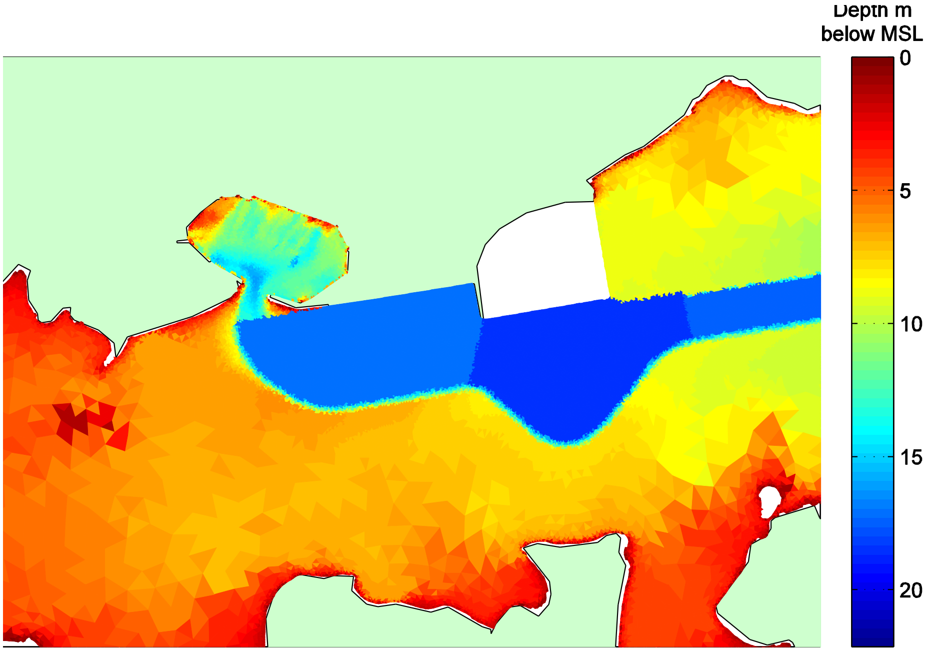
Scenario 0:

Present configuration



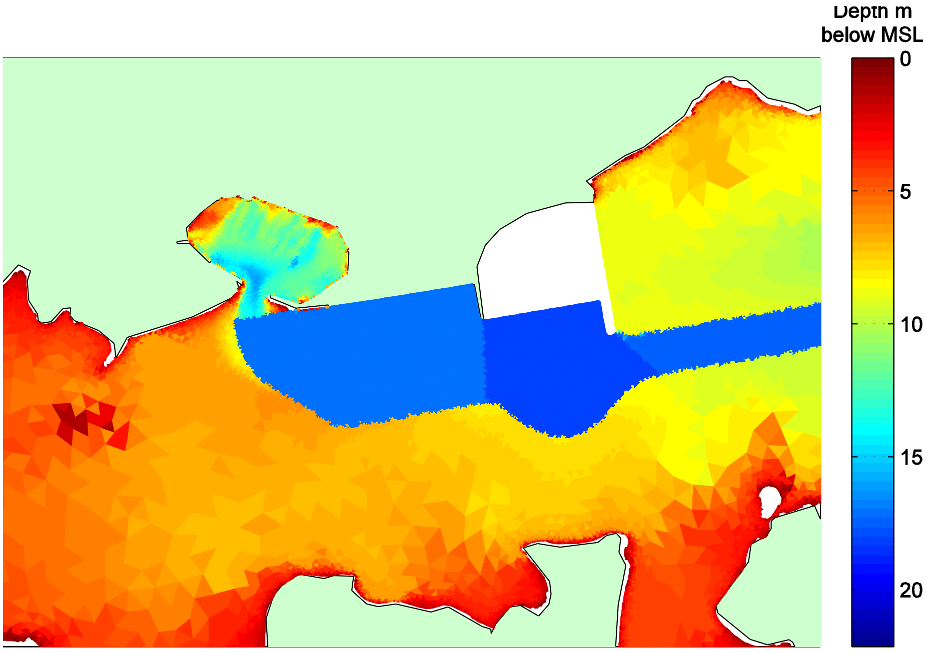
Scenario 1:

Partial Reclamation



Scenario 2:

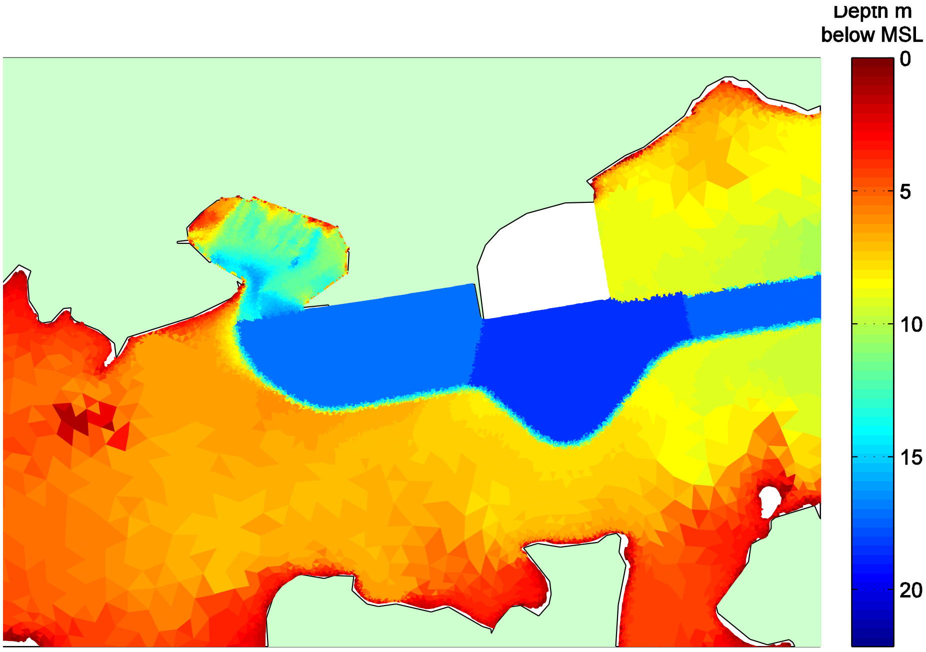
Full reclamation



Scenario 3:

Full reclamation

with breakwater

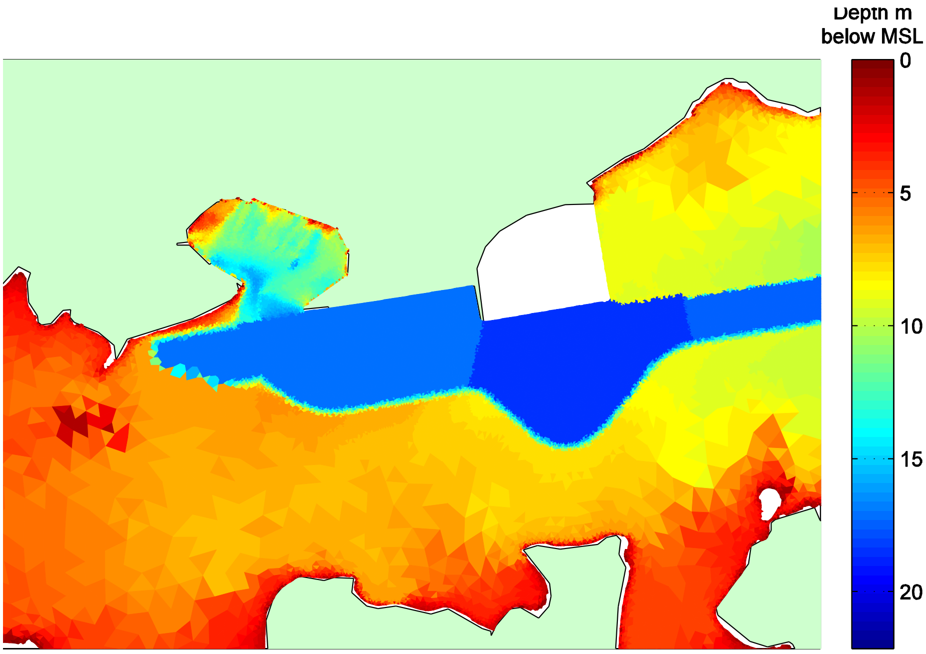


Scenario 4:

Full reclamation,

with removal of

Z-Berth

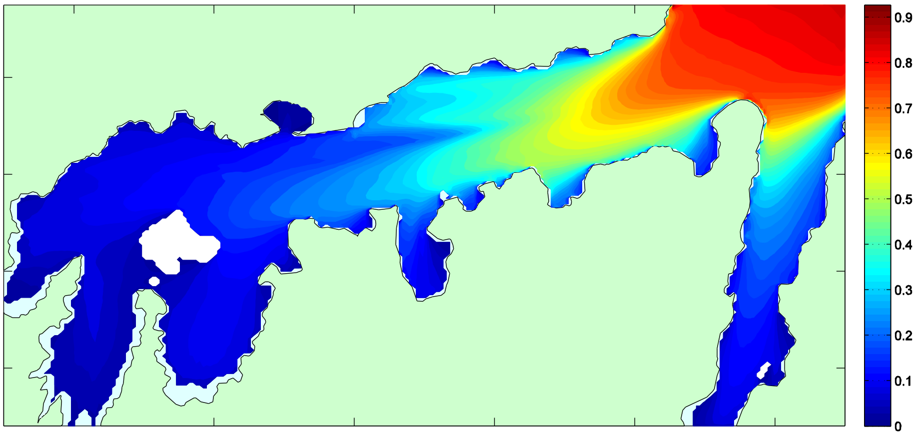


Scenario 5:

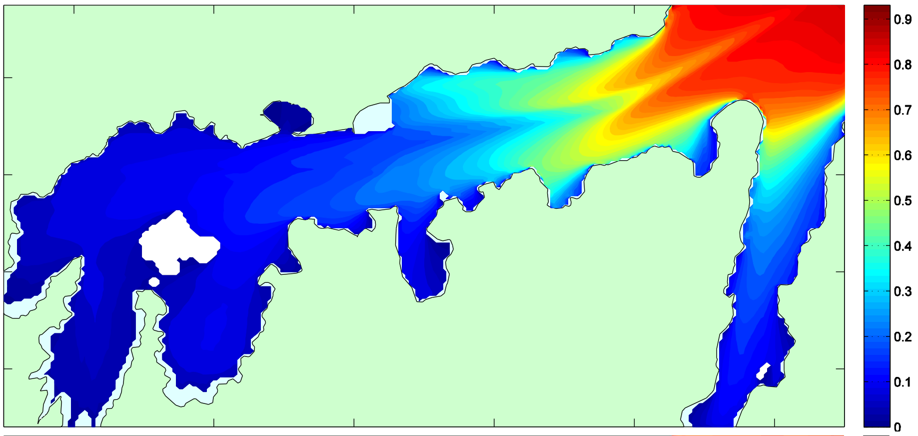
Full reclamation, with removal of Z-Berth and a dredged oil berth

7 Appendix II: Contour Plots of the Various Scenarios

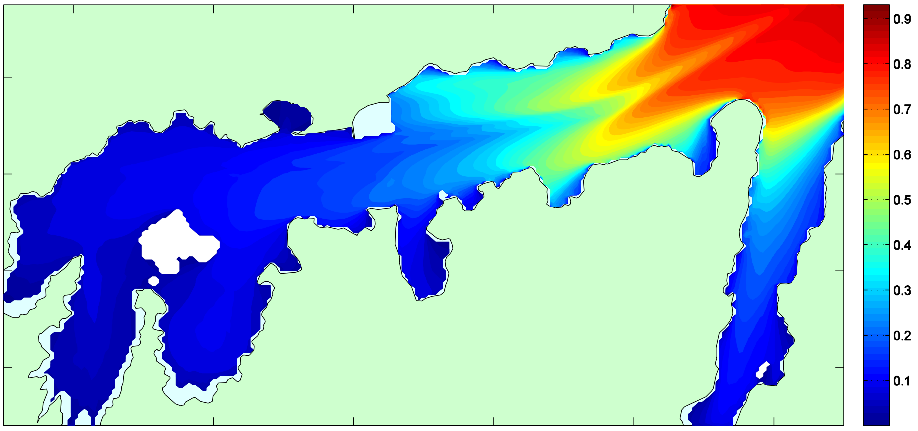
7.1 Wave Heights (m)



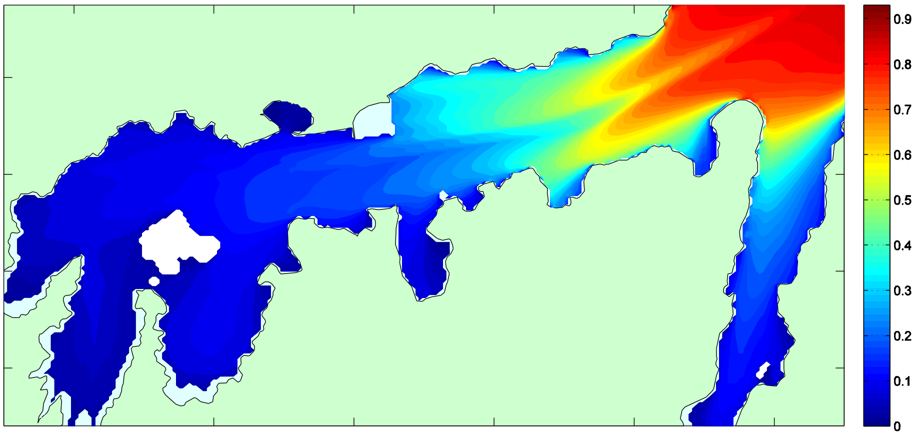
Scenario 0



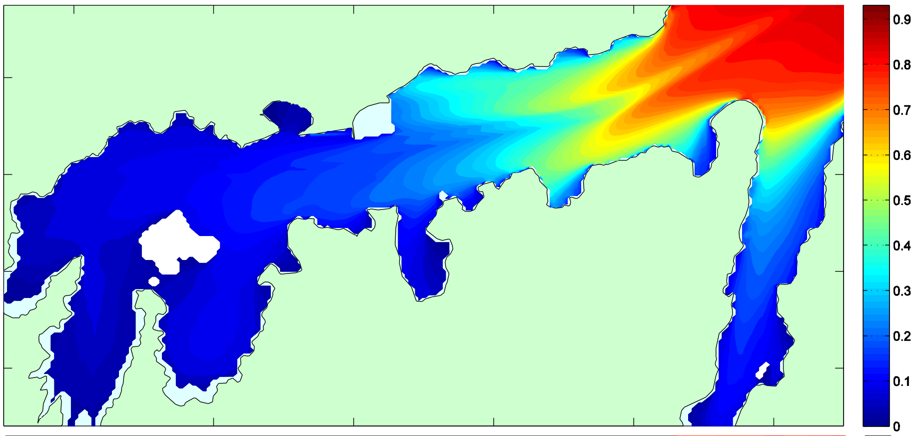
Scenario 1



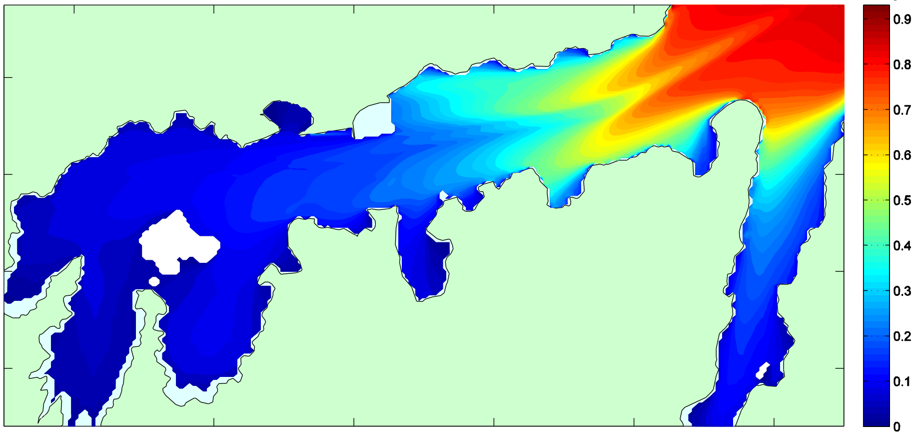
Scenario 2



Scenario 3

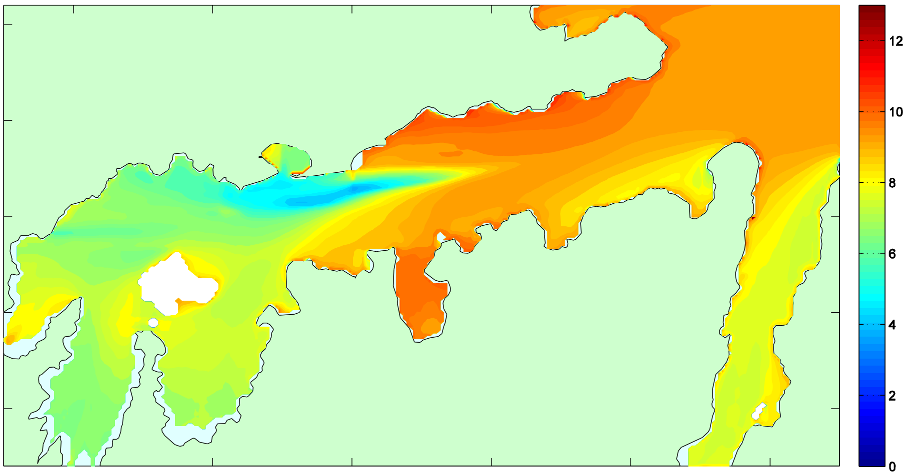


Scenario 4

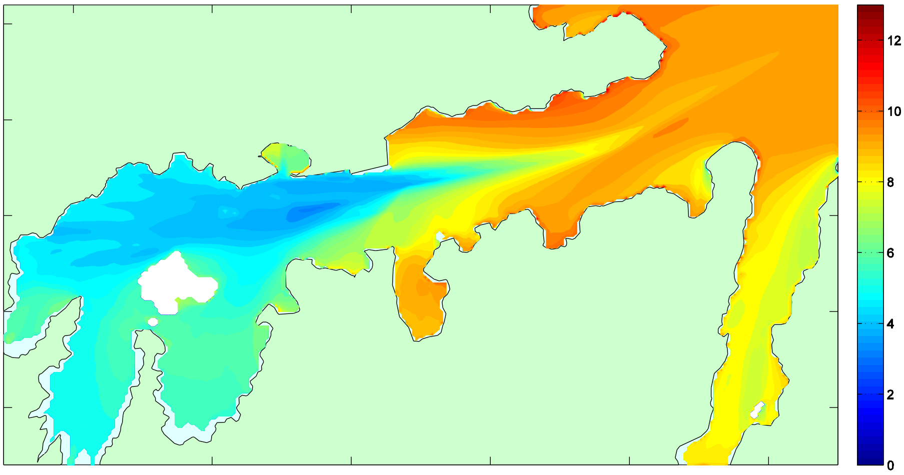


Scenario 5

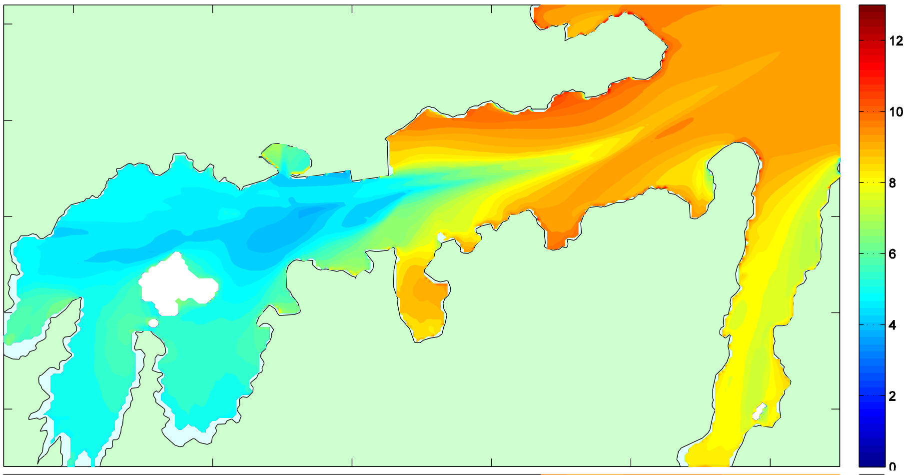
7.2 Wave Periods (s)



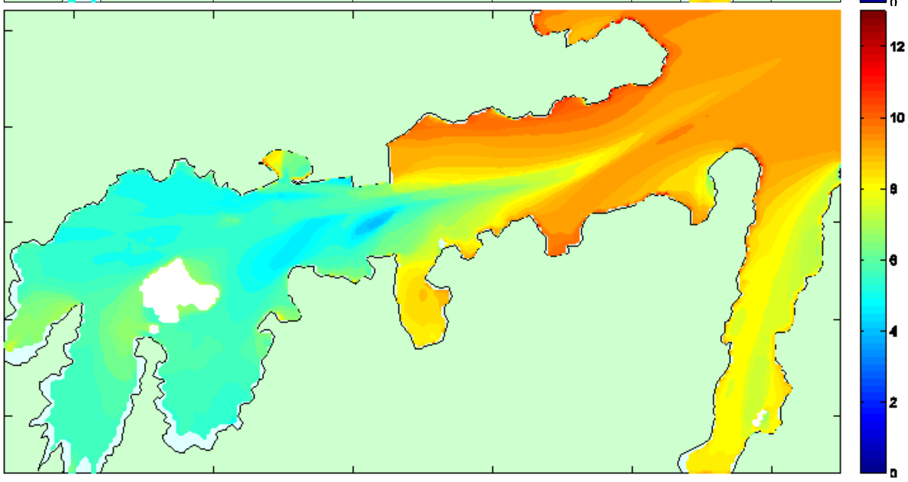
Scenario 0



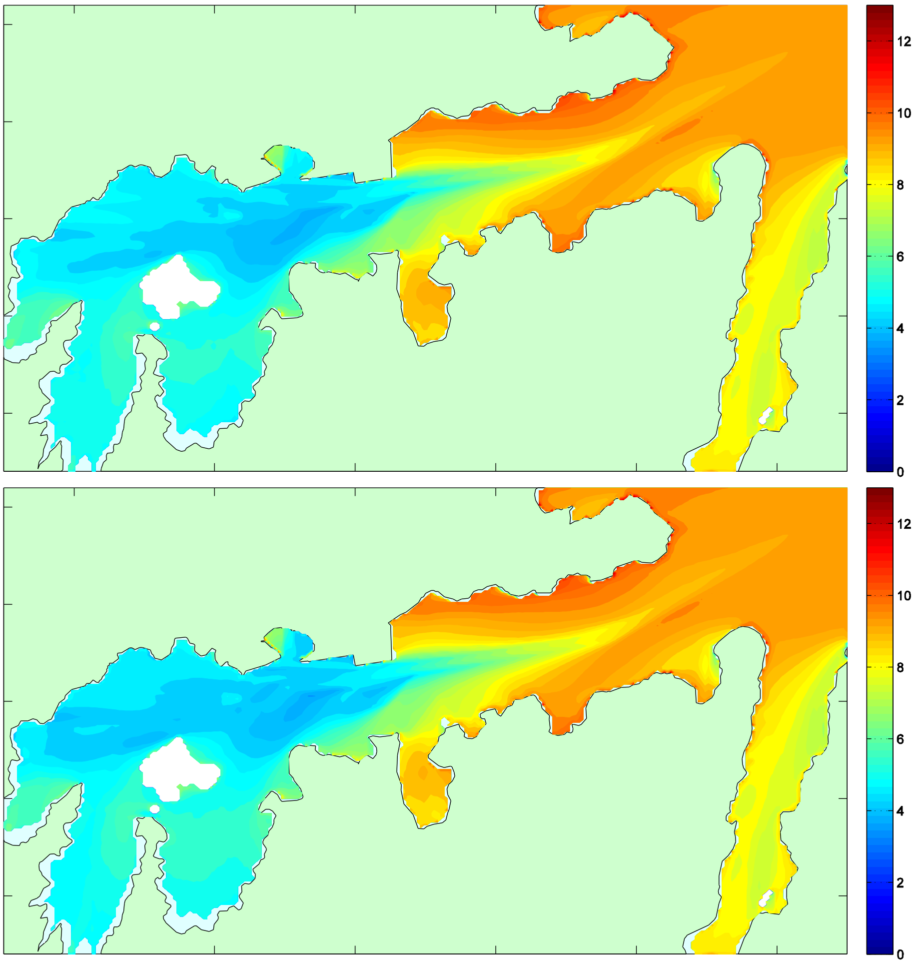
Scenario 1



Scenario 2



Scenario 3



Scenario 4

Scenario 5

8 Appendix III: Wave Mechanics

In this appendix, we present some details of the wave mechanics presented in the main body of the report

8.1 Wave Spectra

A wave spectrum is the distribution of energy with period (or frequency — the inverse of period). Figure III.1 shows typical wave spectra from Scenario 0 for two locations at either end of Lyttelton Harbour. Traditionally, spectra are plotted as "power spectral density" (PSD — a type of energy) as a function of frequency. In this plot, we have used period, not frequency, on the abscissa and consequently the direction is reversed.

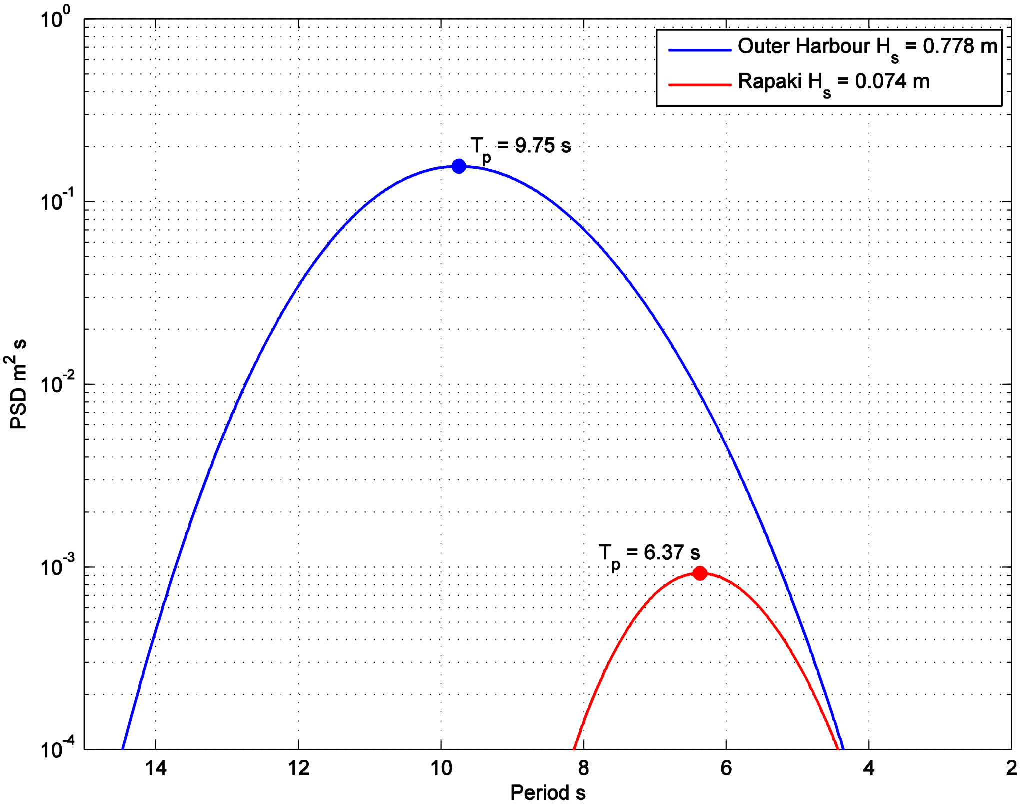


Figure III.1 Wave spectra at either end of Lyttelton Harbour for Scenario 0

Significant wave height is defined as $H_s = 4\sqrt{M_0}$, where M_0 is the area under the spectrum.

In the propagation up the harbour, the waves have attenuated as a result of shoaling, friction, and refraction with consequent wave breaking on beaches, so that the wave heights at Rapaki are 1/10th of the wave heights at the entrance. The attenuation of longer-period waves is more pronounced than it is for shorter-period waves, so the peak period has reduced from 9.75 s to 6.37 s.

By dividing one spectrum by the other, we can calculate the attenuation in energy as a function of period as shown in Figure III.2. For waves with periods less than 4 s, there is an increase in energy corresponding to the effect of shoaling on short period waves and waves generated by local winds, but for waves with periods greater than 4 s, there is attenuation of energy and for waves with periods longer than 8 s (swell waves), the energy is reduced to zero. This explains why the waves in the Upper Harbour will not be affected to any large extent by development of any of the scenarios.

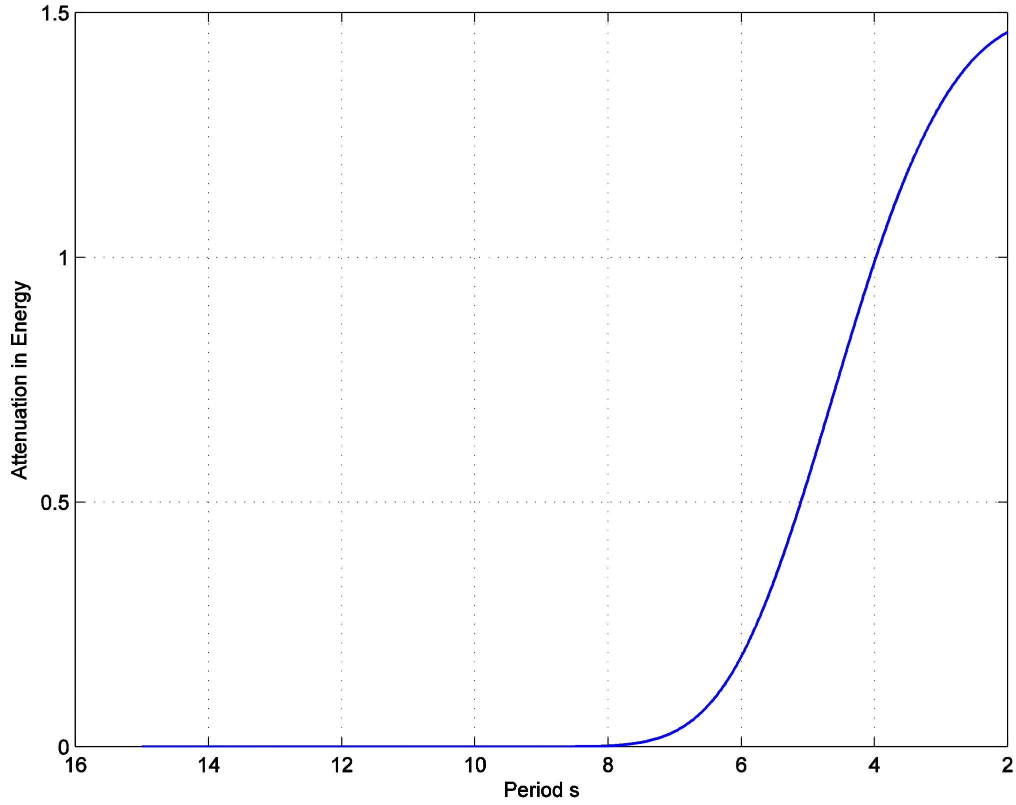


Figure III.2 Attenuation in energy from Outer Harbour to Rapaki.

8.2 Particle Velocities

In this section, the calculations of particle velocities at the bed in Diamond Harbour (depth 5 m) for the event shown in Figures 4.6 and 4.7 are presented.

The calculations assume that the particle velocities under a wave field can be represented by the significant wave height, H_s, and the period at the peak of the spectrum, T_p. The maximum velocity at the bed for a monochromatic wave is:

$$u_0 = \frac{gH_sk}{2\sigma\cosh(kh)}$$

where g is the acceleration of gravity, H_s is the wave height, k is the wave number, and σ is the frequency (=2π/ T_p).

For Scenario 0, H_s = 1.071 m and T_p =7.95 s, whence σ = 0.7903 radian/s and using the dispersion relation k = 0.119 radians/m. Thus, u_0 = 0.669 m/s.

For Scenario 3, H_s = 0.968 m and T_p =4.00 s, whence σ = 1.571 radian/s and using the dispersion relation k = 0.2830 radians/m. Thus, u_0 = 0.392 m/s.

For a cosine wave given by:

$$u = u_0 \cos(\sigma t)$$

The time per cycle when the velocity exceeds a threshold u_t is given by:

$$t = \frac{4}{\sigma} cos^{-1} \left\{ \frac{u_t}{u_0} \right\}$$

Thus, the time per hour when the velocity exceeds the threshold for motion of 0.25 m/s is 2722 s for Scenario 0 and 2015 s for Scenario 3.

01-Jul-2014

Port Lyttelton Recovery Plan

Hydrodynamics Model Validation

1. Introduction

A hydrodynamic model has been developed by MetOcean Solutions Ltd for determining the change in tidal velocities that will occur as a result of various proposed development schemes as part of the Port Lyttelton Recovery Plan. In this report, the velocities produced by the model for the present configuration are compared to those measured in 2011 by acoustic instruments at Parson Rock and at Site 14 (north of Quail Island), as shown in Figure 1. These sites are considered optimum for validation because they are close to locations that will be critical in the assessment of effects. Also, they are far from the forced boundary of the model, so they provide a good check that the physics of the tidal propagation are being correctly modelled.

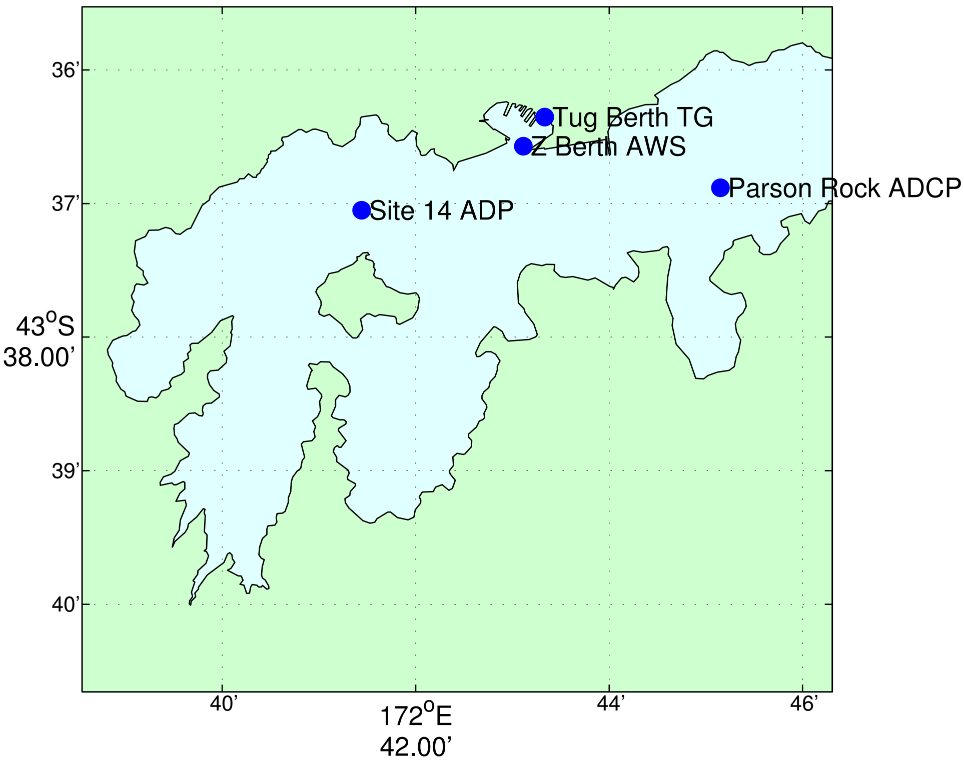


Figure 1. Map of middle and upper Lyttelton Harbour, showing the location of instruments.

2. Data and Methods

2.1 Measurements

The data from the acoustic instruments have been processed as follows:

1. The velocities were averaged from the bottom up to 8 m above the bed for Parson Rock and to 2 m above the bed for Site 14.
2. The velocity field was rotated clockwise by 23.25º to convert from magnetic North to true North.
3. The velocities were band-pass filtered using orthogonal wavelet decomposition to reject all timescales except those at 6, 12, and 24-h periods (i.e., the tidal band).

2.2 Model

Output from the model is in the form of 25 tidal constituents at each of 123,616 nodes for tide height and eastward and northward velocities. The constituents for the nodes closest to Parson Rock and Site 14 were extracted from the database and these were used to hindcast the tide for the times of the measurements.

3. Results

Comparisons of the time series for the two sites are presented in Figures 2a and b. The figures show very good agreement between measurements and the model, especially for the eastward velocities which are much larger than the northward velocities. For Site 14, the modelled northward velocity is significantly less than the measured velocity, but such an error can arise from a slight error in the orientation of the instrument, which is not attributable to the model. To accommodate this, the statistics of the errors in speed are listed in Table 1.

Table 1. Errors in speed estimated by the model (RMSE is root mean square error).

Station	Bias m/s	RMSE m/s
Parson Rock	0.0020	0.0308
Site 14	-0.0018	0.0339

The bias is very small and can be considered negligible. The RMSE is affected by non-tidal components in the measurements. These are characterised by the departures from a uniform tidal signal evident at high and low tides in Figures 2a and b. The effect of these departures is to shift the measured signal in time by several minutes backward or forward of the modelled signal, thus generating differences between measured and modelled speed. The bias being very small indicates that these errors compensate each other and cancel out, but they are reflected in the RMSE. Thus, the RMSE is more a reflection of inaccuracies in the measurements than it is an indication of errors in the model.

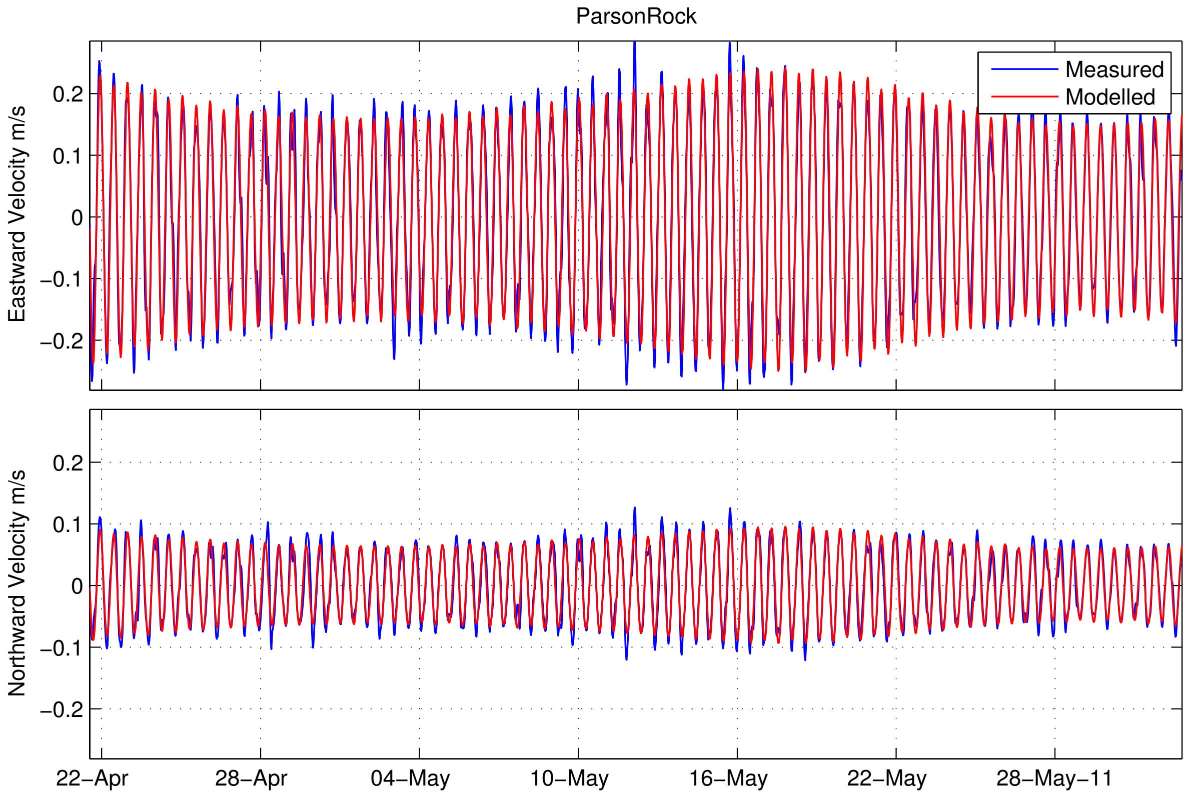


Figure 2a. Comparison of tidal velocities at Parson Rock.

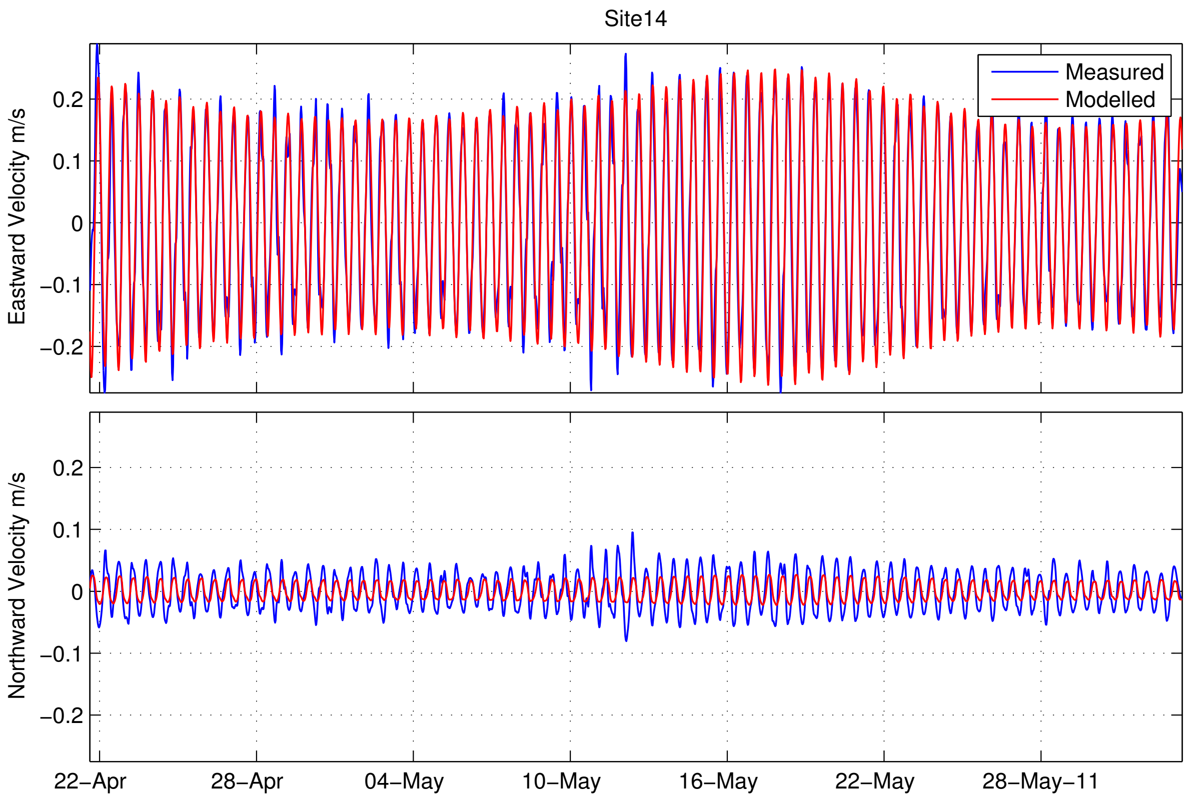


Figure 2b. Comparison of velocities at Site 14.

4. Conclusions

A comparison between measurements of depth-averaged velocity from acoustic instruments located in the middle and upper harbour and the tidal velocities from the MetOcean model indicate good agreement. Thus, the model data can be accepted as accurately representing the tidal velocities in the harbour.

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09-Jul-2014

Port Lyttelton Recovery Plan

Wave Model Validation

1. Introduction

A SWAN wave model has been developed by MetOcean Solutions Ltd for determining the change in waves that will occur as a result of various proposed development schemes as part of the Port Lyttelton Recovery Plan. In this report, the waves produced by the model for the present configuration are compared to those measured in 2011 by an ADCP at Parson Rock (Figure 1).

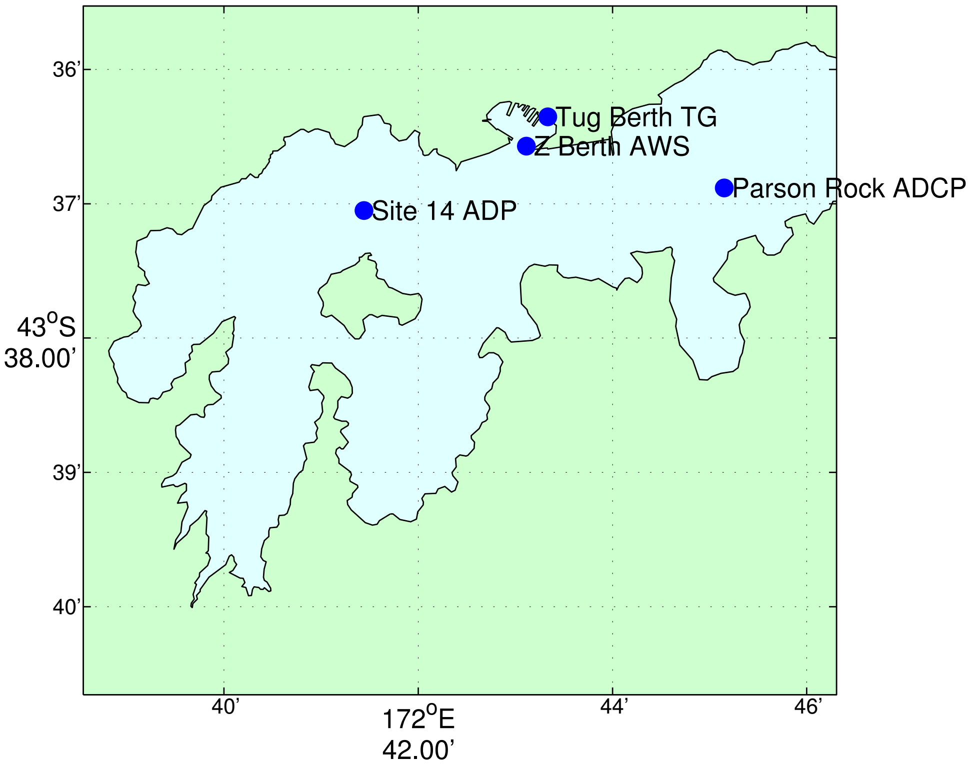

Figure 1. Map of middle and upper Lyttelton Harbour, showing the location of instruments.

2. Data and Methods

2.1 Measurements

The ADCP measures waves using a pressure transducer, sampling the height above the instrument every 0.5 s. The raw data were processed in hourly windows with depth correction to allow for the attenuation of short period waves. The average depth of the instrument was 10 m and frequencies were cut off at 0.333 Hz to avoid excessive amplification of short period waves. The analysis produced numerous parameters, but those used here were: significant wave height, peak period, sea-wave height, swell-wave height. Sea waves were derived from the wave spectra for periods less than 7 s and swell waves for periods between 7 and 25 s.

2.2 Model

Output from the model is in the form hourly records of significant wave height, peak period, and average direction.

3. Results

The measured and modelled wave heights and periods are compared in Figure 2. The timing of the peaks is reasonably accurate, but the heights are not, though they are a reasonable representation of the wave history. The periods are accurately estimated by the model, except for times when the wave heights were low. Thus, the proportion of sea and swell waves is being correctly modelled.

From the model record, the event on 11-May was the 4th largest for 2011.

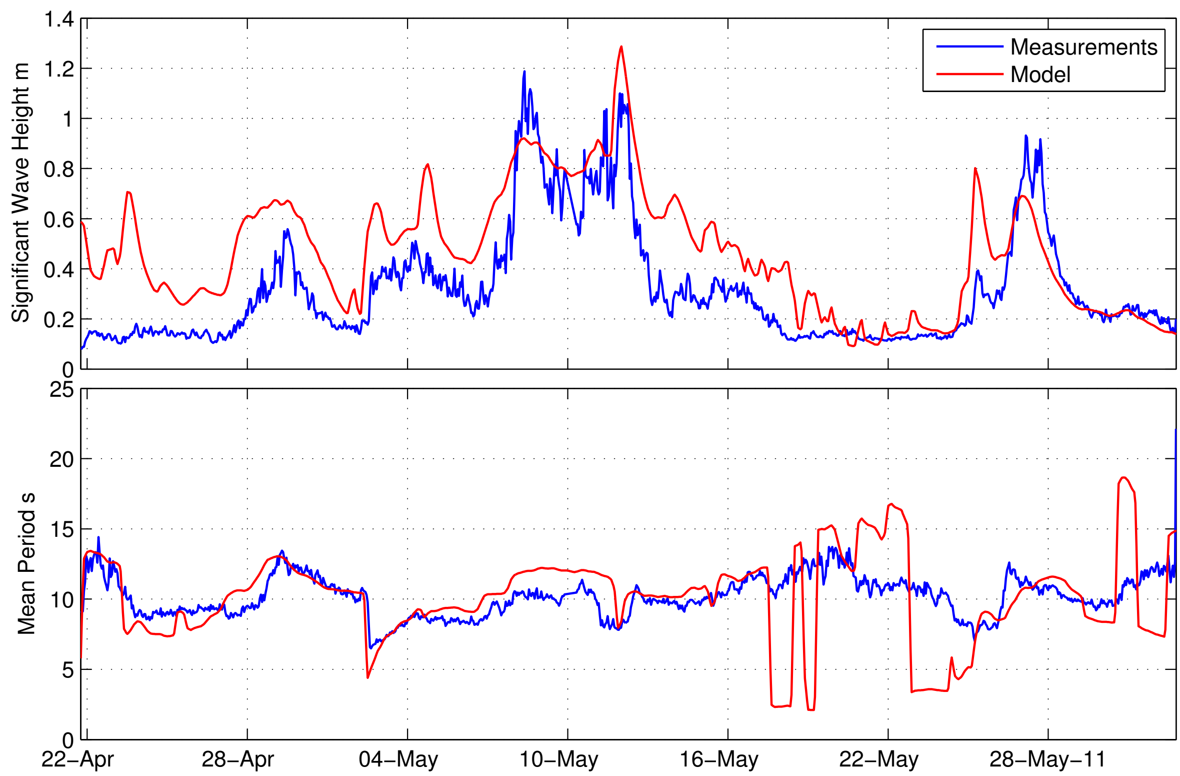

Figure 2. Comparison of measured and modelled wave heights and periods at Parson Rock.

3. Discussion

Part of the reason for the differences in measured against modelled waves is the accuracy of the wind data. For these simulations, the winds came from the MetOcean atmospheric model. A comparison of the wind roses at the automatic weather station (AWS) and the model winds at the same location is presented in Figure 3.

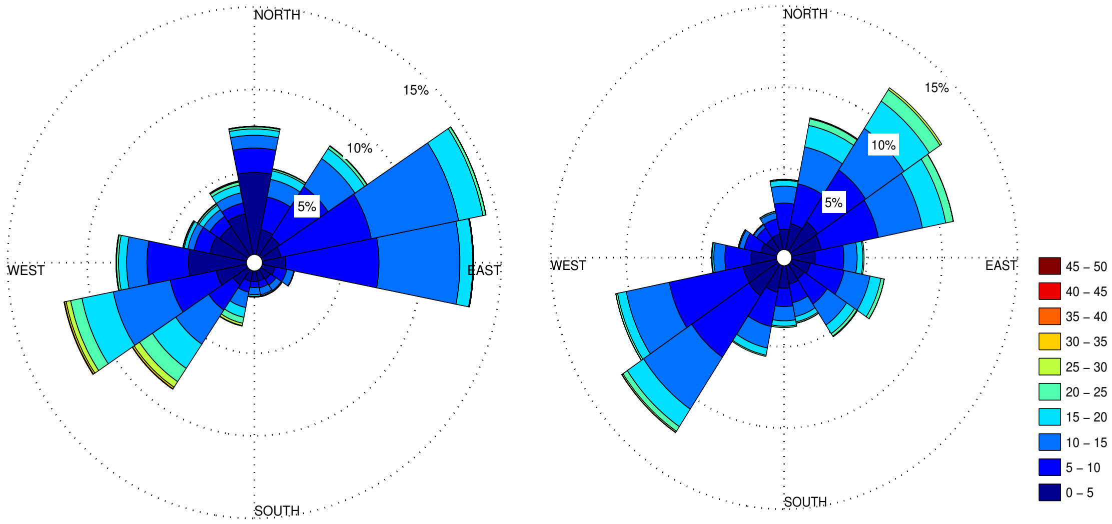

Figure 3. Wind roses for AWS on Z-Berth (left) and model winds (right).

The wind roses are similar, but the wind rose from the model appears to have been rotated anticlockwise by 20º. This could be an effect of sheltering by the crater wall that is not correctly handled by the wind model.

4. Conclusion

From a comparison of the wave heights between measured and modelled data at Parson Rock, we conclude that the model gives a reasonable approximation of the wave history. This is adequate for the purposes of comparing scenarios, but is not adequate for purposes of absolute estimation of wave heights.

The periods are accurately estimated by the model, indicating that the proportion of sea and swell waves is being correctly modelled.

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