APPENDIX 14

EFFECTS ON SEDIMENTATION AND TURBIDITY

LYTTELTON PORT COMPANY

IMPLICATIONS OF THE PORT OF LYTTELTON RECOVERY PLAN ON SEDIMENTATION AND TURBIDITY IN LYTTELTON HARBOUR

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by

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1.0 INTRODUCTION

The purpose of the Lyttelton Port Recovery Plan (LPRP) 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 results in:

- The container terminal being established 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 associated 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 a deeper draft. The deepening and widening of the current navigation channel to enable access of 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 sedimentation and turbidity in Lyttelton caused by the 37 ha reclamation, combined with the proposed deepening of the harbour and, in addition, potential changes resulting from wharf construction/pile driving activities on the face of the reclamations.

As the design of the reclamation (including the exact area requirements) and configuration of the port is still being progressed, a number of scenarios were modelled. This provided a way to understand how different sizes and layouts of reclamation changed the waves and tidal currents, and by extension sedimentation and turbidity in the harbour. It is important to note that these scenarios were produced for the purpose of this modelling exercise only and do not represent a design. They are just to provide a way to test the harbours sensitivity to different reclamation sizes and also to different widths of the navigation channel.

Specifically five scenarios described below were developed to compare with the existing environment (Scenario 0). Scenario 1, for example, equals the 37 ha reclamation envelope; Scenario 2 is inside the envelope; while Scenario 3 includes a breakwater that is outside the project envelope. Scenario 3 is not part of the recovery proposal but it is important to test each side of the 37 ha reclamation envelope to provide a better understanding of how the waves and tidal currents respond.

The plans showing the various scenarios are attached in Appendix I.

- Baseline Scenario 0:
  Present port layout (existing bathymetry) with a 180 m wide navigation channel of 13.5 m depth below Mean Sea Level (MSL);

- Scenario 1:
  A 33 ha reclamation that extends out to 50 m from the end of the existing Cashin Quay breakwater (750 m wide), and also a 180 m wide navigation channel dredged to a depth of 17.5 m below MSL;

- Scenario 2:
  The 37 ha reclamation envelope extending 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:
  The 37 ha reclamation which extends out to the end of the existing Cashin Quay breakwater as in Scenario 2 but also has an additional 200 m long breakwater added. It includes the 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 to enable 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.

The primary influences on sedimentation and turbidity within the harbour are the wave energy environment and tidal currents. The principal determinant of sediment mobility in the outer harbour is swell action. In the shallow waters at the head of the harbour where swell action is much attenuated by refraction, diffraction and bottom friction short period locally generated waves become the principal agent for the disturbance and entrainment of the seabed sediment. Once entrained either by swell or by locally generated short period wave action the suspended sediment is then available to be moved by tidal currents.

The tidal current changes that would occur for each of the five development scenarios, relative to the existing port facilities configuration, Scenario 0, were derived using SELFE 2D hydrodynamic models of the existing configuration and the different development scenarios run by MetOcean Solutions Limited (MSL). SELFE (Semi-implicit Eulerian Lagrangian Finite Element) is an open-source community-supported modelling system based on unstructured grids. The model of the existing harbour configuration was validated against tidal current data recorded using Acoustic Doppler Current Profiler (ADCP) instruments at sites within the harbour.

The changes to the wave energy environment that would occur for each of the five development scenarios, relative to the existing port facilities configuration, Scenario 0, were identified using the Simulating Waves Nearshore (SWAN) open source software, a 3rd generation wave program developed by the Delft University of Technology. The model for the existing harbour configuration was validated using wave data collected at the Parsons Rock beacon.

This report is structured in six sections. Section 1 covers the background information and reports that built up an understanding of the harbour regime an understanding that has been deepened and expanded by the latest hydrodynamic modelling undertaken as part of the LPRP. The Lyttelton Port Company (LPC) has utilised the latest modelling and instrumentation technology as it has become available to develop a comprehensive and evolving picture of the harbour regime. The LPRP follows on from and extends the investigation work undertaken for the proposed deepening and extension of the navigation channel which would be part of the LPRP.

Section 2 covers the geomorphology of Lyttelton Harbour, the nature of the seabed sediment and its susceptibility to entrainment by wave action. Once the seabed sediment is suspended in the water column it alters the clarity and colour of the water producing in the case of Lyttelton Harbour the characteristic aquamarine colour of the sea. Turbidity a description of the clarity of the water is the subject of Section 3.

Sedimentation the process of the conversion of discrete soil particles in a suspension to a loose (initially) seabed sediment is covered in Section 4 along with a description of the nature of the fluid mud layer found at seabed level. The fluid mud layer is one stage in the progression from suspended sediment to soft coherent, cohesive, seabed soil.

Waves – swell and locally generated short period waves – and tidal currents are the primary influences on sediment disturbance, transport and sedimentation within the harbour are covered in Section 5 along with the changes from the present regime consequent on the harbour development scenarios.

Section 6 considers the impact of the changes to the tidal currents and the wave energy environment, consequent on the implementation of the various development scenarios, on sedimentation and turbidity within the harbour. Included in the turbidity assessment is the effect on turbidity of construction activities associated with construction of wharf facilities along the berthing face of the reclamation – pile driving, dredging.

2.0 BACKGROUND – DATA COLLECTION AND MODELLING

This report has drawn on a number of earlier studies of the harbour regime and built on that information. The accumulated information, and its interpretation, supplemented by the results of the hydrodynamic modelling is now able to provide a close to complete understanding of the harbour and the coastal processes in operation.

The early study work focused on tidal currents and the harbour tidal circulation progressing from the use of fluorescein dye in the 1950s to the use of a clockwork powered self recording directional current meter in the 1970's. Later studies for the LPC in the early 2000s utilised Acoustic Doppler Current Profiler (ADCP) instruments in the mobile and fixed modes and current drogues, one equipped with a mobile phone tracking capability. The understanding of the environment has been helped in no small measure by the advent of highly sophisticated current measuring instruments such as the ADCP also known, by a different manufacturer, as the ADP.

The ADCP/ADP instruments represent a quantum leap in the performance of current meters and have made it possible to collect huge amounts of current data in a short space of time. Rather than being stationary at one point recording current speed and direction at one depth it is now possible to record current speed and direction through the full depth of the water column while on the move. The ADCP is a hydro acoustic current meter similar to a sonar, no moving parts, measuring water current velocities over a depth range using the Doppler effect of sound waves scattered back from particles in the water column. In addition to its principal use to measure current speed and direction through the water column the ADCP/ADP instrument can also be used to track turbid suspensions. By combining acoustic and optical information the instrument can also provide information about the quantity of particulate matter. This information is obtained from the intensity of the received reflection, also referred to as the backscattering strength or signal amplitude. Although no specific suspended solid concentrations can be calculated from the echo intensity alone the echo intensity is an indication of the amount of sediment suspended in the water.

The width of the harbour is relatively constant along its complete length. It does not expand into a large estuary at the head of the harbour greatly increasing the size of the tidal prism relative to the entrance width. There is then no strong concentration of current flow at the harbour entrance, the maximum tidal current speeds are relatively constant along the length of the harbour. There are local increases in current strength around the tips of the Cashin Quay breakwater and the breakwater stub at Naval Point and in the Head of the harbour around Quail Island where the water is shallow and the island displaces tidal flow.

Tidal flow in and out of Lyttelton Harbour however is not a simple uniform flow in and a corresponding ebb flow out, there is a pronounced asymmetry to the tidal circulation. This asymmetry in the flow was known from earlier work. Garner and Ridgway remarked on it in 1955 following experiments with floats and fluorescein and later work in the 1970's by Bushell and Teear for the Lyttelton Harbour Board confirmed it and quantified a tidal imbalance on the north side of the harbour. Although the magnitude of the ebb and flood tide currents were found to be similar the ebb tide volume and duration exceeded those for the flood (up to 30%). This formed the basis for the decision to dump dredged material from the maintenance dredging on the north side of the harbour after it had been determined that the bays on the south side of the harbour previously used as dump sites had reached and exceeded capacity. The dumped material also had a secondary effect of promoting wave refraction and reducing the wave energy reaching Cashin Quay. The duration of the flood tide on the south side of the harbour was found to be more than for the ebb.

R J Curtis in his doctoral thesis entitled 'Sedimentation in a Rock-Walled Inlet, Lyttelton Harbour' produced in 1985, built on the earlier work on asymmetric flow. He noted the generally clockwise circulation imparted by the tidal imbalance either side of the harbour and postulated the existence of large scale tidal gyres in the outer harbour. One of the objectives of the 2003 OCEL study for the Lyttelton Port Company using an ADCP in the mobile mode was to provide data to close gaps in the knowledge of the harbour regime and to either confirm or deny the existence of Curtis' gyres.

The tidal imbalance can be expressed as a tidal residual which corresponds to the average movement at a location over the full tidal cycle. The tidal residual indicates the net direction in which a notional particle rolling on the sea floor would move. It indicates a net movement or pumping effect the implications of which are of importance for the movement of suspended sediment. The finding of a net flow out on the north side of the harbour meant that more of the dredge dump material would be flushed out on the ebb than carried in on the flood.

The OCEL tidal current study in 2003 for the LPC using an ADCP in the mobile mode confirmed the harbour circulation as asymmetric. The maximum current speed recorded on the ebb tide for a 2 m spring tide tidal range was 0.77 knot and occurred in the channel near the breakwater 3 hours after high tide. The maximum flood tide current speed was 0.72 knot 9 hours 30 minutes after high tide on the south side of the flood tide eddy that forms in the lee of Godley Head. The tidal residuals on the north side of the harbour are directed east while those on the south side are directed west. This imparts a weak clockwise circulation to the harbour. The circle is not however closed by a tidal gyre at the entrance to the harbour as conjectured earlier by Curtis. Large scale tidal eddies develop fully at two locations in the harbour: in the region of the Cashin Quay breakwater and inside Godley Head, as shown in Figure Nos 1 and 2. The breakwater and Godley Head constitute two major obstructions to the flow and vortices or eddies form in their lee.

The formation of an eddy in the lee of Godley Head is a direct result of the northerly aspect to the flood tide flow into the harbour. The Godley Head eddy is not the tidal gyre postulated by Curtis. It is less in scale than the one he proposed, stays close to the north shore of the harbour and does not extend across the complete width of the harbour. It also rotates clockwise, not counter clockwise, on the flood and does not reverse on the ebb. The eddies act to speed up the tidal flow in their immediate vicinity, on the side where the flow has the same direction as the prevailing flow. For example the residual clockwise rotating flood tide eddy inside Godley Head acts to speed up the ebb tide current on its north side. Any suspended sediment caught in it will be ejected from the harbour. Other eddies start to form at various stages in the tidal cycle, off Purau and off Breeze Bay, but do not develop fully. The tidal vortex persists even after the tidal currents start to run out of the harbour. Given the persistence of the ebb flow the Godley Head location is now the preferred dump site for the maintenance dredging material collected from the channel.

The latest hydrodynamic modelling work undertaken by MSL to model the effect of proposed harbour development scenarios further advances the understanding of the harbour tidal regime, using earlier data to validate the hydrodynamic model, and adds a predictive capability that enables the effect of harbour changes to be modelled in advance. The successive tidal models- Princeton Oceanographic Model (POMS) and SELFE - used each add another level of detail to the understanding.

While the primary interest in tidal currents over time has been in the identification of residual currents because of the important implications for suspended sediment movement the hydraulic modelling can also be used to track the movement or trajectory of dummy tidal drogues over the tidal cycle at any point in the harbour. These trajectories also offer important insights into sediment movement. The dummy tidal drogues are modelled as neutrally buoyant particles. While all sediment particles eventually sink the fall velocities of the finer silt and clay size particles are very low and they can be effectively considered as neutrally buoyant particles over a tidal cycle.

The harbour wave energy environment and the part played by swell waves in entraining seabed sediment has been understood for much longer than the tidal current circulation. Lyttelton Harbour being relatively long and narrow effectively acts as a wave direction filter and only waves aligned with the harbour axis can pass up the harbour. In reality this is not much of a restriction on wave energy as long period swell waves from the south/southeast can refract around Banks Peninsula to run straight up the harbour. Only waves from the north/north northeast are filtered out by the harbour axis alignment and break on the southern shore of the harbour.

Because the seabed is naturally flat swell waves aligned with the harbour axis run up the harbour little attenuated by refraction in the harbour's natural state however seabed friction and diffraction/refraction effects resulting from the harbour navigation channel significantly reduce the wave height as the waves progress up the harbour. The harbour channel is deeper than the natural seabed either side and because the wave speed is dependent on depth, once the wave 'feels' the seabed when the depth is less than half the deepwater wavelength, that part of the wave crest travelling up the channel is moving faster than the crest either side in shallow water. The net result is that the wave crest becomes curved in the horizontal plane and the wave orthogonals, imaginary lines drawn normal to the wave crest bend away from the channel axis and become further apart. In theory the wave energy flux is constant between orthogonals so as the gap between orthogonals increases the same wave energy is spread over a wider area and the wave height reduces. In practice the wave orthogonals coming out of the channel could cross indicating a caustic or singularity, an infinite concentration of wave energy which increases the wave height at that point causing it to break. Wave diffraction effects then come into play, well before breaking, the wave energy flows away laterally along the crest to the lower energy levels to the side.

The SWAN model is driven by boundary conditions from MSL's wind and wave models of the New Zealand region. The model has been validated again wave measurements at Parson's Rock beacon.

3.0 GEOMORPHOLOGY AND SEABED SEDIMENT

3.1 Geomorphology of Lyttelton Harbour

Lyttelton Harbour is the eroded caldera remnant of an extinct volcano, the older of two interlocking Miocene volcanoes that form Banks Peninsula – Lyttelton in the northwest and Akaroa in the southeast. The high marine cliffs at the entrance to, and along the sides of, Lyttelton Harbour were cut during the Pleistocene age when the average sea levels were much lower. The cliffs were drowned when the sea level rose rapidly at the end of the last ice age.

The drowned cliffs and steeply sloping inside walls of the old crater – evident in Photograph No 1 - plunge into the harbour and continue underwater until they intersect with a flat seabed. In its natural condition the seabed is unusually flat, both in harbour cross section and along the longitudinal axis of the harbour.

Photograph No 1

From the head of the harbour to the Heads is almost a constant 1:1000. The flatness is indicative of a fluid seabed condition. As a consequence of its naturally flat seabed and plunging sides waves running up the harbour in its unaltered state suffer little attenuation of wave energy through refraction.

The rock sides of the harbour mean that the seabed is the only boundary that is free to respond to coastal processes.

The fine sediments forming the seabed are predominantly (60%) silt size, primarily derived from the loess silt that mantles Banks Peninsula and the harbour catchment area. The seabed sediment on the south side of the navigation channel however is slightly coarser than on the north side although this demarcation ends inside the Heads.

Fine sands are exposed on the seabed only on the south side. The harbour is further unusual in that the sediment size contours run parallel to the longitudinal axis of the harbour rather than normal to it.

3.2 Seabed Sediment

The harbour seabed sediment can be generally categorised as a very fine clay silt mixture with an in situ density of 17 kN/m^3. A typical sediment size analysis of the sediment shows the particle size distribution and Atterberg limits as:

- Fine Sand (0.25 to 0.05 mm) 1%
- Silt (0.05 to 0.005 mm) 45%
- Clay (smaller than 0.005 mm) 54%
- Liquid Limit LL 30 - 45
- Plastic Limit PL 20 - 30
- Plasticity Index PI 10 - 15

Outside the Heads the material changes more to a fine sandy silt with the silt fraction predominant. Typical shear strengths range from 10 kPa at the seabed to 50 kPa at the dredged depth limit.

The fine sand component increases with distance offshore. Further out in Pegasus Bay the seabed consists of dense fine sand overlain by a fluid silt layer.

While generally the seabed sediment is soft there is however a hard layer at the bottom of the existing channel that will need to be removed as part of any deepening process. The drag heads of the previous Lyttelton Harbour Board dredges 'Canterbury' and 'Peraki' periodically bounced off the top of this layer in the section of the channel off Camp Bay during the course of dredging operations over the years. The layer is quite distinct, a definite transition from soft silt to very hard material, and was initially identified as rock. This layer consists of alternating layers of stiff sandy silt material up to 4 m thick underlain by soft silt material to great depth, 60 m plus.

The depth of the existing navigation channel is approximately 12.2 m below CD.

3.3 Susceptibility of the Sediment to Entrainment by Wave or Current Action

The fine sediment, predominantly silt sized sediment characteristic both of the harbour seabed is susceptible to disturbance by wave or current action, either in its natural undisturbed state or even more so in its as dumped, unconsolidated state.

The most important hydrodynamic property of waves and currents for sediment transport/disturbance purposes is the bed shear stress they produce. The bed shear stress is a function of the square of the water particle velocity irrespective of whether the water particle velocity results from wave or current action.

For a smooth seabed and relatively small wave particle velocities the boundary layer may be laminar, but more often in cases where sediment is in motion it will be turbulent. The boundary layer - in which the water particle velocity rapidly decreases to zero at bed level - is only a few millimetres or centimetres thick for waves but can be of the order of metres thick for steady currents.

This has the effect of producing a much larger velocity shear in the wave boundary layer which in turn causes the bed shear stress produced by a wave with orbital velocity U_w to be much larger than the bed shear stress developed by a steady current U_c of equal speed. Waves are more effective in stirring the seabed than currents.

The critical condition for incipient motion of sediment is measured against the critical bed shear stress τ_c. When rendered non-dimensional by fluid and sediment parameters it is referred to as the critical Shields parameter $\theta_c = \tau_c / (\rho_s - \rho_w)gd = u_*^2 / sgd$ where u_* is the bed shear velocity, d is the sediment particle diameter, g is the gravitational acceleration , $s = \rho_s / \rho_w - 1$ = submerged specific weight of the sediment and ρ_s and ρ_w are the respective densities of the sediment and the fluid.

The Shields diagram which establishes a relationship between the critical Shields parameter and the shear Reynolds number $R = d.u_*/v$ is the most widely used criterion for incipient motion of sediment. The difficulty is the implicit nature of the criterion, u_* appears on both axes of the diagram and for a specific set of fluid and sediment an iterative process is required to find the critical bed shear stress.

A recent paper by Cao, Pender and Meng develops an explicit formulation of the Shields diagram, using Guo's logarithmic matching method, enabling the critical Shields parameter to be determined directly from fluid and sediment characteristics without resorting to iteration, see Figure No 3.

The Hjulstrom diagram, Figure No 4, is a much more simplistic representation of the process of sediment entrainment for steady state currents but it has value because it gives the order of magnitude for the current speed required to suspend fine sediment.

The entrainment of fine sediment is a complex process. The silt particles are so small that electrochemical force and viscosity become significant. The current speed required to erode consolidated silt and clay material is higher than for fine sand because of the cohesion exhibited by the fine particles and the smoothness of the seabed. From Figure No 4 the erosion velocity for silt is of the order of .3 m/sec bearing in mind the greater effectiveness of waves relative to steady currents in disturbing the seabed.

If the sediment is unconsolidated as in the case of dumped dredged material and recently deposited previously suspended material then the velocity thresh hold for movement is lower. Once in suspension the velocity required to keep it there is lower than the erosion velocity - as indicated on the diagram. The entrained material slowly drops out of suspension in slurry or fluid mud form as the swell wave height drops and the turbulence decreases. The slurry or fluid mud transforms slowly into a soil through a process of consolidation under self weight. Self weight consolidation starts at the bottom of the deposit while sedimentation continues at the top.

During the process of transformation from a fluid mud into soil the shear strength of the newly deposited material increases and as it is increases the susceptibility of the material to entrainment by wave action decreases to approach that of the undisturbed soil.

The mud is defined as a sediment-water mixture which consists of particles that are predominantly less than 63 μm in size, exhibits viscoelastic rheological behaviour when the mixture is particle-supported, and is highly viscous and non-Newtonian when it is in a fluid like state.

The viscosity is dependent on the solids volume fraction φ (or porosity $\eta = 1 - \varphi$) and interparticle interaction. At low values of φ the viscosity increases slowly with increases in φ but tends to increase rapidly when particle packing becomes dense. For randomly packed spheres this change occurs at about $\varphi = 0.60$.

A simple viscoplastic model is the Herschel-Buckley, equation $\tau = \tau_y + K\gamma^n$ where τ_y is the yield stress γ is the flow shear (strain) rate, K and n are the constants for a given sediment and n = 1. For fluid muds n typically ranges from 0.3 to 0.9.

When n = 1 the equation describes the Bingham model $\tau = \tau_B + \eta m\gamma$, in which the (Bingham) yield stress $\tau_y = \tau_B$ is equal to the threshold stress at and below which the material is a solid, and above which behaves as a Newtonian fluid.

During wave action the rheological state of soft mud almost always changes. This change is dependent on the relative magnitudes of the applied shear stress τ, the shear strength with respect to erosion (or critical shear stress) τ_s and the plastic yield stress τ_y (or the Bingham yield stress τ_B). Three change in bed state cases are considered by Jain and Mehta, Handbook of Ocean and Coastal Engineering.

$\tau \le \tau_s < \tau_y$ wave action is too weak to erode the bed surface. However wave orbits can penetrate the bed and build up excess pore pressure breaking interparticle bonds. Mud rigidity decreased even as particle packing density may remain largely unaffected. The seabed changes to a fluid like transitory state which reverts to bed as soon as wave action ceases and interparticle bonds are re-established.

$\tau_s < \tau < \tau_y$. The bed is subject to pressure work and shear work with the result that pore pressure buildup eventually destabilises the particle matrix. The bed is liquefied and its surface erodes causing the water to become turbid. There may be no significant change in bed density. Fluid like mud reverts to bed when wave action ceases.

$\tau_s < \tau_y < \tau$. The bed yields rapidly, erodes significantly and water becomes highly turbid. When wave action ceases fluid mud develops which is initially significantly lower in density than the original bed. In due course thixotropic gelling and bed consolidation cause the density to increase to its original value.

4.0 TURBIDITY

4.1 Turbidity Description

Sediment in suspension in the water column makes the water turbid. Turbidity is a description of the clarity of water, how clear it is. In simple terms it is a measure of the water's cloudiness. This cloudiness results from the intense scattering of light by fine particles suspended in the water. In more precise terms turbidity is an expression of the optical properties of water that causes light to be scattered and absorbed in the water. Turbidity changes the direction of the light rather than letting it be transmitted through the water in a straight line down to the seabed.

The attenuation of light due to scattering and absorption as rays of light pass through the water reduces visual range in water and light availability for photosynthesis. Scattering of the light by the suspended particles illuminates the particles, much like a ray of sunlight illuminates specks of dust in the air.

The clarity and colour of water are manifestations of the behaviour of light in this optical medium. Essentially all important aspects of the clarity and colour of water can be explained in terms of the light absorbing and light scattering properties of water. These are inherent optical properties of the water and its suspended sediment. The distinctive, characteristic aquamarine colour of the water in Lyttelton Harbour results from the fine sediment - silt and clay size – particles suspended in the water.

Colour depends on the light scattered back to the observer. Brightness depends on the amount of scattered light. Hue depends on the wavelength of the scattered light which is determined primarily by selectivity of light absorption. Clay size suspended particles scatter light most efficiently.

Turbidity is a natural background phenomenon that occurs in most bodies of water. The waters of Lyttelton Harbour are naturally turbid. The turbidity of the harbour water fluctuates in response to natural processes, being increased by rain events, and swell waves that stir up the seabed sediment. When calm returns turbidity levels decrease.

4.2 Turbidity Measurement

Turbidity is measured using a nephelometer which is a meter that measures the intensity of light scattered at 90˚ to a beam of light – optical back-scatterance (OBS). It is based on a photoelectric detector that is very sensitive to changes in attenuated light. Measurement of the optical properties of suspended sediment is more relevant in many instances than the measurement of its actual mass concentration given that much of the impact of suspended sediments relates to its light attenuation which reduces visibility and photosynthesis.

OCEL's turbidity sensor measures turbidity in FTU's or Formazine Turbidity Units, an expression of the optical properties of water that cause light to be scattered or absorbed and is directly related to turbidity. The other common unit for the measurement of turbidity is the NTU or Nephelometric Turbidity Unit. The FTU and NTU numbers are close to equivalent – FTU for OBS based on 180° scatterance and NTU for OBS based on 90° scatterance.

Nephelometric turbidity, an index of light scattering by suspended particles, has been widely used as a simple, cheap, instrumental surrogate for suspended sediment it is however only a relative measure of scattering that has no intrinsic environmental relevance until correlated against a proper scientific quantity such as a direct measure of the total suspended solids (TSS) concentration in milligrams per litre.

The turbidity readings. In FTU or NTU units, can however be correlated with TSS values and this was done by CRL Energy Limited for 5 different samples, taken by OCEL at varying depths and locations in Lyttelton Harbour.

Turbidity in the harbour varies both spatially, and vertically with depth, in the harbour, dependent principally on weather and seastate conditions and vessel movements. Propeller wash from large vessels moving in and out of the port along the navigation channel stirs up the seabed putting sediment into suspension. This is evident from Photograph No 2 which shows a turbidity plume generated by the passage of a vessel – shown outside the harbour off Godley Head – superimposed on natural turbidity in the central and upper harbour. Given the blue clean water in the outer harbour and offshore the turbidity evident in the upper and middle harbour areas could have been generated by a rainfall event.

Photograph No 2

Turbidity plumes on the sea surface resulting from vessel movements and dredging are transient and soon fade away by merging with the background turbidity.

OCEL's OBS turbidity sensor was deployed from the OCEL survey boat at a number of locations around the harbour to investigate turbidity levels and the variation of turbidity with depth at those locations under a range of conditions. Plumes resulting from vessel movements were also investigated.

The turbidity depth profiles typically show a hockey stick profile, the turbidity increasing close to the seabed. This is a natural condition as a consequence of the greater density of the water containing suspended sediment relative to water with no suspended sediment. The denser fluid gravitates to the seabed where it forms a layer. The suspended sediment gradually transforms from a fluid to a soft fluid mud which, as it consolidates, develops cohesion. The NIMROD dynamic penetrometer device, described in Section 5.3, was used to investigate the fluid mud layer.

The particles that contribute to light attenuation in the water must stay suspended for a reasonable length of time and are therefore slow settling. Coarse particles drop out quickly once the source of the sediment disturbance, typically wave action, drops below the entrainment initiation level. Fine particles may only drop out when complete calm returns.

The settling velocity of fine particles v_s, is given by Stokes' law:

$$v_s = \alpha.g.d^2(\rho_s - \rho)/ 18\eta$$

Where α is a dimensionless shape factor, g is the gravitational acceleration, d is a characteristic linear dimension (diameter for a sphere), ρ_s is the density of the particle, ρ is the density of water and η is the absolute viscosity of water. The equation shows that the settling velocity is mainly dependent on the particle size and density relative to water although shape – deviation from sphericity as indicated by α – also has an effect.

Mineral particles typically have densities similar to or greater than quartz, $\rho_s = 2.65$, and generally only remain in uniform suspension if particle diameters are smaller than the sand-silt boundary at 50 µm. This is the case for the bulk of the Lyttelton Harbour sediment. The settling velocities for silt sized material, 2 – 50 µm diameter range from 3 µm/sec < vs < 2 mm/sec. A particle at the clay–silt boundary settling at around 3 µm/sec takes about 4 days to settle 1 m in perfectly calm water. It takes very little turbulence to maintain the fine sediment in suspension.

The natural condition for the harbour, exposed as it is to swell wave action, is to have fine sediment in close to permanent suspension. A range of factors but principally swell wave action increases the volume of material in suspension (turbidity) during an event and the particles are distributed right through the water column. As the turbulence decreases following the event there is a strong selection towards removal from the water column of the coarser silt ranges because v_s depends on the square of d in the Stokes' law equation but the finer sizes remain in suspension.

4.3 Turbidity Currents

Dense suspensions of suspended sediment, unlike low concentration suspensions are not transported solely by tidal flow. They are also driven by gravitational and rheological mechanics which can advect the suspension across the bed with minimal vertical mixing and settling until a balance of forces arrests the suspension.

Gravitational turbidity or density currents are a possible transportation mechanism for the harbour sediments once they are in suspension. While down slope turbidity flows will be a factor in the movement of suspended sediment they will not be dominant due to the relatively low driving force provided by the low slopes. The areas of greatest siltation in the channel however are directly opposite the dumping grounds.

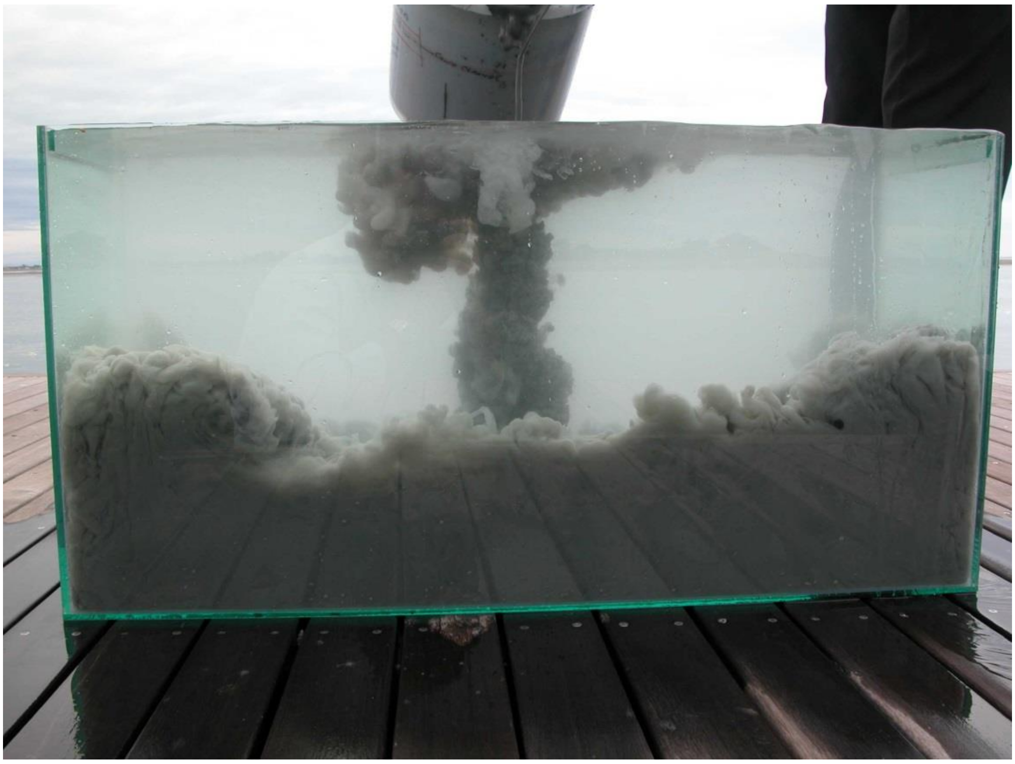
Turbidity currents can also be set up however by the act of dropping the dredged sediment down through the water column, as occurs when the dredge opens the hopper doors to dump a load.

While the dredged material that accumulates in the dredge hopper is typically thought of as a solid material the reality is that it is more in the nature of a dense fluid. Photograph No 3 shows the fluid nature of the dredged material filling the hopper of the dredge 'New Era'. When the contents of the dredge's hopper are dumped it is less a matter of dropping solid material through the water column rather than releasing a dense fluid into a less dense one.

Photograph No 3

The hopper contents are released in a very short period of time and the material is released as a liquid slug into the receiving water overlying the dumping area. The specific gravity of the fluid dredged material is 1.3. The output from the dredge pump is discharged overboard until the specific gravity of the fluid reaches 1.3 at which point the discharge is directed into the hopper. The dense fluid sinks down through the seawater in a three step process: convective descent during which the material falls under the influence of gravity; dynamic collapse when the descending cloud impacts the bottom, transforming into the third stage horizontal outflow from the impact point. The outflow disperses radially outwards until passive transport dispersion commences when the material transport and spreading are determined more by ambient currents and turbulence than by the dynamics of the disposal operation.

To gain a better intuitive understanding of the process a sample of the dredged material recovered from the dredge pump discharge pipe into the hopper of the Pelican was tipped into a seawater filled fish aquarium tank. The result is shown in Photograph No 4. The dredged material suspension forms a jet through the receiving fluid, strikes the seabed and spreads out horizontally underneath the seawater. In the photograph the dredged sediment suspension is shown colliding with the ends of the tank and reflecting back. In the real case no such restraint exists and the fluid continues to spread radially out from the discharge point. Of note is the clear separation between the two fluids until the turbulence produced by reflection off the ends of the tank produces mixing of the two.



Photograph No 4

This mechanism was investigated as part of the earlier 2003 study and this study by tracking the movement of the turbidity plume resulting from the dumping of a hopper load of dredged material from the maintenance dredge ‘Pelican’. For the 2007/2008 study two dumps were undertaken at the proposed new dumping location for the capital dredging material 4 nautical miles off the Heads and one dump near Godley Head.

Separately, in a second component of the turbidity study, an OBS turbidity meter was used to determine the relative levels of turbidity in the harbour under calm sea conditions, while the dredge was operating and during swell conditions.

4.3.1 Dispersion of a Hopper Load

The dispersion of the dredged material dumped from each load dumped by the Pelican was investigated at full scale using an ADCP instrument deployed from the OCEL survey boat shadowing the Pelican as it moved to empty its hopper. The survey work was undertaken in calm seastate conditions, swell wave height 0.5 m. The work carried out for this study replicated the earlier work (2003) inside the harbour for the Lyttelton Harbour siltation study.

The backscatter measurement technique was used to measure the suspended sediment transport of dredged material dumped from the ‘Pelican’. An RDI 1200 kHz Workhorse Monitor ADCP was used to measure suspended sediment in the water column. Positioning was input into the ADCP via a Trimble 5700 RTK GPS. Again this is a qualitative rather than a quantitative measure, it does not give TSS values.

A number of ADCP transects through the centre of each dump position were carried out to measure relative suspended sediment through the water column. The ADCP data was processed and output to an ARCVIEW GIS application that converted the data into a GIS format.

The initial transects into the sediment plume for all of the dumped dredge hopper loads proved unsuccessful as the acoustic signal of the ADCP could not penetrate the extremely high initial suspended sediment concentrations near the water surface at the drop zone. However as the descending sediment plume hit the seabed it spread away from the initial drop zone enabling the ADCP to measure the advancing front on the seabed. Transects were then conducted towards and away from the advancing seabed flow.

The work carried out in 2003 inside the harbour gave quite clear results from the echo intensity plots the principal two features of which, Figure No 5 shown were:

- A turbid surface plume of 2 to 3 m thickness away from the drop zone
- A bottom layer of suspended sediment visible approximately .25 to 1.5 m above the seabed.

This is the same pattern as shown in the aquarium representation of the process, see Photograph No 4.

Tracking the leading edge of the plume indicated that the material dumped by the dredge could travel some 300 m from the drop zone in a period of approximately 40 minutes following the time of the dump, see Figure No 6. The volume of material shifting cannot be quantified by the results obtained although it must be noted that the echo sounder traces on the dump location indicated that there was no perceptible reduction in the water depth at the dump location. This in turn indicates that the dumped material was widely dispersed. This confirms the visualisation of the dumping process as a mixing of fluids of differing densities rather than a drop of solid material. The echo sounder trace did show a transient turbidity plume immediately after the dumping, the same as shown in Photograph No 5 for the proposed offshore dump location.

Photograph No 5

For the 2007/2008 work outside, and at the entrance to, the harbour the results were not so clear cut. It proved difficult to track the plume produced by the dumping once the plume had started to spread out, and the back scatter levels decreased, because of relatively high levels of ambient or natural background turbidity. The plume can only be tracked while the back scatter values are elevated, higher than the ambient back scatter values otherwise the plume melts into the natural background. Tracking was also complicated by stratification at the offshore site and small differences in current speed and direction through the water layers.

At the offshore dump location the plume cloud moved south east, roughly parallel to the line of the coast, consistent with an ebbing tide. As for the in harbour work the surface plume was much smaller than the plume at depth. At depth a plume footprint approximately 200 m wide was observed before it became indistinguishable from, melted into, the natural background. An absolute plume extent at depth could not be estimated. Some qualification of the phrase 'melts into the natural background' is required. The suspended sediment does not literally melt away but becomes indistinguishable from the natural background.

The turbid plume produced by the dumping adds to the natural background turbidity to produce a transient turbidity spike. The speed of sedimentation or dropout of the sediment particles from the turbidity plume, is related to the concentration of the solid particles in the fluid. The setting rate u can be expressed as u = u(c) where u(c) is a function of the particle concentration in the suspension fluid.

The higher the concentration or saturation of the water column with suspended solids the faster the sediment will settle out. With increasing interparticle collisions as a consequence of the higher concentration of particles the probability of formation of flocs from dispersed (non flocculated) particles increases.

For any given level of wave disturbance of the seabed there will be an associated natural background or equilibrium level of turbidity. A sudden addition in the form of a plume of dumped dredged material will be a transient spike with no lasting enhancement of the natural background level.

Until the dumped material consolidates to become closer to the natural seabed at the dump location the natural turbidity levels in the immediate area will be higher than was originally the case because the same level of wave action will entrain more of the unconsolidated material.

4.4 Turbidity Results From The Static ADCP

An ADP was positioned at the proposed offshore dump location primarily to record tidal currents but in a secondary role it monitored the turbidity at the location. The ADCP was deployed 1 km from the trial offshore dumping sites. The ADCP record was checked to see if there was an increase in turbidity that could be attributed to the trial dump. There was no effect on the backscatter or inferred turbidity.

The ADP was used to monitor turbidity at the entrance to Port Levy and efforts were made to correlate the turbidity with swell and rainfall events and with periods during which maintenance dredging was undertaken in the harbour. A distinct correlation was established for the rainfall events. Peak turbidity readings correlated with rainfall events. This confirmed earlier work by R M Kirk who suggested there would be such a correlation.

The correlation of turbidity with the rain events is shown in Figure No 7 (Mulgor 2008).

Work remains to be done to relate the turbidity measurements made by the ADP in decibels to Total Suspended Solids (TSS).

4.5 Turbidity Sensor Results

The OCEL OBS turbidity sensor was deployed from the OCEL survey boat to determine turbidity levels around the harbour under a range of different seastate conditions in the early 2000s. The turbidity sensor output is a plot of the FTU number versus depth in the water column at the location sampled.

The first deployment of the turbidity sensor was undertaken at the end of the 2003 dredging program while the Pelican was still working in the outer harbour. Contrary to the received wisdom around the wharves in Lyttelton the dredging operation was found to have no significant effect on turbidity levels in the harbour. The turbidity levels were virtually the same all around the outer harbour.

At the time of that survey a south west wind was blowing and the greatest turbidity levels were encountered up in the upper harbour where the locally generated short period waves were stirring up the seabed. A strong southwest wind blowing over the fetch from Governors Bay to the Naval Point reclamation at Lyttelton can generate a steep, short period sea, H_s = 1 m, T_p = 3.5 secs, in the shallow waters of the upper harbour. This can cause the harbour water to become discoloured and highly turbid. A 1m high wave 3.5 sec period in 4 m water depth – off Rapaki – produces a water particle velocity at seabed level U = 0.44 m/sec, in excess of the erosion velocity for silt.

A turbidity survey was undertaken on 19 August 2004 following a sustained period of seabed disturbance by swell waves running straight up the harbour. Sampling in the navigation channel, the graphs contained in Appendix A, showed that the turbidity level increased sharply at a depth just above the natural depth to the side of the channel at the point surveyed.

The thickness of the turbidity layer observed in the channel supports the view of the channel as a sediment sink. The pronounced turbidity layer over the natural seabed level to the side of the channel continues across the channel at the same height and the turbidity remains relatively constant through the full depth of the channel trench – see reference Graph C2 Appendix A.

Measurements of turbidity made using the OCEL turbidity meter show that the turbidity in the harbour is typically constant or increases only gradually down to 2 m above the seabed after which it increases rapidly. In swell conditions the turbidity is distributed throughout the water column as evidenced by the discoloured water in and outside the harbour. The bottom concentration increases even higher. Examples of the turbidity readings taken on 19 August 2004, displaying the characteristic increase of turbidity in the layer close to the seabed are included in Appendix A.

A number of locations around the harbour and Port Levy were tested on 1 July 2008 following a heavy rain event from the south west. The plots are included in Appendix A. The seastate was characterised by less than 1 m swell. The highest turbidity level recorded was in the navigation channel following the arrival of an incoming container vessel attended by a tug.

The sea water was strongly discoloured by the sediment plumes stirred up by propeller wash. At Godley Head, Adderley Head, the entrance to Port Levy, in Port Levy and at Rapaki the turbidity levels were elevated but similar. At Gollans Bay the turbidity level was higher but this may have been related to ship traffic in the navigation channel raising plumes that drifted into the Gollans Bay area.

The natural background levels of turbidity are relatively high and only drop off after sustained calm seastate periods. They are elevated by rain events.

The impetus or driving force for the turbidity current away from the dump location is provided by the denser fluid falling through the water column, potential energy is converted to kinetic energy. Because of the generally low underwater slopes the potential energy or driving force is very much less. Density currents are very important in producing the initial dispersion following dumping but of much less significance in distributing or transporting re-suspended sediment.

4.6 TSS FTU Correlation

As noted turbidity is a description of how clear water is. In simple terms it is a measurement of the water's cloudiness. It is not a direct measurement of the Total Suspended Solids (TSS) in grams per litre in the water but it is an indication.

Turbidity measured in FTU's or NTUs can be translated into milligrams of solid per litre through a correlation based on simultaneously taken water samples. This was done by CRL Energy limited for six samples collected from the harbour by OCEL on 15 October 2008. The TSS correlations and the turbidity meter outputs are given in Appendix A.

The highest FTU number 750, was obtained for a sample taken immediately behind the dredge close to the seabed following a dump of a lopper load of dredged material. The TSS value is 935 gm/m^3. Elevated values of the FTU number as high as 750 are transient as the water column becomes saturated with sediment and rapidly drop back as the material drops out of suspension. The turbidity cloud associated with the dump can be clearly seen on the screen. This is only apparent immediately after the dump, it is a transient feature only.

If the FTU number in the bottom turbid layer in a swell event – example 19 August 2004 - is taken as an average of FTU 80 the suspended solid content is .191 gm/m^3. In the area of the outer harbour, from Lyttelton to the Heads, the weight of sediment in the bottom turbid layer can be approximated as in excess of 4000 tonne.

Water sample 6 was taken directly behind the dredge while it was dredging in the channel. The NTU number was 160 corresponding to a TSS of 281 gm/m^3. The turbidity plume – reference Photograph No 6 - behind the dredge is transient and soon fades from view. The turbidity plume disperses in both the horizontal and vertical planes – vertically as the sediment falls to the bottom and horizontally as the plume is broken up by the turbulence in the vortex train wake behind the dredge as it moves.

Photograph No 6

5.0 SEDIMENTATION DEPOSITION

5.1 Sedimentation in the Harbour

Sedimentation is the conversion of discrete soil particles in a suspension into loose sediment. R Curtis researched the background of the history of sedimentation in the harbour as part of his PhD thesis (1985) and provided an assessment of sedimentation and dredging effects in the harbour to the LHB in 1986. From a comparative study of hydrographic charts and dredging records over time it is apparent that the harbour is in a state of quasi-stability in terms of net sedimentation.

The hydrographic survey data collected by the LPC over time as part of the routine monitoring of the maintenance operation dredging and the dumping areas confirms the quasi-stability.

Curtis calculated the quantity of new sediment entering the harbour each year, principally as a result of the erosion of loess, at between 16,000 and 44,000 tonnes per year. This occurs principally at the Head of the harbour. While this is a significant volume it pales in comparison to the quantities of fine sediment involved in internal recirculation in the harbour each year.

The major sedimentary process within the harbour is the maintenance dredging program which removes in the order of 1 million tonnes per year from the navigation channel. He estimated for the harbour as a whole that the total quantity of sediment involved in transport and sedimentation each year was between 700,000 and 1 million tonnes. There is an apparent clear link with the maintenance dredging operation. Note that this is the sediment being transported and trapped by the navigation channel.

Irrespective of the dredging operation the harbour seabed is disturbed by swell induced water particle velocities at seabed level disturbing the sediment and entraining it into suspension. Large volumes will be in suspension naturally but not trapped. Once the fine materials have been suspended the sediment can then be moved by tidal currents. In the natural state this results in a flattening or levelling of the harbour seabed.

Starting in 1969 sediment dredged from the channel as part of the maintenance dredging operation was dumped along the north side of the harbour to create wave refraction mounds. In the natural flat seabed condition waves pass up the harbour unattenuated by wave refraction effects. The shallower water over the wave refraction mounds slows that part of the wave front passing over it, turning the wave front in towards the shore and reducing the wave energy passing up the harbour.

The wave orthogonals, imaginary lines running perpendicular to the wave front, spread out as the wave refracts and the energy contained between them is then spread out over a wider wave front resulting in lower wave heights. The natural processes act over time to level these mounds to return the seabed to its natural flat condition.

The channel has its own wave refraction effect. That part of the wave front passing up the channel moves faster than the wave front sections to the side of the channel causing the wave orthogonals to bend outwards away from the channel and even to converge increasing wave heights to the side. Where there are wave peaks diffraction effects result in energy being transferred along the crest.

While the outer and central – opposite the port – parts of the harbour are in general quasi stability sediment accumulation has occurred in the three main bays of the upper harbour, Hart et al 2008b. The same study also suggested that pulses of sediment from catchment development may be increased in recent years.

5.2 Channel Siltation

Predicting the rate of siltation in dredged channels is difficult and inexact due to the complex nature of sediment transport processes. For the case of Lyttelton however there is a long history to draw on since dredging in the channel outside the inner harbour started in 1880. The siltation in the channel is heaviest opposite the dumping grounds on the north side of the harbour although it has been found that the siltation volumes are relatively insensitive to the location of the dumping grounds. Dr Derek Goring of Mulgor has shown that successive tracks of neutrally buoyant particles released on the north side of the harbour migrate laterally over a series of tides toward the channel.

Deposition of sediment from suspension occurs in areas of low bed shear stress below a critical value. The bed shear levels in the bottom of the navigation channel are lower than on the seabed either side of the channel because of the greater depth. Wave induced water particle velocities and related bed shear values drop off exponentially with depth.

There is a form of dynamic equilibrium in operation as a result of the lower bed shear stress levels in deeper water. This acts to cause deposition in deeper areas, filling them in and promoting a return to the naturally flat seabed characteristic of the harbour. The converse is also true, the same mechanism acts to level shallower areas where the bed shear stress levels are higher.

The navigation channel tends to act as a sediment trap because it is deeper than the natural bed levels. This tendency is reinforced by density differences. Sediment suspended in the seawater makes it denser relative to clean seawater and the suspended sediment sinks to the bottom of depressions in the seabed. The suspensions are still moved by tidal currents in the channel but have a natural tendency to accumulate there. Much also depends on the net movement of the tidal currents in a complete tidal cycle, whether the suspensions are swept back and forth in a balanced movement, no net progress, or whether the tidal current can move the suspended sediment completely away from the channel in one tidal cycle.

Deepening the channel will not change the amount of siltation experienced along the length of the existing channel it is just deepening the sediment trap. Extending the channel will extend the length of the trap. The extra volume of sediment that needs to be removed as part of the maintenance dredging will most likely be less than proportionate to the increase in channel length. Although the channel will extend out past the Heads and part of the wave filtering effect of the harbour will be lost as the wave environment comes closer to open sea conditions with more bottom disturbance the effect is ameliorated by the greater depth and the fact that the extended channel is outside the harbour system and not opposite to the dumping grounds.

Whether the sediment stays in suspension is determined by the prevailing wave energy and the depth. In its fluid state however the sediment is readily disturbed by any significant wave action anywhere in the harbour, particularly along the former dumping grounds on the north side of the harbour. The tidal currents however are not strong enough to mobilise the sediment into suspension by themselves, they act only to transport the sediment once suspended. Given the previous, prior to the decision to dump at Godley Head, location of the dumping grounds on the port side of the halfway line between the Cashin Quay breakwater and the Heads the bulk of any dumped material disturbed by wave action will be retained within the harbour - recirculated. Essentially the harbour functions as a closed system.

5.3 Fluid Mud Layer

The turbidity meter identifies the increasing density of the turbid seawater close to the seabed but does not fully resolve the fluid mud layer. The NIMROD, a hand carried dynamic penetrometer has been developed by MARUM to address the problem of resolving very soft to fluid mud layers. The device has a high sensitivity for low sediment resistances and has a range of different tip geometry configurations – flat cylinder, hemisphere and cone – to achieve this. A hemisphere was used for the Lyttelton work.

The NIMROD is deployed by throwing it overboard - reference Photograph No 7. It is a fluid dynamically shaped device with tail fins and a fall stabilising relationship between the centre of gravity (CofG) and the centre of buoyancy (CofB). The CofG is below the CofB. This ensures that whatever the initial orientation on entering the water the NIMROD impacts the seabed vertically.

Photograph No 7

NIMROD impacts the seabed at the terminal velocity it reached during its fall through the water column and is then decelerated depending on the sediment properties, the properties of the probe itself and its free-fall behaviour. The device is equipped with four accelerometers with different ranges and resolutions. Layers of different strength and density can be distinguished from each other using the deceleration-depth profiles.

The seabed impact signature in the form of a deceleration-depth profile is recorded onboard and later downloaded and processed to derive the quasi-static bearing capacity using a strain rate factor. This transforms the dynamic sediment resistance to a quasi-static sediment resistance that relates to penetration with constant velocity v_o = .02 m/sec. Dividing the quasi-static sediment resistance by the cross section area of the NIMROD gives the quasi-static bearing capacity (qsbc).

The survey work undertaken at Lyttelton with the NIMROD was classified in to three areas – the dredged channel, the existing dredged material disposal grounds on the north side of the harbour and the proposed offshore disposal site. In the dredged channel the seabed was pre-dominantly characterised by a two layer system of a very soft top layer, q_{sbc} < 1 kPa, over a stiffer substratum. The top layer showed a thickness ranging from 5 – 8 cm +/-1 cm inside the harbour increasing to 10 – 17 cm thick at the harbour entrance. The soft top layer in the channel was thickest, 45 cm, +/- 1 cm, and 20 cm, +/- 1 cm, opposite the disposal grounds on the north side of the harbour. The substratum had a q_{sbc} ranging from 5 – 9 kPa +/- 2 kPa with maximum penetration depths ranging from 32 – 60 cm +/- 1 cm. Closer to the port the top of the hard layer in the channel was picked up. On the northern flank of the harbour the soft top layer was present but the second layer sediment appeared predominantly softer, 2 – 5 kPa +/-1 kPa. The maximum penetration depth ranged from 39 – 88 cm +/- 1 cm.. This confirms the low consolidation rate of the dumped dredged material on the north side of the harbour. A hard bottom was identified off the shoreline at Te Awaparahi Bay.

The NIMROD results for the proposed disposal site offshore showed a natural soft top layer similar to that in the dredged channel but not as thick as at the harbour entrance. The q_{sbc} value for the substratum ranged from 9 – 10 kPa +/- 3 kPa. The maximum penetration depth was 24 cm +/- 1 cm.

As for the mobile ADCP current studies the dynamic penetrometer results represent a snap shot in time but clearly identify the persistent, natural, highly mobile fluid layer on top of the seabed.

Representative graphical results of the NIMROD results are given in Figure Nos 8 (position 24) and 9 (position 71). The locations of the NIMROD test positions are shown on Drawing No DR-030901-026.

6.0 ENVIRONMENTAL FACTORS – WAVES AND TIDAL CURRENTS

The primary influences on sedimentation and channel siltation within and outside the harbour are the waves and tidal currents. While wind (local wind as opposed to wind blowing over distant wave fetches to produce swell) can induce surface currents in the same direction as the wind, current speeds 2-3% of wind speed, has little significance for sediment disturbance and movement in the outer harbour and Pegasus Bay. Locally generated wind waves are short period and do not affect the seabed other than in the shallow water in the head of the harbour.

6.1 Wave Energy Environment

The wave climate both within and outside the Lyttelton Heads is relatively benign – compared to elsewhere on the New Zealand coastline – both in terms of the height of the wave experienced offshore and the frequency of occurrence of big sea conditions. It has no exposure to the waves generated by the prevailing westerly winds over essentially unlimited fetch lengths to the south west of New Zealand. While there is not the same long period swell background on the east coast as on the west coast depressions off the east coast can create severe weather and seastate events. Such events however are infrequent.

Waves within Lyttelton Harbour generally fall into two categories, locally derived wind generated waves and swell waves from more distant storms in the southern ocean which refract around Banks Peninsula. The wave directions exhibit seasonal variations with north-east waves prevailing in summer and south-east waves predominating in winter. Longer weather windows are generally available in the summer period when extreme weather events are less likely, however, periods of complete calm occur in early to mid winter.

The present wave climate in Lyttelton Harbour, derived from the SWAN model is presented in Figure No 10 which shows a contour map of the mean significant wave height. The wave height is a maximum at the entrance and reduces with penetration into the harbour through a combination of refraction, diffraction and bottom friction effects. The dissipation of wave height with distance is more clearly shown in Figure No 11 which shows the variation along in various wave height statistics along the thalweg, the line of maximum depth, reference Figure No 12. The 95% and 99% statistics represent the percentage of time the wave heights are less.

From earlier work undertaken for the channel deepening project, in particular the for derivation of the necessary underkeel clearance in swell conditions wave probability, height exceedance and directional data derived by Dr Derek Goring are given in Table No 1 below for a site at the start of the proposed channel just outside the Heads in 16 m water depth. For the highest 1% of waves, significant wave heights exceeding 2.16 m > 95% come from the north east and east north east.

	Wave Height Exceeding m			
Direction	**>0.76**	**>1.65**	**>2.16**	**>2.86**
N	4.6	0.1	0.0	0.0
NNE	10.3	5.2	1.2	0.0
NE	19.5	32.6	46.9	60.0
ENE	38.6	51.0	48.6	34.4
E	10.8	9.2	3.2	5.6
ESE	1.6	0.6	0.0	0.0
SE	0.9	0.3	0.0	0.0
SSE	0.6	0.2	0.0	0.0
S	0.8	0.2	0.0	0.0
SSW	1.4	0.3	0.0	0.0
SW	2.2	0.1	0.0	0.0
WSW	2.2	0.1	0.0	0.0
W	1.0	0.0	0.0	0.0
WNW	0.9	0.0	0.0	0.0
NW	1.5	0.0	0.0	0.0
NNW	3.0	0.0	0.0	0.0
% of time	50.0	5.0	1.0	0.1

Table No 1

The wave data was generated using the NOAA (National (USA) Oceanic and Atmospheric Administration) NWW3 (NOAA Wave Watch 3) global wave model to derive, hindcast, wave parameters – significant wave height H_s, peak period Tp and direction for a deepwater site offshore Banks Peninsula. A wave refraction analysis using the SWAN (Simulating Waves Nearshore) wave model was run to transfer the wave data inshore to the site at the start of the proposed channel extension.

Waves in shallow water produce an oscillatory velocity at the seabed which acts to disturb the seabed sediment by creating bed shear stress. As noted the oscillatory bed shear stress is a function of the square of the water particle velocity. Shallow in this context means approximately

$d < 0.1gT^2$ or alternatively $d < 10.\,H_s$

where d is the depth of water, T is the wave period and H_s is the significant wave height. Short period locally generated wind waves T_p = 3 – 6 seconds period, only effect the seabed in the upper reaches of the harbour. Long period swell waves, 10-12 seconds can reach and disturb the seabed over the full extent of Pegasus Bay and the harbour inlet.

Although monochromatic – uniform wave period – swell wave conditions can be experienced in the harbour the typical sea comprises a spectrum of waves of different heights, wave periods and directions. This produces a random time series of orbital velocity at the seabed. The seastate can be characterised by the significant wave height H_s, and the zero up crossing period T_z where $T_z \approx 0.71.T_p$,. the peak wave energy period.

The wave induced water particle velocity at the seabed produced by the significant wave height can be calculated using the applicable wave theory for the particular combination of wave height, period and water depth. For a 1 m high 12 second period swell wave in 16 m water depth - at the site for the wave height exceedance data given (Table No 1) Stokes 5th order wave theory is applicable and the significant water particle velocity U_s at the seabed is .34 m/sec.

This water induced water particle motion is sufficient, in conjunction with the wave induced pressure fluctuations as the wave crest passes overhead, to mobilise fine sand and silt into suspension. From Table No 1 significant wave height exceeds 0.76 m significant 50% of the time but since locally generated short period NE/ENE wind waves can easily attain this height the swell waves capable of entraining the seabed sediment will only be a small proportion of the 50%. The distribution by period (%) of waves that exceed various significant wave height for the site at the start of the proposed channel are given in Table No 2 below. For the NE/ENE waves higher than 2.16 m approximately 30% have periods greater than 10 seconds.

A 0.76 m significant wave height 12 second period swell wave produces a significant on bottom water particle velocity of 0.26 m/sec in 16 m water depth. The significant wave height is the average of the 1/3 highest waves. While this is just less than the approximate erosion velocity for silt, 0.3 m/sec, the largest swell waves of a swell wave spectrum characterised by H_s = 0.76 m will be capable of entraining the seabed sediment in 16 m water depth. Since H_{max} (U_{max}) can be taken at 1.8 H_s (U_s) for a 4 hour period.

	Wave Height Exceeding m			
Peak Period s	**>0.76**	**>1.65**	**>2.16**	**>2.86**
<=7.4	64.2	30.2	36.0	14.40
8.3	7.4	12.4	22.9	38.9
9.4	9.7	8.1	10.6	24.4
10.6	10.2	15.3	7.9	10.0
12.0	6.0	23.6	10.8	12.2
13.6	1.9	10.0	11.8	0.0
15.3	0.5	0.4	0.0	0.0
>=17.3	0.1	0.0	0.0	0.0
% of time	50.0	5.0	1.0	0.1

Table No 2

Distribution by period (%)of waves that exceed various heights,
for node ltc1 at the entrance to the harbour

Inside the Heads along the 12 m depth contour the water particle velocity produced at the seabed by a 1 m significant swell wave height, wave period 12 secs is 0.42 m/sec; even the smaller swell wave heights in a seastate characterised by H_s = 1 m, T_p 10 – 12 secs can entrain bottom sediment. In contrast a 1 m high 3.5 second period wind wave in 12 m of water produces a water particle velocity of .04 m/sec, insufficient to entrain sediment. A comparison of the maximum wave induced water particle velocities throughout the water column is give in Figure No 13. The approximate erosion velocity limit is also shown.

Swell waves in excess of 1 m significant wave height and 10 – 12 second period can disturb and entrain sediment over the full extent of the harbour inlet. The locally generated wind waves cannot, they have minimal effect on harbour siltation other than in the upper harbour.

As the height and steepness of the waves increases the velocity under the crest, directed onshore, is greater than the velocity under the trough, directed offshore, and there can be movement onshore. For a 6 m high wave in 16 m water depth the velocity under the crest is 2.2 m/sec. and the reverse velocity under the trough is 1.45 m/sec., calculated using Stokes 5th order wave theory.

A 6 m significant wave height corresponds to close to the 50 year return period significant wave height for inshore Pegasus Bay. The maximum wave height in a 4 hour period for a seastate characterised by H_s = 6 m would be of the order of 11 m. The high water particle velocity, well in excess of the minimum entrainment velocity, is associated with an increasing height of turbulence up off the seabed. The effect of this is to distribute sediment throughout the water column.

In the relatively deep water of the outer harbour and Pegasus Bay the wave orbital motion is close to sinusoidal for the waves well less than 6 m, the onshore velocity under the crest is close to equal to the return velocity under the trough. There is no net wave induced current such as occurs in the surf zone. so there is no net movement in the direction of wave travel as there would be in shallower water where the wave profile becomes more asymmetric.

The wave directions are not particularly significant. The waves and swell action entrain the sediment into suspension making it available to be transported by tidal currents.

In the shallow waters of the Upper Harbour the dominant waves in the wave energy spectrum are the locally generated short period waves. The swell waves are much attenuated in the Upper Harbour and not capable of disturbing the seabed and entraining sediment into suspension. However the short period waves are fully capable of generating high enough water particle velocities to entrain sediment. Figure No 14 gives a comparison of the maximum wave induced water particle velocities throughout the water column for a 12 sec period swell wave, H_s = 0.15 m, and a 3.5 second period short period wave H_s = 1 m off Rapaki in 5 m water depth.

6.2 Tidal Currents

The relatively low tidal current speeds and the consequent limited tidal excursion distances on a tide – typically of the order of 3.5 km maximum, as determined both by drogues and neutrally buoyant particles released in the MSL hydrodynamic models – mean that Lyttelton Harbour inlet is effectively compartmentalised into three tidal compartments: outer, central and upper. Approximate locations for the tidal compartments are shown in Drawing No DR-030901-054. The size of the upper harbour compartment has been confirmed by the results of the self tracking drogue, Figure No 15.

While the harbour has a more or less constant width of 2 km over the greater part of its length, tidal flow in and out of the harbour is not a simple block flow in plan view, as was noted in the Background Section 2.

Asymmetry of the tidal flow in all three compartments of the harbour however allows the interchange of water between the tidal components, allowing water to ultimately leave the upper harbour. Asymmetry in the tidal circulation predates, and was identified well before, the construction of the Cashin Quay reclamation.

The Cashin Quay breakwater acts as a local control feature on the tidal current flows. The breakwater directs the incoming tidal flow out into the middle of the harbour and in doing so promotes the development of a large anticlockwise rotating circulation cell of Cashin Quay.

This was shown by the drogue tracking and current monitoring work undertaken by OCEL for the LPC in 2000. The study work was undertaken to gather data for a ship handling model of the port. Single point or 2 dimensional (2d) ADCPs were used in conjunction with drogue tracking. The principal interest was in the tidal currents affecting ship handling in the vicinity of the port.

In the upper harbour the strongest tidal currents, 1 knot maximum ebb and flow, occurs in the channel between the Naval Point reclamation and Shag Reef. This introduces an element of asymmetry into the flow. In addition the tidal streams from either side of Quail Island in the upper harbour exit their respective embayments at an angle to each other resulting in mixing.

The greatest mixing occurs in the central tidal compartment, opposite the Port.

Because of the limited tidal excursion distances it will take some time, several tidal cycles, for the bulk of the water in the upper harbour to leave the harbour system. In an effort to illustrate this a self tracking buoy was released in the upper harbour and tracked over a period of 2 days. The buoy/tidal current drogue carried a Global Positioning System (GPS) capable mobile telephone that automatically reports its position at a given time interval – set at 30 minutes for the upper harbour survey work.

The movement of the buoy can be followed in real time on the mobile telephone tracking website. The buoy was released in Governors Bay on the north side of the Upper Harbour and tracked for two days, during which time it did not leave the Upper Harbour. The excursion track is shown in Figure No 15.

The buoy reached as far east as the Diamond Harbour pipeline but was then swept back in by the flood tide and ended up around the back of Quail Island. The wind conditions ranged from light north east to calm. The drogue tracks correspond very well with the trajectories of neutrally buoyant particles released in similar positions during model runs of the MSL SELFE hydrodynamic model.

The buoy was also released in Charteris Bay on the south side of the Upper Harbour and tracked for two days. The wind conditions varied from calm to strong north east. The tidal currents were found to be weaker on the south side of the harbour and the tidal excursion less than on the north side of the Upper Harbour. The buoy track is shown in Figure No 16. The buoy became trapped in kelp fringing Quaill Island three times.

The implications of a relatively long dwell time or changeover time in the upper harbour are reflected in the fact sediment accumulation has continued to occur over the last 50 years in the upper harbour with bed level shallowing of around 0.2 m in the three main upper harbour bays – Hart et al 2008b. The upper harbour area is relatively shallow and subject to sediment disturbance by short period waves generated by strong south west winds sweeping down the harbour. Sediment entrained by these waves remains in suspension the upper harbour area. There is no apparent significant movement of sediment out of the upper harbour area.

If there was this would be reflected in the volume of dredged material taken out of the navigation and berthing areas inside the Cashin Quay breakwater.

Sediment entrained into suspension either by wave action or dredging activity in the outer harbour cannot reach the upper harbour in one tidal cycle. To get there it has to pass the sediment traps represented by the navigation channel and berthing areas.

Only sediment entrained on the south side of the channel can escape the sediment traps on the incoming tide. Any suspended sediment reaching the central compartment is likely to be swept over the navigation channel on the outgoing tide. There is no evidence of any accumulation of sediment or shallowing in the central compartment of the harbour.

The source of the sediment causing the shallowing in the upper harbour is likely to be derived from erosion of the local catchment. Transport of sediment from the outer harbour to the upper harbour can be discounted on the basis of the number of tidal cycles it would take to get there and the sediment traps on the way.

6.3 Tidal Models

In addition to the earlier ADCP survey work in 2003, 2007 and 2008 the predictions of the NIWA tidal model for the area were checked. The relatively coarse scale of the model meant that it could not provide detail around the harbour entrance Heads but it did give a good indication of the tidal current directions offshore. Dr Derek Goring found an excellent fit between the NIWA tidal model predictions and the data gathered by the ADCP on the proposed offshore dump site for the dredged material from the extended and deepened channel.

The MSL report Finite Element Hydrodynamic Model of Lyttelton Harbour Rev A 2011 provided an accurate, validated, model of tidal currents in the harbour, supplanting the NIWA model for the harbour however the NIWA model is still valid, and validated, for the offshore tidal currents. The MSL SELFE model used for the latest tidal current predictions further extends the tidal current modelling and predictive capabilities. Each model evolution has added greater detail.

The earlier MSL Princeton Oceanographic Model (POM) summarised in the Mulgor Report has been used by Dr Derek Goring to develop the trajectories of neutrally buoyant particles over a tidal cycle giving results comparable to the physical drogue studies. The trajectories provide a confirmation of the harbour compartmentalisation discussed in Section 6.2.

7.0 IMPACT OF THE PROPOSED CHANGES ON SEDIMENTATION AND TURBIDITY

Prior to considering the effects of the proposed changes on sedimentation the changes to the tidal regime and the wave energy environment derived respectively from the SELFE and SWAN model runs will be considered.

7.1 Tidal Current Changes and their Significance

The results of the tidal modelling work have been synthesized for a perigean spring tide (aka 'King Tide'). These occur every 7 months when lunar perigee coincides with a Full or New Moon. In Lyttelton Harbour, high tide heights at perigean spring tides are 2.51 m above CD and are exceeded by only 6.5% of all high tides.

The changes to the tidal currents consequent on the adoption of the various reclamation scenarios are presented in the Mulgor report as a series of contour maps showing the differences in speed at mid-ebb tide relative to the existing harbour configuration. The maps for the flood tide are essentially the same. Figure No 17 taken from the Mulgor report shows the differences in speed in m/sec. at mid-ebb tide between Scenario 0 (present) and Scenario 2. Positive means the scenario will result in an increase in speed. For Scenarios 1 and 2 the differences are similar indicating that increasing the reclamation by 50 m and widening the channel from 180 to 220 m will not have a significant effect.

To enable the changes to be examined in more detail and to make it easier to compare the different scenarios the data for a set of points shown in Figure No 18 were extracted. Table Nos 3 and 4 were prepared to show the difference in current speeds at the different locations.

		Present	Difference from Present				
	Scenario	**0**	**1**	**2**	**3**	**4**	**5**
1	Reclamation	0.317	-0.040	-0.041	-0.175	-0.041	
2	Parson Rock	0.221	-0.012	-0.018	-0.019	-0.018	
3	Purau Bay	0.060	-0.002	-0.002	-0.002	-0.002	
4	Little Port Cooper	0.035	-0.000	-0.000	-0.000	-0.000	
5	Mouth Port Levy	0.076	-0.000	-0.000	-0.000	-0.000	
6	West Mussel Farm	0.062	-0.001	-0.001	-0.001	-0.001	
7	East Mussel Farm	0.070	-0.000	-0.000	-0.000	-0.000	
8	Diamond Harbour	0.145	-0.020	-0.021	-0.018	-0.021	
9	Charteris Bay	0.233	-0.005	-0.005	-0.005	-0.005	
10	Naval Point B/W	0.412	-0.009	-0.010	-0.009	-0.009	
11	Quail Island North	0.273	-0.012	-0.012	-0.012	-0.012	
12	Cass Bay	0.125	0.012	0.012	0.012	0.012	
13	Rapaki	0.148	0.005	0.006	0.006	0.006	
14	Governors Bay	0.091	0.001	0.001	0.001	0.001	
15	Head of the Bay	0.553	-0.004	-0.005	-0.005	-0.002	
16	Inner Harbour	0.012	-0.000	-0.000	-0.000	-0.016	

Table No 3

Comparison of mid-ebb tide speeds (m/s) between various scenarios for the sites shown in Figure No 18

		Present	Difference from Present				
	Scenario	**0**	**1**	**2**	**3**	**4**	**5**
1	Reclamation	0.323	-0.020	-0.025	-0.147	-0.025	
2	Parson Rock	0.235	-0.014	-0.019	-0.023	-0.019	
3	Purau Bay	0.059	-0.003	-0.003	-0.003	-0.003	
4	Little Port Cooper	0.037	-0.001	-0.001	-0.001	-0.001	
5	Mouth Port Levy	0.081	-0.001	-0.001	-0.001	-0.001	
6	West Mussel Farm	0.062	-0.002	-0.002	-0.002	-0.002	
7	East Mussel Farm	0.072	-0.001	-0.001	-0.001	-0.001	
8	Diamond Harbour	0.155	-0.024	-0.026	-0.025	-0.026	
9	Charteris Bay	0.236	-0.004	-0.004	-0.004	-0.004	
10	Naval Point B/W	0.430	-0.002	-0.002	-0.002	-0.003	
11	Quail Island North	0.290	-0.012	-0.012	-0.012	-0.012	
12	Cass Bay	0.132	0.012	0.012	0.012	0.012	
13	Rapaki	0.156	0.006	0.006	0.006	0.006	
14	Governors Bay	0.098	0.001	0.001	0.001	0.001	
15	Head of the Bay	0.555	-0.002	-0.001	-0.000	-0.001	
16	Inner Harbour	0.012	-0.000	-0.000	-0.000	-0.013	

Table No 4

Comparison of mid-flood tide speeds (m/s) between various scenarios for the sites shown in Figure No 18

- For all scenarios the current speeds at Cass Bay, Rapaki and Governor's Bay will increase slightly. Speeds in Purau Bay, Diamond Harbour, Charteris Bay and the Head of the Bay and at Parson's Rock, Naval Point and Quail Island North will decrease. The largest change in current speed will be in Diamond Harbour where the speeds will decrease by almost 14%. Speeds in Port Levy and Little Port Cooper will not change significantly.
- The largest differences will occur at the Reclamation and for Scenario 3 where the existing speeds will be more than halved.
- In the Inner Harbour the speeds will be more than doubled under Scenario 4 though they are still small.
- There is no significant difference between the ebb and flood tides.

The tidal current speeds are not sufficient to entrain sediment for Scenario 0 and this does not change for any of the scenarios modelled. The only significance of the changes in tidal current speed for sediment transport, sedimentation and turbidity is in the tidal excursion distances. These changes can be ascertained by examining the trajectories of neutrally buoyant particles dropped in to the flow field generated by the SELFE model.

Figure No 19 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 for the present scenario. The trajectories are for two tidal cycles. Except for the particle released in Charteris Bay there is remarkably little variation in the trajectories between one tidal cycle and another, confirming the results of the mobile telephone equipped tidal drogue. Further analysis of the Charteris Bay trajectory shows that it is insensitive to the exact position where the particle is released; the trajectories always drift towards Quail Island like this.

The trajectories of particles released at mid-ebb and mid-flood tides at Diamond Harbour got for the present scenario are shown in Figure No 20.

The simulations shown in Figure Nos 19 and 20 were repeated for Scenarios 1 to 4. Figure No 21 shows the trajectories of the neutrally buoyant particles for Scenario 2, Scenario 0 (present bathymetry) is shown as the grey lines.

For release sites to the west in the 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. 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.

For a particle released at Diamond Harbour at ebb tide, the trajectories for all scenarios follow the trajectory for Scenario 0 and there is essentially no difference between them. The flood tide trajectories are slightly different, especially in the vicinity of Quail Island.

7.1.1 Implication of the Tidal Current Changes

In sum the changes to particle trajectories are insignificant and the implications for sediment transport and turbidity will be correspondingly insignificant and undiscernible.

7.2 Changes to the Wave Energy Environment

SWAN analyses of the various reclamation scenarios – Mulgor report – Implications of the Lyttelton Port Recovery Plan on Waves and Tidal Currents in Lyttelton Harbour - show a similar pattern, with reductions in wave height to the south of the reclamation and along the dredged shipping channel, and increases in wave height either side of the shipping channel. The effects in the Upper Harbour are very small. This is confirmed by the results for Scenario 2. Figure No 22 shows the difference in mean wave height for Scenario 2.

To examine the differences in more detail and compare the effects of the various scenarios Mulgor extracted data for several points as shown in Figure No 23. The wave heights at these locations before and after reclamation are presented in Table No 5.

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

Table No 5

For the Sites Shown in Figure No 23, Mean Wave Heights for the Present Bathymetry and Differences for the Various Scenarios (positive means an increase, negative means a decrease from present)

The following points are apparent from an examination of Table No 5. Under any of the proposed scenarios:

- waves in the central harbour will decrease by up to 39%
- waves at Livingstone and Camp Bays will increase by 13%
- waves in Little Port Cooper will increase by a small amount
- waves at Putiki in Port Levy will increase by 10%
- at Purau Bay and Diamond Harbour the waves will decrease by up to 30%
- at Rapaki the waves will decrease by a small amount, except for Scenario 3 where waves will increase by 5%
- for Scenario 4 – removal of the Inner Harbour eastern mole, removal of Z 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
- the effect of the breakwater in 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 No 6. The pattern is similar to Table No 5 and the comments on that table listed above also apply for the data in Table No 6, except for Rapaki where the 99% wave height increases by up to 5% under any of the scenarios.

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

Table No 6

For the Sites Shown in Figure No 18, Wave Heights that are exceeded by 1% of the Time for the Present Bathymetry and Differences for the Various Scenarios
(positive means in increase, negative means a decrease from present)

7.2.1 Implication of the Changes in the Wave Energy Environment

On the face of it a 39% reduction in the wave height in the central harbour appears to be significant. The mean significant wave height for the existing situation is 0.45 m reducing to 0.290 for Scenarios 2 and 4. The corresponding maximum wave particle velocities at seabed level for a 12 second period wave are respectively 0.34 m/sec and 0.21 m/sec calculated using stream function theory. For Scenario 3 the wave particle velocity reduces to 0.20 m/sec. The wave particle velocities for the mean significant wave height is close to or just under the wave particle velocity that will cause erosion of the seabed. For the significant wave heights that are exceeded only 1% of the time for all scenarios the wave particle velocities are comfortably in excess of the approximate erosion velocity figure. This coupled with the fact that the seabed is generally firmer in this area than elsewhere, being well away from the previous dumping grounds on the north side of the harbour, and separated from them by a sediment trap in the form of the navigation channel, means that the significance of the wave height reduction is less than minor. There is no significant change to the erosion regime. Any sediment that drops out of suspension in this location is still likely to be readily mobilised and swept away.

An inspection by engineer/diver (7 November 2014) of the seabed at the central harbour location, Figure No 23, confirmed a firm cohesive seabed underlying a thin (50 mm) layer of very soft mobile silt. An inspection of seabed at Diamond Harbour found a firm seabed.

The central harbour area is where both the swell waves and the locally generated short period waves are effective in mobilising the seabed sediment. The swell waves have attenuated with passage up the harbour but still have enough height in this area to entrain sediment. The short period waves start to be effective as sediment mobilisation agents. The maximum wave particle velocity for a 3.5 second period 1.2 m significant wave height at seabed level is 0.29 m/sec.

At the Diamond Harbour location the mean significant wave height is .154 m. The reduction in height for Scenarios 2 and 4 is 23%. The practical difference is insignificant because the swell wave height is so low. Wind waves dominate the wave energy spectrum at this location and they are unchanged.

At Rapaki the reduction or, for Scenario 3, the 5% increase in swell height is insignificant. The wave energy environment in this area is dominated by the short period locally generated waves. Only they are capable of stirring the seabed and entraining sediment. The significant wave height at Rapaki that is exceeded 1% of time, H_s =0.3 m induced water particle velocities of 0.2 m/sec, less than the erosion velocity.

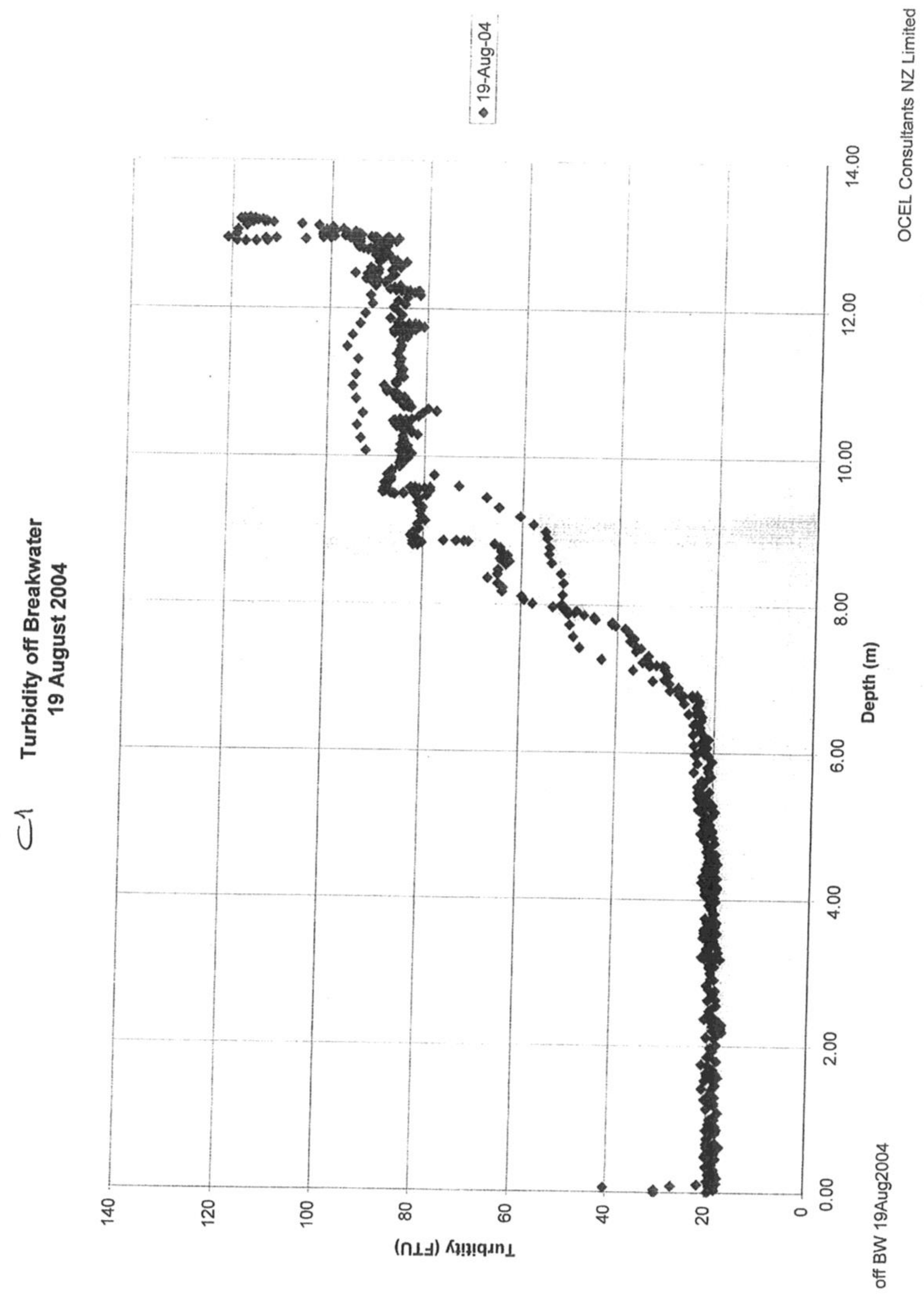
The net effect of the changes for all the scenarios will be indiscernible.

7.3 Implications for Construction Activities

The new reclamation will have wharf structures built in place on the face of the reclamation. The wharf construction activities both on the face of the new reclamation and in the Inner Harbour area redevelopment will involve pile driving, rip rap placement and some limited dredging using a clam shell. There will be some local increases in turbidity as a result but these will only be visually apparent in the immediate vicinity of the construction work and will soon be lost against the natural background turbidity. There will be no discernible change from the present situation.

Lyttelton is a naturally turbid environment so a turbidity plume generated by construction activities causes only a transient spike in the suspended sediment/turbidity before becoming indistinguishable from the background turbidity. Turbidity plumes are self limiting to the extent that the higher the concentration or saturation of the water column with suspended solids the faster the sediment will settle out. With increasing interparticle collusions as a consequence of the higher concentration of particles the probability of formation of flocs from dispersed (non flocculated) particles increases. The generation of turbidity plumes associated with the recovery is not predicted to be significant.

APPENDIX A


C1
Turbidity off Breakwater
19 August 2004
Turbidity (FTU)
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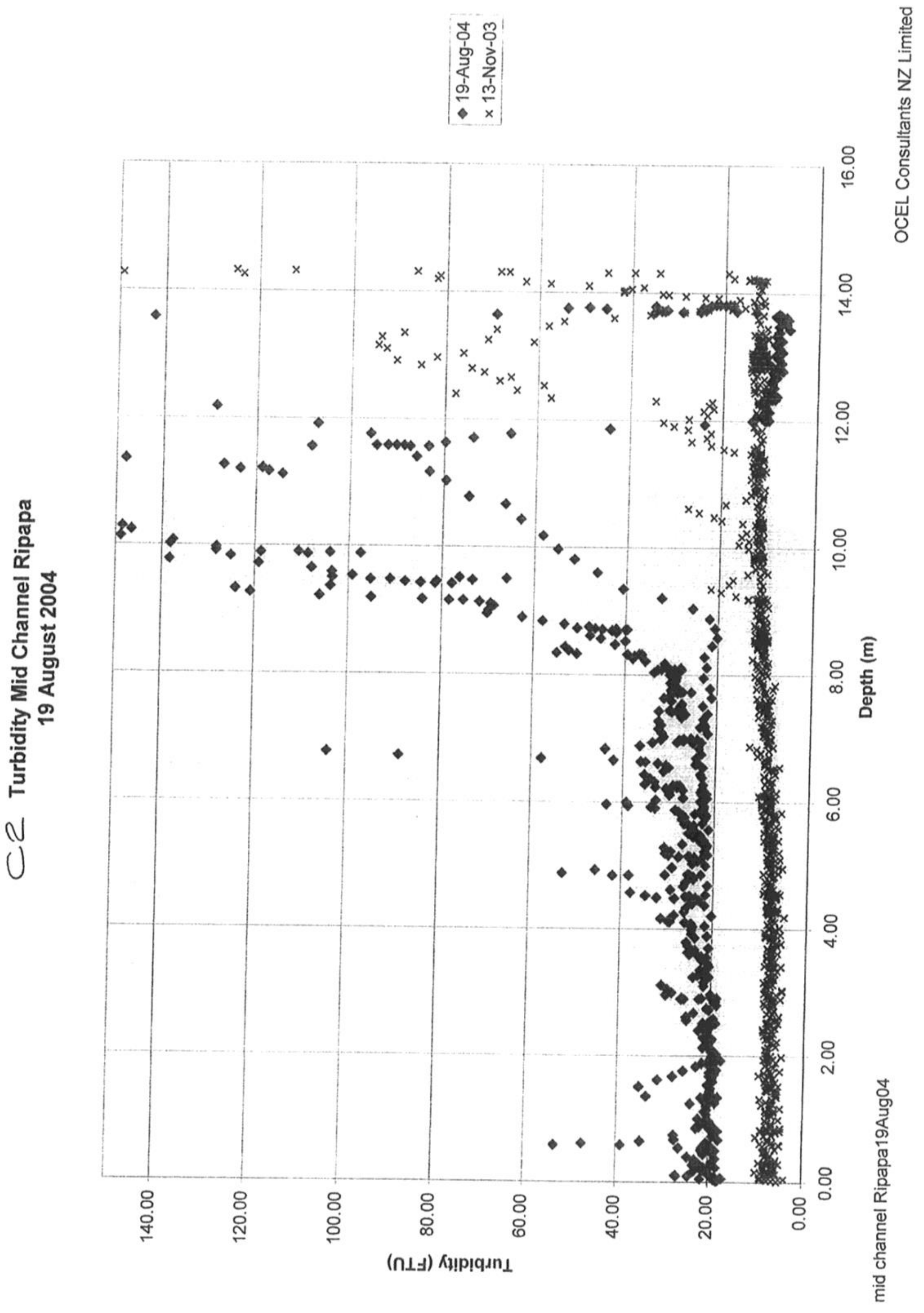
120
100
80
60
40
20
0
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Depth (m)
19-Aug-04
off BW 19Aug2004
OCEL Consultants NZ Limited



C2
Turbidity Mid Channel Ripapa
19 August 2004
19-Aug-04
13-Nov-03
Turbidity (FTU)
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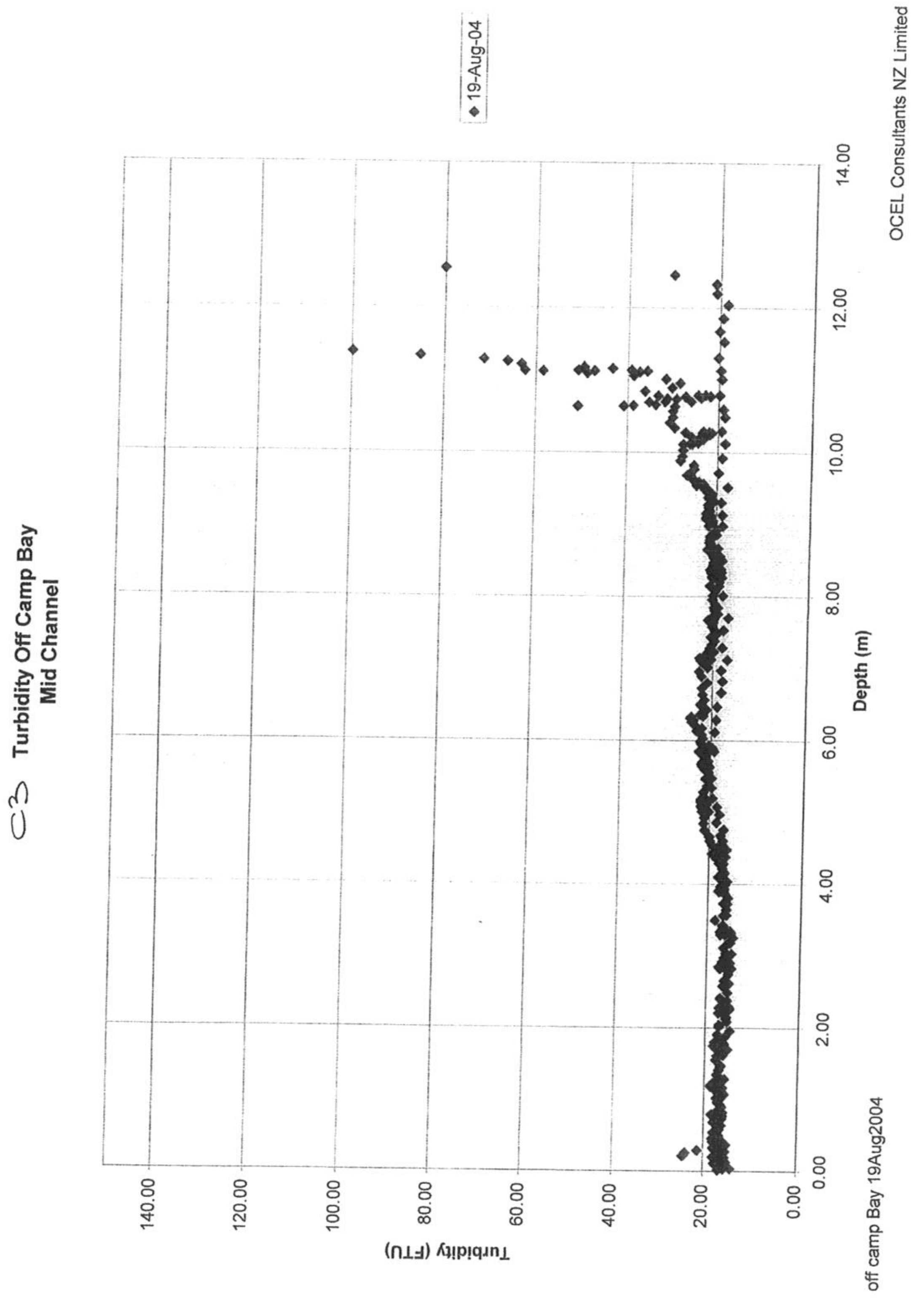
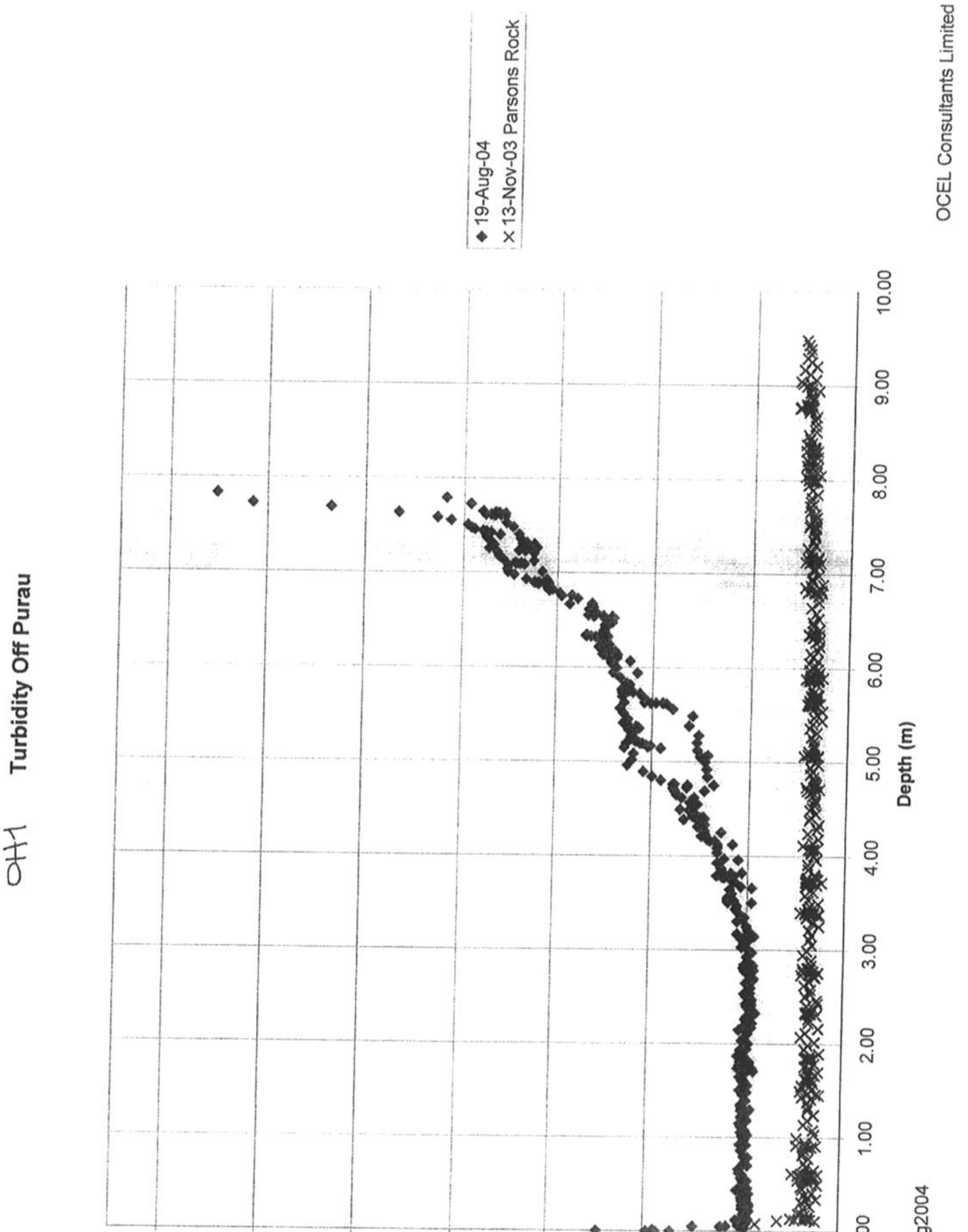
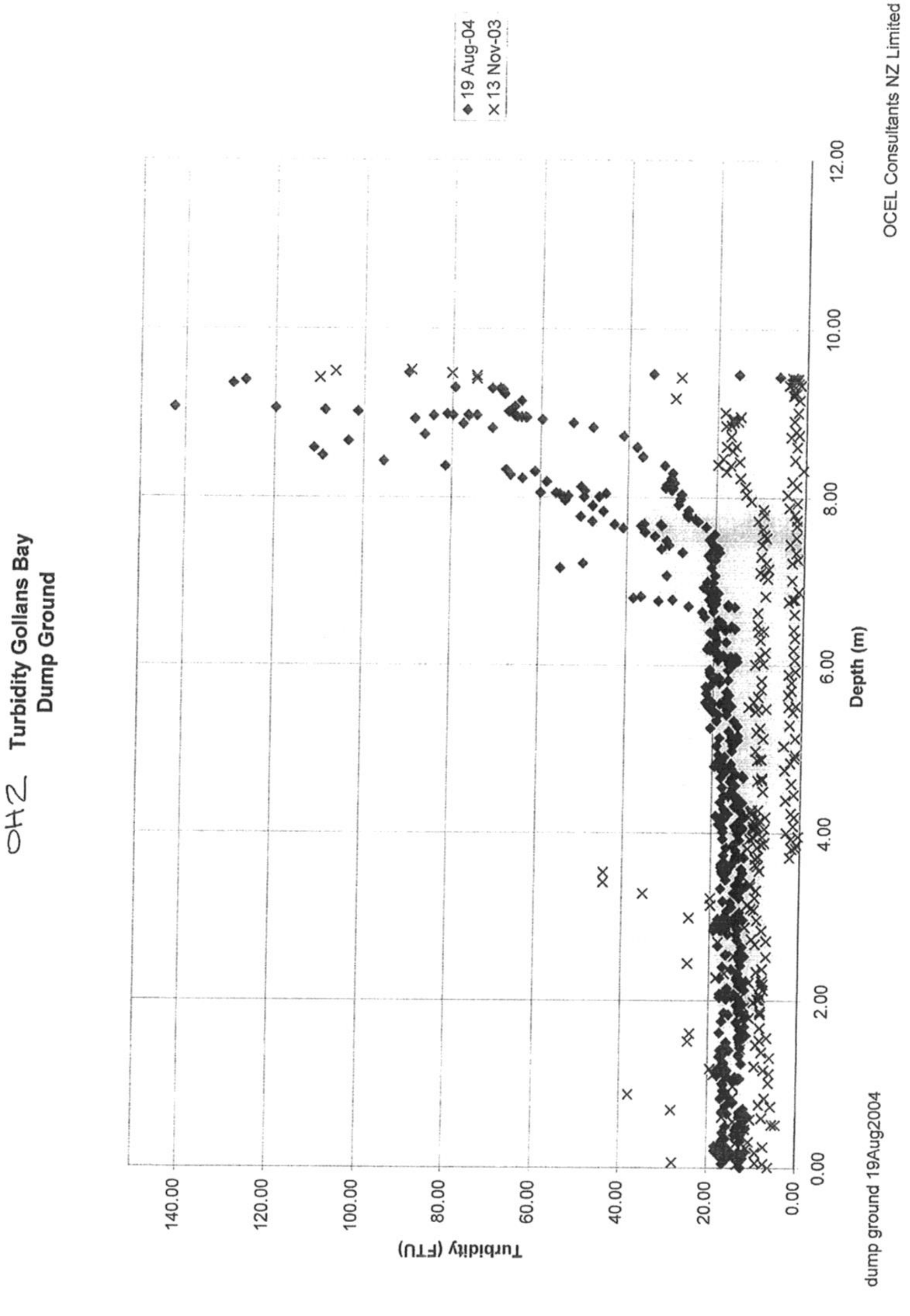
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Depth (m)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
mid channel Ripapa19Aug04
OCEL Consultants NZ Limited


C3
Turbidity Off Camp Bay
Mid Channel
19-Aug-04
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Depth (m)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
off camp Bay 19Aug2004
OCEL Consultants NZ Limited



OH1
Turbidity Off Purau
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
Depth (m)
19-Aug-04
13-Nov-03 Parsons Rock
off Purau 19Aug2004
OCEL Consultants Limited


OH2
Turbidity Gollans Bay
Dump Ground
19 Aug-04
13 Nov-03
Turbidity (FTU)
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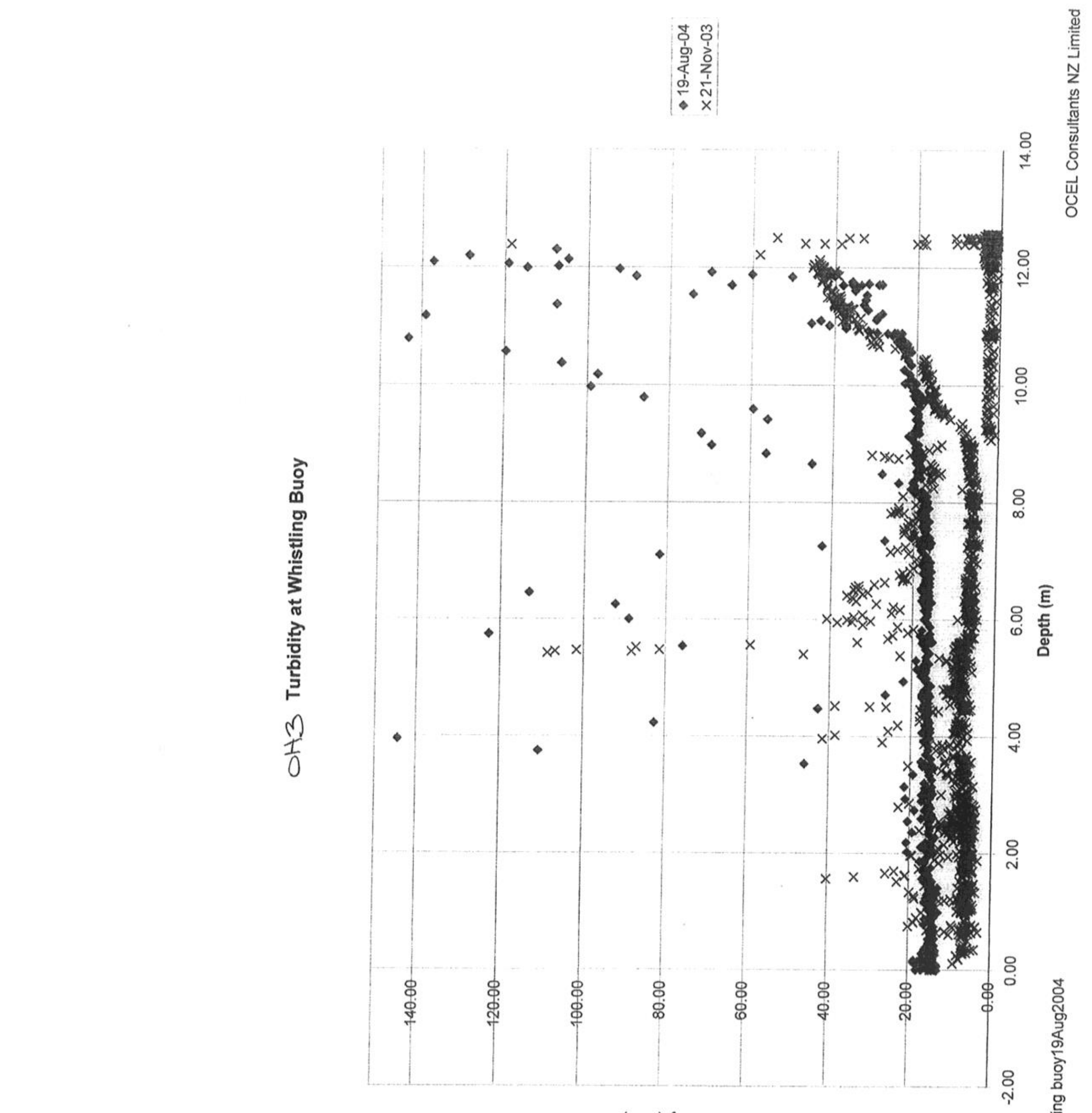
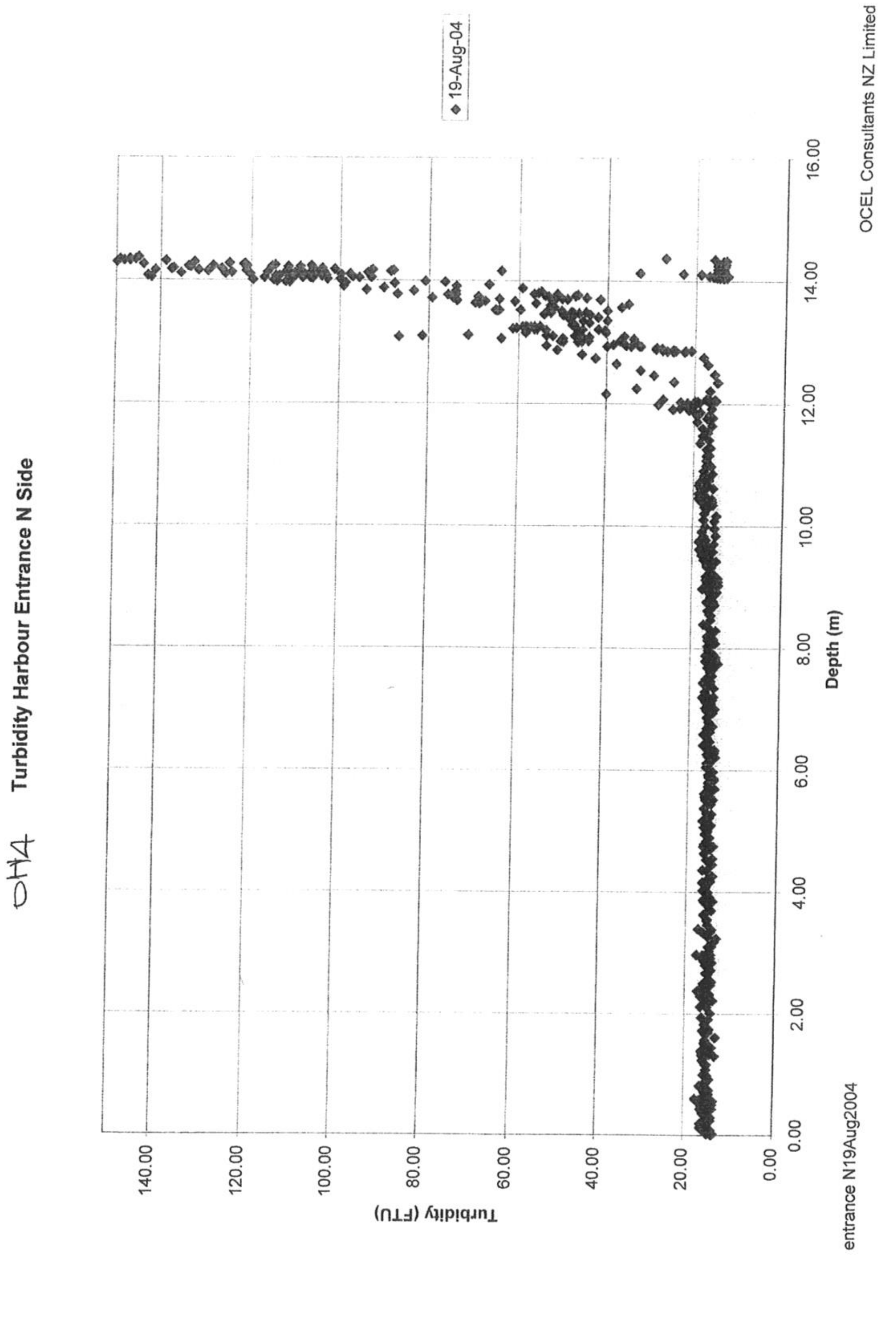
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
Depth (m)
dump ground 19Aug2004
OCEL Consultants NZ Limited


OH3 Turbidity at Whistling Buoy
Turbidity (FTU)
Depth (m)
19-Aug-04
21-Nov-03
whistling buoy19Aug2004
OCEL Consultants NZ Limited
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00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Turbidity Harbour Entrance N Side
◆ 19-Aug-04
Turbidity (FTU)
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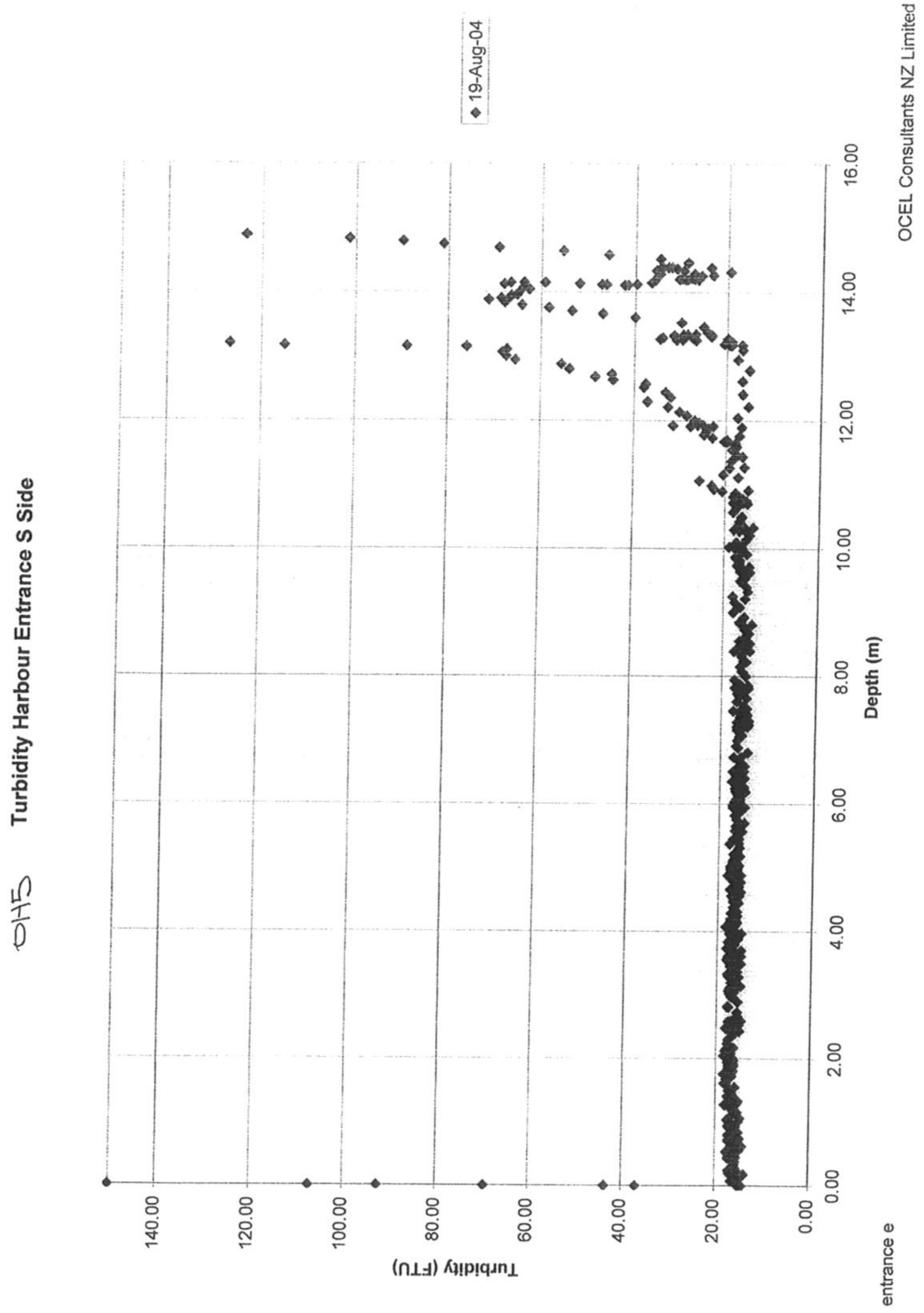
100.00
80.00
60.00
40.00
20.00
0.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
Depth (m)
entrance N19Aug2004
OCEL Consultants NZ Limited


0H5
Turbidity Harbour Entrance S Side
19-Aug-04
Turbidity (FTU)
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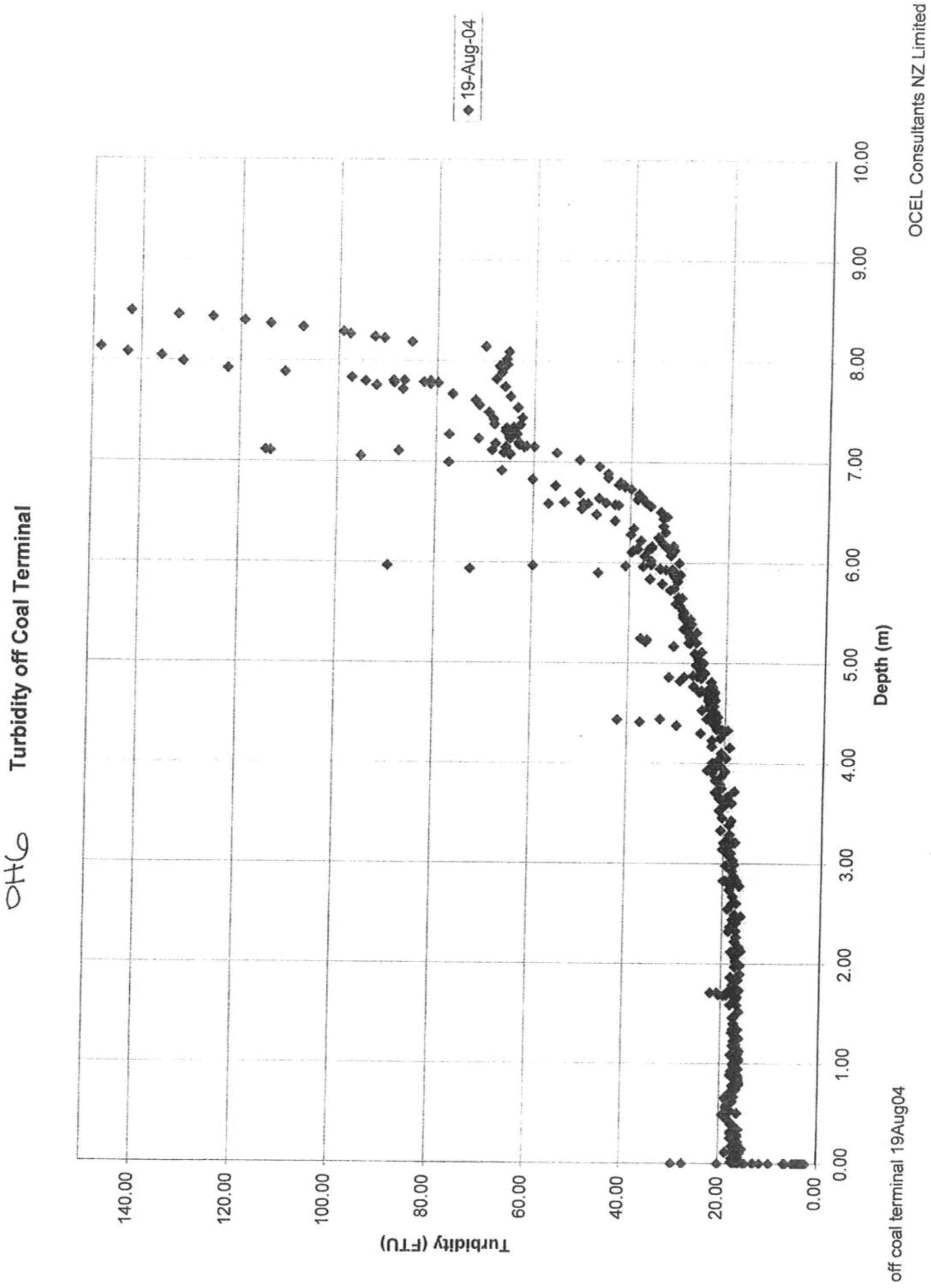
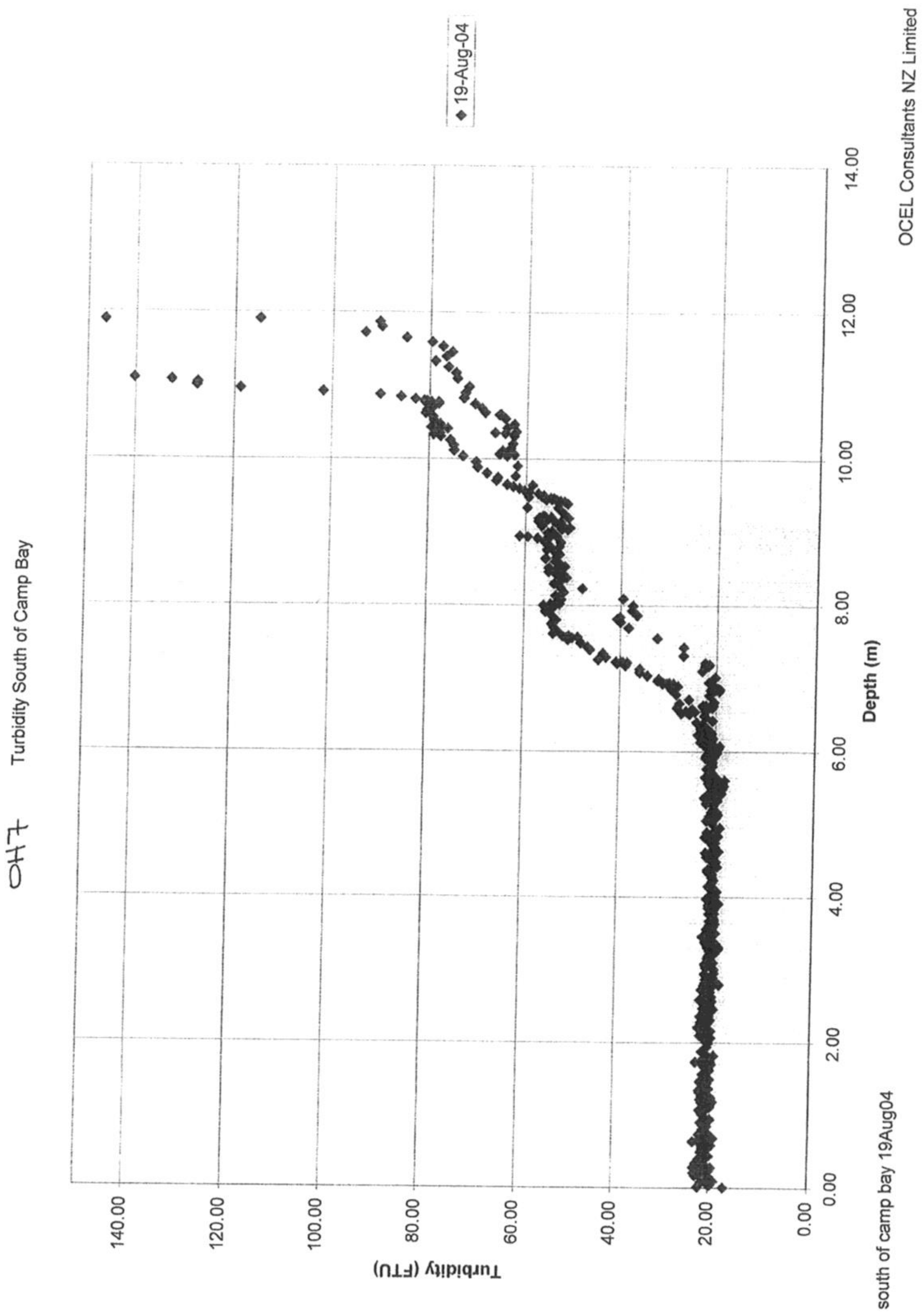
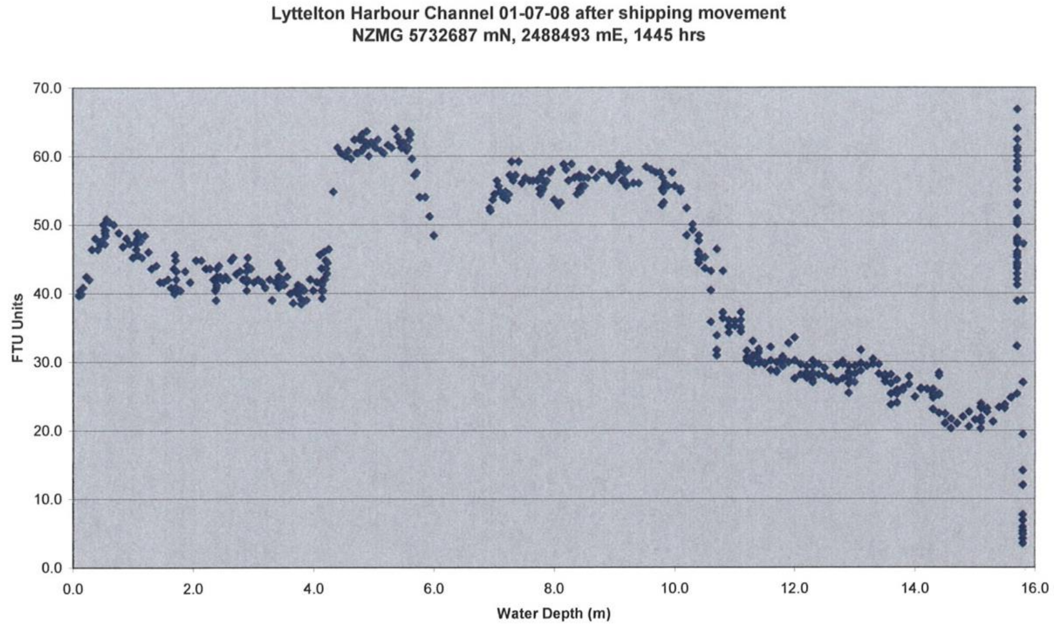
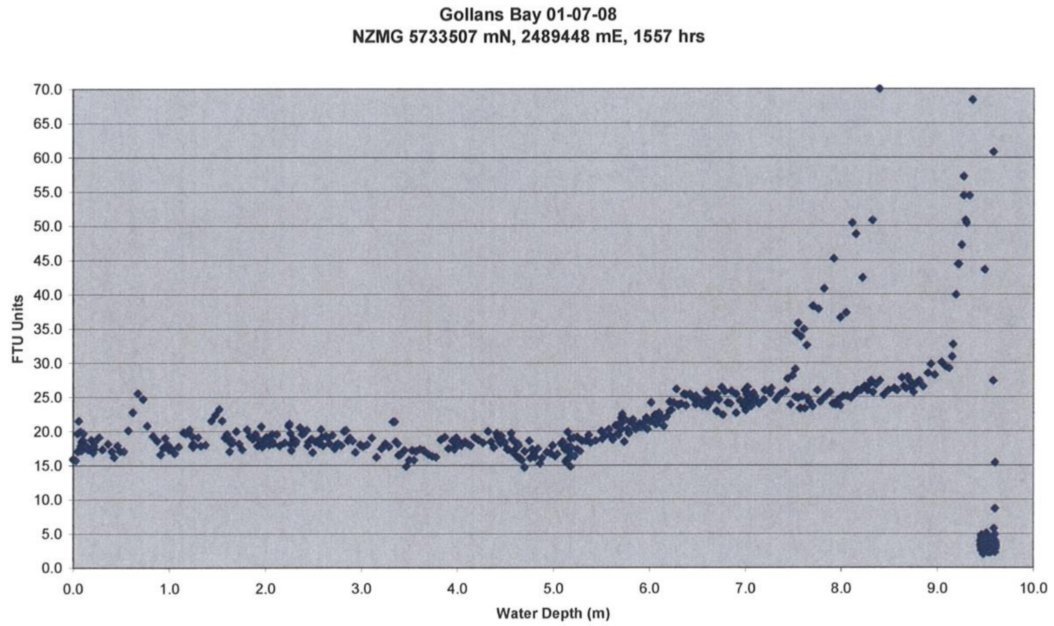
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
Depth (m)
entrance e
OCEL Consultants NZ Limited

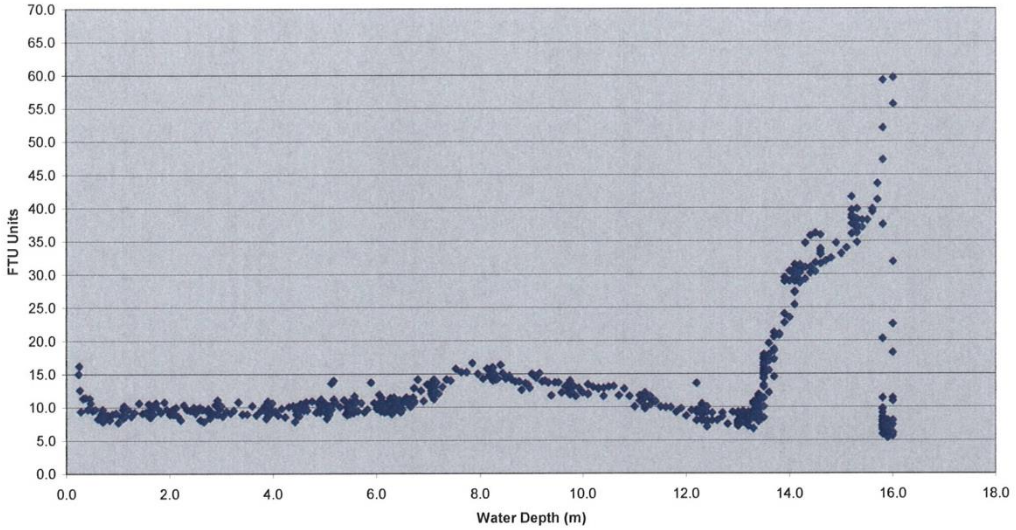

Turbidity off Coal Terminal
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
Depth (m)
19-Aug-04
off coal terminal 19Aug04
OCEL Consultants NZ Limited


OH7
Turbidity South of Camp Bay
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Depth (m)
19-Aug-04
south of camp bay 19Aug04
OCEL Consultants NZ Limited

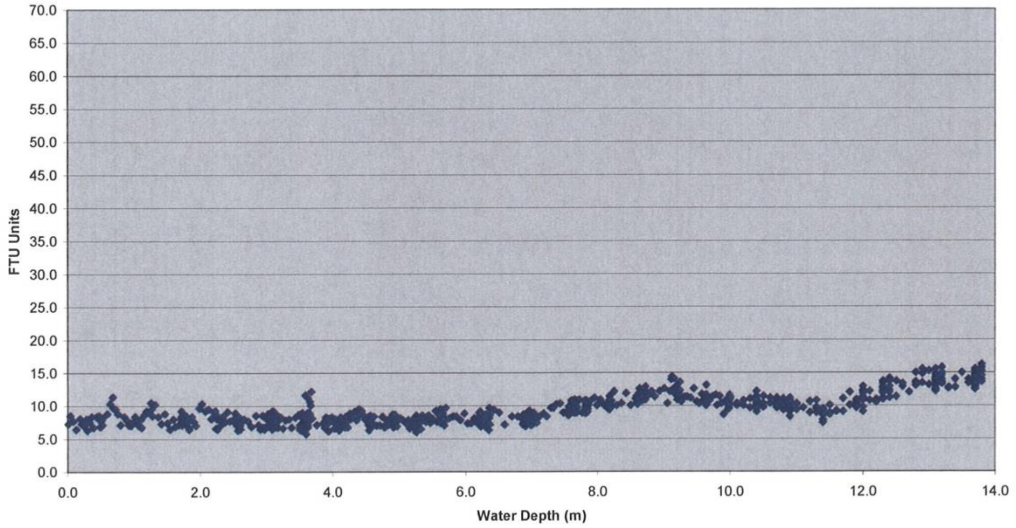

Lyttelton Harbour Channel 01-07-08 after shipping movement
NZMG 5732687 mN, 2488493 mE, 1445 hrs
FTU Units
Water Depth (m)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0


Gollans Bay 01-07-08
NZMG 5733507 mN, 2489448 mE, 1557 hrs
FTU Units
Water Depth (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
60.0
65.0
70.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

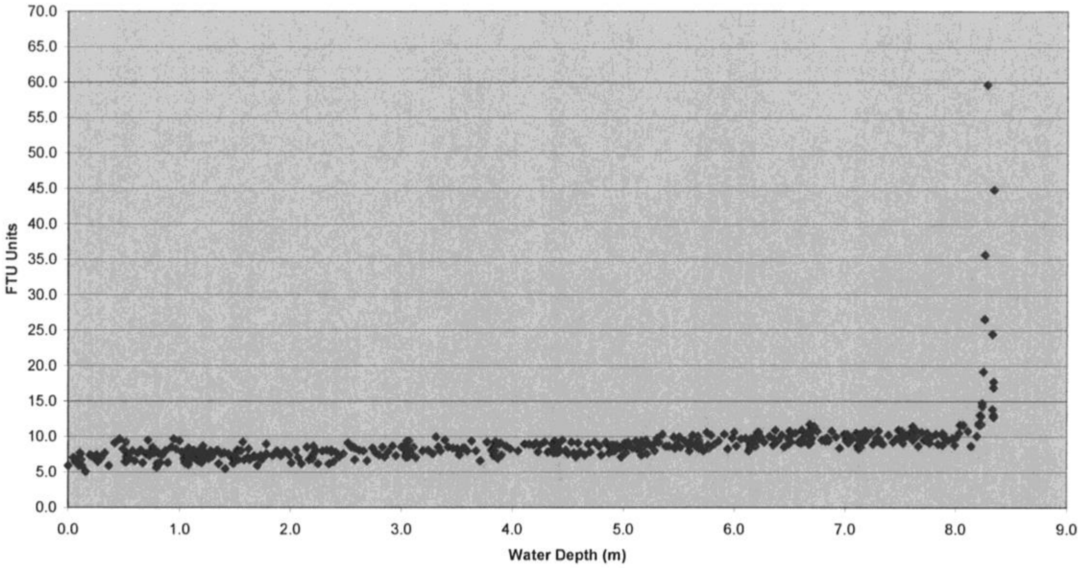
Adderley Head 01-07-08
NZMG 5733796 mN, 2495784 mE, 1520 hrs



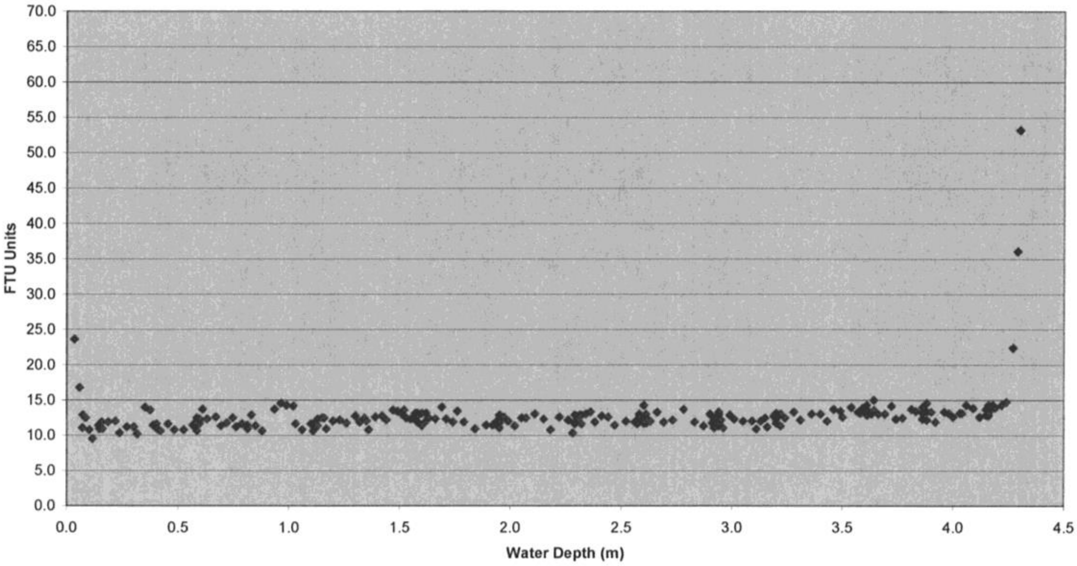
Port Levy Heads 01-07-08
NZMG 5732966 mN, 2497069 mE, 1538 hrs



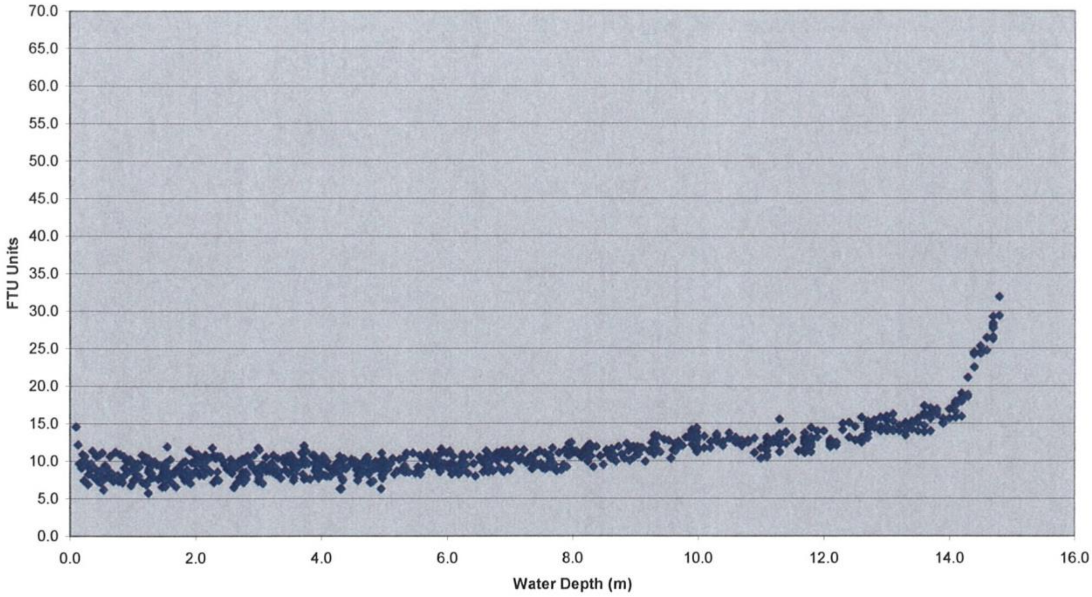
Port Levy 01-07-08
NZMG 5730609 mN, 2496180 mE, 1529 hrs



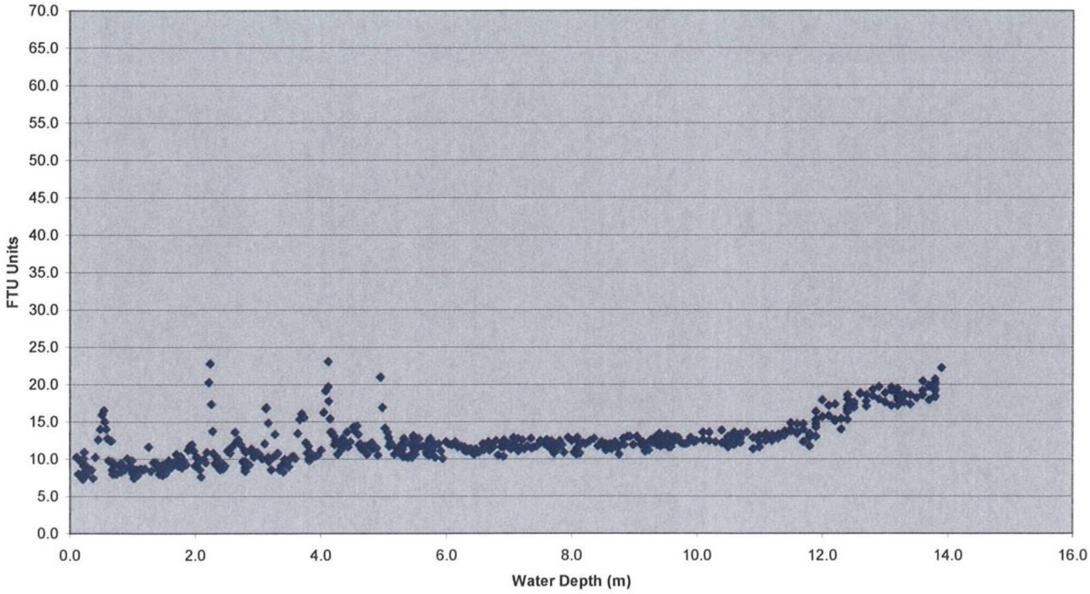
Rapaki Bay 01-07-08
NZMG 5732657 mN, 2488039 mE, 1607 hrs

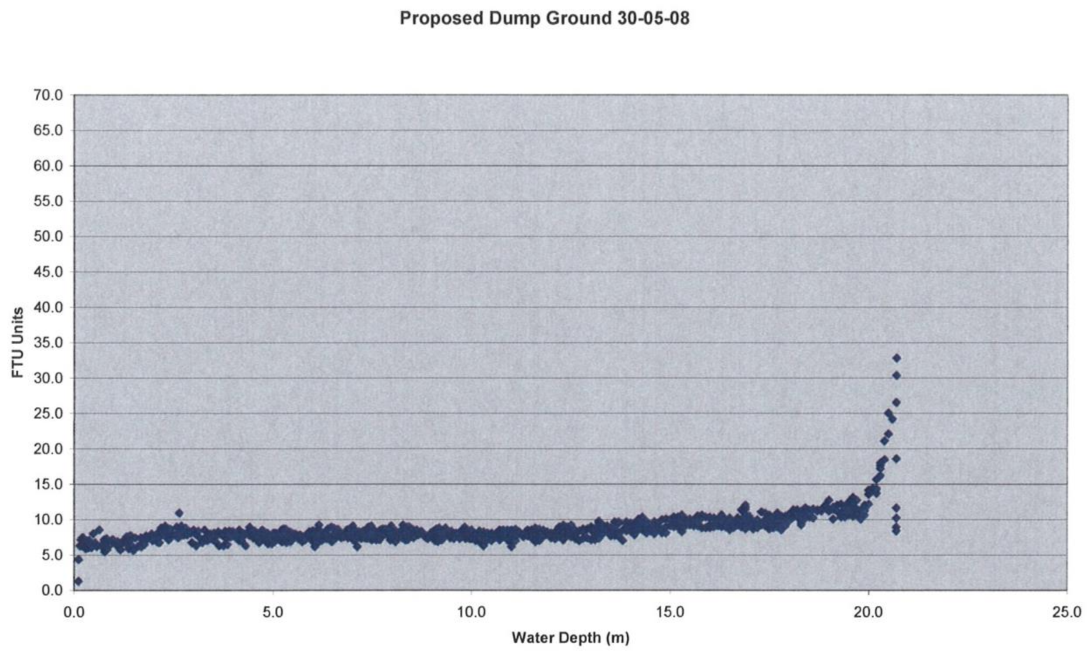


Adderley Head 30-05-08



Godley Head 30-05-08




Proposed Dump Ground 30-05-08
FTU Units
Water Depth (m)
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0

CRL Energy Ltd

Water Quality Report

OCEL Consultants NZ Limited
276 Antigua Street
Christchurch
Christchurch 8140
Attention: Gary Teear

Report Number: 08/1565
Issue: 1
Date: 21 October 2008

Sample : 08/1565-01 **Order No.** :
Sample Date : 15/10/2008 **Time**: 00:00 **Date Received** : 17/10/2008
Description : TPAC-00 Trackpack samples
Sample Number 1
Notes : Lyttelton Harbour Channel Extension Project

Test Code		Result
0120	Turbidity	600 NTU
0121	Suspended Solids	870 g/m3

Sample : 08/1565-02 **Order No.** :
Sample Date : 15/10/2008 **Time**: 00:00 **Date Received** : 17/10/2008
Description : TPAC-00 Trackpack samples
Sample Number 2
Notes : Lyttelton Harbour Channel Extension Project

Test Code		Result
0120	Turbidity	60 NTU
0121	Suspended Solids	138 g/m3

Sample : 08/1565-03 **Order No.** :
Sample Date : 15/10/2008 **Time**: 00:00 **Date Received** : 17/10/2008
Description : TPAC-00 Trackpack samples
Sample Number 3
Notes : Lyttelton Harbour Channel Extension Project

Test Code		Result
0120	Turbidity	750 NTU
0121	Suspended Solids	935 g/m3

Sample	: 08/1565-04	**Order No.** :
Sample Date	: 15/10/2008 **Time**: 00:00	**Date Received** : 17/10/2008
Description	: TPAC-00 Trackpack samples Sample Number 4	
Notes	: Lyttelton Harbour Channel Extension Project	

Test Code		**Result**
0120	Turbidity	120 NTU
0121	Suspended Solids	233 g/m3

Sample	: 08/1565-05	**Order No.** :
Sample Date	: 15/10/2008 **Time**: 00:00	**Date Received** : 17/10/2008
Description	: TPAC-00 Trackpack samples Sample Number 5	
Notes	: Lyttelton Harbour Channel Extension Project	

Test Code		**Result**
0120	Turbidity	80 NTU
0121	Suspended Solids	191 g/m3

Sample	: 08/1565-06	**Order No.** :
Sample Date	: 15/10/2008 **Time**: 00:00	**Date Received** : 17/10/2008
Description	: TPAC-00 Trackpack samples Sample Number 6	
Notes	: Lyttelton Harbour Channel Extension Project	

Test Code		**Result**
0120	Turbidity	160 NTU
0121	Suspended Solids	281 g/m3

All samples analysed as received

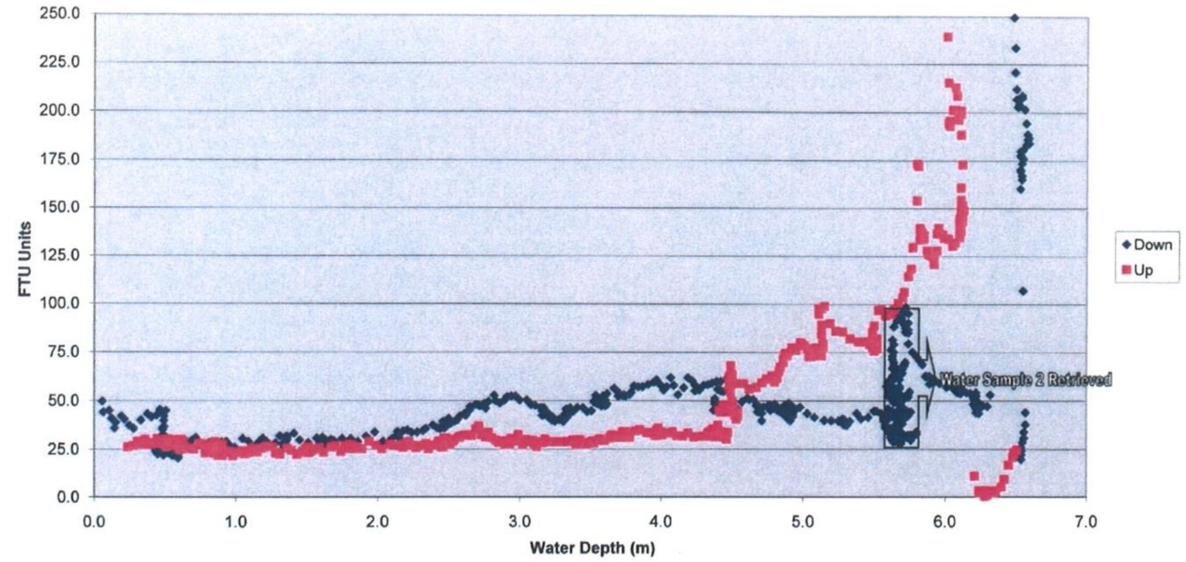
Comments:

All testing is performed in accordance with APHA Standard Methods, 21st edition 2005. The methods of analysis and their precision are available on request.

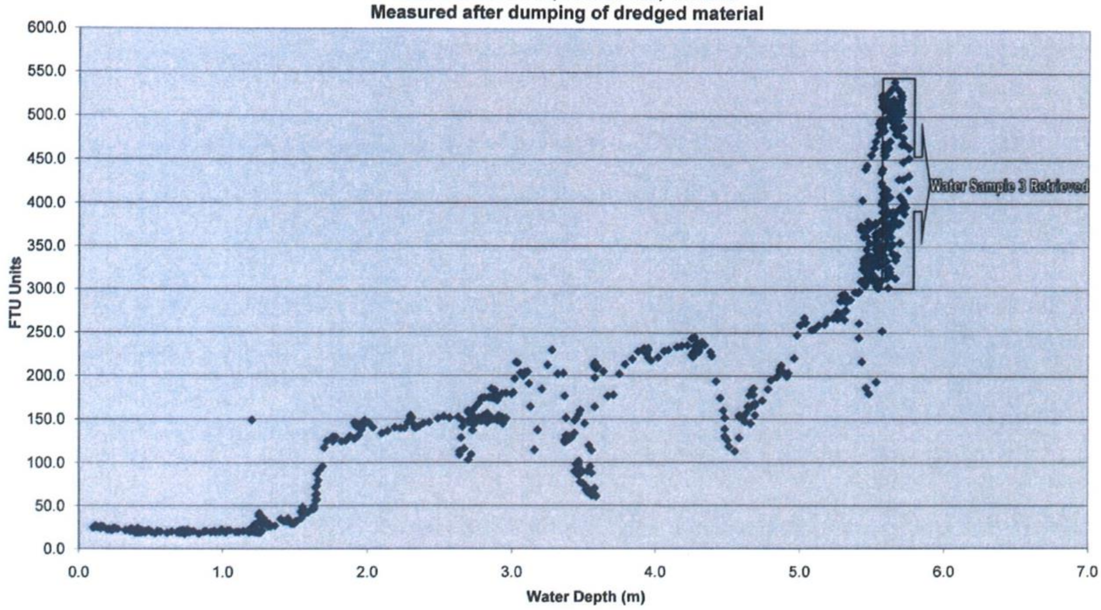
This report may only be reproduced in full.

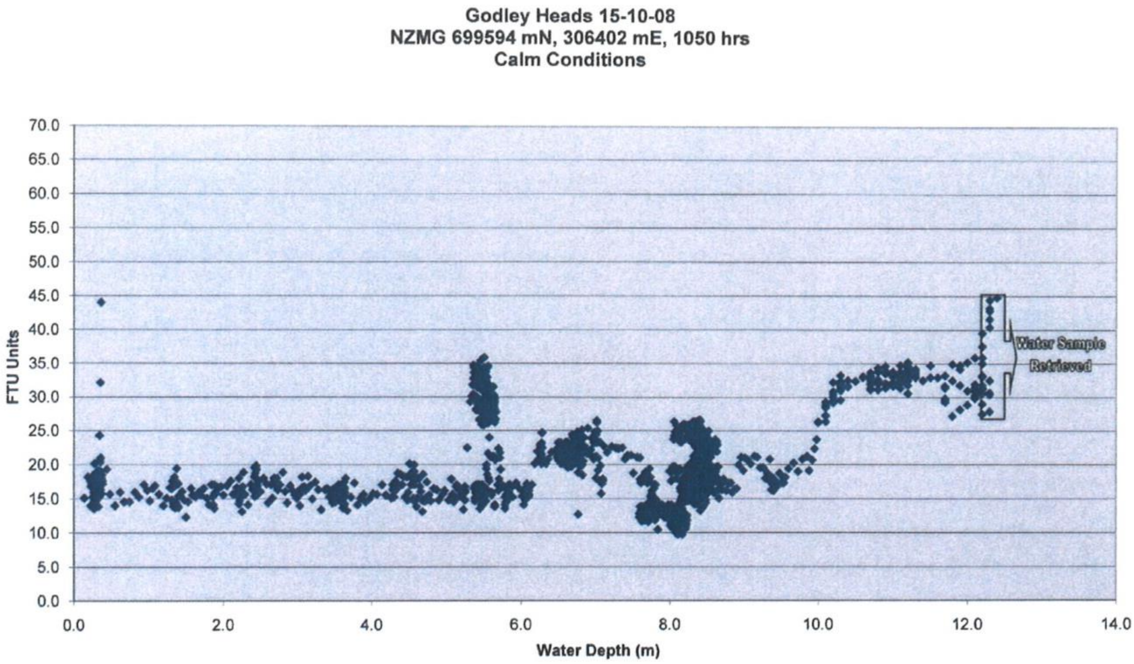
Malcom Watts
Laboratory Manager

Gollans Bay 15-10-08
NZMG 698603 mN, 301994 mE, 1005hrs
Measured after dumping of dredged material

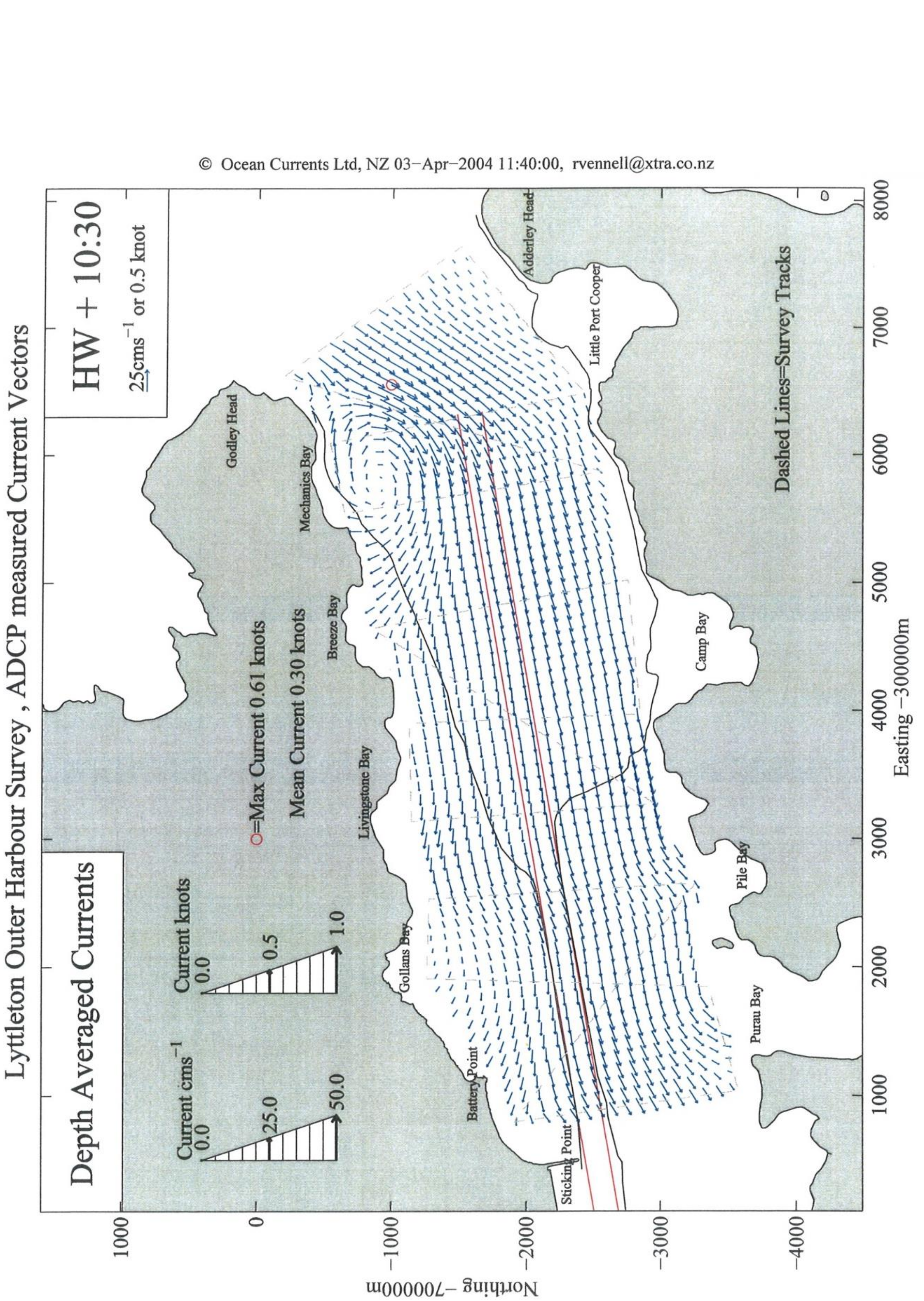


Gollans Bay 15-10-08
NZMG 698603 mN, 301994 mE, 1032hrs
Measured after dumping of dredged material




Godley Heads 15-10-08
NZMG 699594 mN, 306402 mE, 1050 hrs
Calm Conditions
FTU Units
Water Depth (m)
Water Sample Retrieved
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0

GRAPHS



© Ocean Currents Ltd, NZ 03−Apr−2004 11:40:00, rvennell@xtra.co.nz
Lyttleton Outer Harbour Survey , ADCP measured Current Vectors
HW + 10:30
25cms−1 or 0.5 knot
Depth Averaged Currents
Current cms−1
0.0
25.0
50.0
Current knots
0.0
0.5
1.0
O=Max Current 0.61 knots
Mean Current 0.30 knots
Godley Head
Mechanics Bay
Breeze Bay
Livingstone Bay
Gollans Bay
Battery Point
Sticking Point
Adderley Head
Little Port Cooper
Camp Bay
Pile Bay
Purau Bay
Dashed Lines=Survey Tracks
Easting −300000m
Northing −700000m
1000
2000
3000
4000
5000
6000
7000
8000
0
−1000
−2000
−3000
−4000

Figure No 1

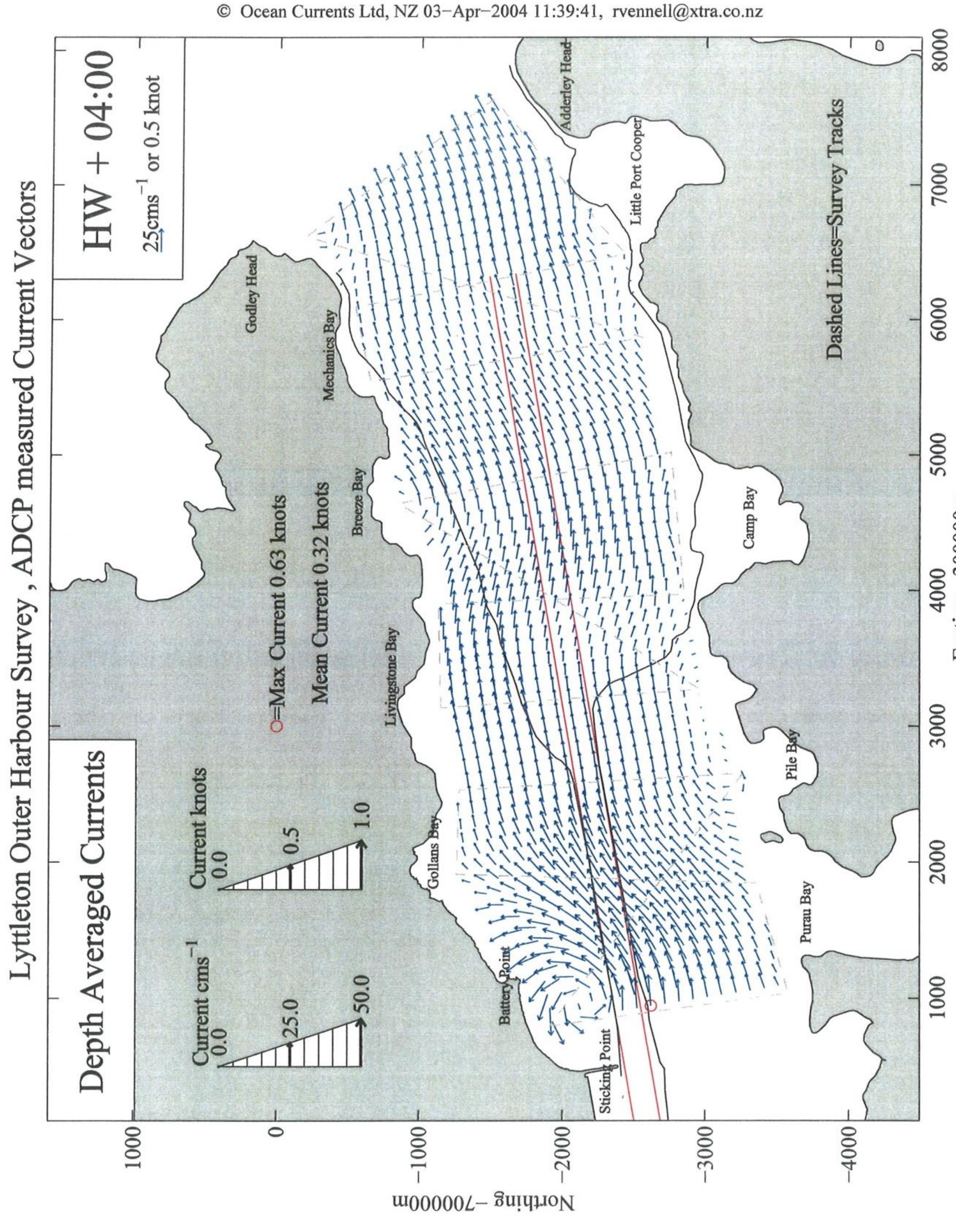
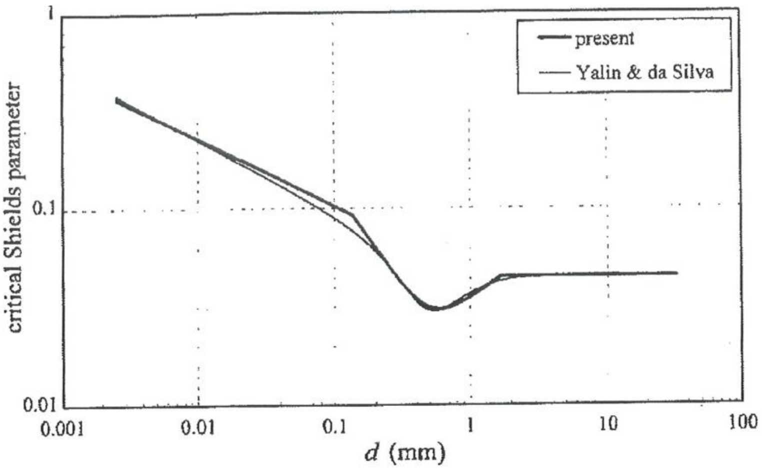
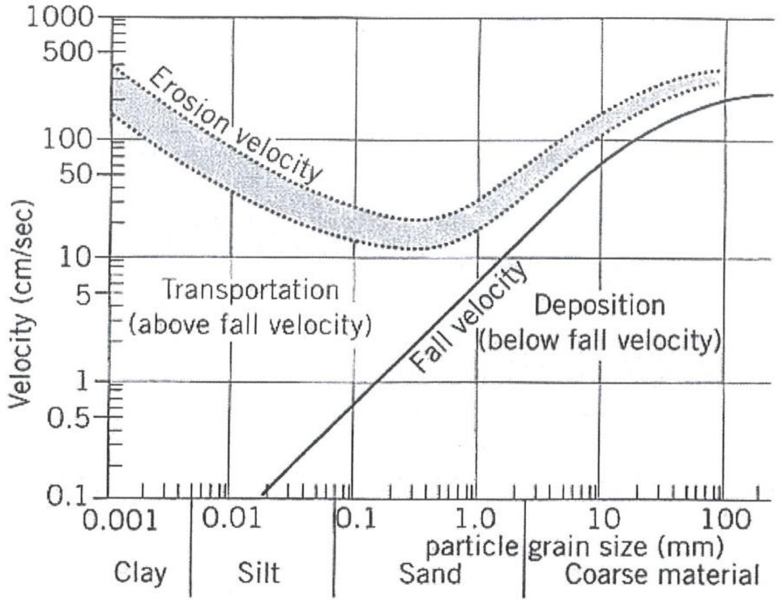

© Ocean Currents Ltd, NZ 03-Apr-2004 11:39:41, rvennell@xtra.co.nz
Lyttleton Outer Harbour Survey , ADCP measured Current Vectors
HW + 04:00
25cms^-1 or 0.5 knot
Depth Averaged Currents
Current cms^-1
0.0
25.0
50.0
Current knots
0.0
0.5
1.0
=Max Current 0.63 knots
Mean Current 0.32 knots
Godley Head
Mechanics Bay
Breeze Bay
Livingstone Bay
Gollans Bay
Battery Point
Sticking Point
Adderley Head
Little Port Cooper
Camp Bay
Pile Bay
Purau Bay
Dashed Lines=Survey Tracks
Easting -300000m
Northing -70000m
1000
2000
3000
4000
5000
6000
7000
8000
0
-1000
-2000
-3000
-4000

Figure No 2



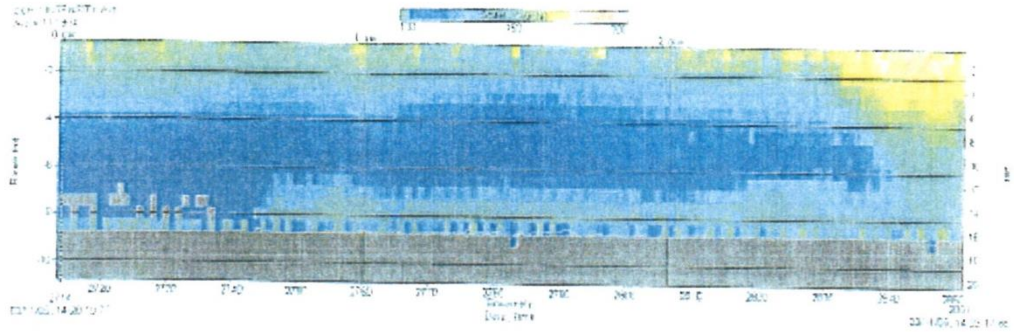
Critical Shields Parameter as Function of Particle Diameter (0

Figure No 3

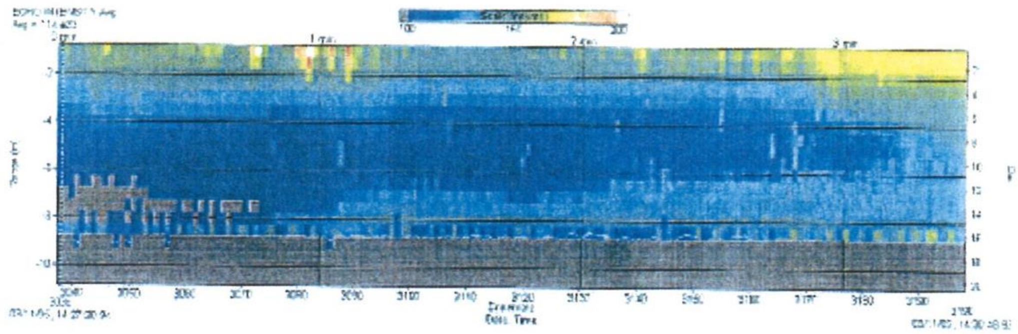


Hjulström Curve

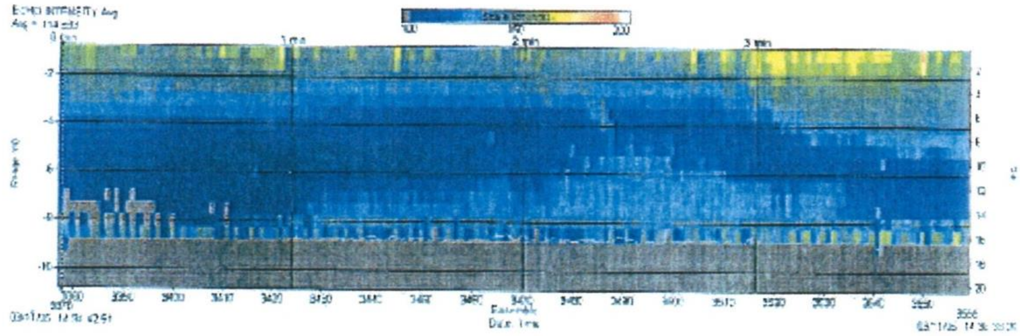
Figure No 4



Echo intensity along ADCP transect 6 (drop zone at right of figure, start transect time 14:120, time since release ~16 minutes)

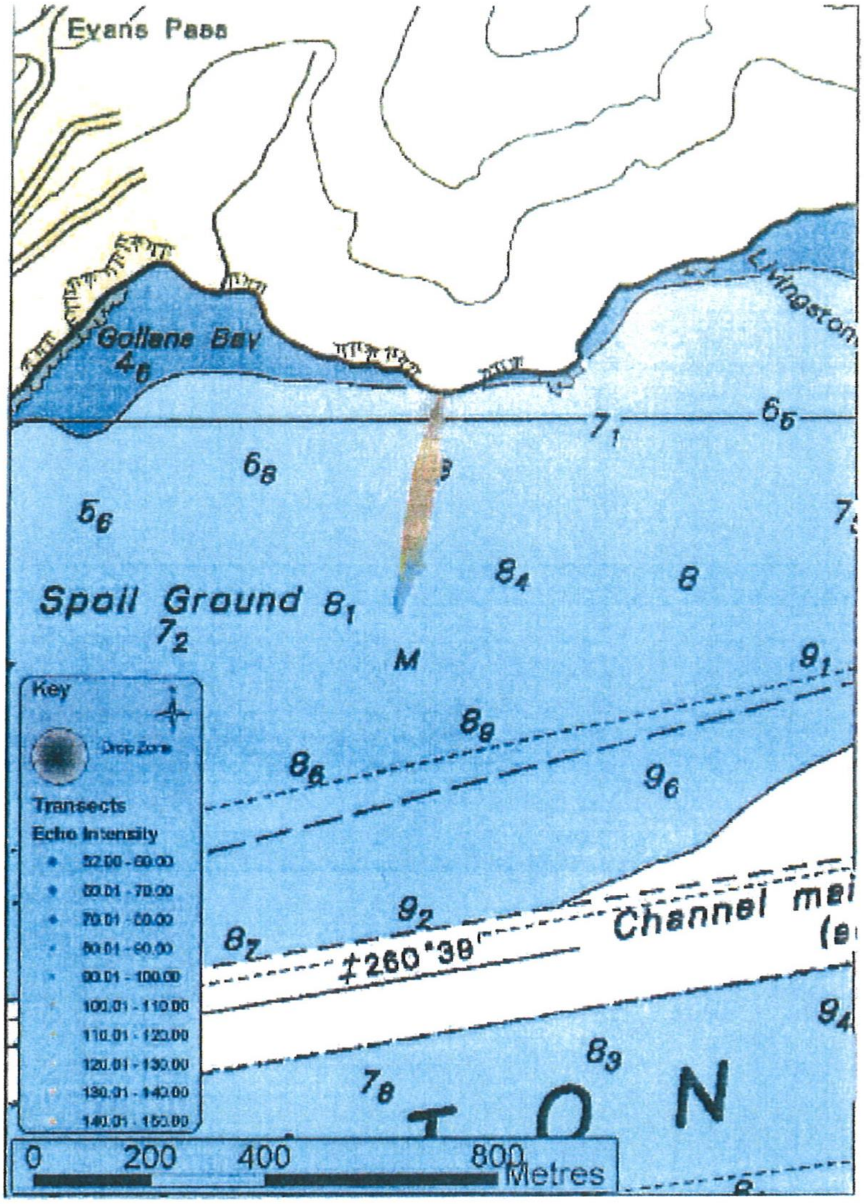


Echo intensity along ADCP transect 8 (drop zone at right of figure, start transect time 14:27, time since release ~23 minutes)



Echo intensity along ADCP transect 10 (drop zone at right of figure, start transect time 14:34, time since release ~30 minutes)

Figure No 5



Location diagram of drop zone, ADCP transects and main channel (in white). (Based on NZ Chart 6321, LINZ 2000).

Figure No 6

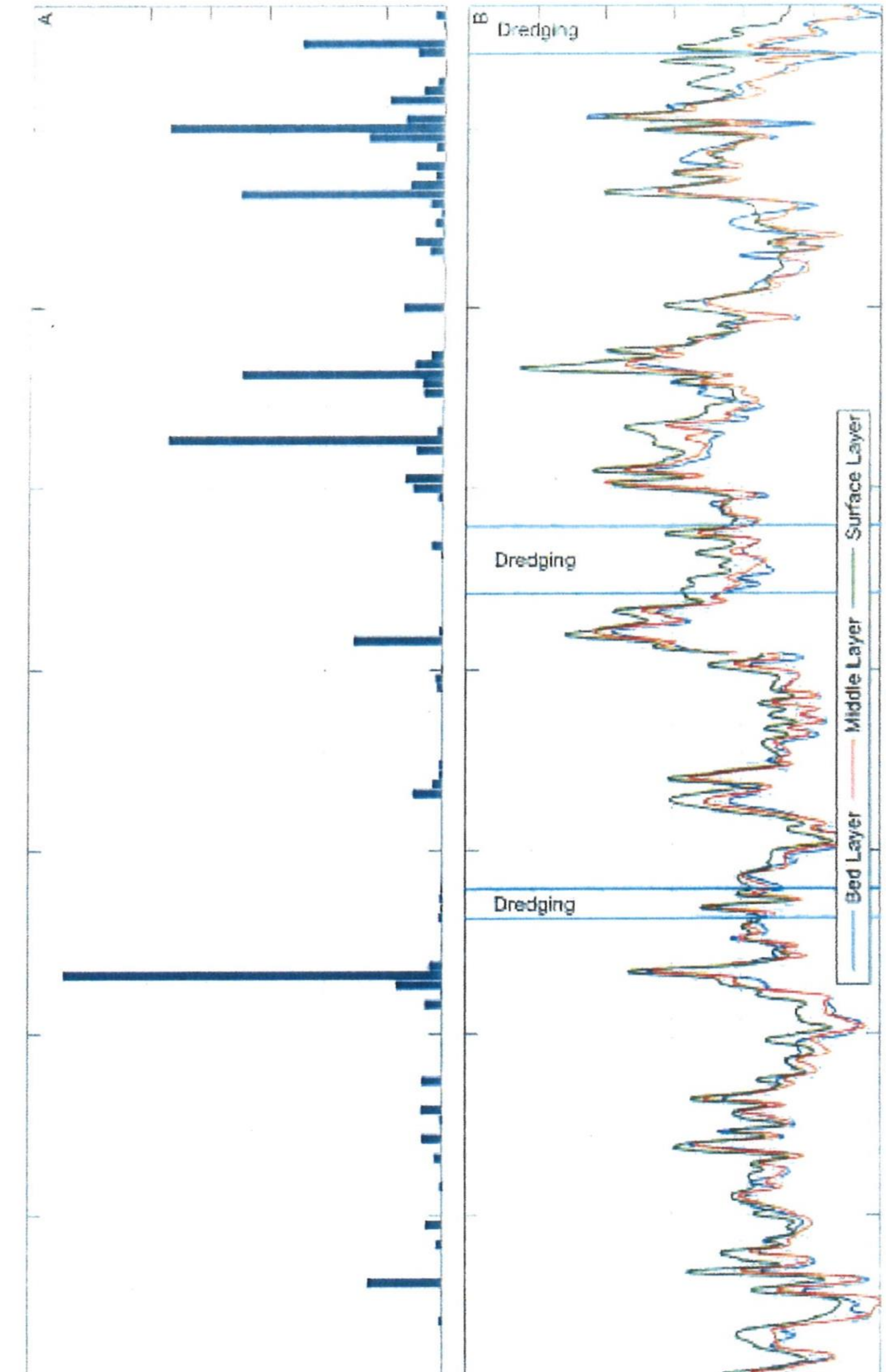

A
B
Rainfall mm/day
Rel. Sus. Sed. Conc. dB
Dredging
Dredging
Dredging
Bed Layer
Middle Layer
Surface Layer
20-Mar
08-Apr
27-Apr
16-May
04-Jun
23-Jun
12-Jul
31-Jul-08

Figure No 7

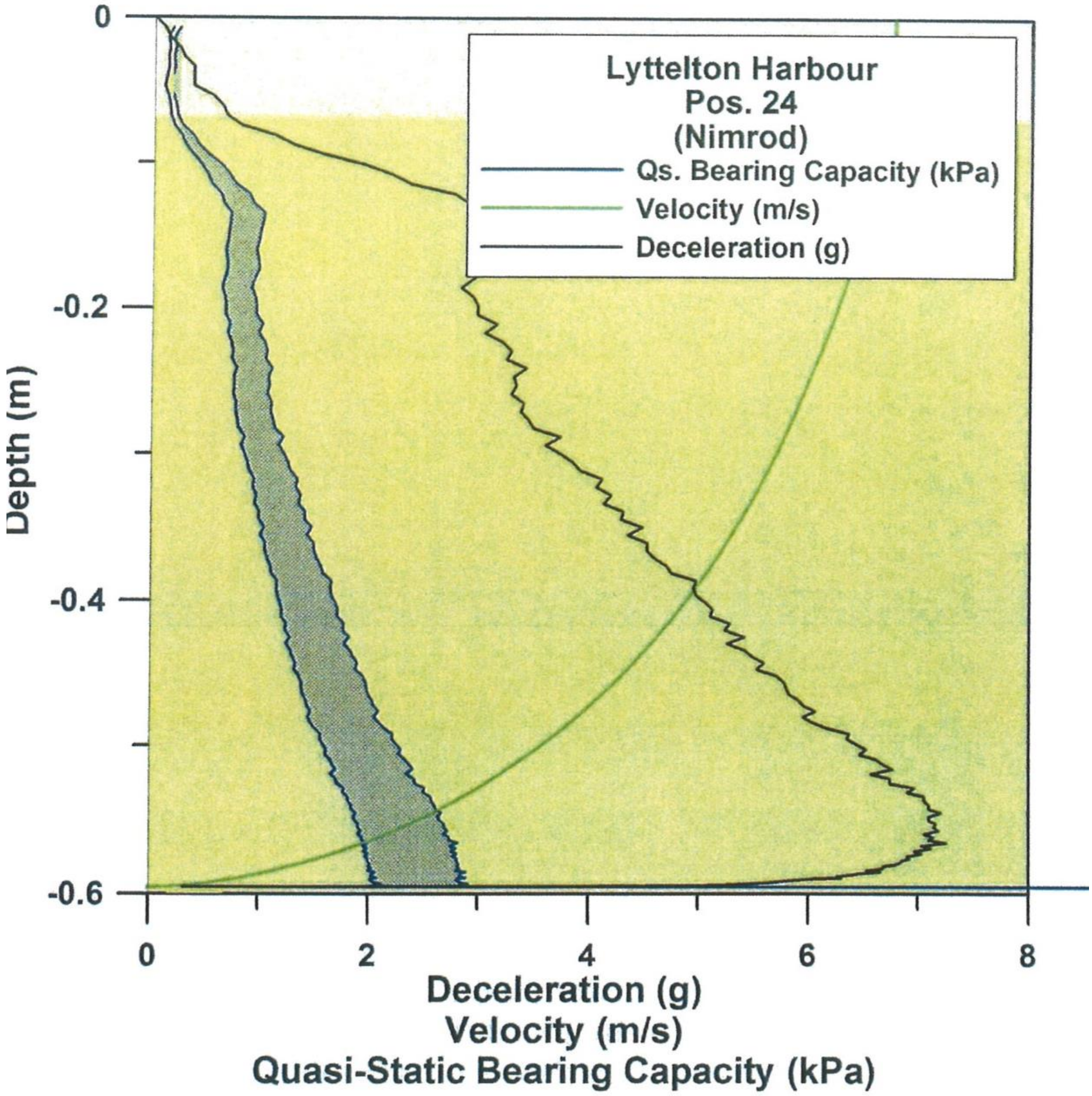

Lyttelton Harbour
Pos. 24
(Nimrod)
Qs. Bearing Capacity (kPa)
Velocity (m/s)
Deceleration (g)
Depth (m)
0
-0.2
-0.4
-0.6
0
2
4
6
8
Deceleration (g)
Velocity (m/s)
Quasi-Static Bearing Capacity (kPa)

Figure No 8

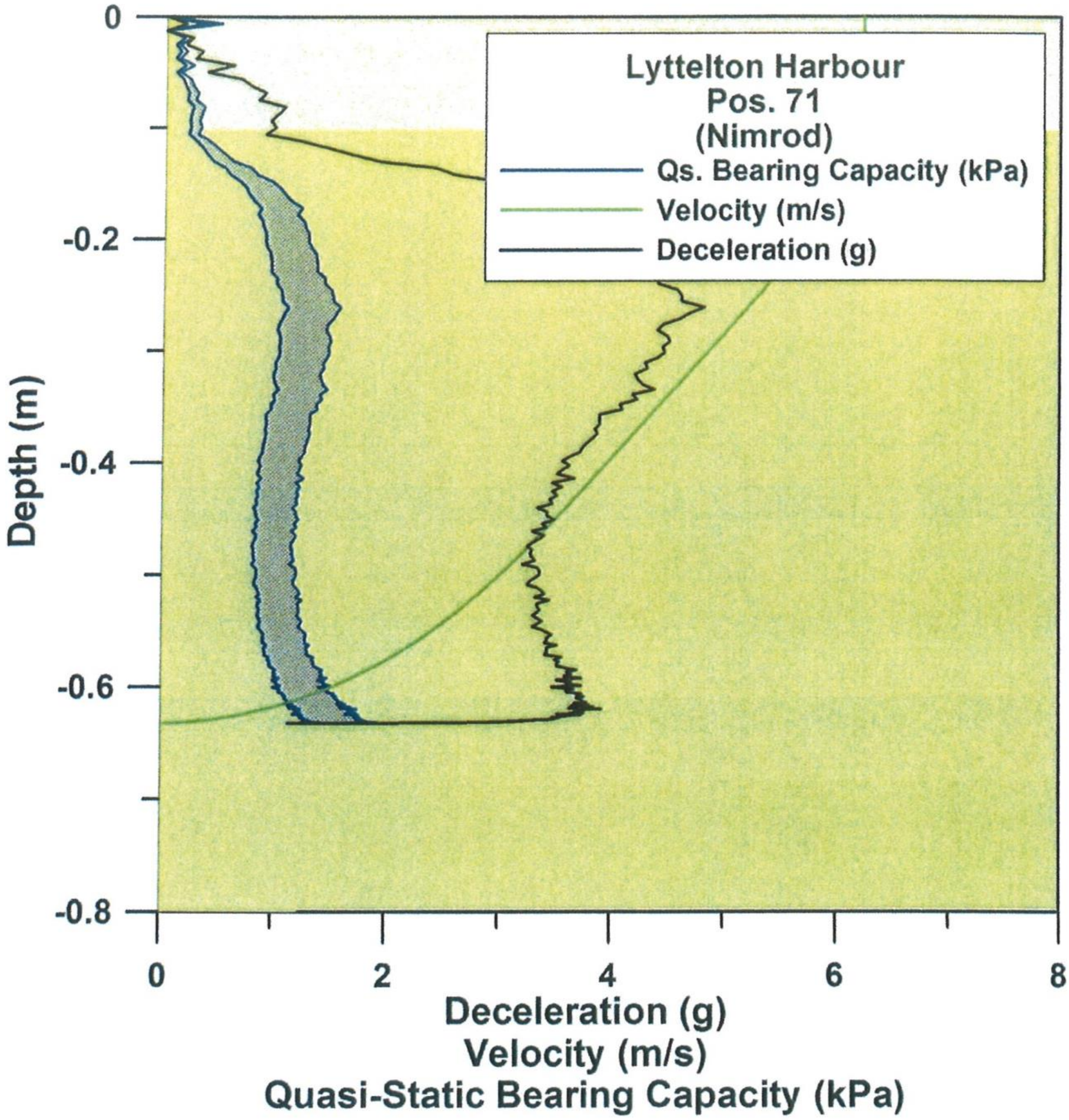
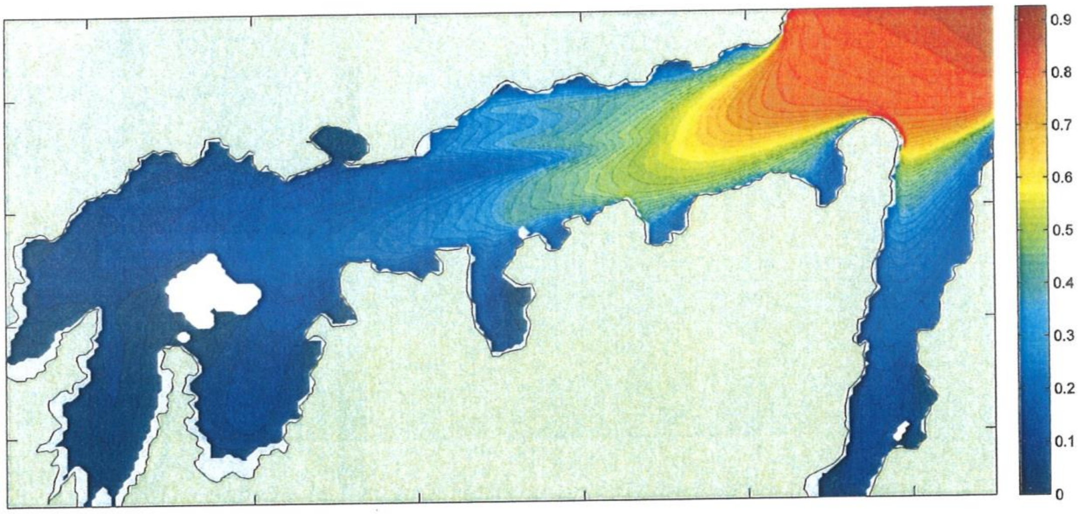
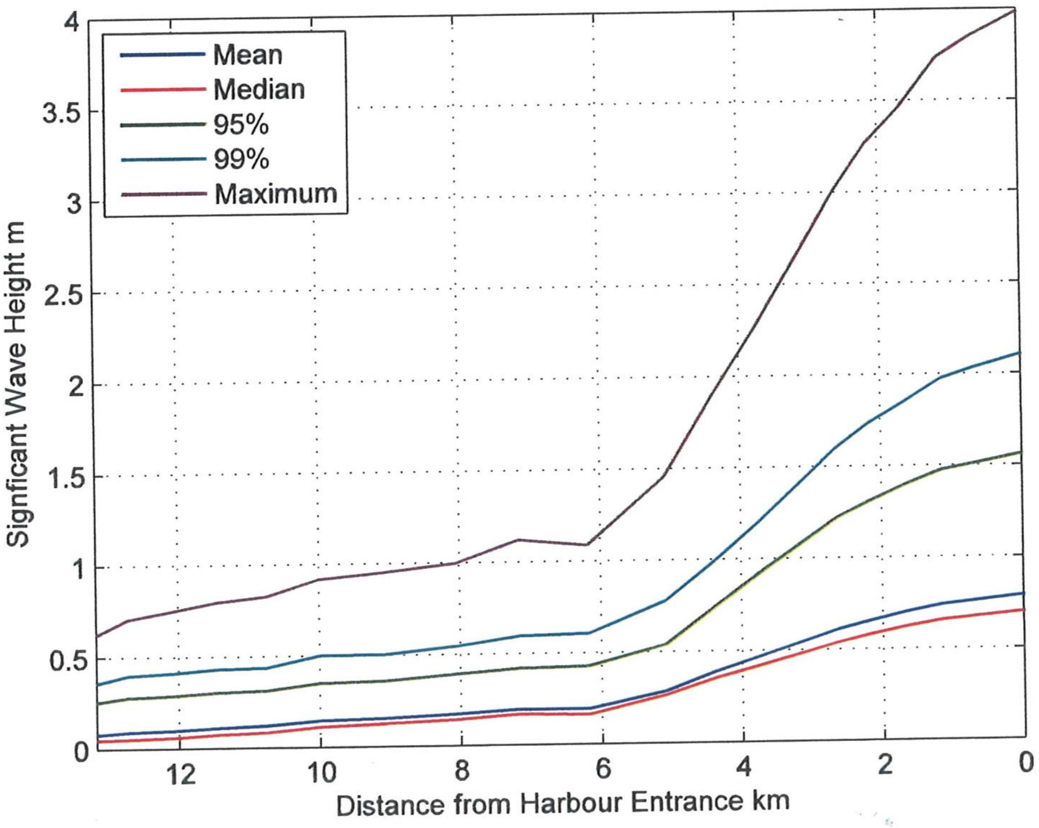

Lyttelton Harbour
Pos. 71
(Nimrod)
Qs. Bearing Capacity (kPa)
Velocity (m/s)
Deceleration (g)
Depth (m)
0
-0.2
-0.4
-0.6
-0.8
0
2
4
6
8
Deceleration (g)
Velocity (m/s)
Quasi-Static Bearing Capacity (kPa)

Figure No 9



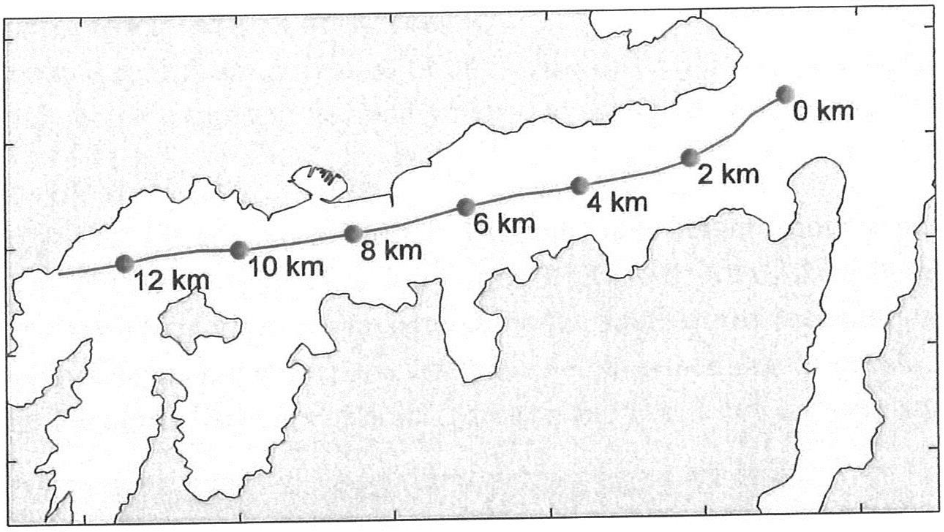
Distribution of mean significant wave height in Lyttelton Harbour and Port Levy

Figure No 10



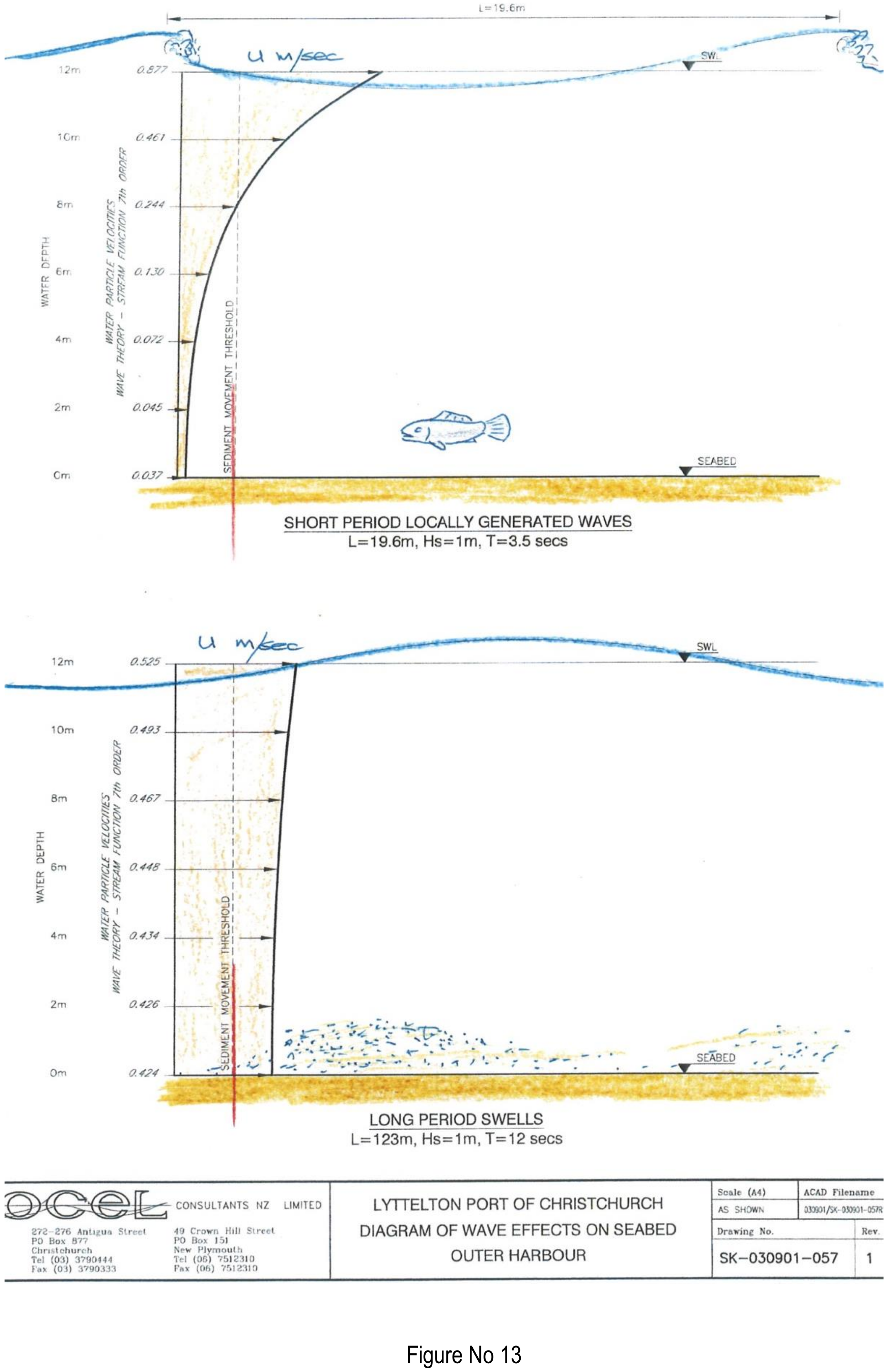
Dissipation in wave height up the harbour

Figure No 11



The thalweg in Lyttelton Harbour and distances from the entrance

Figure No 12



L=19.6m
u m/sec
SWL
12m
10m
8m
6m
4m
2m
0m
WATER DEPTH
WATER PARTICLE VELOCITIES
WAVE THEORY - STREAM FUNCTION 7th ORDER
0.877
0.461
0.244
0.130
0.072
0.045
0.037
SEDIMENT MOVEMENT THRESHOLD
SEABED
SHORT PERIOD LOCALLY GENERATED WAVES
L=19.6m, Hs=1m, T=3.5 secs
u m/sec
SWL
0.525
0.493
0.467
0.448
0.434
0.426
0.424
SEABED
LONG PERIOD SWELLS
L=123m, Hs=1m, T=12 secs
OCEL CONSULTANTS NZ LIMITED
272-276 Antigua Street
PO Box 877
Christchurch
Tel (03) 3790444
Fax (03) 3790333
49 Crown Hill Street
PO Box 151
New Plymouth
Tel (06) 7512310
Fax (06) 7512310
LYTTELTON PORT OF CHRISTCHURCH
DIAGRAM OF WAVE EFFECTS ON SEABED
OUTER HARBOUR
Scale (A4)
AS SHOWN
ACAD Filename
030901/SK-030901-057R
Drawing No.
SK-030901-057
Rev.
1

Figure No 13

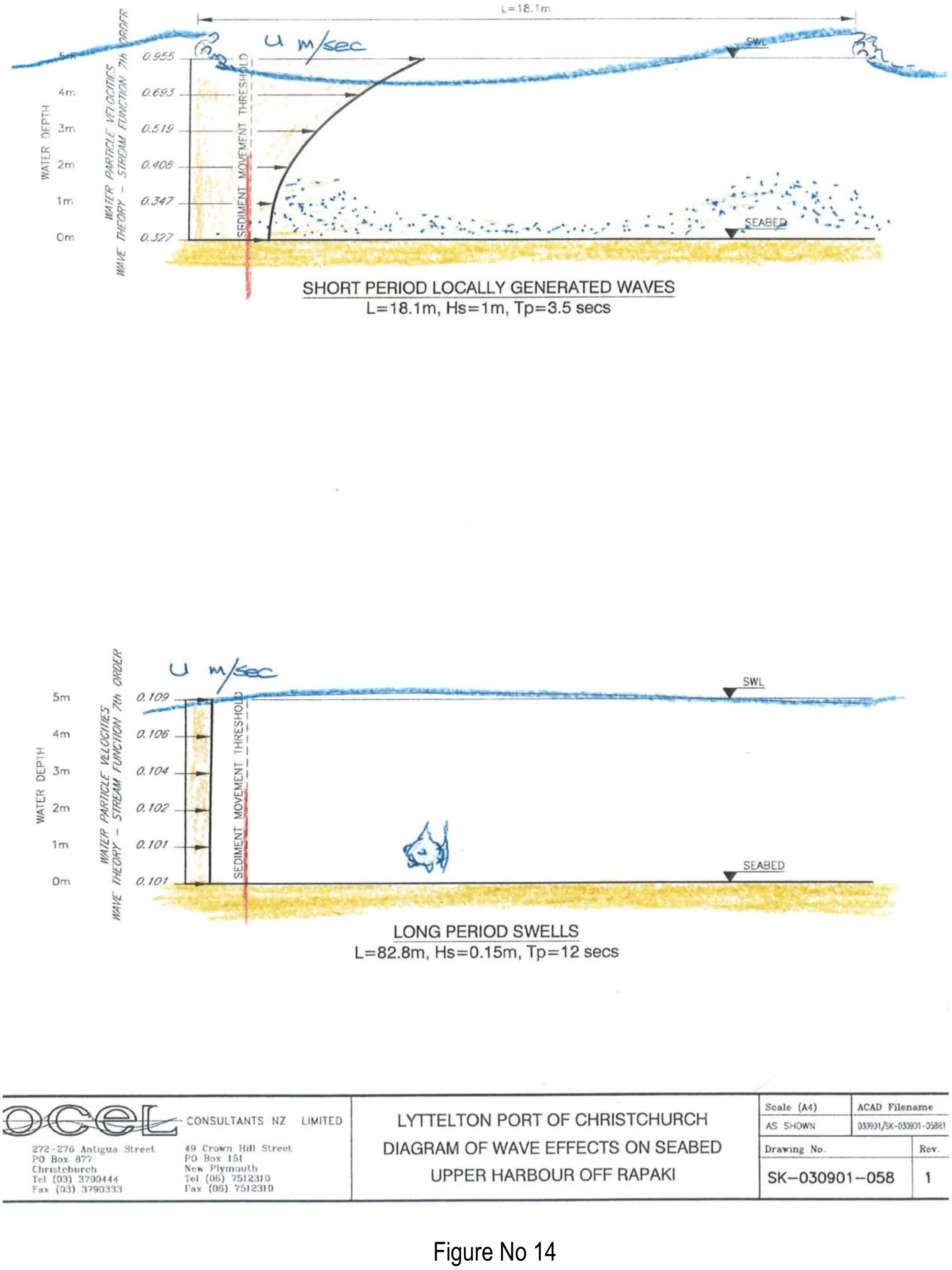

L=18.1m
u m/sec
SWL
SEABED
WATER DEPTH
5m
4m
3m
2m
1m
0m
WATER PARTICLE VELOCITIES
WAVE THEORY - STREAM FUNCTION 7th ORDER
0.955
0.693
0.519
0.408
0.347
0.327
SEDIMENT MOVEMENT THRESHOLD
SHORT PERIOD LOCALLY GENERATED WAVES
L=18.1m, Hs=1m, Tp=3.5 secs
u m/sec
SWL
SEABED
0.109
0.106
0.104
0.102
0.101
0.101
LONG PERIOD SWELLS
L=82.8m, Hs=0.15m, Tp=12 secs
OCEL CONSULTANTS NZ LIMITED
272-276 Antigua Street
PO Box 877
Christchurch
Tel (03) 3790444
Fax (03) 3790333
49 Crown Hill Street
PO Box 151
New Plymouth
Tel (06) 7512310
Fax (06) 7512310
LYTTELTON PORT OF CHRISTCHURCH
DIAGRAM OF WAVE EFFECTS ON SEABED
UPPER HARBOUR OFF RAPAKI
Scale (A4)
AS SHOWN
ACAD Filename
030901/SK-030901-058R1
Drawing No.
SK-030901-058
Rev.
1

Figure No 14


Te Awaparahi
Lyttelton
South Island
Diamond Harbour
Corsair Bay
Cass Bay
Rapaki
Taukahara
Governors Bay
Ohinetahi
Godley Quay
Church Gully Rd
Main Rd

Figure No 15

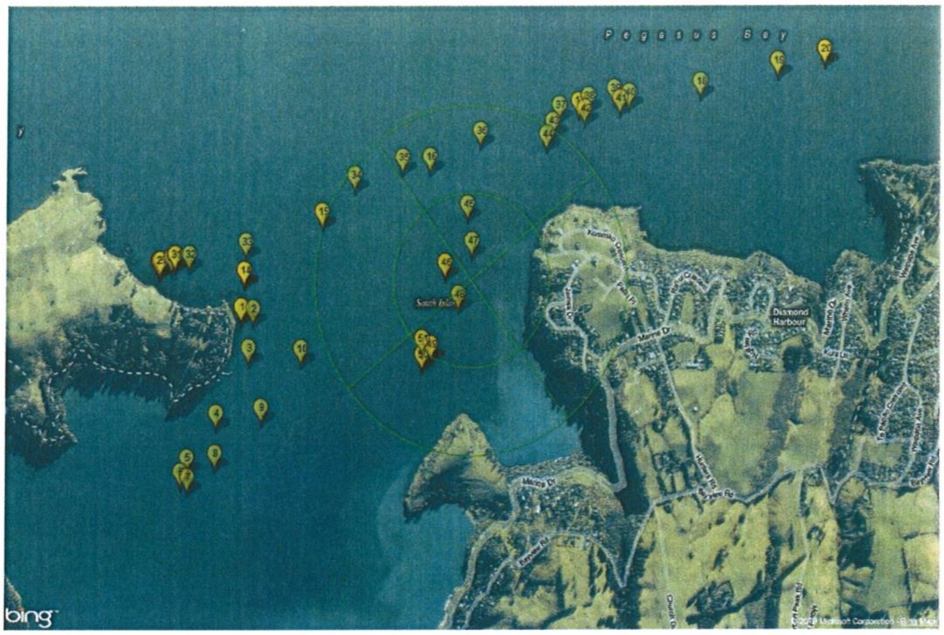
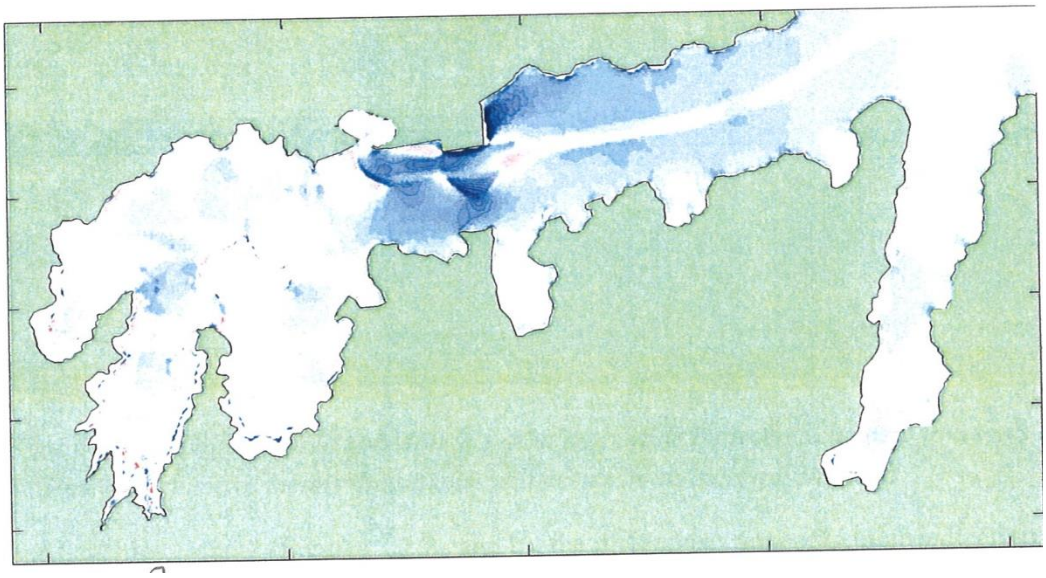
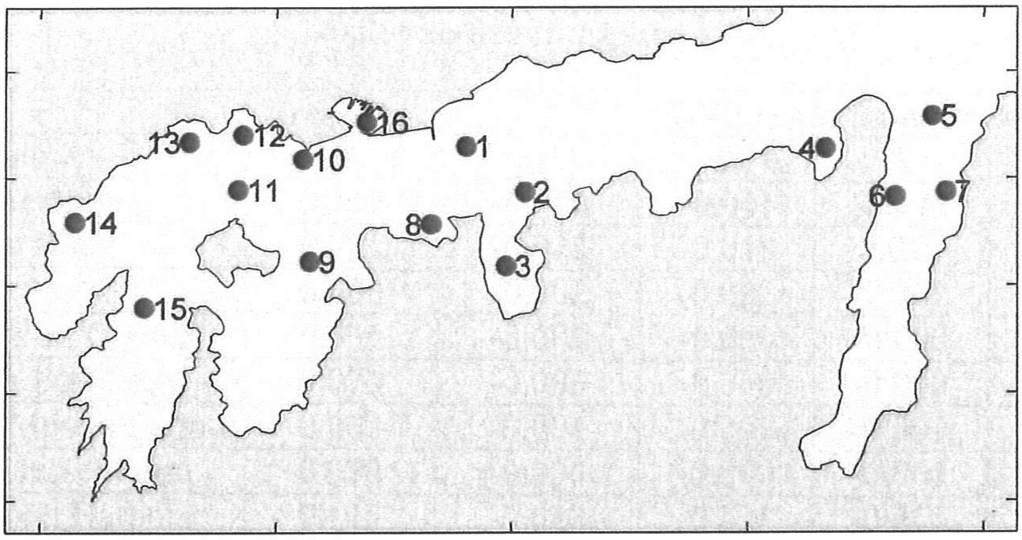


Figure No 16



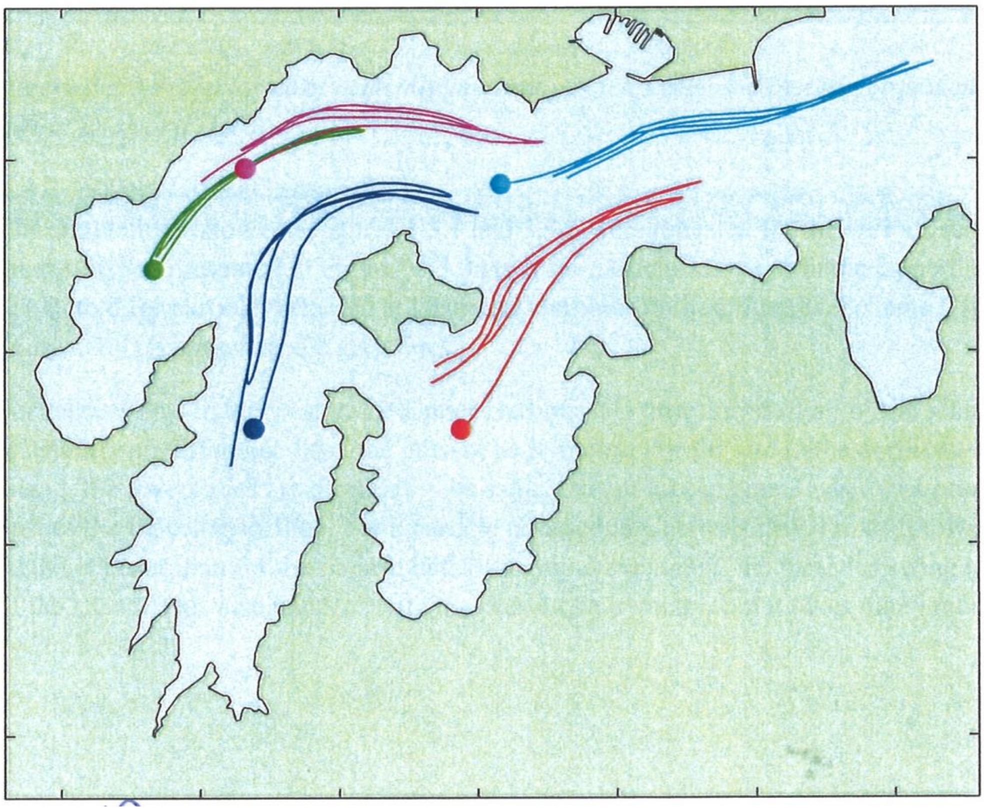
Difference in speed in m/s at mid-ebb tide between Scenario 0 (present) and Scenario 2
– positive means the scenario will result in an increase in speed

Figure No 17



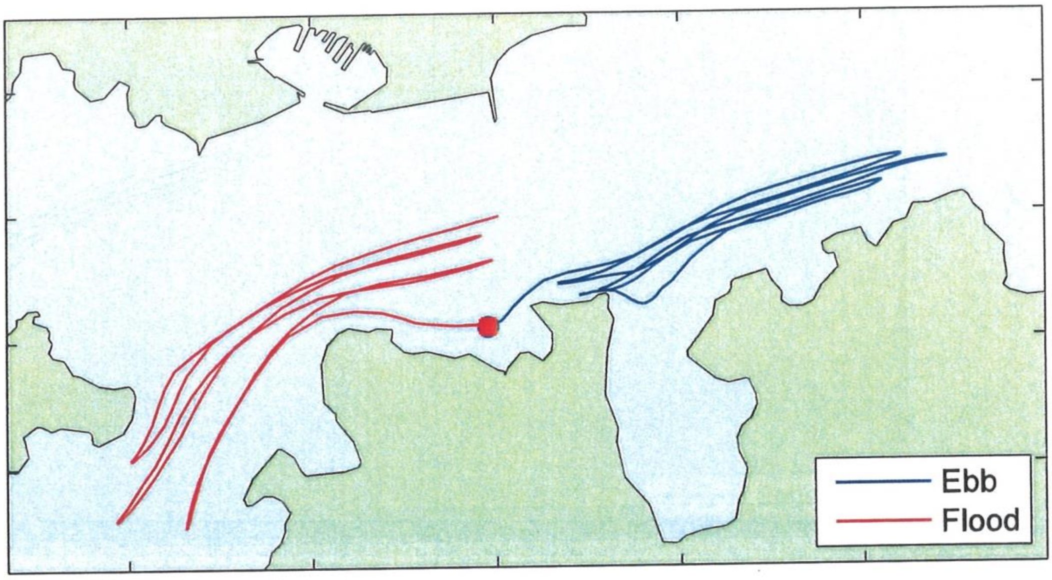
Location of sites for detailed examination

Figure No 18



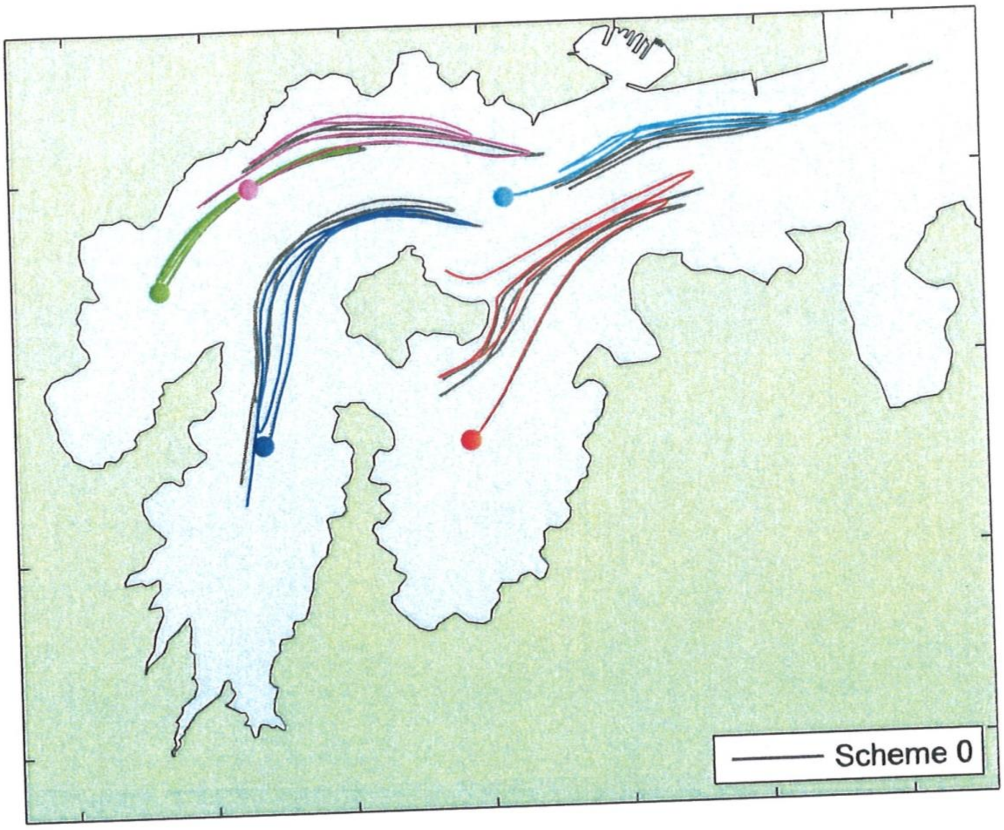
Trajectories of neutrally-buoyant particles released in the Upper Harbour for the present scenario.
The blobs are at the point of release

Figure No 19

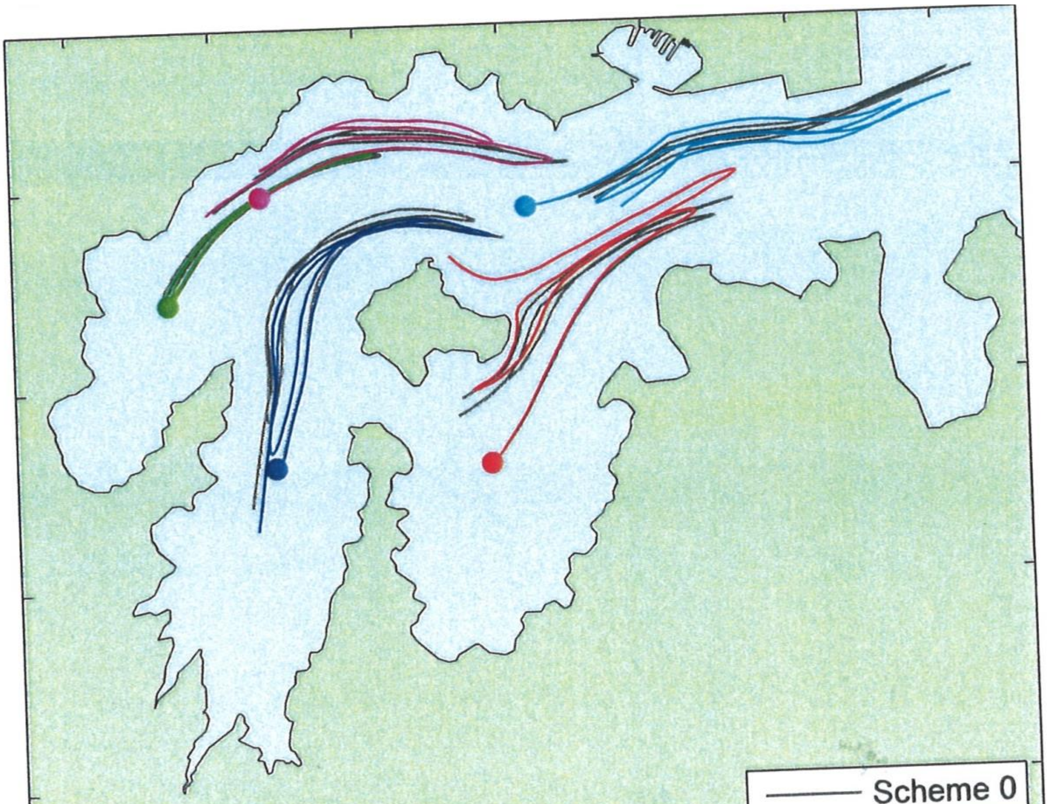


Trajectories of neutrally buoyant particles released at mid-ebb and mid-flood tide at Diamond Harbour

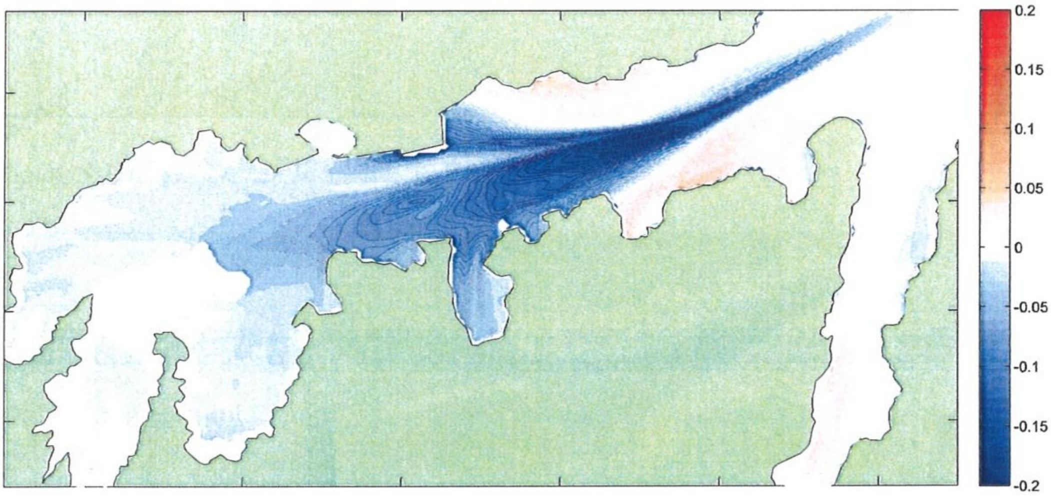
Figure No 20



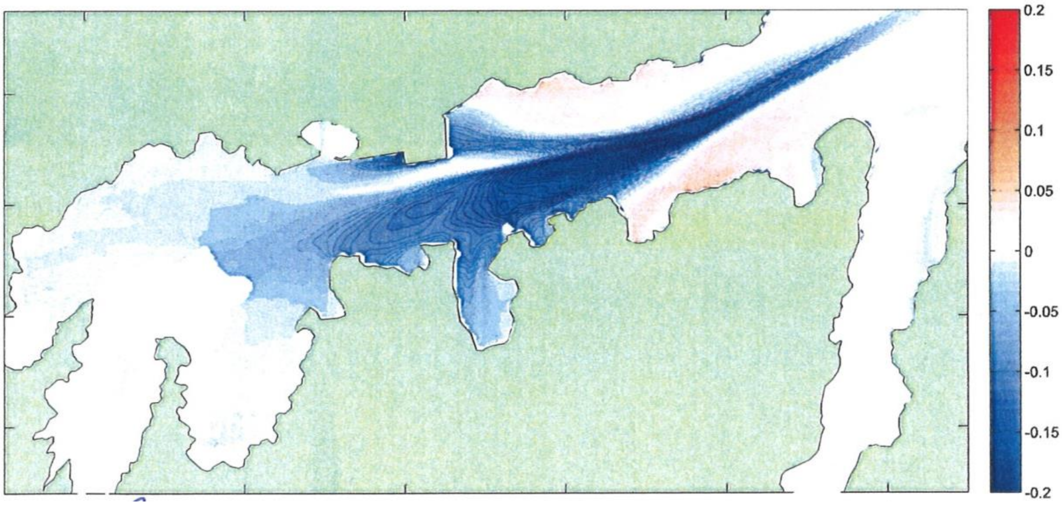
Trajectories of neutrally buoyant particles for Scenario 1



Trajectories of neutrally buoyant particles for Scenario 2
Figure No 21

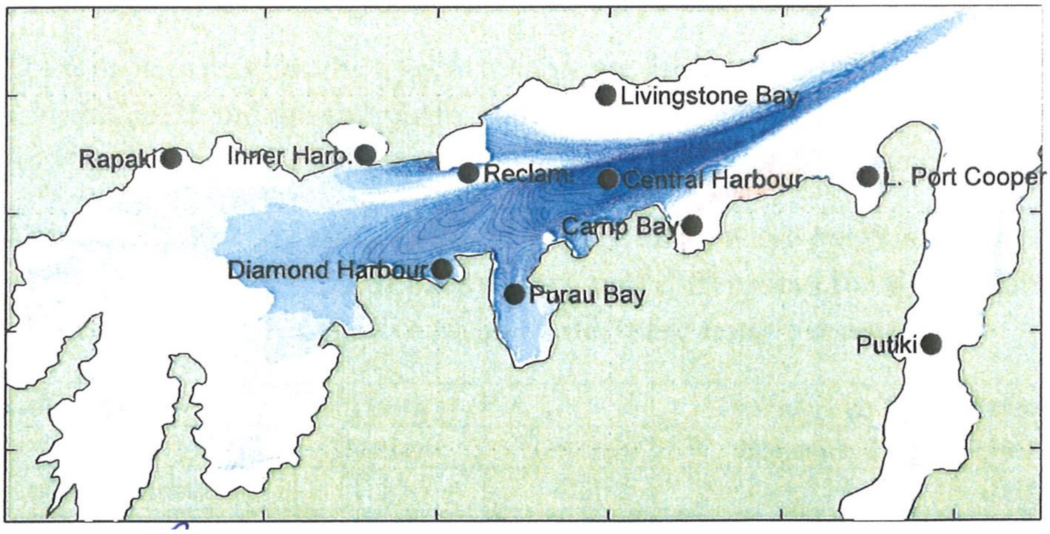


Difference in mean wave height for Scenario 1



Difference in mean wave height for Scenario 2

Figure No 22



Locations for points where statistics have been extracted (Table 5)

Figure No 23